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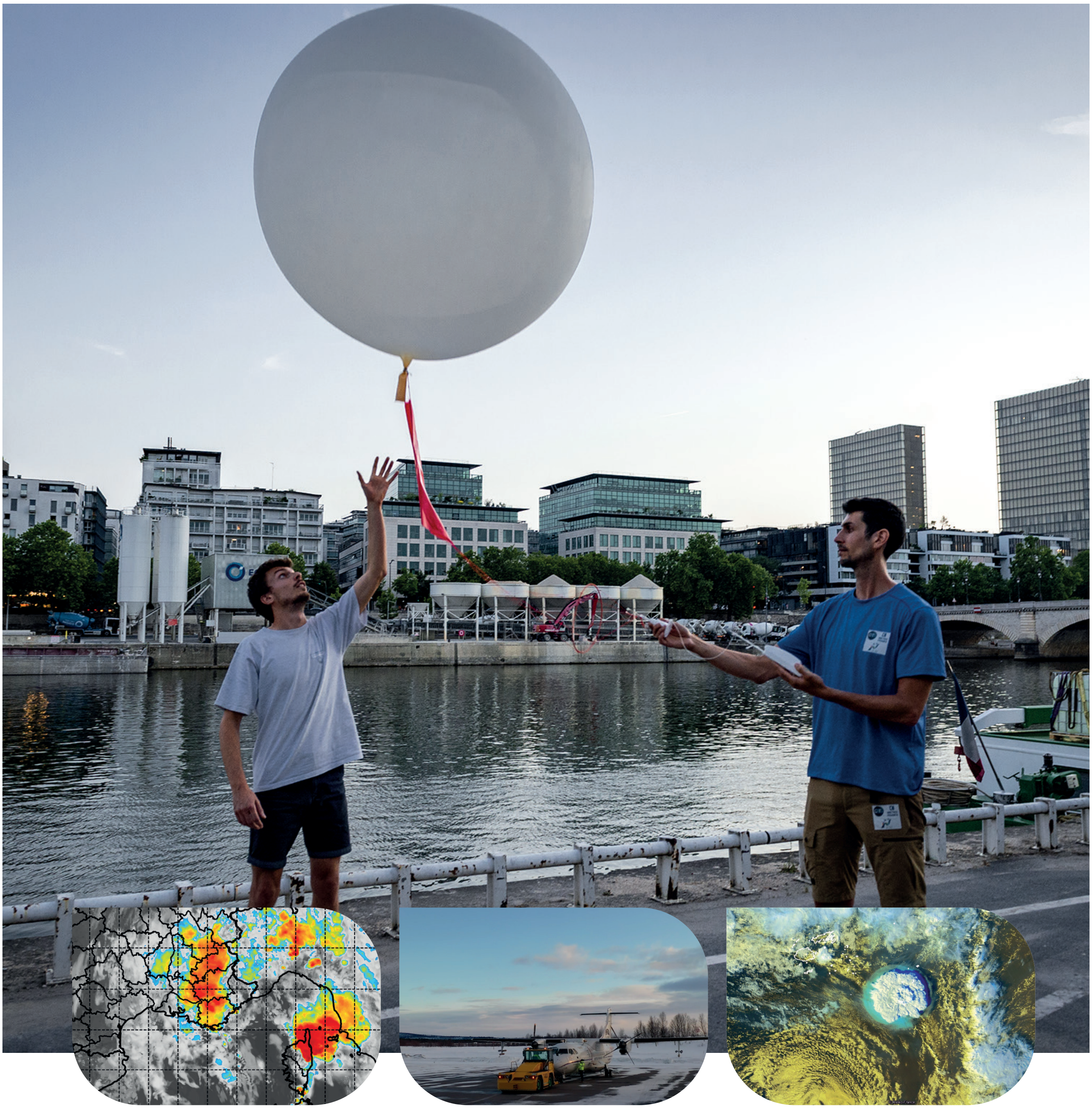

# Research **Report** 2022

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The year 2022 marks the start of the new Contract of Objectives and Performance (COP) with the French Govenment for the period 2022 to 2026. It has been built in line with the Scientific Strategy 2020-2030. Research occupies a privileged place in the contract, as it supports all of the Establishment missions. It is the source of the progress that is then implemented in terms of observation, modeling, numerical weather forecasting and climate studies. It enables the Establishment to constantly improve the quality of its operational products and services and to open new areas of activity to meet the expectations of society and public authorities.

The research entities of Météo-France are involved in many national and international research projects, particularly in Europe. Météo-France is leading, with 26 European partners, the DE330 project "Destination Earth On Demand Extremes" in response to a call for tenders from the European Centre for Medium-Range Weather Forecasts (ECMWF) under the auspices of the European Commission. It is a structuring project for the evolution of the AROME model, in close collaboration with the ACCORD consortium coordinated by a scientist from Météo-France. One of the challenges of these initiatives, and which is in line with a major concern of Météo-France shared with the ECMWF, is the adaptation of numerical forecast codes to hybrid-accelerated computing architectures.

At the national level, after the success in 2021 of the OneWater Exploratory Program and Priority Research Facilities (PEPR) focused on the challenges of Water, a common good, three new successes have been obtained in 2022: TRACCS on climate modeling and climate services (TRACCS) co-piloted by Météo-France and CNRS; IRIMA on the study of risks; BRIDGES on the study of the Indian Ocean. These programs will structure the scientific communities concerned for the next decade. Another element initiated in 2022 is the preparation of the regrouping of the SAFIRE research infrastructure and the "CNES balloons" and the inclusion of future large-scale scientific drones, in a distributed national infrastructure whose name has already been found: IN-AIR for Infrastructure Nationale des Aéronefs Instrumentés pour la Recherche.

The year 2022 was marked by the PANAME campaign in Paris within the framework of the RDP (Research Demonstration Project of the WMO) Paris Olympics 2024 and the associated projects (in particular ANR H2C on the impact of the urban heat island on health, ANR and LEFE ACROSS on urban pollution and its transport). Significant instrumental means have been deployed: ground stations, remote sensing instruments, instrumented masts and aircraft flights. One of the objectives is to progress on the development of the 500m version of AROME which will become operational in 2024.

In the summer of 2022, an important milestone was reached with the operational implementation of the new numerical weather prediction chain, which includes the operational

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exploitation of many scientific advances from previous research, and major elements expected with the installation of the latest supercomputers. In particular, the resolutions of global and regional deterministic forecasts have converged to those of "deterministic" forecasts. Also, the regional forecasts on the ultra-marine domains now have the same resolution as in metropolitan France (1.3 km). And at the very end of the year, these same overseas territories were provided with overall forecasts already highly appreciated by the operational services concerned.

In Toulouse, Météo-France is part of the local dynamic around the PIA4 project "Excellence in all its forms" TIRIS (Toulouse Initiative for Research's Impact on Society) of the University of Toulouse. The success of TIRIS will be decisive for the structuring and dynamics of higher education and research in Toulouse, a project in which Météo-France participates through the head of the DESR, the CNRM and the ENM.

This research report 2022 presents a great density and variety of results. It includes work on data assimilation, whose new algorithms will optimize the quantity of assimilated observations, and in particular those provided by the latest generation of European geostationary satellites, starting with MTG-I1 put in orbite in December 2022. There are descriptions of work on the processes involved in the fog, clouds, boundary layers, ..., original climatic work including the increase in temperature, especially for the mainland. Also It is presented the exploitation of various artificial intelligence algorithms in connection with our models and data, either in post-processing of our weather forecasts or in support of our climate downscaling activities. Finally, it is about measurement campaigns enriching our knowledge of the Earth system, innovation and instrumental synergy, ..., impossible to summarize in a few words all the richness of the articles proposed for your reading.

Let us also mention that the year 2022 saw the celebration of the 100th anniversary of the Ecole Nationale de la Météorologie (ENM) and the 40th anniversary of the Centre National de Recherches Météorologiques (CNRM) during a festive symposium organized on October 17 and 18 on the campus of Météo-France in Toulouse. These days were an opportunity to celebrate several decades of scientific progress in the field of understanding, modeling, weather forecasting and the study of past and future climate change. They brought together several generations of students and research and teaching staff mobilized for these activities.

Perhaps a last word to project ourselves in 2023. Some articles, at the end of 2022, exposed how "machine learning" of ECMWF reanalyses allowed to produce weather forecasts, competing with ECMWF forecasts, based on the numerical and explicit resolution of the physical equations of the atmosphere... what to encourage us to an ever greater appropriation of these methods of artificial intelligence which continue to open new perspectives.

Have a good reading.

Marc Pontaud
Director of Higher Education and Research

# The PANAME 2022 campaign

The PANAME[1] 2022 experimental campaign took place in the Paris region in the summer of 2022, in order to better understand the processes governing the influence of the city on the atmosphere, such as urban heat islands or air quality. Numerous research laboratories have contributed to this experimental initiative through various projects. Three periods of heat wave affected the Paris region in the summer of 2022, mid-June (the earliest ever recorded) which corresponded to the very beginning of the campaign and aircraft flights, mid-July and early August.

The CNRM[2] has been a major actor of PANAME 2022, involved in 4 of the flagship projects of the campaign: Heat and Health in Cities (H2C, on the links between heat and health), Pairs 2024 RDP (on weather modeling in cities), ACROSS (aerosol transformation in pollution plumes downstream of Paris) and MOSAI (surface-atmosphere exchanges in heterogeneous areas).

The CNRM has deployed numerous instruments. Meteorological stations have been placed on lamp posts to observe the variability of the urban heat island between different districts and to observe the effect of parks, large squares and boulevards or the Seine. The CNRM and the Observations Department of Météo-France have deployed radiosonde balloons in Trappes and, exceptionally, from Paris intra-muros and remote sensing systems from roofs. Combined with balloons and similar instruments deployed by other laboratories, in particular the IPSL, this allows to observe the effect of the city on the atmosphere, in particular the vertical extension of the heat island and the cool islands. The SAFIRE[3] research aircraft explored the lower layers in the plume of pollutants downwind of Paris up to more than 100km from the capital.

Finally, numerical simulations of weather forecasting over the whole summer at 500m horizontal resolution with the AROME model and at 100m with the MesoNH model will allow both to prefigure future operational forecasting systems and to analyze the processes involved via a combined observation-model approach. Complementary observations will also be carried out in 2023 to continue these studies.

To learn more about PANAME 2022 as a whole, see the complete dossier put online by INSU:
Paname : L'atmosphère et le climat de Paris à la loupe, https://www.insu.cnrs.fr/fr/Paname
and
Paname 2022 : premières observations d'une campagne de mesure inédite sur le climat et la qualité de l'air de Paris, https://www.insu.cnrs.fr/fr/cnrsinfo/paname-2022-premieres-observations-dune-campagne-de-mesure-inedite-en-plein-paris-et-en

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*1. PAris region urbaN Atmospheric obser-vations and models for Multidisciplinary rEsearch : Observations atmosphériques de la région parisienne et modèles pour une recherche multidisciplinaire*
*2. Centre national de recherches météorologiques*
*3. Service des Avions Français Instrumentés pour la Recherche en Environnement – UAR 2859 Météo-France, CNRS, Cnes.*

## Experimental deployment to study the horizontal variability and vertical extension of the urban heat island

V. Masson, A. Lemonsu

The existence of the heat island phenomenon in the city is well known. However, although its maximum intensity between an agglomeration and the countryside has been the subject of many studies, its variability at the sub-urban scale from one neighbourhood to another is poorly quantified. Moreover, the vertical extension of the urban influence on the atmosphere, a key phenomenon especially at night, is very little detailed. This is important because it determines the thickness of the heat emitted by the surface and thus the local intensity of the urban heat island.

As part of the PANAME 2022 campaign, the CNRM has installed the CNRM has installed connected weather stations on street lights in the central boroughs of Paris to observe the horizontal variability of the urban heat island within relatively homogeneous Haussmannian neighbourhoods, to detail the effect of squares, boulevards, urban parks, and the river Seine. Others, located in the 13th district, which is much more heterogeneous, allow us to observe and compare the effect of different urban forms, from town houses to skyscrapers.

Weather balloons were also launched from the centre of Paris during periods conducive to the urban heat island to observe its vertical structure. Comparison with the Trappes soundings showed that the urban influence could reach 200m altitude at night. As for the mini-balloons operated from Vincennes Park by the PANAME partners, they allowed to quantify a refreshing effect of the park up to 100m height. In order to observe more closely the effect of parks of different sizes, it is planned in the summer of 2023 to also use in-situ stations and drones

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## Heterogeneity of the surface energy budget

Guylaine Canut

The MOSAI (Model and Observation for Surface-Atmosphere Interactions) project aims to contribute to the detailed quantification and reduction of model biases on surface fluxes. This project coordinated by LAERO has been funded by the ANR for a period of 4 years (2021-2025) and includes the 3 surface energy balance stations of the IR ACTRIS-FR and four stations of the IR ICOS-FR. The experimental setup consists in deploying 3 or 4 stations over a period of one year around the long-term sites in order to document the representativeness of local measurements in a heterogeneous landscape, at the scale of the grid cell ranging from a few hundred meters to several kilometers. In order to reconcile the objectives of the PANAME and MOSAI projects, the instrumental deployment for the year 2022 has been focused on the SIRTA site (Palaiseau, Paris region). The GMEI/4M team of CNRM has deployed 2 surface energy budget stations, one in a clover field a few hundred meters from SIRTA and a second on the site of Polytechnique on a 30m mast as shown in Figure 2 (left). The station was operational between January 15 and November 15 2022. The LAERO also deployed an additional station on the roof of the LMD at the Polytechnique site during the same period. In the context of MOSAI, ICOS data from the Grignon (INRAE agricultural) and Barbeau (INRAE forest) stations will be integrated into the project database available at: https://mosai.aeris-data.fr/. Within the framework of the project, a homogenized data processing of the turbulent fluxes is operated. The exploitation of this dataset is in progress via an ongoing PhD thesis in collaboration between LAERO and CNRM in order to establish an index to determine the uncertainty and representativeness of surface-atmosphere exchanges measured on heterogeneous landscapes. More widely, within the framework of the PANAME project, these measurements will complement the data sets of surface energy stations implemented by other institutes in more urban sites, which will allow to study the strong contrasts between city and periphery in urban heat island conditions.

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Launching of a weather balloon to observe the vertical structure of the urban heat island from the Bercy quays (photo credit: Cyril Frésillon, CNRS).

2

Surface Energy Budget station (left) on a 30m mast on the Polytechnique site, (right) in the middle of an agricultural field on the Saclay plateau.

# ACROSS-AO: airborne research at the heart of PANAME

Jean-Christophe Canonici, Cyrielle Denjean

Within the PANAME initiative, the ACROSS-AO[1] project funded by the French National Research Agency aims to elucidate the details of the evolution of the properties of atmospheric pollutants during their transit within the Paris plume.
Safire has integrated into the ATR42 of Météo-France a heavy configuration gathering two tons of measurement means from French and international laboratories: LISA[2], UCP[3], JHU[4]. For nearly two years before the start of the flights, Safire's teams carried out the aeronautical certification of all the instruments, prepared them to work as well as possible, and also negotiated with the authorities for the many specific overflight authorizations required for the samples to be taken, depending, for example, on the wind direction.
From June 15 to July 7 2022, Safire sent the aircraft, all the specialists and the necessary equipment to Pontoise airport, near Paris. About 50 hours of flight time were used to produce an unprecedented inventory of gaseous and particulate chemical species from the Paris pollution. The contribution of the CNRM to the project is to study more specifically the physicochemical processes involved in the formation, evolution and radiation balance of aerosols.

*1. Atmospheric Chemistry of the Suburban Forest : chimie atmosphérique des forêts suburbaines.*
*2. Laboratoire Interuniversitaire des Systèmes Atmosphériques*
*3. Université de Chieti-Pescara*
*4. John Hopkins University*

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# Evaluation of hectometric simulations using PANAME datae

Jean Wurtz

Within the framework of PANAME2022, near-real-time simulations have been carried out using the future operational weather prediction model AROME-500m and the research weather model MESO-NH at 100m resolution over Paris and its closest suburbs from mid-June to the end of August 2022.
These simulations have shown, in particular with a spatial resolution of 100m, that it is possible to simulate within the city sharp heterogeneities of meteorological surface parameters.
The evaluation of these simulations at hectometric scales is very challenging. Indeed, thanks to their finer resolution, they should be more realistic and should allow to solve physical phenomena of finer scales. However, they must be evaluated carefully based on observations at the same spatial scales and on sufficiently long and representative samples.
PANAME2022 offers the opportunity to verify whether these simulated heterogeneities are realistic or not. Indeed, during the summer of 2022, 24 autonomous stations measuring temperature and humidity have been installed in Paris at judiciously chosen locations to sample these heterogeneities at the hectometric scale. Indeed, many parameters can strongly impact the local urban climate, such as the structure of the urban space, the height of buildings or the properties of materials.
The evaluation of these models on the vertical will also be possible with the help of numerous vertical profiles obtained in Paris and its region during PANAME2022.

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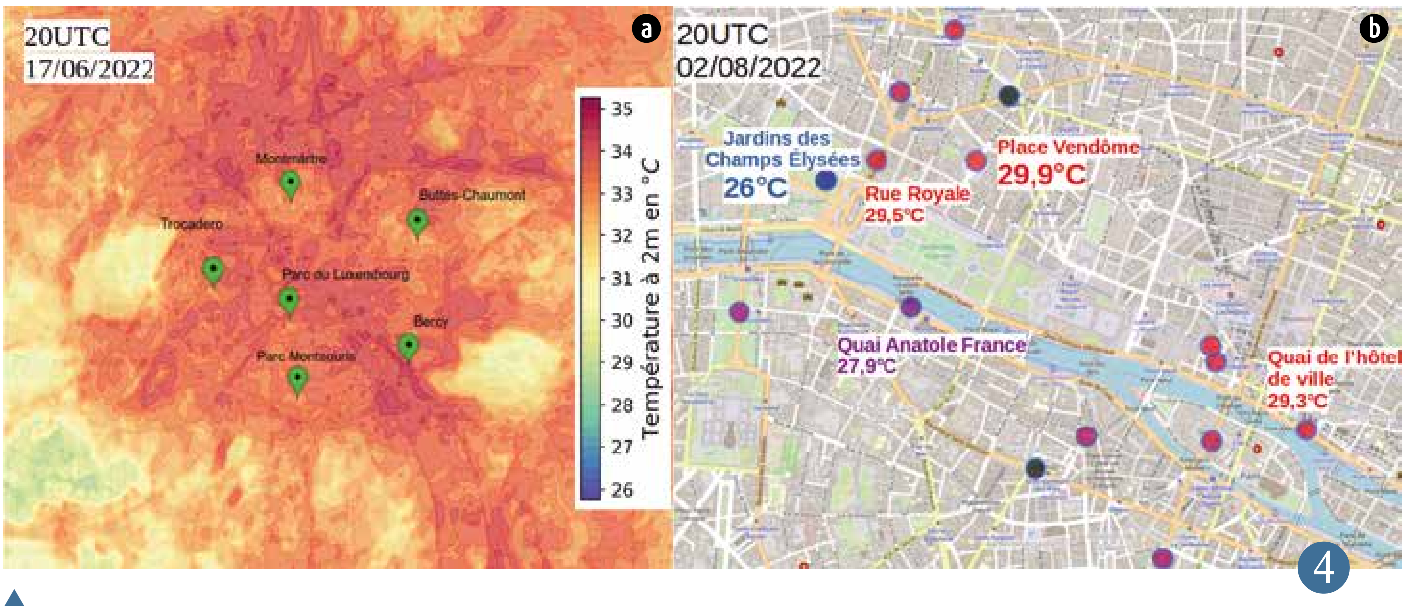
Main figure: Preparation of the SAFIRE ATR-42 research aircraft before take-off. Bottom left: Particle number concentration measured during a scientific flight. Bottom middle figure: Preparation of the instrumentation on board the aircraft. Bottom right: Calibration of the HTDMA-SP2 newly developed by CNRM.

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2 meters temperature simulated by MESO-NH at 100m over Paris and its inner suburbs on 17/06/2022 at 20UTC (a) and 2 meters temperature measured in Paris by several autonomous stations on 02/08/2022 at 20UTC (b).

# AROME-500m in real time during PANAME-2022

Rachel Honnert, Jean Wurtz

During PANAME2022, the NWP AROME model was operated on a 250km side domain centered on Paris with a horizontal resolution of 500m and 120 vertical levels. This configuration was coupled in dynamic adaptation to AROME-France (1.3km resolution and 90 levels). A real-time forecast was provided up to 36 hours from 00h from mid-June to early September 2022 for PANAME2022 campaign operations. To finely represent the surface, finer and more recent databases were used: SRTM30m for topography, Soilgrids for soils, ECOCLIMAP-SG for vegetation characteristics. In urban areas, OpenStreetMap data processed by the Geoclimate tool of the Lab- STICC made it possible to obtain precise data on land use (city, water, etc.) and on building characteristics (height, etc). Gardens were also modeled there. The first results are encouraging and show more surface heterogeneities and a more realistic boundary-layer structure than with AROME-France.

A posteriori, these simulations will make it possible to better understand the observations made during PANAME2022. This configuration provides a working basis for future operational implementations of AROME-500m, to help anticipate the urban heat island in Paris, but also to improve the representation of fog, cloud ceiling lowering, icing conditions for aeronautics as well as to better represent coastal circulations and thunderstorms.

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# The 'Heat and Health in Cities' project

Valéry Masson, Aude Lemonsu

The Heat and Health in Cities (H2C) project, coordinated by the CNRM and funded by the ANR, is studying the links between high heat, air quality and health in cities, with the Paris region as the study framework. The consortium includes meteorology and urban climatology laboratories, Airparif (for air quality), the CSTB (for conditions in buildings), Santé Publique France, the Paris-Region (urban planning) Institute and the Observatoire Régional de Santé. The project aims to develop a prototype system for predicting environmental conditions and exposure in cities, in relation to heat-related health risks; the final objective is to refine climate services to support prevention and public policies for urban planning.

Vulnerability is based on increased exposure to high temperatures, individual sensitivity, and adaptive capacities (individual or collective). The project studies these relationships at the communal level to better understand the factors of regional variability of vulnerability and associated health risks. An important challenge of the project is to better characterize sub-communal exposure, and thus to better predict fine-scale weather conditions, particularly in relation to urban influences.

The measurements carried out during PANAME allow the monitoring and understanding of urban climate variability, as well as the validation of numerical simulations at hectometric resolution. The measurements planned for 2023 will reinforce the current system to monitor thermal comfort conditions (depending on temperature, but also humidity, wind and radiation) in various neighborhoods.

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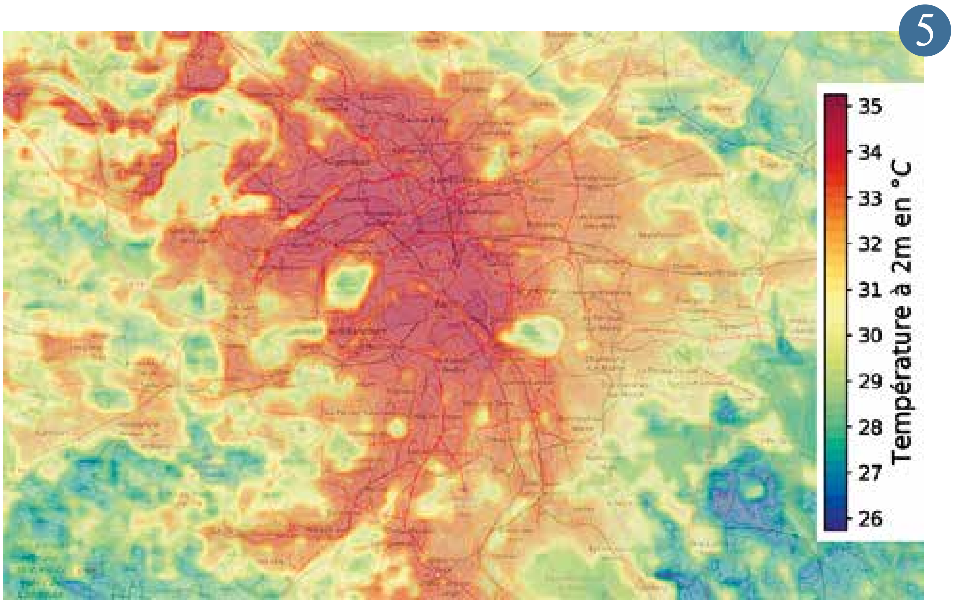


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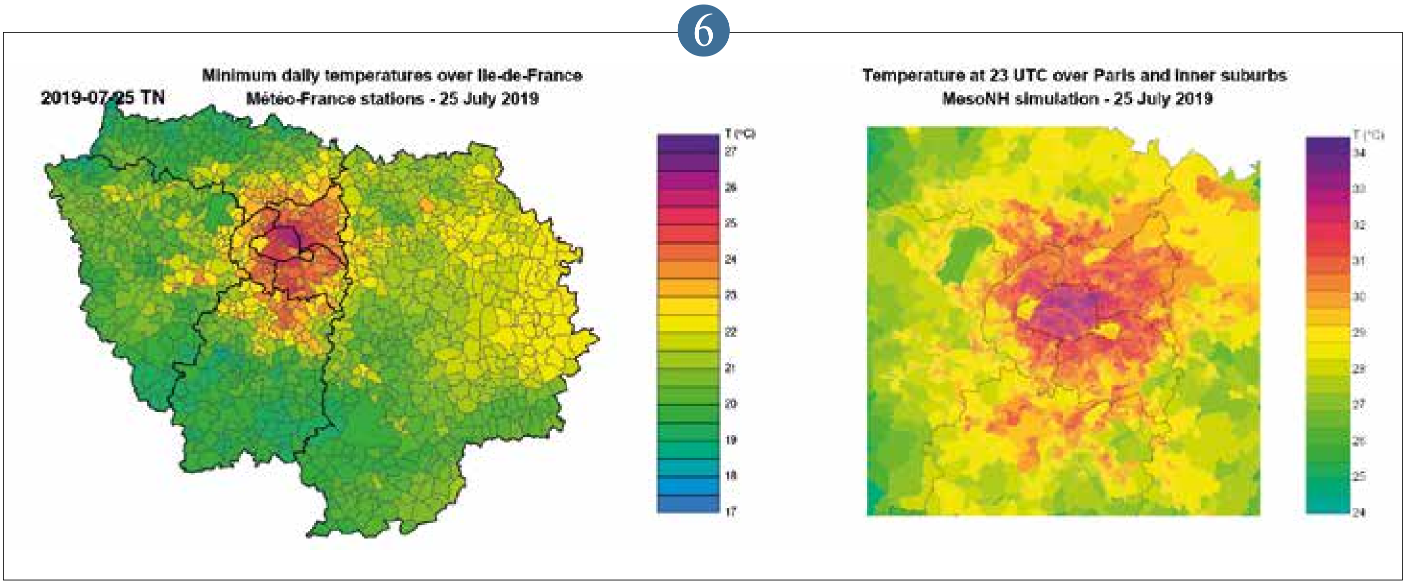
Simulated urban heat island in Paris region
by AROME-500m at 22h local time the 17/06/2022.

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Air temperature map at the scale of communes (and districts), scale that will be used for comparison with epidemiological data
(left: from temperature observations at the end of the night; right: from hectometric simulations of the MesoNH model at the time of the night heat island maximum)

# Fog

Fog strongly disrupts land, air and sea transport. But despite steady progress, its accurate prediction remains difficult due to its high spatio-temporal variability, and there is still much uncertainty about the interactions between the different mechanisms driving the variability of fog at very fine scales.

The exploitation of data collected during the winter of 2019-2020 in the Landes region of France as part of the SOFOG3D research program led by CNRM continued in 2022: the impact of surface heterogeneities was evaluated from the 17 measurement sites and this study showed a tendency for a slightly late formation in the forest, related to the shelter effect and braking that it generates. The synergy between remote sensing and in situ measurements, obtained by an innovative instrumentation under a tethered balloon, allowed to document the evolution of thermodynamic and microphysical profiles during the transition from fine to optically thick fog, which is a key step in the fog life cycle.

A new configuration of the AROME numerical weather prediction model dedicated to fog forecasting with 500 m horizontal resolution, 156 vertical levels and the 2-moment microphysical scheme called LIMA allows to improve the number of predicted fog cases and reduces the overestimation of thick fog often seen in the predictions of the current operational configuration. Finally, the assimilation in the 3D-VAR system of AROME-France (currently operational) of the temperature profiles provided by a network of 6 microwave radiometers is promising; the next step will be to assimilate in addition the humidity and liquid water content.

Data from past campaigns continue to be exploited: the analysis of a 100 m simulation with Meso-NH of a case observed in the North-East of France in 2016 has highlighted the key role of non-local large-scale but also fine-scale transport processes in the formation of fog by stratus lowering. Visibility measurements from Paris-CdG airport have also allowed to study the spatial variability at the kilometer scale, underlining the attention that must be paid to the representativeness of the measurements.

# Fog forecast improvements with a hectometric configuration of the AROME NWP model

Salomé Antoine, Rachel Honnert and Yann Seity

The aeronautical sector is strongly impacted by fog. In view of the issues at stake, the improvement of fog forecasts made by the AROME model has been identified as a priority work.

A new configuration of the AROME numerical weather prediction model has been built taking into account recent improvements adapted to fog forecasting: improved horizontal and vertical model resolutions, better representation of cloud droplets life cycle with a more advanced microphysical scheme (LIMA) and modeling the deposition process (capture of cloud water by vegetation).

Data collected during the SoFog3D field campaign were used to evaluate new AROME configuration forecasts (500L156, for a 500 m horizontal resolution and 156 vertical levels) and to estimate its added value compared with the operational model configuration (1250L90). The statistical study showed an increase in the number of fog cases predicted by 500L156 and more particularly in thin fogs (less than 50 m), which were underestimated by 1250L90 (figure). We could also observe a significant decrease in the number of thick fogs (more than 100 m), overestimated by 1250L90. Their decrease induces a decrease of the associated false alarms rate and would reduce the number of false alerts for airport authorities concerning low visibility procedures. The increase in the number of forecast fog cases is inevitably accompanied by an increase in the number of false alarms. However, as they mainly concern thin fogs, they are less problematic for aviation. Cloud droplet concentrations and liquid water contents were also closer to the observations in the new model configuration.

Even if the use of the LIMA microphysical scheme is not planned for the first version of the AROME-500m configuration, to be deployed operationally in 2024, the improvements brought by the scheme on fog prediction allow to consider its future implementation.

1

# Impact of surface heterogeneities on the fog life cycle during the SOFOG3D fog experiment

Marie Taufour

The SOFOG3D measurement campaign, which took place from November 2019 to March 2020 over the Landes region, sampled 34 fog cases over a selected area including 17 observation sites located in forests or crops, spread over a 70 x 20 km² area. The fine scale variability of fog is analyzed on all cases thanks to visibility and meteorological parameters measurements on these 17 sites, allowing to evaluate the impact of the vegetation cover on the fog life cycle.

The occurrence of fog at the 17 sites does not appear to be correlated with vegetation type. In contrast, when fog is observed, forest sites show a mean delay in the time of formation of up to two hours (Figure a). Conversely, variability at dissipation, which is lower than at formation, does not distinguish forest sites from others. Fogs in forests also tend to be shorter and less dense (mean visibility up to 250m higher) (Figure b). In terms of meteorological parameters, forest sites have on average lower near-surface temperatures, humidities and winds during the three hours preceding fog formation (Figures c-d-e), in contrast to slightly higher soil temperatures and humidities under forest cover.

Simulations at 100 m resolution are used in a second step to better understand the impact of surface heterogeneities observed on the fog life cycle.

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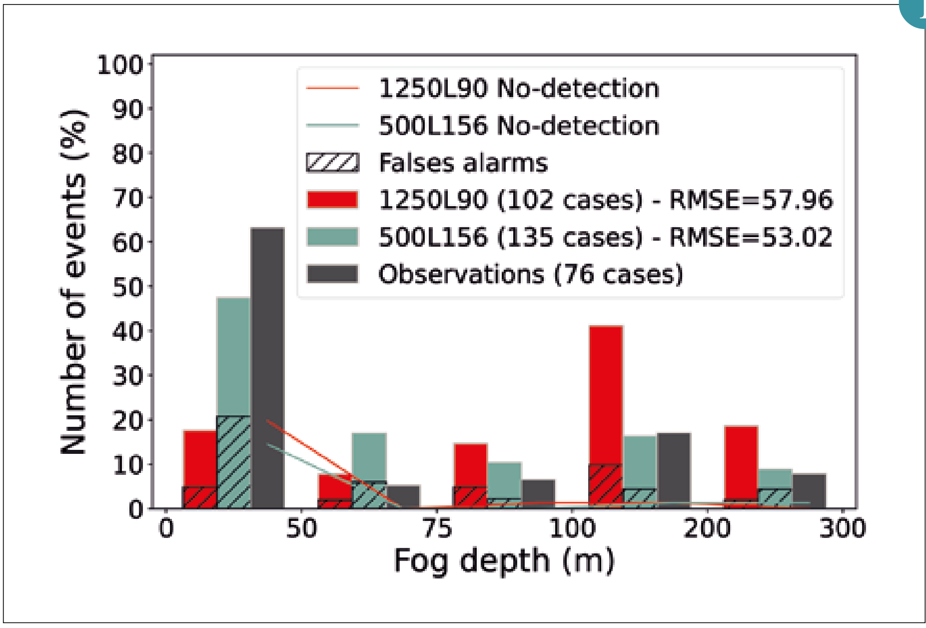


Mean fog top height distribution computed on Super-site and Agen site forecast by 1250L90 (red) and 500L156 (green) and estimated with the cloud radar observation (black).

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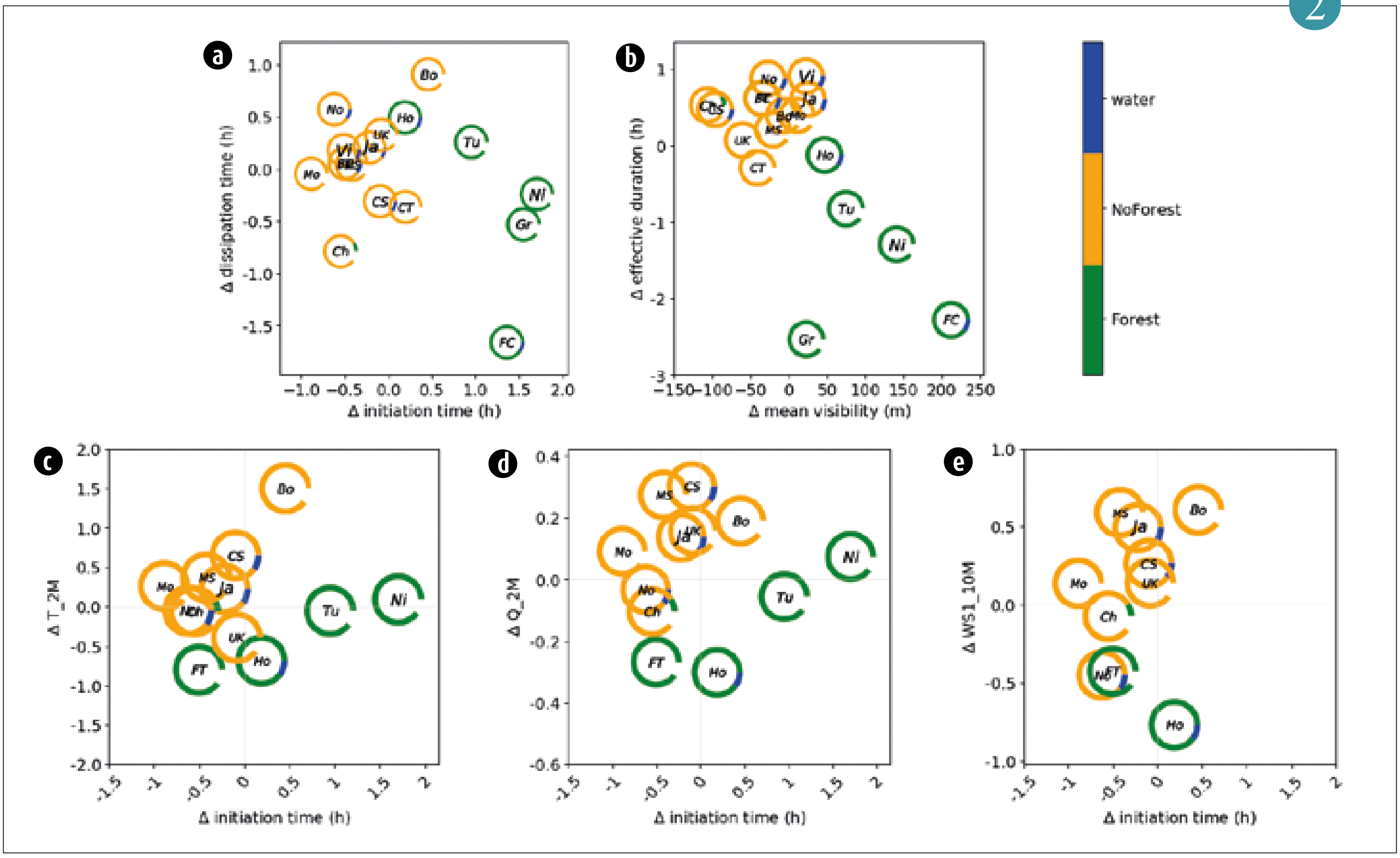


For the 34 fog cases at the 17 observation sites, marked by their first two letters, surrounded by a circle representing the cover type within a radius of 100 m around of the measurement point: average deviations from (a) the times of fog initiation and dissipation; (b) fog episode duration (period during which visibility is less than 1 km) and mean visibility during the fog; (c) mean temperature at 2m (T_2M in °C), (d) humidity at 2m (Q_2M in g/kg), and (e) wind speed at 10m (WS1_10M in m/s) over the three hours prior to fog initiation of the first formation site as a function of the mean deviation from the initiation time.

# Process study of a fog by stratus lowering during the Bure experimental campaign

Maroua Fathalli, Frédéric Burnet, Christine Lac

Numerical weather prediction models still have difficulties in correctly forecasting fog formed by stratus lowering. A numerical study was carried out to investigate the processes responsible for a fog event sampled in December 1-2, 2016 during an experimental campaign leaded by the CNRM in the North-East of France.

A Meso-NH simulation at 100 m resolution, with a 2-moment microphysical scheme where droplet concentration is a prognostic variable, reproduced the main observed features of the stratus life cycle leading to fog, despite the 4-hour delay in stratus formation due to large-scale conditions (figure 3a).

A budget analysis of the thermodynamical and microphysical variables on this case has shown that the advection of cloud water in the stratus and at its top is a major process driving the stratus lowering. This promotes the settling of droplets by generating cooling and moistening of the sub-cloud layer by evaporation (figure 3b). The other non-local process, which completes the stratus lowering until the fog formation, is the advection of cold air towards the base and under the stratus, induced by fine-scale orographic circulations and which confers a spatio-temporal variability to the occurrence of fog due to the hilly terrain.

Given the predominance of non-local processes on this case study, a 3D high resolution model seems mandatory to perform accurate forecast of fog by stratus lowering, unlike a model based on a 1D approach

**References:**

Fathalli, M., C Lac, F Burnet, B Vié. Formation of fog due to stratus lowering: An observational and modeling case study. Quarterly Journal of the Royal Meteorological Society, Wiley, 2022, 148 (746), pp.2299 - 2324. 10.1002/qj.4304. hal-03795958

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# Experimental study of the transition from thin to thick fog during SOFOG3D

Théophane Costabloz

During the 15 intensive observation periods (IOP) of the SOFOG3D campaign, a tethered balloon was operated at the super site with an innovative payload composed of a turbulence probe and a Cloud Droplet Probe (CDP) sensor measuring the size distribution of water droplet from 2 to 50 µm in diameter. These measurements allow us to document the temporal evolution of the vertical profile of thermodynamic and microphysical properties for 8 thin fog layers (thickness less than 50 m) and 7 developed layers including 3 episodes exceeding 200 m in thickness. These data are analysed to study the transition from thin to optically thick fog. From ground measurements, fog becomes optically thick when the downwelling infrared radiation (LW) becomes very close to the upwelling LW, i.e. around 0h45 UTC for the episode of 08-09/02/2020 (figure 4b). CDP measurements show that the liquid water content (LWC) profile reverses during this transition. At the beginning of the episode, in stable condition, the LWC is maximum near the ground and decreases with altitude (figure 4d), while in the mature phase just before dissipation into stratus, the temperature profile is neutral and LWC increases with altitude (figure 4e), except near the top due to mixing processes.

Figure 4f) shows the vertical gradient of potential temperature ($\theta$), as function of LWC, normalised by the thickness of the layer, for the 12 profiles. It appears that for this case, the transition between the formation in stable condition ($d\theta/dZ > 0$ and $dLWC/dZ < 0$) and the developed phase which is more adiabatic ($d\theta/dZ \sim 0$ and $dLWC/dZ > 0$) is not continuous over the fog life cycle.

These unique observations highlight a contrasting evolution of the thermodynamic and microphysical profiles during the transition from thin to optically thick fog. This analysis will be extended to all IOP in order to better understand the different processes involved.

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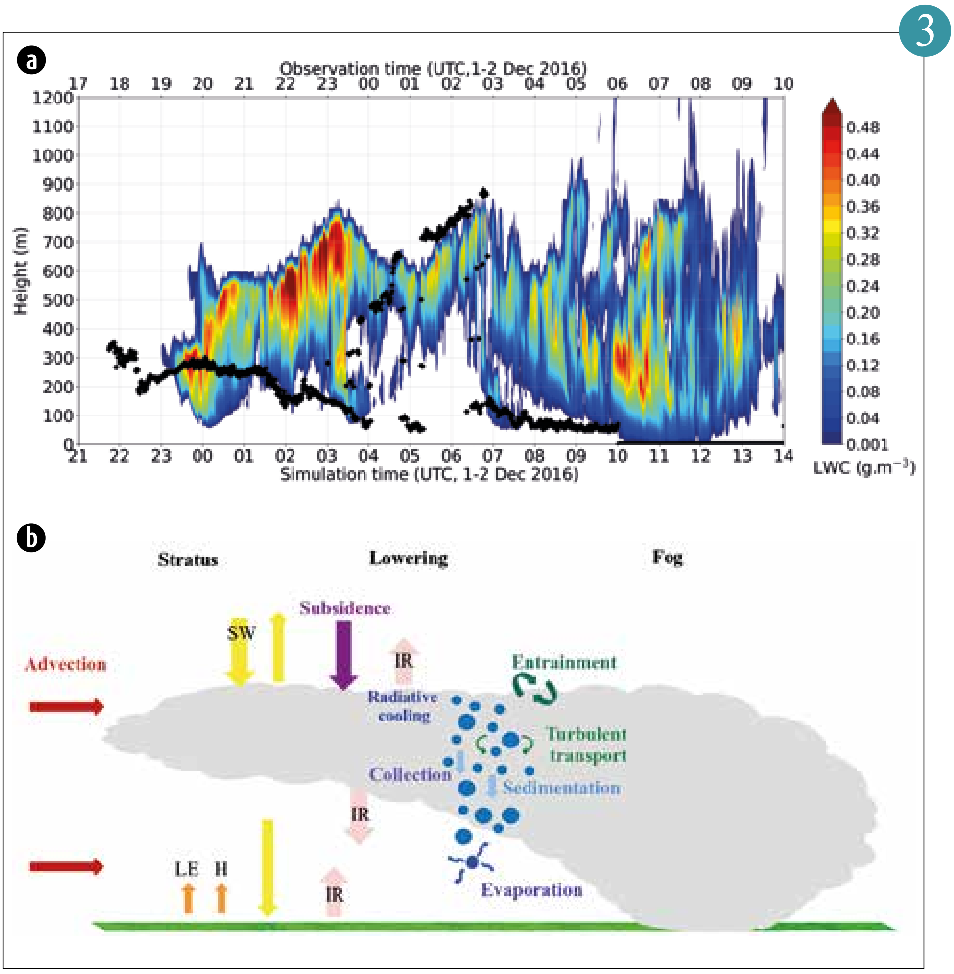
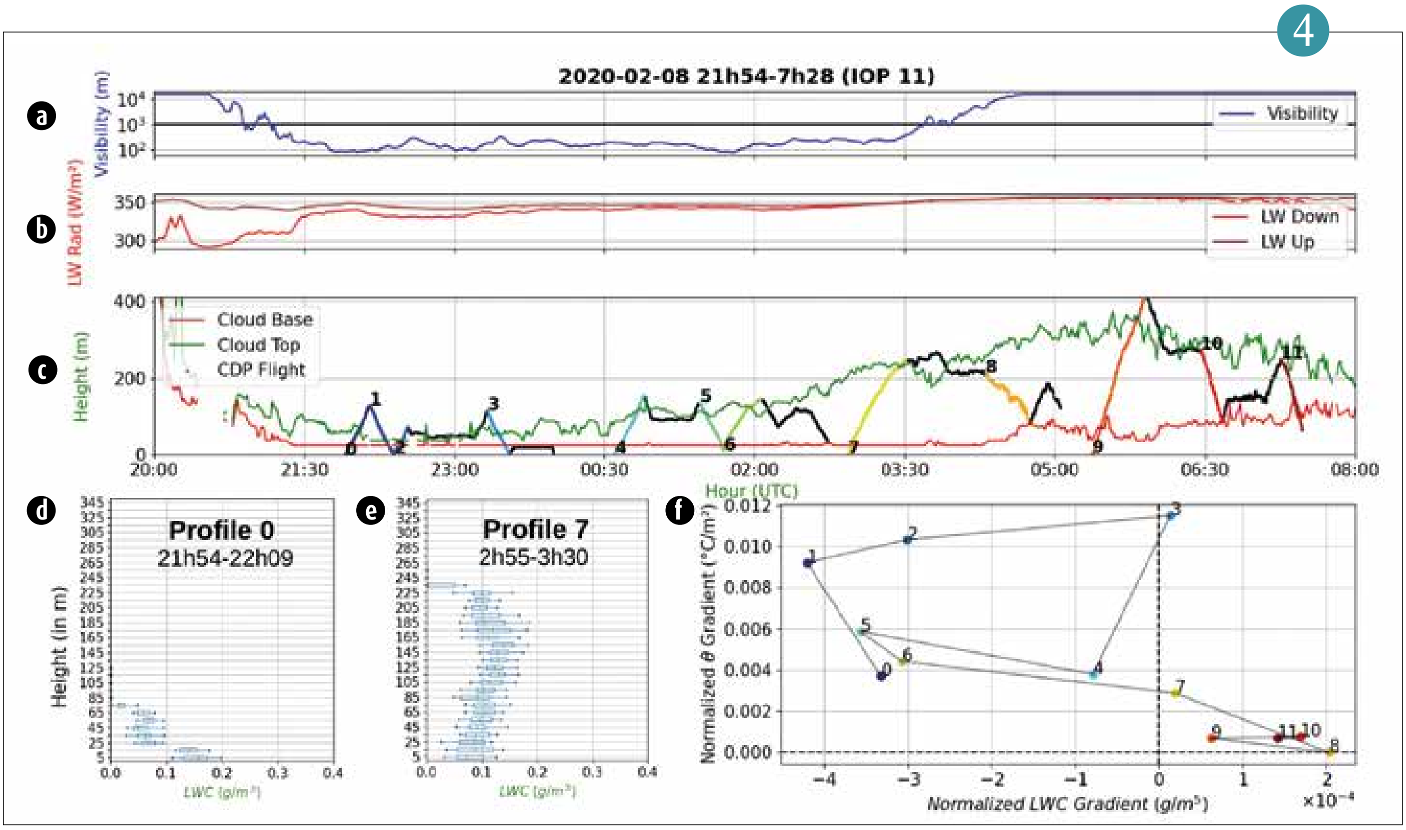



(a) Temporal evolution of the vertical profile of the simulated liquid water content LWC (g.m$^{-3}$). The real time axis of the measurements is at the top of the figure, and the time axis of the observations shifted by 4 hours corresponding to the time of the simulation at the bottom of the figure. Measurements of cloud base height (CBH) derived from the ceilometer are superimposed in black dots. (b) Schematic representation of processes involved in stratus lowering up to fog formation.




Fog case sampled during the night of 8 to 9 February 2020 (IOP 11): Time series of (a) ground visibility, (b) upwelling and downwelling infrared radiation, and (c) altitude of cloud base (red) and cloud top (green) derived from the 95 GHz BASTA radar, and of the tethered balloon (black) carrying the CDP droplet counter, with the 12 selected soundings coloured and numbered; LWC profile measured by the CDP (d) between 21:54 and 22:09 and e) between 2:55 and 3:30; (f) Gradient of θ as a function of the LWC gradient, normalized by the thickness of the fog layer.

# Impact of the assimilation of the SOFOG3D ground based microwave radiometers on AROME-France forecasts

Guillaume Thomas, Pauline Martinet, Pierre Brousseau and Philippe Chambon

Despite steady progress, the prediction of fog (a phenomenon with a strong socio-economic impact, especially for the transportation sector) remains a challenge. Bergot and Guedalia (1994) showed that better initial conditions in the boundary layer could be a source of improvement. During the winter of 2019/2020, the latter was particularly studied in the framework of the SOFOG3D (Southwest FOGs 3D experiment for processes study) campaign. Numerous observational systems were deployed to improve knowledge of processes related to the fog life cycle. Among these measurements, temperature profiles have been retrieved from a network of ground-based microwave radiometers (MWR).

These observations were used in the 3D-Var data assimilation system of the AROME-France model and their impact on the forecast quality and their contribution to fog forecasting were evaluated. Figures a) and b) show the mean absolute errors of the first 24 hours of temperature forecasts from two experiments: one without (a) and one with (b) MWRs assimilation compared to temperature profiles from MWRs that were not assimilated. Figure c) shows the difference between the two and highlights a significant decrease (white squares) in temperature forecast errors for the first 5-6 hours.

However, these experiments did not show an improvement in forecasts of fog itself. Nevertheless, the encouraging results on other variables like on temperature forecasts could motivate future works of joint assimilation of temperature profiles and variables related to humidity from MWR data to study their impact on fog forecasts.

**References:**

Bergot, T., & Guedalia, D. (1994). Numerical forecasting of radiation fog. Part I: Numerical model and sensitivity tests. *Monthly Weather Review,* 122(6), 1218-1230.

5

# Fine scale variability of fog over CDG airport

Thierry Bergot, Renaud Lestringant

The twelve visibility measurements installed at Paris-CdG have allowed the estimation of spatial variability of visibility at sub-kilometre horizontal scale. This work is a pioneering attempt to quantify the variability of fog at local scale.

The variability inside the sub-kilometre area is significant for fog, whatever the studied fog characteristics, indicating the importance of local scale in the evolution of fog events. This study indicated that one point of measurement may be far from the representativeness of the sub-kilometre scale area and can create problems if used for verifying or initializing numerical models. Observation of mean visibility would be more useful for verifying forecasts than local-scale observation. The representativeness error of fog clearly follows an asymmetric distribution. It is impossible to deduce fog characteristics at a kilometre scale from a local measurement, even for very low visibility events such as Low Visibility Procedures (LVP) cases. Consequently, significant biases may be introduced in the calculated scores of forecasted fog events. This dispersion has the same order of magnitude as the current NWP forecast quality of fog.

Observations remain a key point for the improvement of fog forecasting by providing new insights into fog behaviour. However, it is very difficult to document all processes affecting fog due to their local nature. One can therefore wonder about the representativeness of microphysical measurements at local scale, e.g. during fog field experiments. It is clear from this study that there is a local scale variability in visibility and consequently in the fog microphysical properties.

There is a great deal of variability in the observed microphysical properties of fog and the NWP microphysical parameterizations should be adjusted to draw the probability density function of microphysical properties for use in stochastic physics schemes for ensemble forecasts..

**References:**

Lestringant, R.; Bergot, T. Analysis of Small-Scale Spatial Variability of Fog at Paris-Charles de Gaulle Airport. Atmosphere 2021, 12, 1406. https://doi.org/10.3390/atmos12111406

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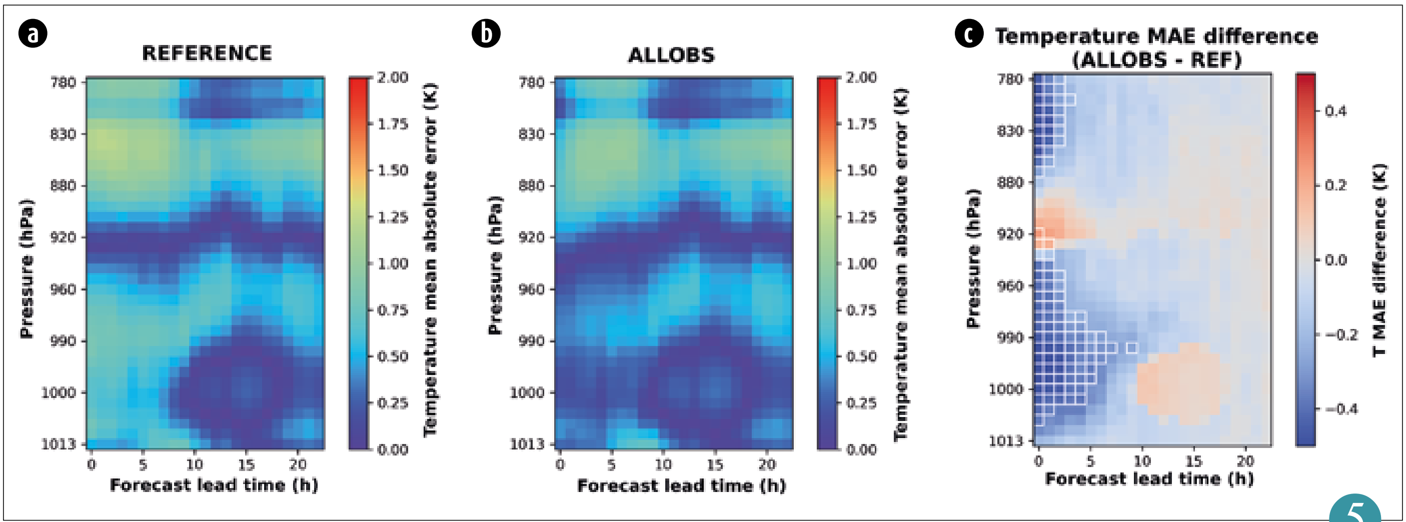


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Mean absolute error of temperature forecasts in comparison to non assimilated MWR temperature profiles for (a) an experiments without MWR data assimilation, (b) an experiment with MWR data assimilation and (c) the difference between both (white squares indicating statistically significant differences).

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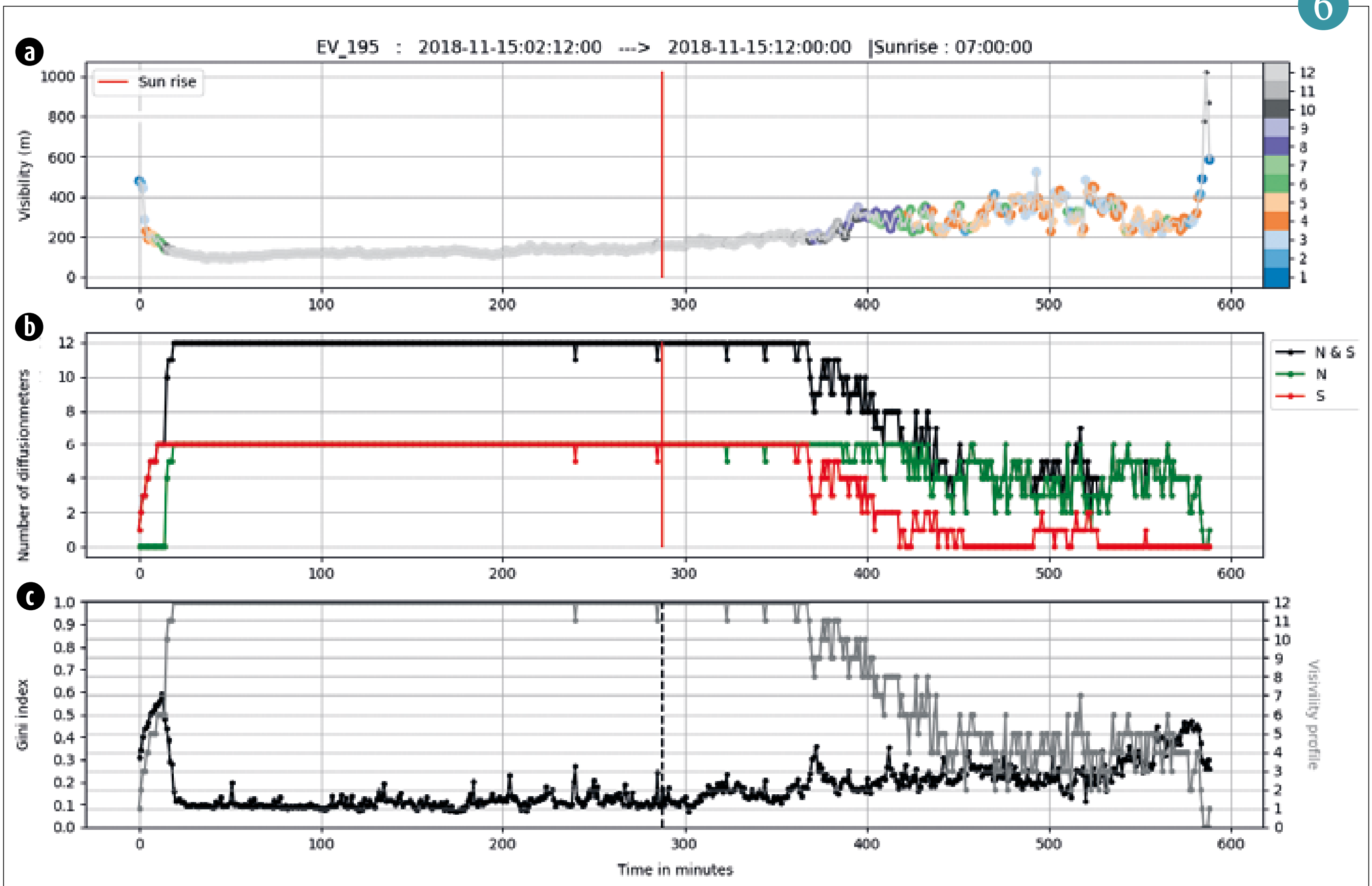


Example of fog event. (a) Time series of the minimum visibility values of the event. The colors indicate the number of visibilities below 600m (LVU).
(b) Time series of LVU for northern (N) and southern (S) sensors separately and altogether (N & S). (c) Time series of LVU in gray and Gini indexes in black.

# Data assimilation

The forecasting models used by the different services of Météo-France, allowing the forecasting of weather, ocean waves and air quality, all need to be initialized. In order to produce good forecasts, the initial conditions of these models must reflect reality as closely as possible, by seeking an accurate estimate of the current geophysical state. This geophysical state is obtained from the optimal combination of new observations and a previous short-range forecast (called background state). The development of this combination takes into account the uncertainties of the different elements it merges. This includes the implementation of ensemble systems, aiming at simulating the uncertainties of the observations and the model, and thus providing a statistical sample of the background errors.

In recent years, significant progresses in data assimilation have been made thanks to the work carried out within Météo-France and CNRM. These progresses concern both the mathematical algorithm of data assimilation and the use of new observations. These two elements have strong links, because an improvement in the algorithm can lead to an improvement in the exploitation of the information content of the observations, as we will see in this chapter.

The first article describes the evolution of assimilation schemes for the numerical weather prediction models of Météo-France using an object-oriented approach and a formulation that better takes into account the information coming from the ensemble systems. An illustration of application of this new scheme for the use of observations is given in the second article, showing the developments related to radar data and the future lightning imager of the new European geostationary satellite Meteosat Third Generation. The next two articles are examples of ongoing research work around the use of opportunity observations, personal weather station data and aircraft data collected by national air navigation services. An article then shows the recent progresses around the assimilation of microwave satellite data in cloudy and precipitating areas. Finally, the four articles that close this chapter show the latest work on the use of observations for snow cover forecasting, wave forecasting and aerosol forecasting, as well as algorithmic developments related to atmospheric chemistry assimilation.

# Evolution of ARPEGE and AROME assimilations towards an object-oriented approach and a first step of EnVar

L. Berre, E. Arbogast, V. Vogt, P. Brousseau

Major developments are being prepared for ARPEGE and AROME data assimilations. This relies on a software overlay called OOPS (Object Oriented Prediction System), joint development of ECMWF and Météo-France,coded in the C++ language. This object-oriented approach, which will be applied to all data assimilation systems used for numerical weather prediction, facilitates the maintenance and development of assimilation systems. Indeed, it is based on the definition of objects characteristic of the assimilation algorithms, which can be arranged in a specific and flexible manner according to targeted assimilation configurations. It is thus planned to take advantage of this transition to OOPS to carry out a first evolution towards an EnVar formulation of AROME and ARPEGE assimilations.
For AROME, this corresponds to the replacement of the current 3D-Var by a 3DEnVar scheme. While 3D-Var is based on horizontally homogeneous and temporally static covariances, 3DEnVar relies on anisotropic background error covariances that allow the spatialization of observations in a weather-dependent way. Indeed, these covariances are in this case derived directly from the AEARO ensemble of backgrounds and are filtered using a grid point localisation. Intensive tests carried out on 3DEnVar have shown that this new scheme has a very positive impact on the quality of the AROME forecasts, as illustrated in Figure 1a.
For ARPEGE, the switch to OOPS also allows the preparation of a first step of EnVar, in a formulation called "hybrid 4D-Var". The hybridization is in fact applied to 3D background error covariances. While the current set covariances are quasi-isotropic and wavelet-filtered, it is possible to hybridise them with ensemble covariances localised in gridpoint space. This allows strongly flow-dependent anisotropies to be represented, with characteristic curvatures for tropical cyclones for example. As illustrated in Figure 1b, these new covariances have also a very significant positive impact on the quality of the ARPEGE assimilation system.
These new versions of ARPEGE and AROME will be deployed at the beginning of 2023 in a double suite, thus allowing a very important evolution of the assimilation systems at global and convective scales. This evolution towards OOPS and this first step of EnVar also allows to prepare another major change, corresponding to the later implementation of 4DEnVar approaches for AROME and ARPEGE, among several developments easened by OOPS.

1

# New possibilities with AROME 3d-Envar: assimilation of MTG/LI Flash Extend Accumulation (FEA) and direct assimilation of ground-based radar reflectivity

Maud Martet and Pauline Combarnous

One of the main levers for improving thunderstorm forecasting in the AROME-France model is the use of specific observations in the data assimilation system. The new 3d-EnVar scheme allows to adjust the hydrometeors (three-dimensional variables representing atmospheric water in condensed form) during the assimilation process. This opens perspectives for the assimilation of observations with information content related to hydrometeors and two examples with ongoing research are given below:
– On board the EUMETSAT Meteosat Third Generation (MTG) satellite, a Lightning Imager (LI) is carried. It allows to observe the density of lightning in a cloud. This accumulation is related to the quantity of icy particles, integrated on the vertical. MTG being a geostationary satellite, the LI observations will cover the whole geographical domain of AROME-France at high temporal rate. Work has been underway at CNRM for several years with the support of CNES to prepare the assimilation of these data.
– Ground-based radars allow to observe a reflectivity which is the power returned when the beam meets hydrometeors, the link with these model variables is therefore direct. The instruments of Météo-France and neighbouring countries also allow to cover a large part of the AROME-France domain at a frequency of 15 minutes. These data have been assimilated for many years in the AROME-France model and the new assimilation scheme will allow to explore a more optimal use of their information content.
Thus, these two types of observations are ideal candidates to explore the new possibilities allowed by the 3d-EnVar and hydrometeors. Experiments assimilating these additional data, an example of which is shown in the Figure for the lightning data, show that they provide a better description of convective clouds and precipitation in the first few hours of the forecast.

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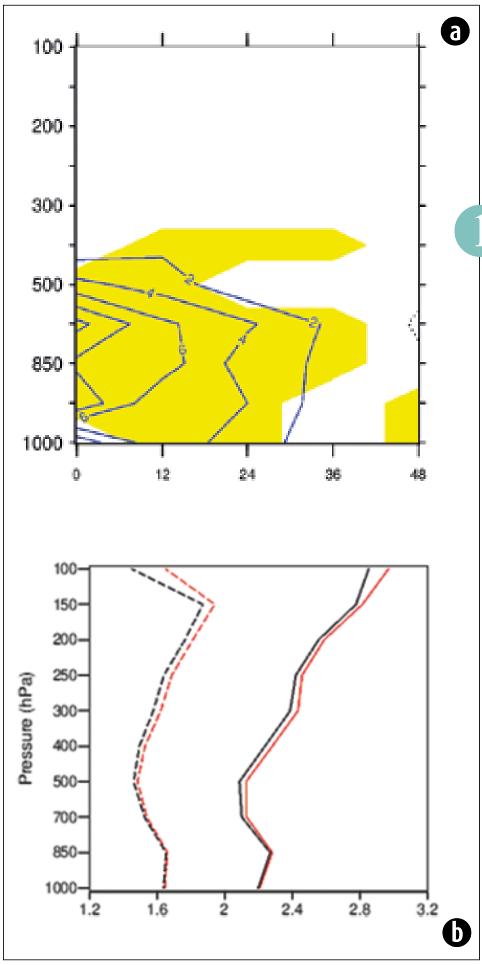
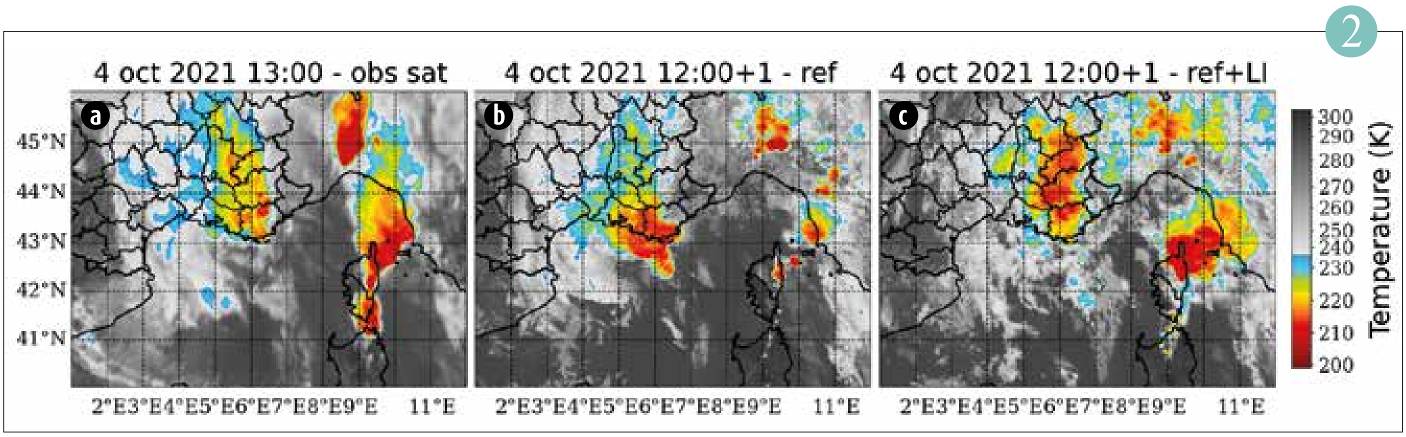



(a) Percentage of reduction in AROME RMSE (root mean square errors) for relative humidity, provided by 3DEnVar compared to 3D-Var, measured over a period of 6 months with respect to radiosondes in terms of relative humidity, as function of pressure height (vertical axis) and forecast range (horizontal axis). The 3DEnVar scheme includes anisotropic ensemble covariances, which allow to spatialise observations in a weather-dependent way. Positive values of RMSE reduction reflect positive impacts of the AROME 3DEnVar.
(b) Vertical profiles of ARPEGE RMS of differences between analyses and observations (dashed curves) and of differences between 6h forecasts and observations (solid curves). The observations used to calculate deviations are wind measurements provided by aircraft over the mid-latitudes of the northern hemisphere, over a period of 2 months. The red curves are those of the current standard 4D-Var, and the black curves correspond to the hybrid 4D-Var, which includes anisotropic flow-dependent ensemble covariances. The smaller values of the ARPEGE hybrid 4D-Var RMS reflect the positive impact of this first step of EnVar for ARPEGE.




Comparison of MSG satellite image (a) and forecast satellite images by AROME-France without lightning assimilation “ref” (b) and with lightning assimilation “ref+LI” (c).

# First assimilation experiments of personal weather station observations into the AROME model

Alan Demortier, Olivier Caumont, Vivien Pourret, Marc Mandement

Numerous objects connected to the Internet and equipped with meteorological sensors now observe the first few metres of the atmosphere at high spatial and temporal resolution. Among these objects, several tens of thousands of personal weather stations installed in private homes share observations in real time, which are now collected by Météo-France. Despite their variable quality, as they do not meet the standards set by the WMO[1], strict quality control procedures makes possible to take advantage of these observations to observe high-impact meteorological phenomena — such as thunderstorms — in addition to observations from the operational network of Météo-France.

To evaluate the benefits of personal station observations in the description of the initial state of the atmosphere (called analysis) of the numerical weather prediction model AROME, assimilation experiments were carried out. For surface pressure, the first variable studied, a specific quality control was implemented, while using the current algorithm for comparing the model to the observations.

The addition of pressure observations from personal stations modifies the correction term that brings the modelled state of the atmosphere closer to the observations (called increment, see figure). An evaluation against operational observations in August 2020 shows a small but consistent improvement in 1-hour forecasts of geopotential, temperature and relative humidity at 2 m, and wind speed at 10 m. Assimilation experiments of temperature and relative humidity observations, and experiments using a new version of the assimilation system, are planned in the future.

*1. World Meteorological Organization*

**References:**

Demortier, A., O. Caumont, V. Pourret, M. Mandement, 2022: Added value of assimilating surface pressure observations from personal weather stations in AROME-France, EMS Annual Meeting 2022, Bonn, Germany, 5–9 Sep 2022, EMS2022-251, https://doi.org/10.5194/ems2022-251.

3

# Impact of the aircraft Mode-S data within the AROME assimilation system

Vivien Pourret

Mode-S/EHS[1] wind and temperature data are derived from information provided by commercial aircraft in response to civil aviation radar interrogations every 4 seconds. These data are available free of charge via agreements with European civil aviation or via the implementation of ADS-B antennas; they represent, in Europe, 50 million observations per day. The EMADDC (European Meteorological Aircraft Derived Data Center) managed by the KNMI (Dutch meteorological service) is a component of the E-ABO (Aircraft Based Observations) program of EUMETNET which collects, controls and corrects these data provided by the meteorological centers or the European civil aviation services (bilateral agreements). These crowdsourced data, of comparable quality to other available aircraft data but with a much higher density, are of great interest for small-scale limited-area models such as AROME.

After filtering and quality control, two million observations are assimilated per day in AROME, multiplying by a factor of 2 to 4 the total number of assimilated observations. Evaluations show that these data can significantly improve forecasts up to 24-30 hours ahead for all parameters over the troposphere. These data will be used in the under construction AROME parallel suite in 2023.

*1. Mode S Enhanced Surveillance (EHS) provides a set of advanced functionalities for the Mode S transponders. Three different types of reports are included and designed to report vertical intent, turning performance, and airspeeds*

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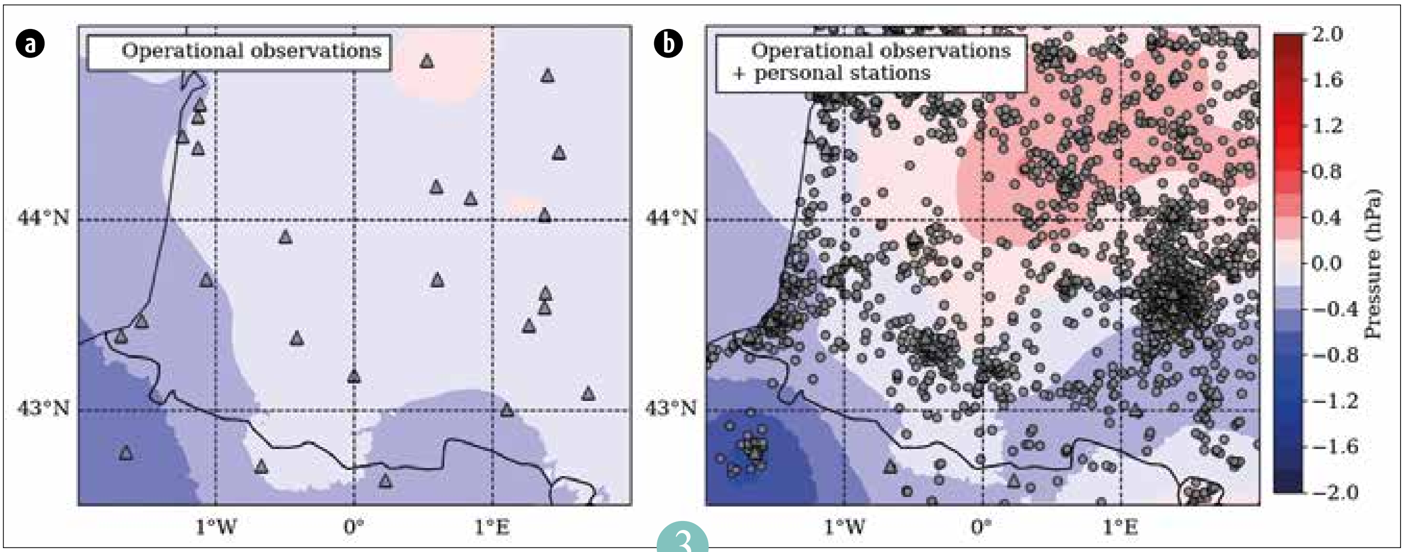


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Surface pressure increments over the south-west of France at 01:00 UTC on 1st August 2020 of two assimilation experiments starting from the same initial state:
(a) using operational observations and (b) adding surface pressure observations from personal stations to operational observations.
Among the set of assimilated observations, those from synoptic surface stations are indicated by grey triangles, and those from personal stations are indicated by grey circles.
Black lines indicate the coasts and boundaries.

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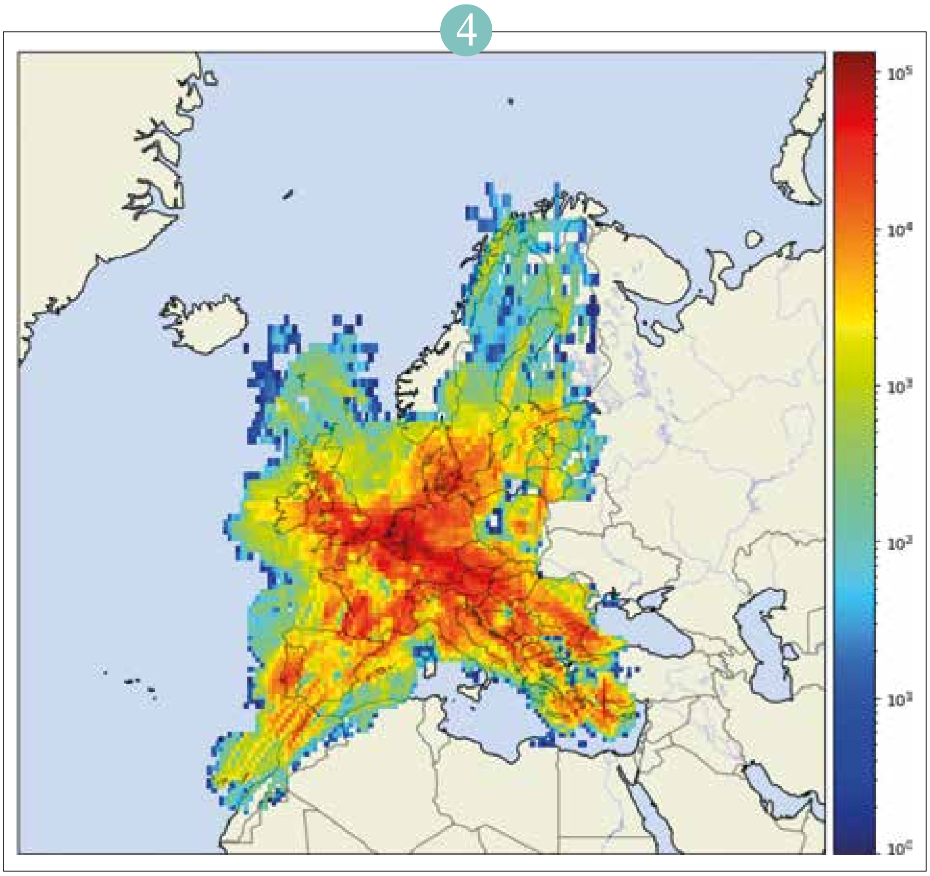

Daily density of Mode-S observations processed by EMADDC (November 2022).

## Impact of the direct assimilation of cloudy and rainy microwave observations within the ARPEGE and AROME assimilation systems

Philippe Chambon and Mary Borderies

Satellites microwave observations currently provide one of the greatest impact of the satellite data used in global Numerical Weather Prediction (NWP) models. These observations, acquired by 13 polar orbiting satellites, provide temperature and humidity information in all types of meteorological situations.

The operational assimilation of these data was, until recently, limited to clear sky conditions. Thanks to research carried out with the support of CNES, a first assimilation method in cloudy areas was developed and transferred to the operations for the ARPEGE model. This first method will soon be replaced in the next operational chain by the so-called "All-Sky" assimilation method, which is a more direct and optimal method developed at the European Centre for Meteorological Research. This work has led to significant improvements in the forecasts of the ARPEGE model, in particular for humidity in the lower layers, as can be seen in the Figure, which shows the reduction in the standard deviation of the forecast errors for the various sensors for which these developments have been evaluated.

In the coming years, this work will be extended to the whole constellation of spaceborne microwave sensors. It will also be evaluated in AROME with the 3d-EnVar assimilation scheme which will allow to update directly the hydrometeors in the initial conditions.

5

## Assimilation of remotely-sensed observations for mountainous snow cover simulation

M. Lafaysse et al.

Numerical modelling is complementary to observations to describe the snow cover state and its spatial variability for the sensitive fields (avalanche hazard forecasting, water resources optimization, etc.)

The quality of simulations depend on their possibility to be constrained by the assimilation of snow cover observations. Given the high spatial variability of snow at multiple spatial scales, point scale observations have an unsufficient spatial representativeness to reach this goal. Thus, CNRM has led research for several years to assimilate the snow cover properties which can be observed at a horizontal resolution compatible with mountain topographies. An assimilation algorithm specifically designed to this topic is now well established and derived from a method so-called « particle filter ».

In recent works in collaboration with CESBIO, assimilation of snow depths obtained bt Pléiades stereo-imagery showed that it was possible to significantly improve the spatial variability of simulations by this technique and to maintain an added value several months after the assimilation date (see figure).

In progress and future works intend to solve the challenges involved by the assimilation of other interest observations : surface optical reflectance, surface temperature, variables derived for micro-wave backscatter, but also precipitation estimates from ground radars. Due to the complex interactions of topography with these different observations, the success of assimilation especially depends on our ability to characterize the high spatial dependencies of observation errors.

The final goal is to assimilate these different observations in operational simulations allowing to better forecasts the snow-related hazards..

**References:**

Cluzet, B., Lafaysse, M., Cosme, E., Albergel, C., Meunier, L.-F., and Dumont, M. : CrocO_v1.0 : a particle filter to assimilate snowpack observations in a spatialised framework, Geosci. Model Dev., 14, 1595–1614, https://doi.org/10.5194/gmd-14-1595-2021, 2021

Cluzet, B., Lafaysse, M., Deschamps-Berger, C., Vernay, M., and Dumont, M. : Propagating information from snow observations with CrocO ensemble data assimilation system : a 10-years case study over a snow depth observation network, The Cryosphere, 16, 1281–1298, https://doi.org/10.5194/tc-16-1281-2022, 2022

Deschamps-Berger, C., Cluzet, B., Dumont, M., Lafaysse, M., Berthier, E., Fanise, P., & Gascoin, S. Improving the spatial distribution of snow cover simulations by assimilation of satellite stereoscopic imagery. Water Resources Research, 58, e2021WR030271. https://doi.org/10.1029/2021WR030271, 2022

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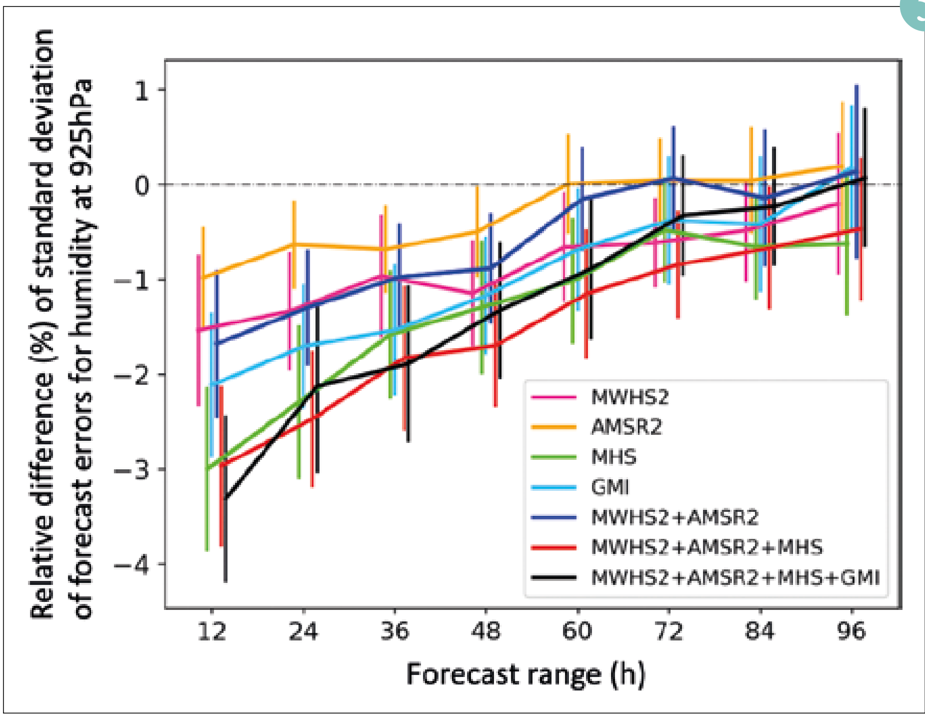


Relative reduction of standard deviation of forecast error for humidity at 925 hPa for the ARPEGE model due to the usage of microwave cloudy and rainy observations in the direct allsky assimilation route, as function of forecast range. Each curve corresponds to an experiment with a given microwave instrument (MHS, MWHS2, GMI, AMSR2) or a combination of them. The forecast errors have been computed over the Europe Atlantic geographical domain for a two-month period in August and September 2021, with the ECMWF analysis as reference.

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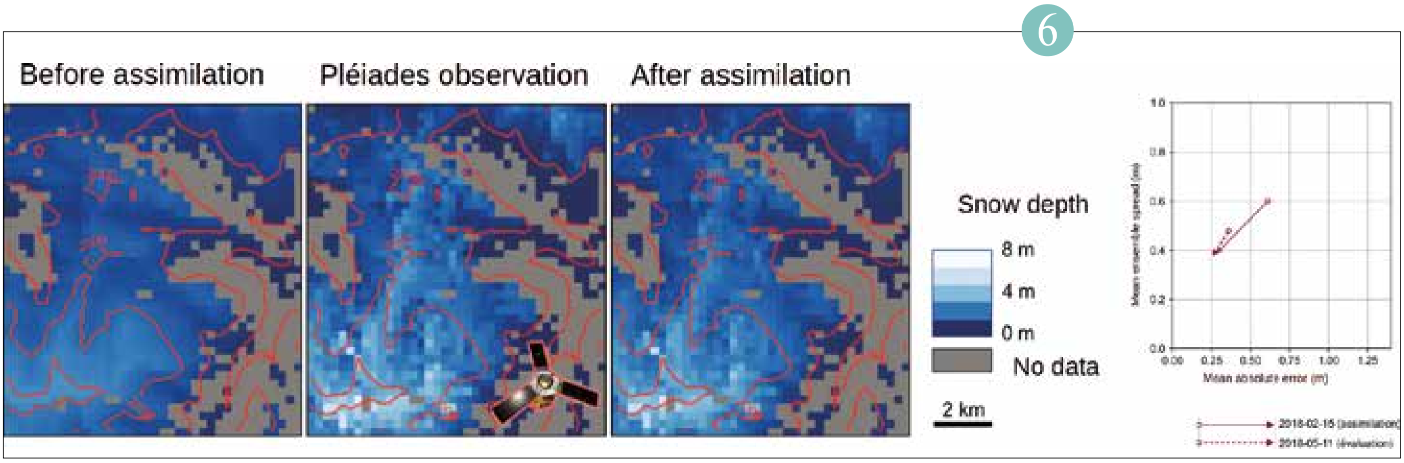


Snow depth on 15 Feb. 2018, simulated before assimilation, observed by Pléiades imagery, and simulated after observation, at 250 m resolution on the Bassiès area in Ariège, France. On the right : reduction of errors by data assimilation, at the assimilation date (plain line), and 3 months after the assimilation date (dashed line). Extract from Deschamps-Berger et al., 2022.

# Assimilation of directional wave spectra in coastal area

Lotfi Aouf

The directional variability of waves near the coast is a crucial topic for the improvement of wave submersion warning and coastal flooding prediction induced by wave overtopping. With the arrival of the CFOSAT (Chinese-French Oceanis SATellite) satellite, developed by the space agencies of China (CNSA) and French (CNES), directional wave spectra describing wave energy in direction and wavelength provide very useful and exploitable information in a data assimilation process in the operational wave model. The use of these wave spectra in a coastal configuration of MFWAM wave model with a spatial resolution of 2.5 km and an adapted atmospheric forcing provided by the AROME system shows a significant impact on integrated sea state parameters such as significant wave height, mean wave period and dominant wave direction. Validation with drifting wave buoys observations deployed in the SUMOS field campaign in the gulf of biscay indicates a significant reduction in the bias and scatter index of the significant wave height. The figure shows the average difference in mean wave period with and without assimilation of CFOSAT wave spectra during a storm event in February 2021 in the North-East Atlantic Ocean near the French coasts. It is clearly observed the impact of the assimilation on the dominant wave trains propagating eastward in the Atlantic Ocean, and the correction of the MFWAM model prediction which underestimates the mean wave period. We can also identify the correction of wind-wave growth in a limited fetch conditions in the Gulf of Lion in the Mediterranean Sea. This results in a significant impact on the mean wave period on the West coast of Corsica, where the wave model is overestimating the mean wave period (negative difference).

7

# Assimilation of satellite Aerosol Optical Depth in MOCAGE

Vincent Guidard

The MOCAGE chemistry-transport model is used operationally at Météo-France to provide 4-day forecasts of chemical species and aerosols, both over the globe and over a large regional domain covering Europe at a finer scale. Aerosol forecasts are of particular interest to the aeronautics, national defence and energy sectors, among others.
In order to have the best aerosol forecasts, an assimilation step has been added to the MOCAGE operational suite in January 2022 to build analyses that initialise the forecasts. On the global domain, satellite aerosol optical depth data are assimilated: they provide information on aerosol content, integrated on the vertical. Real-time observations from MODIS (Aqua and Terra platforms) and VIIRS (S-NPP and NOAA-20) are used, in a 3D-VAR analysis performed every hour.

The figure shows aerosol optical depth forecasts, averaged over 5 months, compared to daily aggregated data from MODIS. The geographical distribution of aerosols is greatly improved over the Southern Pacific, and over the export regions from Africa to the Atlantic and from Asia to the Northen Pacific. Forecasts of significant events are also improved.
This operational transfer results from several years of research on the subject at the CNRM and opens the way to enriching the assimilation system with new sources of observations.

**Reference:**

Laaziz El Amraoui, Matthieu Plu, Vincent Guidard, Flavien Cornut, Mickaël Bacles. A Pre-Operational System Based on the Assimilation of MODIS Aerosol Optical Depth in the MOCAGE Chemical Transport Model. *Remote Sensing,* 2022, 14 (8), pp.1949. 10.3390/rs14081949.

8

# Towards a multivariate formulation in the PFK assimilation

Olivier Pannekoucke, Antoine Perrot, Vincent Guidard

The parametric Kalman filter (PKF) is a technique introduced and developed at CNRM in collaboration with CERFACS, and which proposes an approximation of the Kalman filter, as an alternative to the ensemble methods (EnKF). In this approach, a covariance model is introduced, characterized by parameters (variance, anisotropy...). The temporal evolution of the parameters during the prediction and the analysis allows to reproduce the Kalman filter equations, but at a lower computational cost compared to the use of an ensemble, and while revealing a part of the physics of the uncertainties. The research work that we have carried out has allowed us to extend the PKF formalism to the multivariate framework, i.e. to represent the statistical links between several physical fields. In the targeted application, atmospheric chemistry, we were thus able to describe, in a simplified framework, the multivariate evolution of error statistics affecting the prediction of chemical compounds, for example by predicting the cross-correlation functions of NO and $NO_2$ prediction errors (Figure). Next, we will explore the feasibility of the approach in the MOCAGE air quality forecast model.

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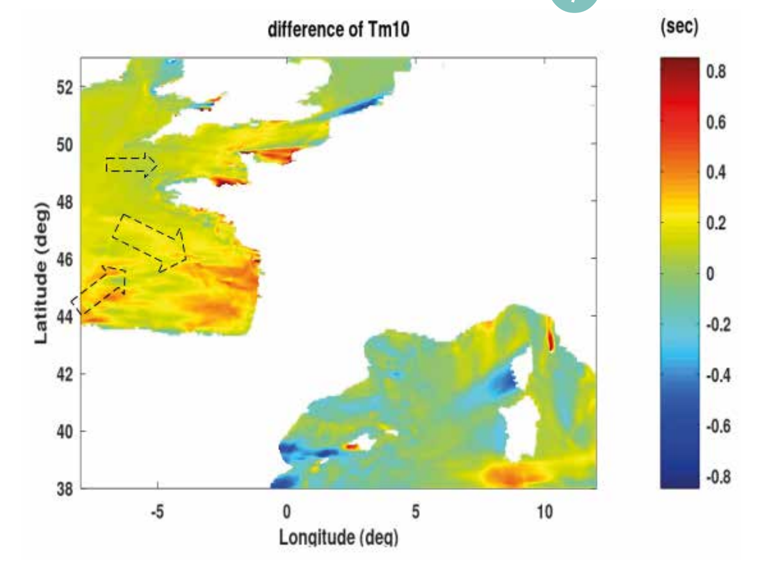


Average difference (in seconds) of the mean wave period from the wave model MFWAM with and without assimilation of CFOSAT wave spectra during the storm event from 23 to 24 February 2021. Negative values in color bar stand for an overestimation of the wave model, while positive values indicate an underestimation of the wave model. The arrows in dashed lines show the direction of the dominant wave trains during the storm event.

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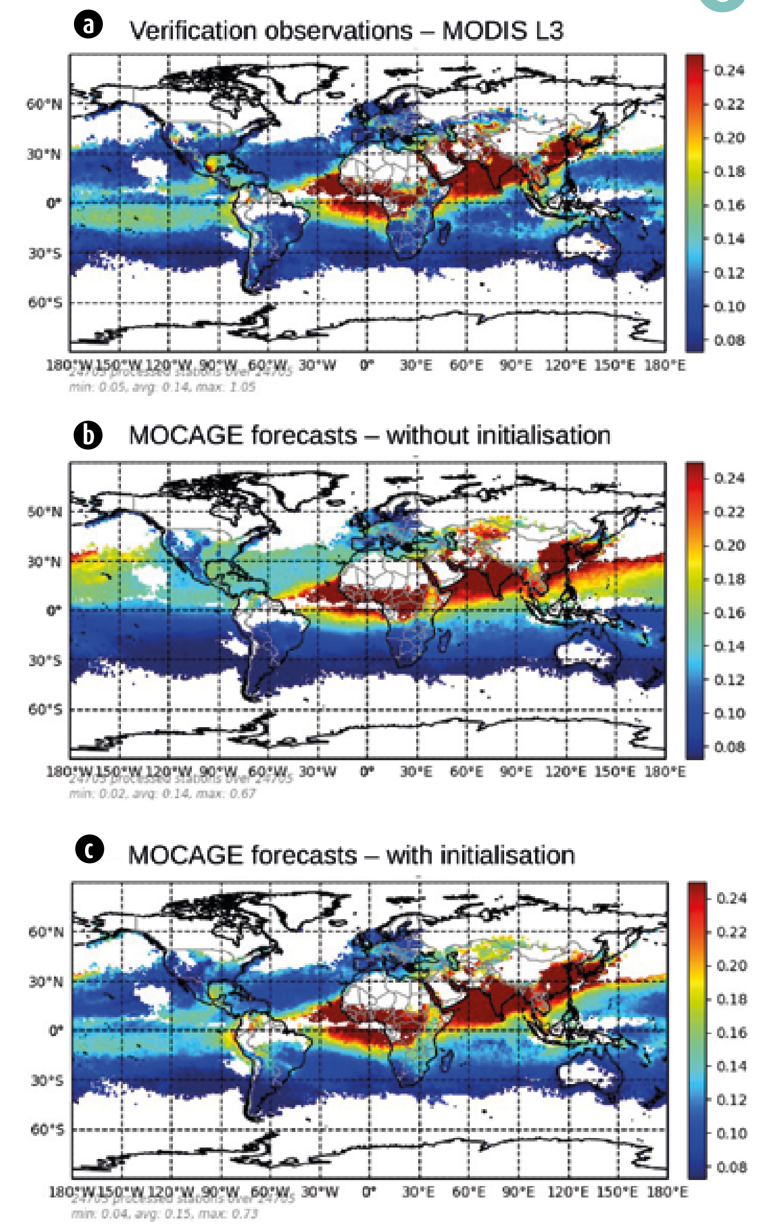


Average of aerosol optical depth (no unit) over 5 months from January to May 2022: from the daily MODIS product as verification (a), from MOCAGE forecasts (collocated with verification data) without satellite data assimilation (b) and from MOCAGE forecasts initialised (collocated with verification data) by satellite data assimilations (c).

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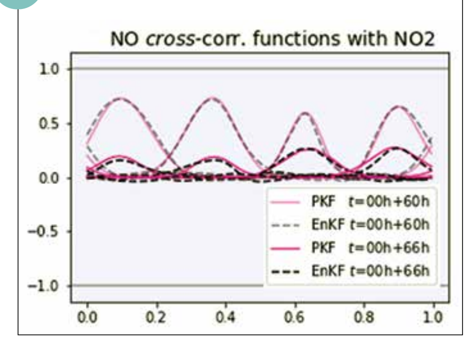


Illustration of some cross-correlation functions characterizing the statistical links of forecast error between NO and NO2 for two time frames, where we observe that the PKF forecast (solid lines) is close to the reference, here the statistics estimated from a large ensemble of 6400 members (EnKF, dashed lines).

# A collection of results illustrating research advances in 2022

# Numerical weather prediction and data assimilation

**Numerical forecasting research directly feeds into developments in the forecasting chain, in order to enrich and improve the products and services provided by Météo-France. An experimental framework has been developed over the last few years to prepare satellite missions dedicated to atmospheric observation in collaboration with space agencies (CNES, ESA, EUMETSAT). Another field of research for the future is to be able to take into account desert dust in forecasting; the effect of transported Saharan dust on temperature forecasts in France has been demonstrated for the first time with Arome. The contribution of the Arome ensemble systems on 5 overseas domains for the forecasting of cyclonic and storm events is demonstrated on the dramatic Fiona event in Guadeloupe; these systems will become operational in 2023. In the field of wave forecasting, too, ensemble prediction systems are being developed. Finally, several advances have been made in the field of probabilistic forecasts adapted to user needs, thanks to innovative statistical processing: the detection and visualisation of storm structures with strong gusts (bow echoes), precipitation forecasting adapted to the needs of flood forecasting services and convection severity for air traffic management. These probabilistic products improve the anticipation of phenomena and effectively support decision-making in each application area.**

## SESAR ISOBAR project: promoting the use of ensemble forecasts for air trafic management

M. Ponzano, L. Raynaud

Flight delays are one of the major concerns in air traffic management. The impact of flight delays represents financial and time losses. The SESAR ISOBAR project (2020-2022) has focused on enhanced convective weather forecasts for predicting imbalances between air traffic capacity and demand in order to select appropriate mitigation measures. The value chain developed in this framework leverages the power of Artificial Intelligence (AI) in the different stages. AI engine is trained using a dataset of selected convective events in summer 2019, which includes forecasts from high resolution ensemble prediction systems (IFS, γSREPS and AROME-EPS), declared capacity in air traffic flow and initial air traffic demand. The value chain produces a solution for tactical (day 0) and pre-tactical (day -1) operations. Météo-France contributed to the meteo engine of the project with the provision of AROME-EPS forecasts and the development of an innovative probabilistic forecast of convection risk based on the automatic detection of convective objects. This product (see figure) has been exploited by the other partners as a benchmark to compare other post-processed weather forecasts. A validation exercise was organized at EUROCONTROL Innovation Hub in March 2022 with the collaboration of Air Traffic Control operational staff and Air Traffic Controllers from Europe. The whole value chain developed in ISOBAR was run for some high convective situations over Europe, which were characterized by high delays due to weather regulations. The predicted air traffic delay has been drastically cut by up 75%

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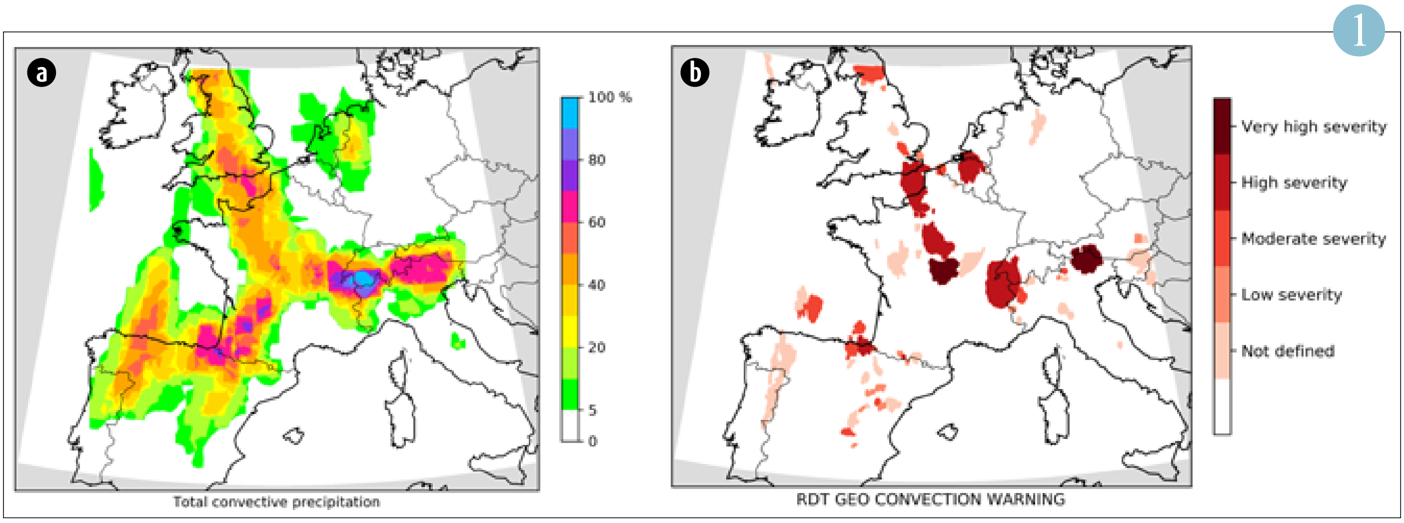


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(a) Probability of convection from AROME-EPS for the 25 July 2019 at 18:00 UTC (the simulation started the 25 July 2019 at 03:00 UTC).
(b) Observed convective cells from RDT (Rapidly Developing Thunderstorm) product from satellite imagery.

# Detection of bow echoes in AROME-EPS and AROME

A. Mounier

Leveraging the huge information provided by weather prediction models is challenging. Existing products to sum up this information are not always appropriate, especially for recognizing severe convective storms such bow echoes . Bow echoes are bow-shaped lines of convective cells, often associated with strong wind gusts.

A possible way to improve the prediction of these events is to automatically detect bow echoes in model outputs using image processing approaches. This approach is in line with the work methods of forecasters as it seeks to detect a particular thunderstorm structure with a known conceptual sheme.

In this work, a Convolutional Neural Network (CNN) is developed to detect bow echoes directly from the reflectivities simulated by AROME or AROME-EPS members. The best CNN configuration has a hit rate of 86% and a false alarm rate of 39%. A detailed examination of the CNN performance shows that the largest bow echoes are correctly detected, while the false alarms and misses mainly correspond to small and weak bow echoes.

Based on a cooperation with forecasters, synthesis plots are proposed that summarize the bow echoes detections in AROME-EPS and AROME and identify risk areas (Figure 2). Forecasters perceive these products as relevant and potentially useful to handle the large amount of available data. To continue the evaluation of this work in a real-time context, a daily production in a research mode has been running at Meteo-France since summer 2021. In future work, other Convolutional Neural Networks could be developed to detect other kinds of severe convective storms.

**Reference:**

Mounier, A., Raynaud, L., Rottner, L., Plu, M., Arbogast, P., Kreitz, M., Mignan, L., and Touzé, B. (2022). Detection of Bow Echoes in Kilometer-Scale Forecasts Using a Convolutional Neural Network. *Artificial Intelligence for the Earth Systems* 1, 2, e210010, available from: ‹ https://doi.org/10.1175/AIES-D-21-0010.1›.

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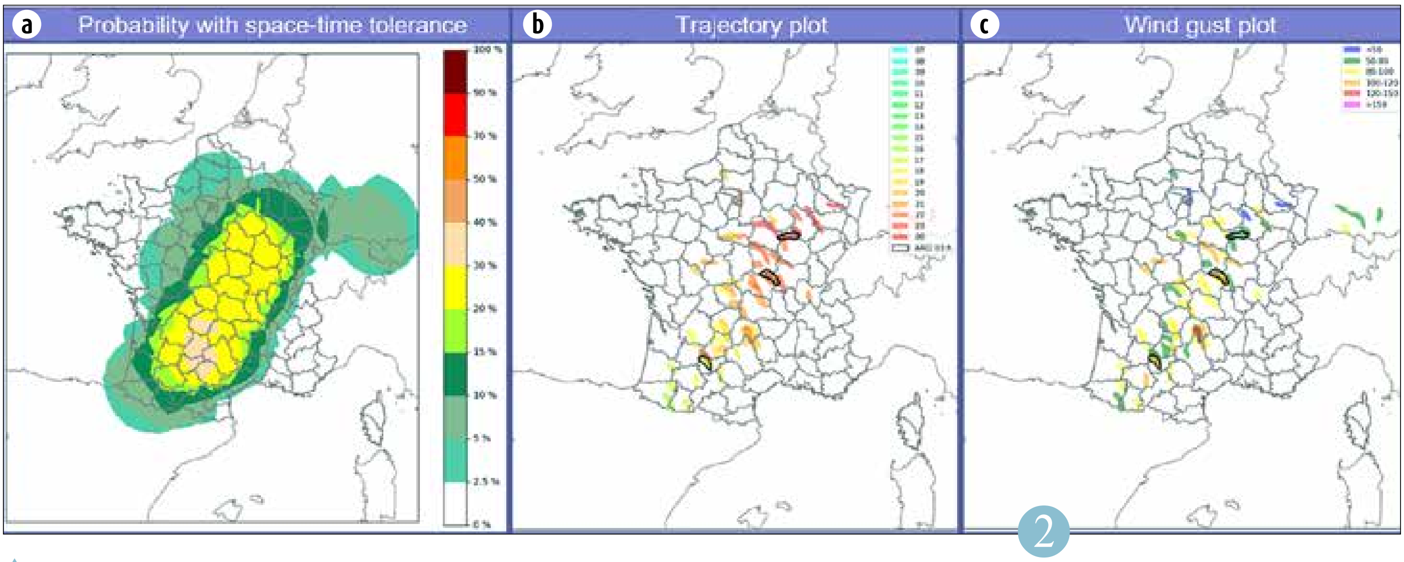


Example of 3 synthesis plots from 4 june 2022 at 07h UTC to 5 june 2022 at 00h UTC.
(a) Bow echo probability with a space-time tolerance.
(b) All bow echo detections in AROME-EPS and AROME (black contours) are overlaid. Colors correspond to UTC hour of bow echoes detections.
(c) Same as (b) but colors correspond to expected wind gusts under bow echoes detections. Wind gusts are most of the time around 80-100 km/h for this day.

## Added-value of using realistic aerosols in AROME

Y. Seity, Q. Libois

In March 2022, significant Saharian dust events were observed over France with various consequences: solar radiation dimming inducing a surface cooling, modification of snow albedo and ice clouds...

In Météo-France Numerical Weather Prediction models (ARPEGE and AROME) the aerosols concentrations are currently taken from monthly climatologies which are unable to account for events like those observed in March 2022, leading to large model errors in 2m temperature and surface solar irradiance. AROME was modified in order to use more realistic aerosols, coming from a chemistry-aerosols model (CAMS). The figure shows the improvements of the 2 m temperature forecasts over France at 14UTC March, 16th 2022. The blue points correspond to locations where the new version (using daily aerosols) is closer to the observation than the operational one (using aerosols climatology), whereas the red ones, much less numerous, indicate a degradation of the forecast. It highlights a significant improvement, with an error reduction up to 2°C for some stations.

In this example, aerosols are only accounted for in the radiation scheme, but ongoing work will allow to use them in the cloud scheme, as cloud condensation or ice freezing nuclei. This paves the way for the use of daily aerosols in operational numerical models.

3

## Implementation of an ensemble wave forecast at the global scale

A. Dalphinet

Until now, Météo-France only operated deterministic wave models. Marine forecasters could only rely on the wave model of the European Prediction Center for ensemble prediction[1] (PE). However, the latter is mainly interested in the medium term, up to 15 days, at a spatial resolution of 0.25°.

A configuration based on the Météo-France atmospheric ensemble forecast[2] (PEARP) and on the MFWAM wave model has been developed. This 0.2° spatial resolution global configuration includes 35 members, forced by the 35 PEARP wind scenarios, and simulates sea states up to 102h.

Evaluations conducted over the winter period from January to April 2021 have shown the benefit of PE-MFWAM over the deterministic MFWAM model, especially beyond the 48h time step. At short time steps, the wave ensemble lacks dispersion because each member starts from the same initial state. After 48h, the mean error of the ensemble is much smaller than that of the deterministic model, according to observations at buoys and altimeters near metropolitan France.

The attached illustration shows a case of significant scatter at 102h between PE-MFWAM members, approaching storm Justine, late January 2021. The deterministic wave height forecast (left) is strongly ahead of the analysis, considered as the reference (center). However, the members reflect the uncertainty and the possibility of a different timing, as shown by the standard deviation of wave height at 102h (right).

The study also showed the value of accounting for uncertainty in the wave model by alternately using two wave model physics for the 35 members. The resulting ensemble has better scores.

The implementation of this global configuration (November 16, 2022 on the operational chain) opens the way to an ensemble forecast of coastal waves over metropolitan France and overseas. Further validations and exchanges with forecasters are also essential for the appropriation of these complex forecasts and to develop downstream applications such as a dangerous sea index

*1. PE for ensemble prediction*
*2. PEARP*

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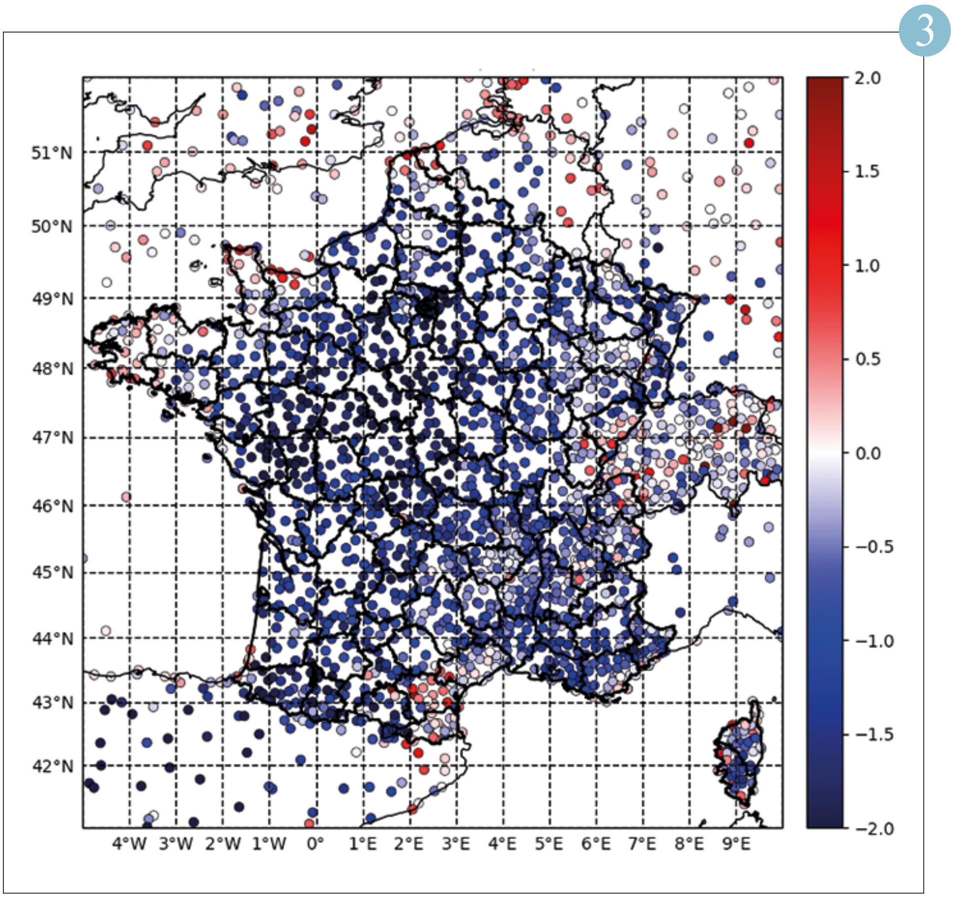
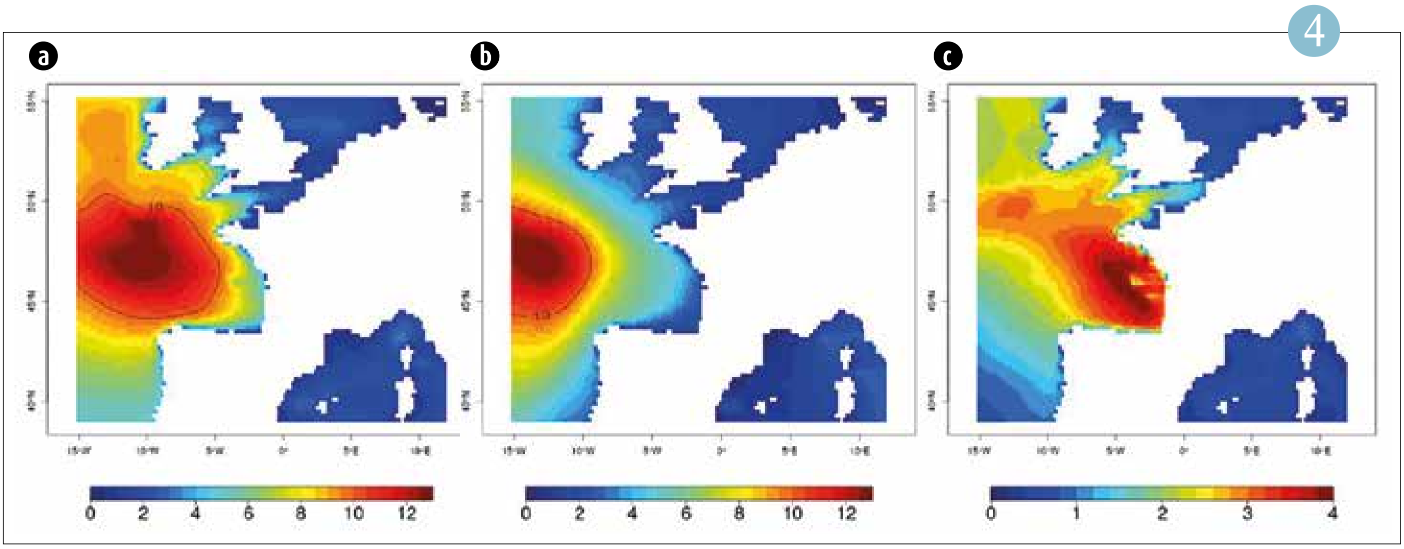



2m temperature bias difference at 14UTC March, 16th 2022.




Significant wave height (m) of the deterministic MFWAM 102h forecast (a), MFWAM analysis (b) and standard deviation of wave height (m) of the 35 members of the PE-MFWAM 102h forecast (c) for 30/01/2021 at 06h UTC.

# Observing System Simulation Experiments (OSSE) at the global scale: a simulated framework in support of the definition of future space missions

P. Chambon, O. Audouin, T. Carrel-Billiard, O. Coopmann, N. Fourrié, R. Marty, and L. Rivoire

The OBS team of CNRM is regularly solicited by space agencies (CNES, ESA, EUMETSAT) to express our future needs regarding future space-based remote sensing instruments. Quantitative feedbacks are often expected in terms of benefits on the quality of our forecasts in order to answer questions, for instance: (i) what revisit rate and what spatial resolution will you need? (ii) would you accept observations of less good quality if you get more of them? (iii) which wavelength do you prefer? ...

Some answers to these questions can be provided on an objective basis, thanks to dedicated numerical experiments allowing the evaluation of the impact of future space-based systems in addition to the currently available observations. These experiments are called Observing System Simulation Experiments (OSSE). Thanks to several past research projects, in partnership with EUMETSAT and ESA, CNRM gained in experience in the design of this kind of framework, which is unique in Europe.

Presently, three OSSEs projects are ongoing with the global forecast model ARPEGE. The first one, conducted with the support of CNES, deals with the preparation to the assimilation of the hyperspectral infrared sounder IASI-NG onboard of the next generation of Low Earth Orbiting satellites MetOp-SG and its impact on weather forecasts. The second project, also conducted with the support of CNES, deals with a Phase 0 called CMIM for Constellation of MIni sounders for Meteorology; it consists of studying the impact of different miniaturized infrared and microwave sounders. The third project, conducted with EUMETSAT, consists of studying the impact of the number of satellites and their orbital planes within a constellation of microwave sounders for the EPS-sterna project. This constellation will be proposed by EUMETSAT to its member states as a complement of the MTG and EPS-SG programs, with our OSSE results in support of the project.

5

# Ensemble nowcasting for flash flood prediction

François Bouttier

Improving forecasts of high precipitation events and flash floods at up to six hour range is a key Météo-France objective, which is being pursued in partnership between Météo-France (as provider of precipitation forecasts) and INRAE[1] and Gustave Eiffel University (as hydrological modelling experts), with DGPR[2] support.

Current flash flood models are usually driven by observed precipitation, not forecasts. This study aims to improve forecasts by a probabilistic approach to cope with high rain prediction uncertainties in terms of timing, intensity and location. A new coupled atmospheric/hydrological ensemble forecasting suite has been set up based on the Météo-France PIAF rainfall nowcasting system (which blends radar data with AROME-NWC atmospheric numerical predictions). It has been evaluated over a large sample of high Mediterranean precipitation events using the SMASH hydrological model that is geared towards flash flood event warnings. Results show that this coupled forecasting system outperforms an observation-based approach, it can be further improved and it is technically well suited for future operational application in flash flood and inundation alert systems.

*1. Institut national de recherche pour l'agriculture, l'alimentation et l'environnement*
*2. Direction Générale de la Prévention des Risques*

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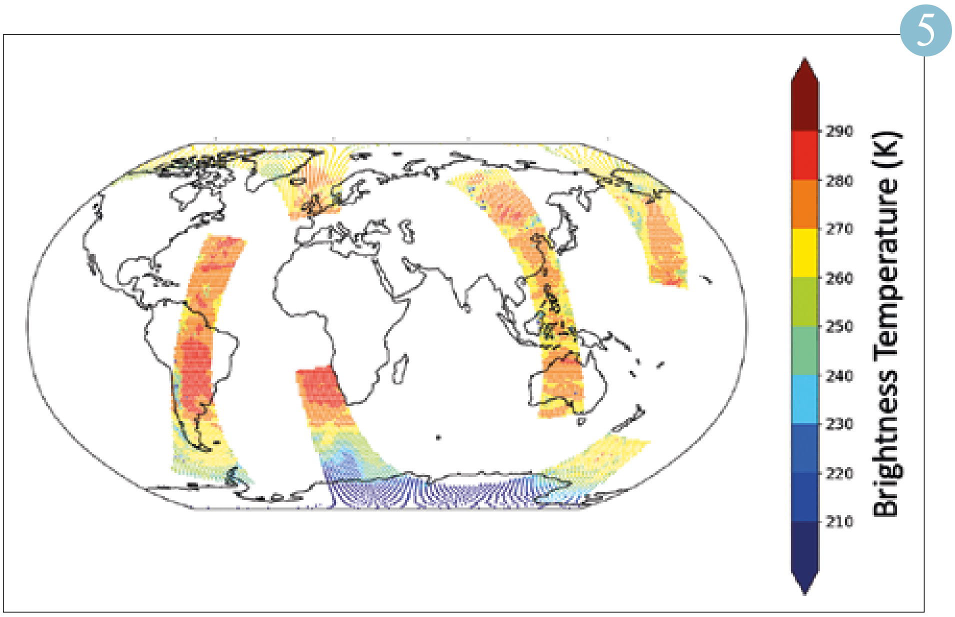
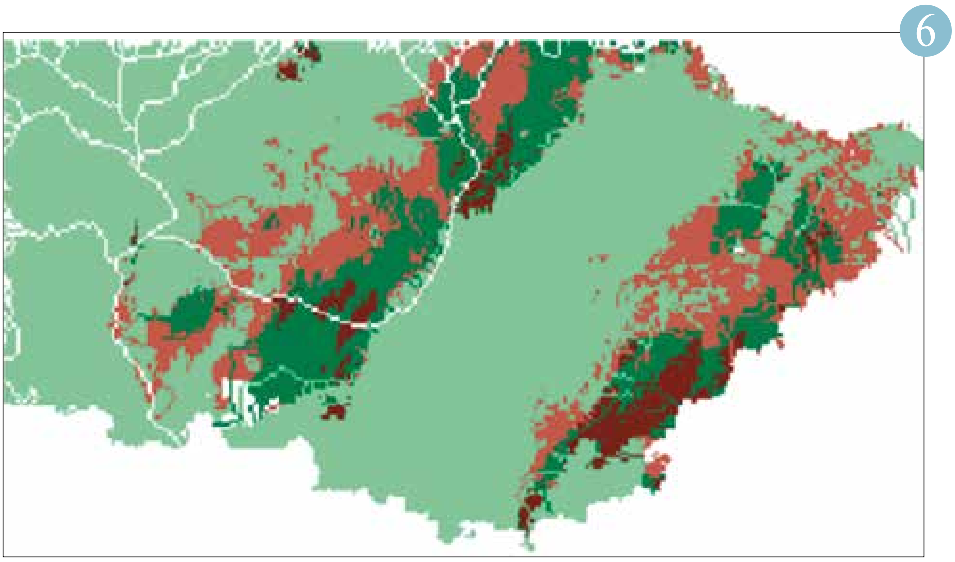



Example of radiative transfer simulation at the 176 GHz frequency of 4 satellites of the EPS-Sterna constellation, based on the ARPEGE global model.




Kilometric-scale mapping of runoff prediction success rates based on a quantile of the hydrological forecast ensemble, over a high precipitation event in southeastern France. Dark green: hit of high runoff prediction, violet: miss, burgundy: false alarm. (credit: J. Godet, INRAE).

## Predictability of torrential rainfall on 16-17 september 2022 over Guadeloupe during tropical storm Fiona

Olivier Nuissier

A major advance in numerical weather prediction (NWP) for overseas regions will be the implementation for operations in 2023 of 5 ensemble prediction systems (EPS) with the Arome-OM model. Since 2020, probabilistic products from such prototypes have already been made available to forecasters, in real time, to help better quantify uncertainty for meteorological hazards.

Fiona was an atypical cyclonic phenomenon with tremendous rainfall activity concentrated behind the center of the storm (Fig. 1a). During the night of 16 to 17 September 2022, Guadeloupe received near record rainfall (> 100 mm in 1 hour) on Southern Basse-Terre (Fig. 1b). One person died from the flooding of the Rivière des Pères in Basse-Terre.

The work presented here proposes an original approach, called "object", to quantify the uncertainty on the structure of cyclones. The forecasts of the cyclonic center of the different members are then grouped using the same trajectory scenario (here the observed track). Figure 1d shows that the calculation of a storm-relative upper 10$^{th}$ percentile targets much better the risk of very heavy rains over Southern Basse-Terre, unlike the classic approach of calculation in grid point strongly impacted by the spatio-temporal variability (Fig. 1c).

Beyond the analysis of the predictability of high-resolution processes within tropical cyclones, this work will help to facilitate the handling and use of this high-resolution EPS by forecasters in an operational framework.

7

## Operational forecasting of the meteorological effect of solar eclipses

Jean-Marcel Piriou, Yann Michel, Marie Cassas, Adrien Marcel

Following the request of Météo-France users in the energy field, the CNRM/GMAP is preparing for the next parallel suite of the ARPEGE-AROME forecast model to take into account all solar eclipses (total, partial, annular). The solar radiation entering at top of atmosphere is reduced by the degree of solar obscuration, at each time step of these models, to take into account the 3D non-linear effect of eclipses on temperature, wind, cloud cover, etc. For the recent partial eclipse of October 25, 2022 from France to Russia, such predictions have been made, we present on the figure the impact of the eclipse on this case. The eclipse reduces the temperature, it also lowers the wind force, as the atmospheric boundary layer becomes more stable. It has a triple effect on the electricity consumption: increase of consumption by decrease of the temperature, decrease of the photovoltaic production, decrease of the wind production.

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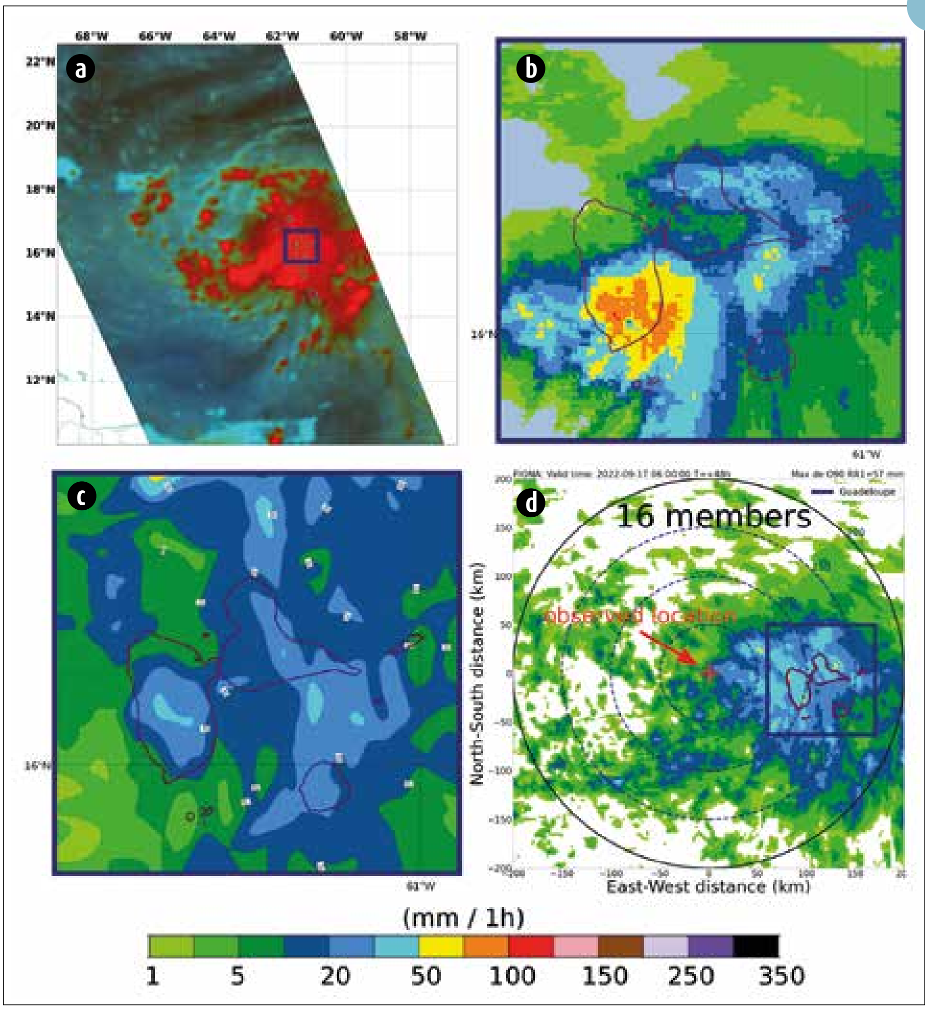


(a) GMP/GMI satellite image at 89 GHz for 09/17/22 at 07:40 UTC, (b) 1h- accumulated rainfall from Antilope observed on 09/17/22 at 06 UTC,
(c) upper 10th percentile of the 1h- accumulated forecast rainfall calculated at classical grid points and valid on 09/17/22 at 06 UTC
and (d) as in c) but in the storm-relative framework.
The point (0,0) indicates the center of all cyclones in each member of the ensemble relocated on observation.

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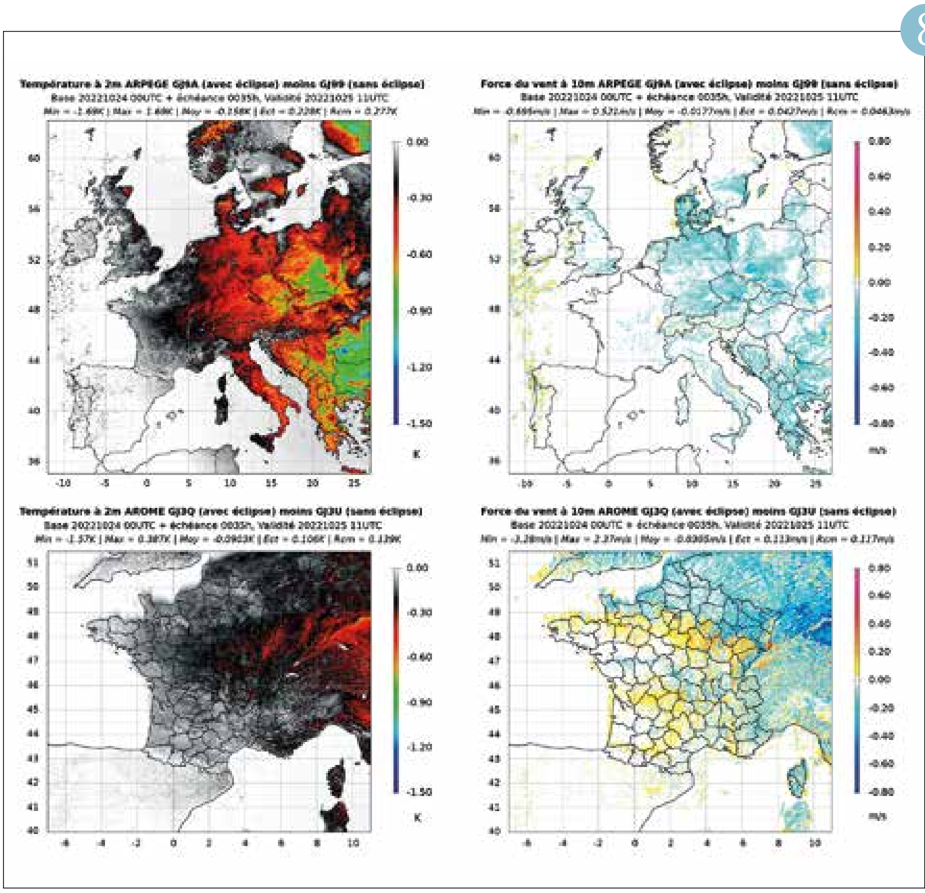

Temperature and wind impact of the eclipse of October 25, 2022, predicted by the global model ARPEGE (top thumbnails) and AROME-France (bottom thumbnails).
On the LHS, impact in temperature of the eclipse at 11 UTC on October 25, 2022. On the RHS, impact in wind force at this time.

# Process studies and modelling

**Research process studies aim to improve the understanding of phenomena and their representation in numerical weather prediction and climate models, up to the design of weather and climate services. Process studies are generally based on a complementary approach between observation and modelling: fine-scale numerical simulations, validated by observations, provide a detailed description that allows a better characterization of the processes, and thus a better representation in larger-scale models.**
**An essential objective for numerical weather prediction is to improve the representation of meteorological issues. Among them, long-lived thunderstorms associated with supercells are particularly violent and present a characteristic signature well observed by polarimetric radars, but they are also difficult to predict. A polarimetric radar observation simulator has shown that the use of more advanced and accurate microphysical schemes improves their representation in the AROME model. Another issue is clear air turbulence for aeronautics, generally underestimated by the atmospheric models. The comparison with observations of turbulent dissipation measured by airliners has highlighted the need of a fine vertical resolution at altitude, and to improve the representation of dissipation in the turbulence parametrisation, in order to better predict these critical areas. Expectations are also high in the energy domain, such as the forecast of photovoltaic production, which is strongly dependent on the good representation of clouds. Thus, the radiation measurements by the pyranometer network of Météo-France have been used to better identify the main weaknesses of cloud forecast by the AROME model and thus to better target the physical parameterizations to be improved.**
**Understanding cloud formation is also important in a context of climate change. Modeling at hectometric resolution at the regional scale of the Landes forest offered the opportunity to better understand and quantify the impact of forest damage generated by the Klaus windstorm on the reduction of cloud cover over forest, which has also been observed over ten years of satellite images.**
**At tropical latitudes, a priority is to better characterize the periods of heavy precipitation associated with climate anomalies driving cyclonic activity. The ESPOIRS research program is thus deployed in the southwest Indian Ocean basin, based on an advanced network of water vapor and precipitation measurements. Another climatic issue is to better understand the phenomenon of shrinkage-swelling of clays to better anticipate it. An indicator has thus been established based on soil moisture produced by the continental surface model, making it possible to establish the link between drought and claims. Studies on the impact of climate change and water resource management require also long and homogeneous series of atmospheric and surface variables: CERRA reanalyses have thus been produced for the period 1984 to 2021, showing very realistic snow heights.**
**Forest fires are another key issue in the context of climate change. A coupled fire-atmosphere system has been developed, allowing to represent the feedback of fire on the atmosphere. Used at high resolution, it allows a better understanding of the atmospheric processes associated with a wildland fire.**

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## Evaluation of surface solar irradiance forecasts by the NWP model AROME

M-A. Magnaldo

Surface solar irradiance forecasts are essential to help incorporating solar energy into the electrical grid and ensure the network stability. However, the current performances of numerical weather prediction (NWP) models remain limited for solar radiation, mainly due to the complexity of correctly representing the radiative impact of clouds. We want to evaluate these performances and better understand models errors.
We focus on AROME by comparing a full year of forecasts to in-situ measurements from the network of pyranometers operated by Météo-France, relying on 168 stations. In order to characterize the cloud conditions corresponding to solar irradiance observations, cloud satellite products developed by the Eumetsat SAF NWC, based on geostationary observations, are used. We can thus associate surface solar irradiance errors in AROME to specific cloud conditions.
A first analysis shows that errors mostly occur when clouds are present in the forecasts and in the observations. To go further, a classification on cloud regimes forecasted by AROME (based on simulated cloud altitude) has shown that high clouds are on average optically too thin, implying a positive solar irradiance bias, while low clouds are generally too thick, inducing a negative bias. This highlights antagonistic behaviors depending on cloud situation, with partially compensating errors.
Several sources of errors can explain the positive bias for high clouds, such as not accounting for snow in the radiation scheme of AROME or a too fast sedimentation of ice crystals. Tests will be done with modifications in the physical parameterization in AROME in order to improve solar irradiance forecasts when high clouds are present.

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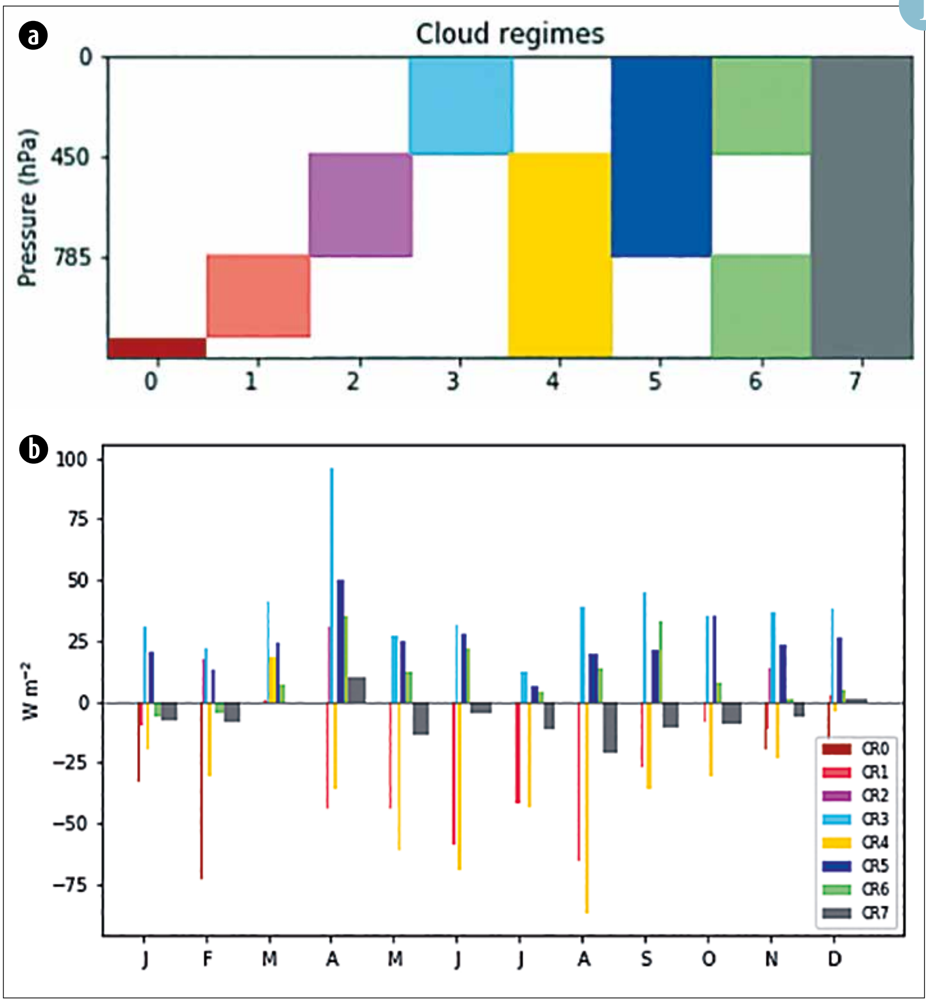


(a) Definition of the 8 cloud regimes in AROME : 7 are based on the vertical distribution of clouds, and regime 0 correspond to the presence of fog.
(b) Monthly mean surface solar irradiance bias (bar height) and relative occurrence (bar width) for each cloud regimes on year 2020.

## Study of a case of clear-sky turbulence at altitude with the AROME and Meso-NH models

Léo Rogel, Didier Ricard, Eric Bazile

Better forecasting of Clear-Air Turbulence (CAT) in stable atmospheric conditions is a major issue for aeronautical activities.

The objective of this study is to evaluate the behavior of the current parameterization of turbulence in stable layers at the tropopause level in the kilometer-resolution meteorological models used at Météo-France: the numerical weather prediction model AROME and the fine-scale research model Méso-NH.

We focus on a case of turbulence over Belgium associated with a winter jet. This clear-sky turbulence is linked to the presence of shear instabilities amplifying in a zone of reduced stability. Observations of eddy dissipation rate from line aircraft (EDR) indicate the presence of a turbulent zone at the exit of this jet, close to an upper air front, which is fairly well reproduced by simulations at kilometer resolution. However, the results also show the important impact of the vertical resolution of the models on the vertical wind shear, especially around the tropopause. The operational vertical resolution of AROME (90 levels) does not capture the CAT event.

Using simulations at hectometric resolution, a systematic deficit of turbulent mixing is diagnosed for the AROME and Meso-NH models at kilometer resolution. It is shown that this lack of turbulent mixing is mainly due to a too strong turbulent dissipation.

In terms of perspectives, it will be necessary to improve the closure of the turbulent dissipation by taking into account the strong anisotropy of the turbulence in stable conditions for these upper air phenomena.

2

## Impact of the Klaus windstorm on the boundary layer clouds over the Landes forest

Gaëtan Noual, Christine Lac, Patrick Le Moigne

Previous studies have shown that land-cover changes such as deforestation can have an impact on cloud cover and precipitation. But the results can be contradictory depending on the region of the world studied. Here, we focus on the temperate Landes forest in southwest France, during the summer period with boundary-layer clouds. The surface and the atmosphere are represented by the SURFEX and Meso-NH coupled models operating at a 500-m horizontal resolution. The system is able to represent boundary-layer clouds forming over the forest (Fig. a,b). The link between the forest and the generated clouds has been investigated, highlighting the prominent role of the larger sensible heat flux and roughness over forested areas. These key factors generate vertical motions and mixing that enable cloud formation. Finally, the damage caused by Klaus storm, which destroyed a third of the Landes forest in its central part in 2009, is considered. Fifteen summer days with clouds over the Landes are simulated and show that the damage induces a decrease in surface sensible heat flux and an increase in latent heat flux over forest (Fig. c), leading to a decrease in the amount of cloud water integrated on the vertical (Fig. d) and in the cloudiness, in agreement with the results of a previous study based on satellite image analysis. At the regional scale, recent models can thus be used to study and quantify the impact of deforestation on cloudiness.

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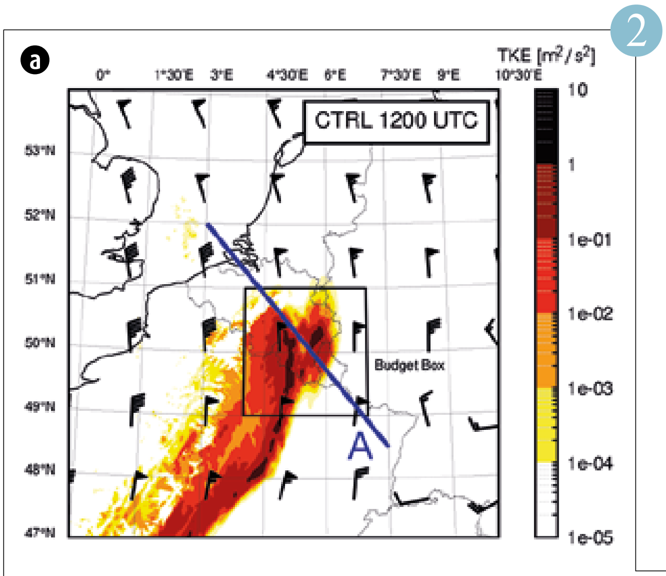
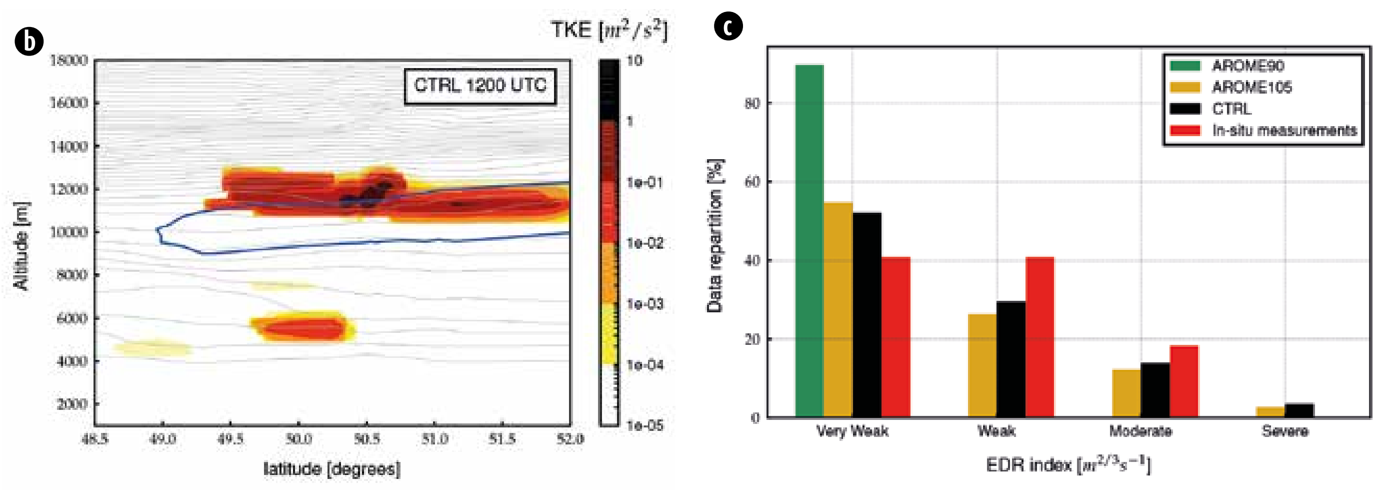
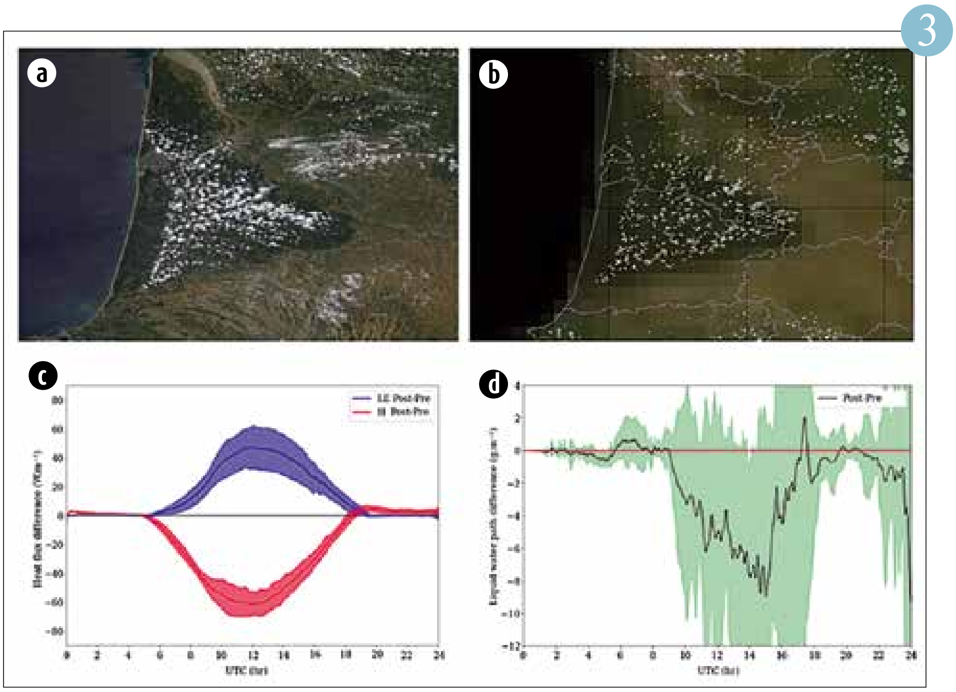



(a) Horizontal cross-section at 12 UTC on 27 January 2018 of the turbulence kinetic energy TKE (colors in m² s⁻²) at 225 hPa and wind barbs (m s⁻¹) at 250 hPa for the CTRL experiment performed with the Meso-NH model (1.3km, 105 vertical levels).
(b) Vertical section at 12 UTC along line A (shown in figure a) for the CTRL experiment of TKE (colors in m² s⁻²), isotherms (gray lines every 3 K) and wind modulus (blue line, 45 m s⁻¹).
(c) Comparison of the percentage distribution according to 4 classes (very weak, weak, moderate, severe) of the eddy dissipation rate values (EDR) between 10 and 14 UTC observed in-situ by the aircraft and from 1.3 km simulations from AROME with 90 levels (AROME90) and 105 levels (AROME105) and Meso-NH 105 levels (CTRL) in the black box (shown in figure a). Values below 0.01 m^2/3^ s⁻¹ have been filtered out.




(a) MODIS satellite image and (b) simulated cloud fraction at 13 UTC on 9 July 2013. Simulated temporal evolutions during 24 hours of the mean (in black) and standard deviation (light areas) of the difference post-pre Klaus over the Landes forest for the 15 cases of (c) sensible heat flux (red) and latent heat flux (blue) (in W m⁻² ), and (d) amount of cloud water integrated on the vertical (g m⁻²).

## High-resolution coupled fire-atmosphere simulation

Christine Lac

Forest fires represent, among the destructive natural phenomena, a major ecological stake and a problem for the safety of people and goods. Modelling realistically the propagation of a fire implies to take into account the impact of the meteorology on the propagation of the fire, but also the feedback of the fire on the atmosphere. In this context, a fire model has been developed and integrated to the atmospheric Meso-NH model. The coupled system has been first validated at high horizontal resolution (10 m) on a real case of prescribed burning on a grassland of about 30 ha (Fig. 4a). In its standard version, the Meso-NH atmospheric model is based on the anelastic assumption. This assumption removes acoustic waves in the atmosphere by neglecting horizontal and temporal variations of air density in the conservation of mass equation. The validity of this assumption is questionable in the vicinity of flame area subject to significant heat release. A new compressible version of Meso-NH, which does not consider any assumption on the air density, has been compared to the standard anelastic version in the coupled model. The results show that the compressible effects become important at very high spatial resolution (10 m), inducing an increase in the horizontal wind ahead of the fire front which tends to accelerate the propagation of the flame front, and triggering wave activity which appears realistic (Fig. b,c). At lower spatial resolution (from 25 m), the differences between the two versions become negligible, allowing to validate the use of Meso-NH in its less expensive standard version. The coupled fire-atmosphere system thus provides a suitable numerical framework to better understand the atmospheric processes associated with a wildland fire.

**Reference:**

Costes, A., M. Rochoux, C. Lac, and V. Masson : Subgrid-scale fire front reconstruction for ensemble coupled atmosphere-fire simulations of the FireFlux I experiment. Fire Safety Journal,2021,103475, ISSN 0379-7112, https://doi.org/10.1016/j.firesaf.2021.103475

Costes, A., Q. Rodier, V. Masson, C. Lac, and M. C. Rochoux, Effects of high-density gradients on wildland fire behavior in coupled atmosphere-fire simulations, J. Adv. Model Earth Syst., 14, e2021MS002955, 2022. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021MS002955

4

## Use of polarimetric radar observations to evaluate the microphysical schemes of Meso-NH on a supercell case

Clotilde Augros, Cloé David, Benoît Vié

Supercells are particularly violent long-lived thunderstorms. The quality of their forecast is partly determined by the performance of the microphysical schemes, which represent the clouds in the models. ICE3, the operational scheme of the AROME model, predicts only the mass of hydrometeors. LIMA, used for research, simulates the evolution of their mass and number. These schemes can (optionally) represent hail explicitly.

Polarimetric radar observations (notably the differential reflectivity Zdr) of supercells show characteristic signatures, such as the "Zdr arc" associated with size sorting of precipitating hydrometeors, or the "Zdr column" associated with the presence of large hail and supercooled water contents in the updraft. The realism of four Meso-NH simulations is here evaluated by their ability to reproduce these signatures for a real supercell case.

Only the LIMA scheme, which predicts the number of hydrometeors and allows us to estimate their size, is able to reproduce the arc of Zdr, with strong values localized on the edge of the supercell (Fig. a-c). To properly simulate the Zdr column, it is additionally necessary to activate the prognostic representation of hail and its wet growth by a strong collection of supercooled liquid water. This study, which shows the ability of LIMA and the radar simulator to represent the polarimetric radar signatures characteristic of supercells, will be continued by a more systematic evaluation in AROME, in order to study the interest of using these observations in the assimilation for severe thunderstorm forecasting.

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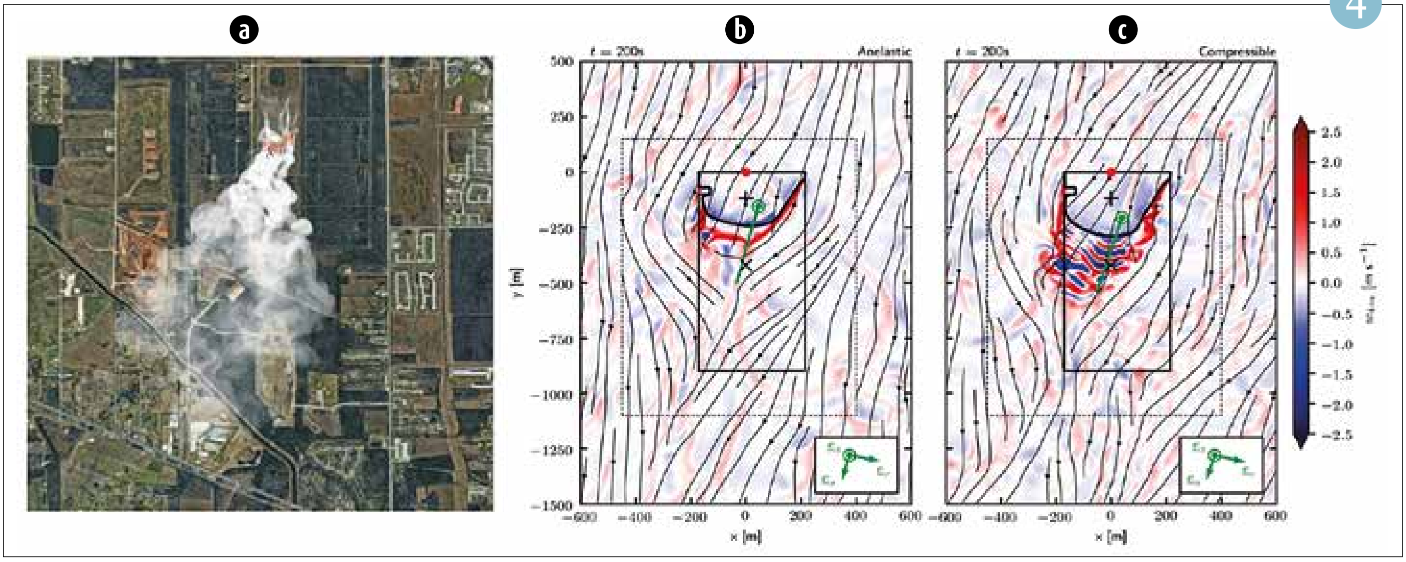


(a) Aerial view of the simulation at 10 m horizontal resolution of the fire with the flame front in red and the smoke plume in white.
(b) and (c) Simulated vertical velocity at 4 m above ground level (in m $s^{-1}$), 200 s after ignition, with the anelastic (b) and compressible (c) versions of Meso-NH.

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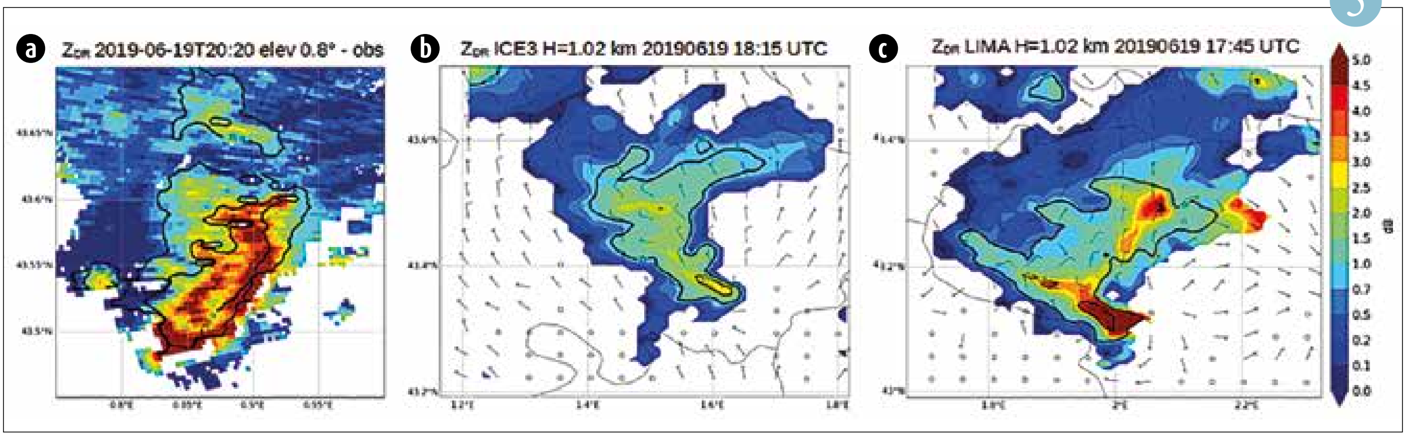


(a) Differential reflectivity Zdr (dB) observed by the Toulouse radar on 19/06/2019 at 2020 UTC at 0.8° elevation.
(b) and (c) Zdr simulated with MesoNH for ICE3 (b) and LIMA (c) simulations at 1 km AGL, zooming in on the supercell with the closest structure to the observed one.

# Investigating clay shrink-swell at the municipality scale through a drought magnitude index

Sophie Barthelemy[1], Bertrand Bonan[1], Gilles Grandjean[2], David Moncoulon[3] and Jean-Christophe Calvet[1]

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2. Bureau de Recherches Géologiques et Minières (BRGM), 3 avenue Claude Guillemin, BP 36009, 45060 Orléans Cedex 2, France
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Clay shrink-swell is the second most costly danger covered by compensation schemes for natural disasters, with more than 15 billion euro compensations since 1989. As illustrated by the 2022 drought in France, these costs are likely to increase as a result of climate change and of the related amplification of annual soil moisture cycles. In this context, new tools need to be developed in order to estimate the house insurance claim rate related to geotechnical droughts. The ISBA land surface model of Meteo-France is used in conjunction with geotechnical models and data from BRGM and with the national claim data base of CCR. First results give a better grasp of the statistical link between drought and municipality level claims. A magnitude index is derived from multi-layer soil moisture time series produced by the ISBA model. The magnitude is calculated from the yearly integral of the soil wetness index (SWI) of deep soil layers under a certain threshold value corresponding to a drought frequency. This index correlates better with the number of claims when soil moisture below a 0.4 m soil depth is considered together with low SWI threshold values. The temporal variability of superficial soil moisture is more dependent on fast meteorological events. It is also shown that vegetation inter-annual variability markedly impacts the magnitude.

6

# CERRA-Land: a new reanalysis of the land surface at a resolution of 5.5 km over Europe

A. Verrelle, M. Glinton, E. Bazile, P. Le Moigne

The Climate Change Service of the European Commission's Copernicus program aims to produce and deliver a terrestrial regional reanalysis of past climate over Europe at a horizontal resolution of 5.5 km. A reanalysis is a means of reconstructing atmospheric and surface variables for past periods covering several years.

The need to know precipitation and surface variables at an ever-increasing spatial and temporal resolution is a recurrent demand. Indeed, they allow, among other things, to address water resources management issues and to carry out climate change impact studies. Regional surface reanalyses make it possible to meet these demands.

Météo-France has worked within the framework of the CERRA project (https://climate.copernicus.eu/copernicus-regional-reanalysis-europe-cerra), based on the know-how of a previous project called UERRA (https://uerra.eu/), in collaboration with the Swedish and Norwegian meteorological services to set up the CERRA-Land system with the aim of producing realistic spatialized fields of near-surface meteorological variables. This new system is a simulation of the SURFEX land surface model developed at Météo-France covering the period 1984 to 2021 and whose input data (temperature, wind, humidity, incident solar and infrared radiation, liquid and solid precipitation) and output data (soil temperature and humidity, snow water equivalent, etc.) are available on the "climate data store" (https://cds.climate.copernicus.eu/), the storage space for climate data made available to users. A first validation (see figure) based on an observation of snow height at about 3000m altitude in the French Alps (black dots) shows that the system is able to simulate realistic snow heights (red curve).

The objective for the coming years is to continue this reanalysis activity with in particular, within the framework of the ARRA project of Météo-France, the production of 50 years of atmospheric and surface data over metropolitan France, based on data from the operational model AROME at a resolution of 1.3 km.

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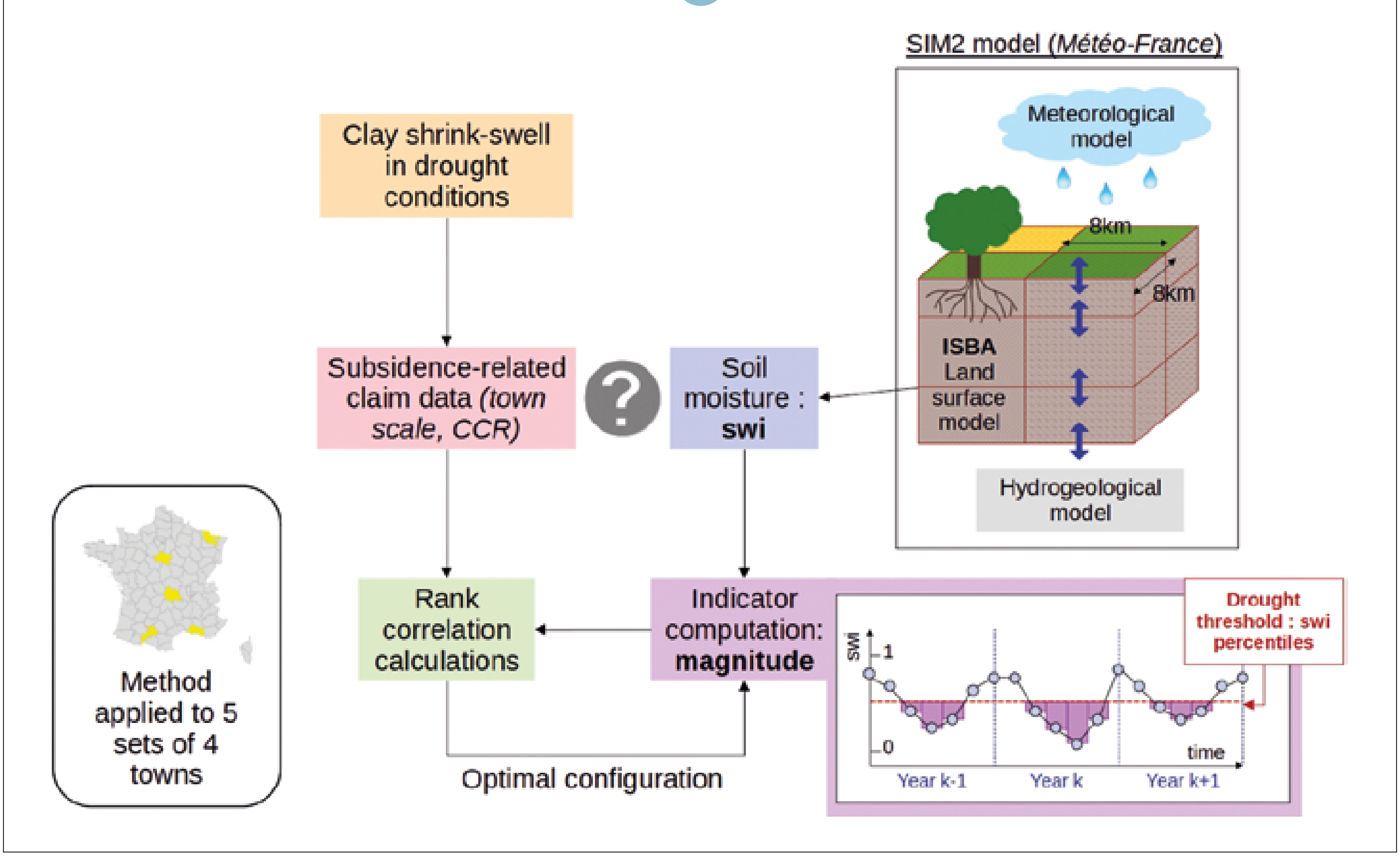


Method for calculating the magnitude drought indicator from the ISBA model and for determining the best configuration to characterize house insurance claims related to clay shrink-swell.

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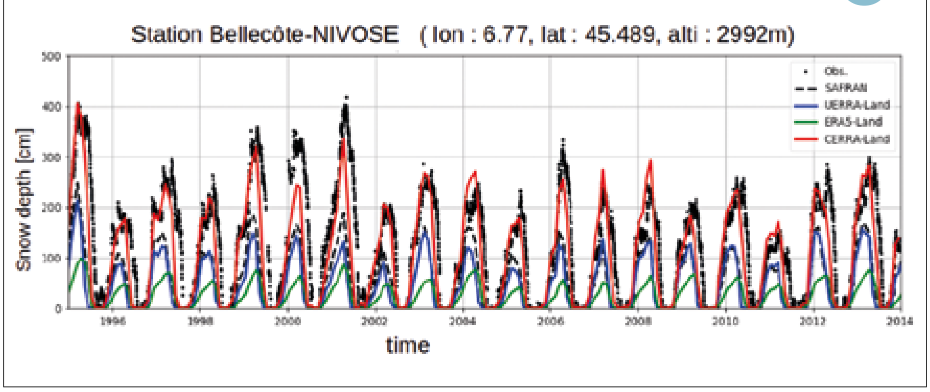


Time evolution of the observed snow depth (black dots) at the Bellecôte-NIVOSE station and simulated one by different land surface reanalysis products (lines in color).

# ESPOIRS
# Study of Precipitating Systems in the Indian Ocean by Radar and Satellites

Joël Van Baelen, Olivier Bousquet, Guillaume Lesage, Ambinintsoa Volatiana Ramanamahefa, Thiruvengadam Padmanabhan

The ESPOIRS research is a collaborative project, developed and conducted in partnership with research centers in the Seychelles, Madagascar and Reunion. This project aims to obtain a better knowledge of the variability, statistical properties and formation mechanisms of tropical precipitation at regional and local scales. ESPOIRS is thus interested in the entire life cycle of precipitation at several spatio-temporal scales. Through the analysis of the distribution of the large-scale humidity field, which drives the formation of precipitation on a regional scale, it aims to understand, and better anticipate, the appearance of periods of heavy precipitation generally associated with Climate anomalies driving cyclonic activity in the South West Indian Ocean (SWIO) Basin. By focusing on the internal (dynamics, microphysics) and external (relief interactions) processes that drive the formation and life cycle of extreme weather events at the local scale, HOPE will lead to better forecasting of highly precipitating systems. and their impacts in three study areas: Reunion, the Seychelles and the north/northeast region of Madagascar.

The ESPOIRS project is structured around three major actions.

The first action aims to improve our understanding of the water cycle in the SWIO basin in order to better understand its impact on the formation of precipitation at regional and, to a lesser extent, local scales. This action is essentially based on the use of observations collected by the GNSS water vapor observation network deployed by LACy and its partners throughout the Indian Ocean.

The second action aims to improve our understanding of the mechanisms of formation of intense precipitation at the local scale by precisely documenting the physical and statistical properties of the precipitating systems on three distinct islands with very marked relief (Réunion, Mahe, Madagascar). This action is based on the implementation of a dedicated cloud and precipitation observation strategy based on a new unique X-band precipitation radar in the SWIO region.

The third action aims to strengthen regional expertise in the field of remote sensing and tropical meteorology in collaboration with LACy partner universities in the Indian Ocean area. It is based on the implementation of training and teaching actions, backed by communication actions aimed at the general public, professionals and the scientific community, making it possible to strengthen research and operational capacities in the SWIO sub-region. It also aims to provide territorial managers with leads for the definition of innovative decision-making support tools.

**Reference:**

Ramanamahefa, A.V., T. Padmanabhan, G. Lesage, M-A. Mant, O. Bousquet, and J. Van Baelen, 2022: LACy X band meteorological radar 2022 observations of cyclonic rains in La Réunion, 11th European Conference on Radar in Meteorology and Hydrology (ERAD), Locarno, Switzerland, Aug. 29 – Sept. 2, 2022.

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(a) ESPOIRS instrumental setup in SWIO and
(b) LACy's ESPOIRS research X-band meteorological radar in Saint-Joseph, La Réunion.

# Climate and seasonal forecast

**The year 2022 was the warmest year on record in France, with an average temperature over the country of 14.5°C, close to the level expected for 2050. With its three summer heat waves, 2022, which was also dry and sunny, easily beat the previous record set in 2020. This new record is consistent with the long-term warming observed over the past half-century, which appears to be faster than that simulated by the regional climate models of the EURO-CORDEX ensemble. This observation has motivated work to adjust future projections using observations to date. Thus, the warming estimate for 2100 has been revised upwards, approaching +4°C compared to 1900 in a median greenhouse gas emission scenario. New studies based on the DRIAS-2020 dataset complete this picture and confirm, in particular, the future increase in the number and intensity of heat waves, as well as a worsening of meteorological droughts, particularly in summer, and of soil droughts throughout the year, with these changes being all the more pronounced as future greenhouse gas emissions are high. These estimates for France and the overseas territories need to be regularly updated in the light of new knowledge, observations and modelling advances. For this purpose, Météo-France has a unique capacity in France to model past and future climate changes from the global to the local scale with a coherent range of models, over periods ranging from a few weeks (sub-seasonal variability and its forecasting) to a few centuries, in particular to provide input for the IPCC assessment reports. Global climate models are the only ones capable of estimating past and future climate change based solely on the evolution of human and anthropogenic forcings. However, they need to be complemented by higher resolution models, which explicitly represent some phenomena whose evolution needs to be estimated in relation to climate change, in particular to feed adaptation strategies. For example, a high-resolution ocean model configuration that takes into account the effect of tides, storm surges and wave processes, as well as their interactions, has been developed in collaboration with Mercator Ocean International in order to provide better information on future sea level rise over the western coast of Europe. Concerning km-scale atmospheric modelling, a previous study conducted with AROME was generalised by exploiting simulations of other convection-permitting models in the framework of the CORDEX FPS-Convection project, resulting in robust messages on the increase in the number, maximum intensity and size of convective cells. However, the simulations studied are rather short due to the computational cost of this generation of models, which hampers the estimation of uncertainties. For this reason, innovative work on downscaling emulation was initiated at CNRM several years ago. This work, which was completed in 2022, has demonstrated that emulating the link between global and regional scales allows to correctly represent the daily variability and mean values of temperature and precipitation. The aim of this work is to achieve spatial resolutions such as those of AROME at a negligible computing cost, and therefore a much more frugal use of computing resources.**

## Climate modelling

### Combining models and observations to assess past and future warming over France

Aurélien Ribes

In order to provide the best possible estimate of past and future warming, the 6th IPCC report (2021) relied on new statistical methods that combine models and observations. In practice, these techniques determine which climate trajectories are consistent with recent observations.
In a recent study, one of these statistical methods has been used to improve estimation of the long-term warming over metropolitan France. The results suggest that, relative to 1900-1930, the warming reaches +1.7°C in 2020 (and +1.8°C in 2023). Almost all of this warming is anthropogenic. However, until the 1980s, the warming effect of greenhouse gases (GHGs) was largely offset by the cooling effect of aerosols (particles suspended in the atmosphere), giving a false impression of stability. Since then, France has experienced rapid and pronounced warming.
According to this new study, the expected warming in the 21st century amounts to +3.8 [2.9 to 4.8] °C in 2100 compared to the 1900-1930 baseline, in an intermediate emissions scenario (SSP2-4.5; i.e., 2°C above the current climate). Depending on the scenario, the warming ranges from +2.3 [+1.5 to +3.1] °C (low emissions) to +6.7 [5.2 to 8.2] °C (very high emissions). In all scenarios, the expected warming in France is higher than the global average (about +20%); it is higher in summer (about +30% compared to the annual mean) than in winter (about -15%). These estimates represent an upward revision of those derived from previous generations of climate models, and place the expected warming over France in the upper range simulated by the current models.
These results are part of the long-term progress in the knowledge of climate change, and will feed the development of adaptation strategies.

**Reference:**

Ribes, A., Boé, J., Qasmi, S., Dubuisson, B., Douville, H., and Terray, L.: An updated assessment of past and future warming over France based on a regional observational constraint, Earth Syst. Dynam., 13, 1397–1415, https://doi.org/10.5194/esd-13-1397-2022, 2022.

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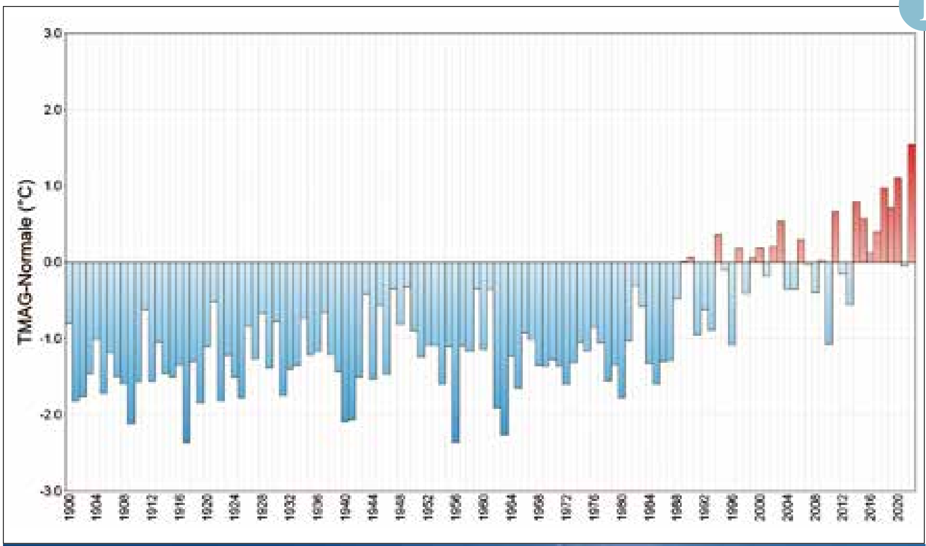


Deviation from the 1991-2020 reference annual mean temperature over France (1900 to 2022). Météo-France.

The "Lac de l'Entonnoir" dried up, in Bouverans, in the Doubs department, on 3 August 2022. afp.com/SEBASTIEN BOZON

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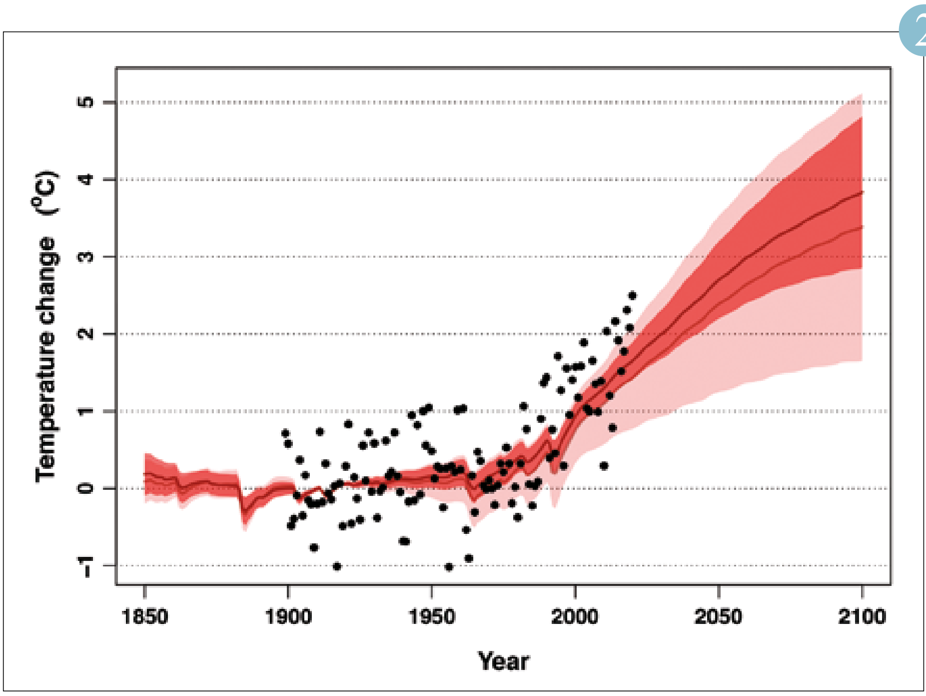


Change in annual mean temperature in mainland France between 1850 and 2100, relative to the 1900-1930 baseline, in an intermediate GHG emissions scenario (SSP2-4.5). Warming simulated by the latest generation of global models (CMIP6) : mean (light brown) and 5-95% confidence interval (pink).
Warming estimated by combining models and observations: mean (dark brown) and 5-95% confidence interval (red).
Black dots: Meteo France observations of annual mean temperature in France for each year between 1899 and 2020.

# Evaluation of the ARPEGE-Climat model using IASI observations

L. Leonarski, Q. Libois, R. Roehrig

Reproducing the radiative budget of the climate system, accounting for all its complexity (solar/infrared spectra, clear/cloudy sky, spatial structures), is a critical constraint for climate modelling. Climate models are usually evaluated using broadband observations of this budget. However, the spectral distribution of radiation, already observed by spaceborne infrared sounders, contains a huge amount of information about the atmospheric state. It is the case of IASI, developed by CNES with Eumetsat and which is already widely used within the numerical weather forecast community. We analyze here the added value of these spectrally-resolved measurements for climate model evaluation in the frame of a CNES project.

The radiative transfer software RTTOV is used to simulate millions of IASI-like spectra based on atmospheric and surface properties provided by the ARPEGE-Climat model and covering 2008-2014. These spectra are compared to IASI measurements in clear-sky conditions (figure a). This comparison emphasizes the spectral structure of the model biases (figure b) related to errors in the representation of geophysical variables (e.g., temperature, humidity) by ARPEGE-Climat. The spatial distribution of the bias for three specific wavenumbers is depicted in figure c. For example, it suggests that surface temperatures are too cold at high latitudes over land and above elevated terrain. The atmosphere is also generally too dry in tropical regions.

Hyperspectral infrared measurements are promising to better document the systematic errors of climate models. The future satellite mission FORUM (Libois et al., 2020) will cover the full range of the Earth emission spectrum, allowing for a better constraint on the energy budget simulated by climate models.

**Reference:**

Libois, Q., Labonnote L. C., & Camy-Peyret, C. (2020). Forum mesurera l'infrarouge lointain émis par la Terre. La Météorologie, (108), 4-6, https://hal.archives-ouvertes.fr/hal-03187068

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# A hybrid downscaling approach to provide a reliable information on local climate change

Antoine Doury, Samuel Somot

An essential challenge for the climate science community is to provide trustful information about the local impacts of global warming. Climate models are the main tool to study climate evolution according to human activities and greenhouse gas emissions scenarios. They are a numerical representation of the Earth System. Global climate models (GCM) produce worldwide simulations at too low resolution to correctly represent extreme meteorological events that strongly impact our societies. Today we use dedicated regional climate models (RCM) that transform a global low-resolution simulation into a high-resolution one over an area of interest. Nevertheless, the high resolution of those models implies a (much) higher cost that strongly limits the number of those climate simulations and, thus, the necessary exploration of the different sources of uncertainties.

To tackle this limitation, a recent study [1] proposes a strategy to recreate, at low-cost, high-resolution simulations from low-resolution ones. The RCM-emulator introduced here aims to estimate the downscaling function included in a RCM using the recent development of neural networks. This study introduces the concept of RCM-emulator and presents a framework to build, train, and evaluate it. The main result of this study is that the RCM emulator is a credible approach to take up this challenge. Indeed it shows an excellent ability to create realistic high-resolution temperature and precipitation fields, consistent with the low-resolution simulation it downscales. We also study the applicability of the tool the various low-resolution simulations. Moreover, because it only focuses on the RCM downscaling function, the emulator does not reproduce the eventual biases introduced by the RCM.

The conclusions of this study open the door to further development and various promising applications. Indeed, the RCM-Emulator makes possible the production of robust messages about the local impacts of climate change. Moreover, another significant result of this work is that the emulator performance relies strongly on the calibration set. It is then essential to design the best simulation set to have the most robust emulator implying maybe to revisit the way of choosing which simulation to make with a RCM.

**Reference:**

Doury, A., Somot, S., Gadat, S. et al. Regional climate model emulator based on deep learning: concept and first evaluation of a novel hybrid downscaling approach. *Clim Dyn* (2022). https://doi.org/10.1007/s00382-022-06343-9

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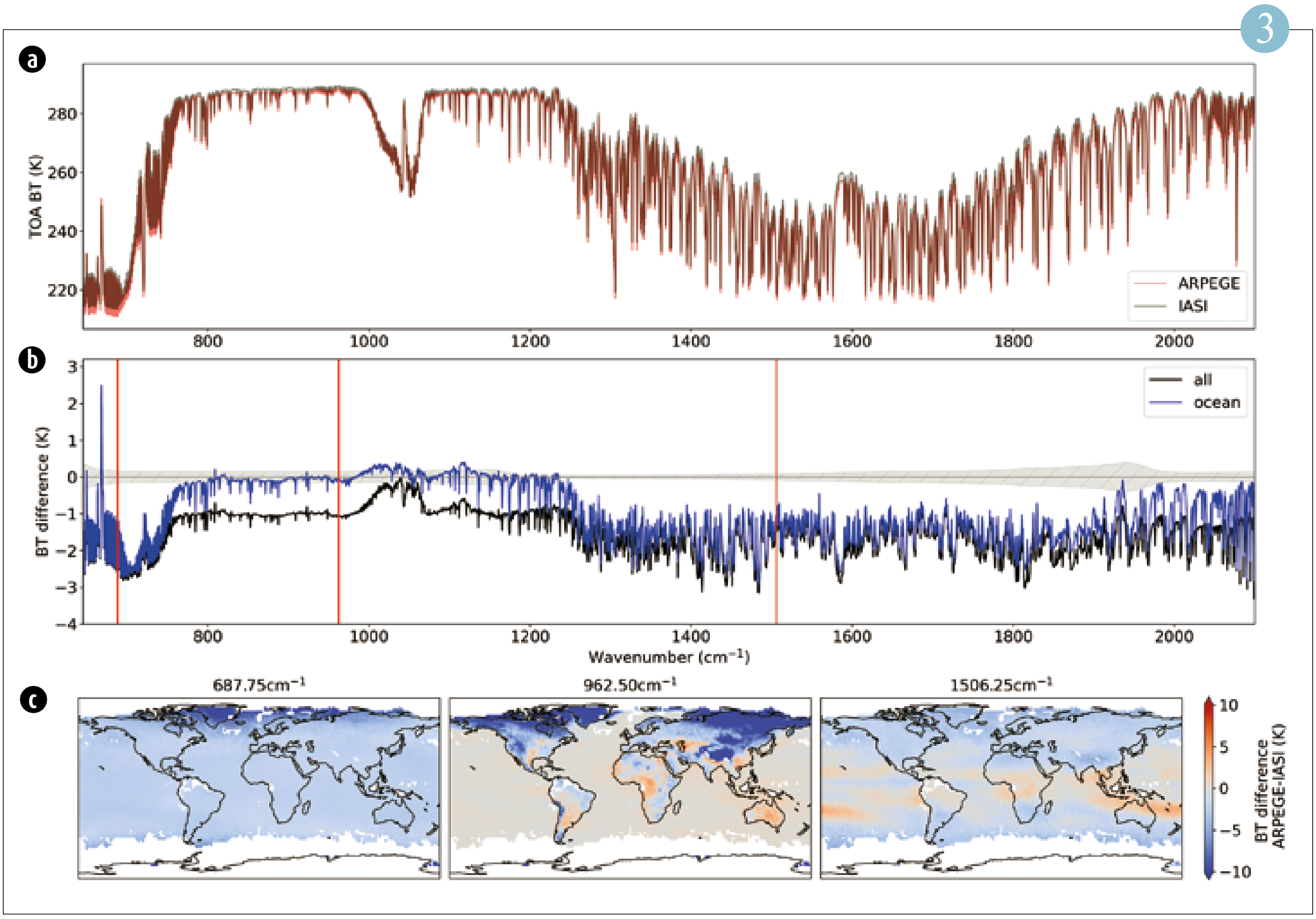


(a) Global mean brightness temperature spectra (2007-2014) measured by IASI (red) and simulated using ARPEGE-Climat model outputs (black) for clear-sky conditions.
(b) Difference between the mean ARPEGE-Climat simulated spectrum and that measured by IASI, for global averages (black) and over ocean surface only (blue).
The IASI instrumental noise given at the 280 K reference temperature is indicated by the gray shading.
(c) Spatial distribution of the mean brightness temperature difference between ARPEGE-Climat simulations and IASI measurements for the three wavenumbers indicated in red in figure b.

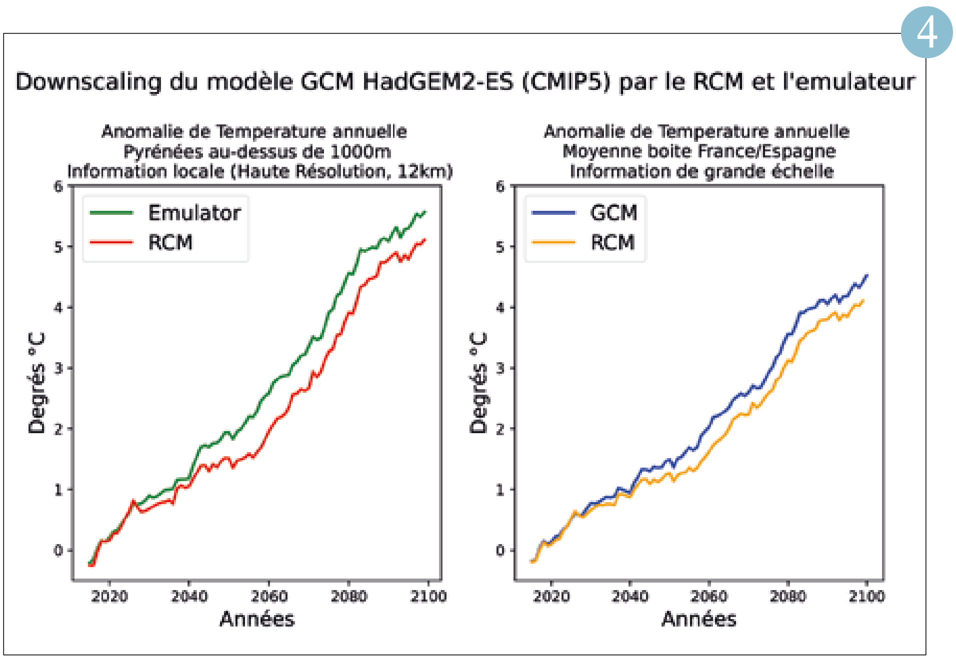


Illustration of the emulator performances for the downscaling of the low-resolution climate model HadGEM2-ES (CMIP5, RCP85). The left panel shows the anomalie of anual temperature over the mid and high altitude Pyrénées points from the RCM and the emulator. The right panel shows the same anomalie for the RCM and the GCM over a large scale box centered on the Pyrénées and coverin both France and Spain. The RCM high resolution allow to properly represent the elevation dependant warming, which is well captured by the emulator. It is also remarkable that the emulator produces a stronger warming (+0.5°C at the end of the century) on the Pyrenees. This is coherent with the one observed on the large scale box between RCM and GCM. It seems then that the emulator is more coherent to the GCM warming level bringing on top the high resolution information brought by the RCM.

# Climate change impacts the vertical structure of marine ecosystem thermal ranges

Yeray Santana, Roland Séférian

Ocean temperatures play a key role in the geographical distribution of marine biodiversity through the thermal tolerance of marine organisms.
Climate change induced by human-induced greenhouse gas emissions is predicted to alter the marine thermal environment, affecting the habitability of the ocean for marine ecosystems.
Current knowledge suggests an expansion of marine ectotherms, such as fish, into high-latitude oceans in search of cooler waters, but research has relied mainly on surface observed or modelled temperature data.
In this new study, published in September 2022 in Nature Climate Change (https://www.nature.com/articles/s41558-022-01476-5), we fill this gap by examining the vertical structure of sea surface environmental heat envelopes at 1000 m depth at six long-term ocean stations providing near-daily measurements over 10 years.
Using recent model simulations of CNRM-ESM2-1 at these ocean sites, the authors were able to estimate the time horizons over which climate change will induce substantial shifts in the environmental thermal envelopes to which marine organisms are currently adapted.
The simulations show that these changes emerge below 50 m depth in the coming decades with high anthropogenic emissions, but are delayed by several decades if emissions are reduced.
Model simulations show that by the end of the century, simultaneous changes in thermal envelope boundaries could expose pelagic ecosystems to thermal environments never before experienced, while surface ecosystems could experience changes of lesser magnitude due to the large thermal envelope's characteristic of surface biomes.
Thus, this work reveals a much more complex picture on how human-made climate change will impacts marine ecosystems when the vertical dimension is added due to differential alteration of marine thermal envelopes across the water column.

**Reference:**

Santana-Falcón, Y., Séférian, R. Climate change impacts the vertical structure of marine ecosystem thermal ranges. *Nat. Clim. Chang.* 12, 935–942 (2022). https://doi.org/10.1038/s41558-022-01476-5

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# Mediterranean events and climate change: first results from a set of kilometre-scale climate models

Caillaud C., Somot S., Douville H., Alias A.

The Mediterranean heavy precipitation events that affect south-eastern France in the autumn are extreme events with strong impacts. The already observed increase in these intense precipitations (Ribes et al. 2019) encourages to take an interest in their future evolution.
In recent years, it has been possible to use a new generation of climate models with kilometre resolution (2-3km), which has demonstrated a strong added value for representing Mediterranean events compared to the coarser gridded models used previously (Pichelli et al. 2021, Caillaud et al. 2021). Thanks to the CORDEX Flagship Pilot Study on Convection programme, a first set of a dozen of 10-year simulations is available for the historical period and for the RCP8.5 high emission scenario mid-century and end-of-century periods, over a domain covering the northwestern Mediterranean. An object-oriented approach is used to study the characteristics of these heavy precipitating systems. Although there is sometimes a strong dispersion between the responses of the different simulations for the end of the century, the multi-model approach indicates, with a good general agreement, an increased frequency of intense autumn rainfall events over the northwestern Mediterranean, as well as a spatial extension of the areas potentially affected by Mediterranean events (cf. figure). Over south-eastern France, the mean and maximum intensity, area, volume and severity are expected to increase, but there is little change in duration or movement speed. However, the short duration of the simulations (10 years) is a limiting factor for providing robust answers to the evolution of these extreme events. In the coming years, longer and more numerous simulations of these high-resolution climate models should help to remedy this.

**Référence :**

Ribes, A. et al. (2019). Observed increase in extreme daily rainfall in the French Mediterranean. *Climate dynamics*, 52(1), 1095-1114. https://doi.org/10.1007/s00382-018-4179-2

Pichelli, E. et al. (2021). The first multi-model ensemble of regional climate simulations at kilometer-scale resolution part 2: historical and future simulations of precipitation. *Climate Dynamics*, 56(11), 3581-3602. https://doi.org/10.1007/s00382-021-05657-4

Caillaud, C., Somot, S., Alias, A., Bernard-Bouissières, I., Fumière, Q., Laurantin, O., ... & Ducrocq, V. (2021). Modelling Mediterranean heavy precipitation events at climate scale: an object-oriented evaluation of the CNRM-AROME convection-permitting regional climate model. *Climate Dynamics*, 56(5), 1717-1752. https://link.springer.com/article/10.1007/s00382-020-05558-y

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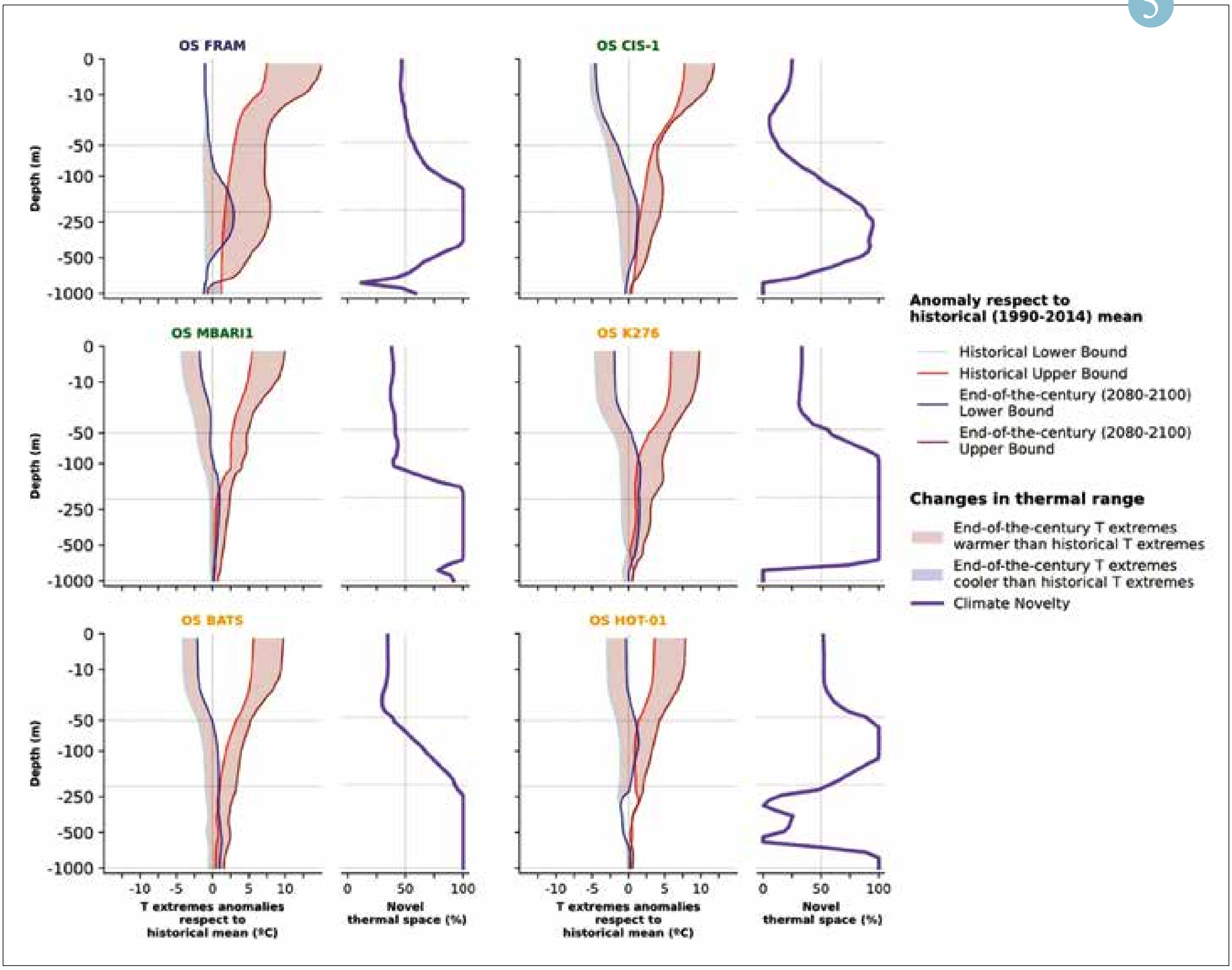
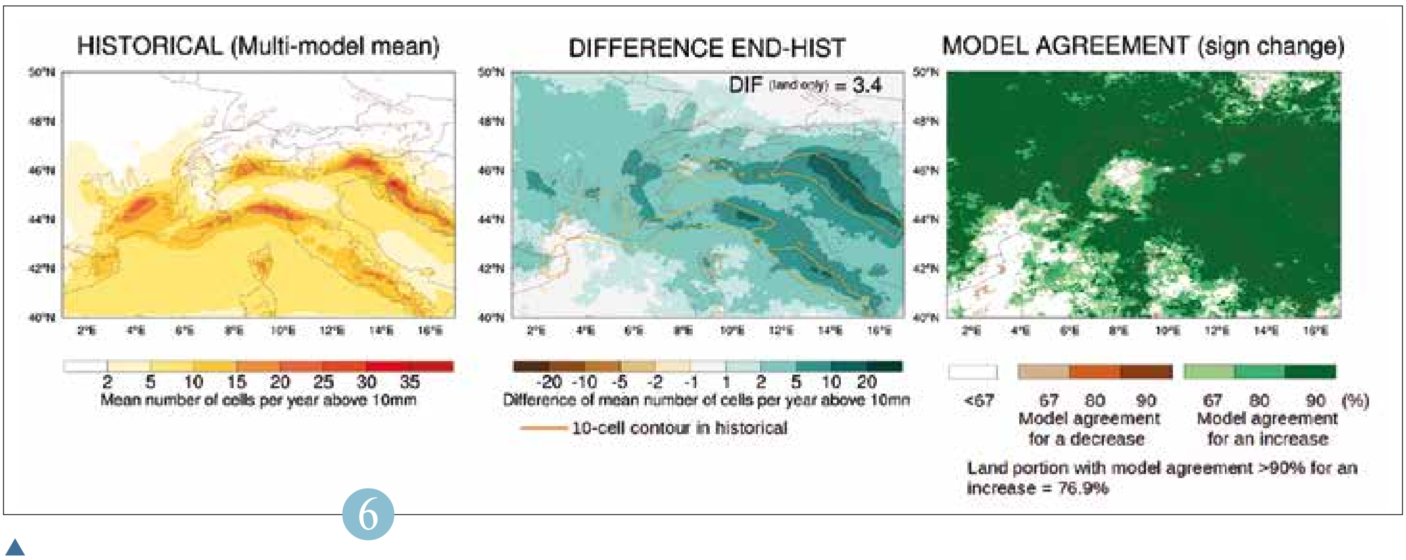



Change in simulated thermal envelopes' boundaries for the end of the century (2080-2100) under a high greenhouse gas emission scenario compared to their current characteristics. The panels to the right of each profile illustrate how much the thermal envelope at a given depth will be transformed due to climate change (also defined as climate novelty).




Spatial distribution of precipitating systems above 10mm/h for an extended fall season (September to December). The first figure shows the mean for the FPS on Convection multi-model ensemble for the historical simulations (1996-2005). The second figure shows the differences between the end-of-century (2090-2099, RCP8.5) and historical simulations. The last figure presents the agreement of the models on the sign of expected change at the end of the century.

## Advancing climate modelling using kilometer-scale weather forecasts

S. Blein, R. Roehrig, A. Voldoire, G. Faure

Atmospheric models used for global climate simulation have a horizontal resolution (grid box) of the order of 100 km. A whole range of atmospheric physical processes of smaller scale (such as turbulence or convection) are therefore not explicitly resolved. However, their effects on the resolved scale are not negligible.

The work presented here is based on the kilometer-resolution weather forecast model AROME, implemented by Météo-France over France and several overseas territories. These simulations offer a unique database to go beyond a few case studies and thus develop some parameterizations based on a wide variety of atmospheric conditions. A parametrization is a simplified representation of physical processes which are not explicitly resolved in a numerical model. In this work (see references), the AROME forecasts over the Indian Ocean and the West Indies are used as a reference to quantify and develop a parameterization, at the scale of a climate model grid cell, of the impacts of mesoscale phenomena (typically from 1 to 10 km) on air-sea interactions. These phenomena correspond for example to isolated or organized convective systems, or to dynamic processes associated to meteorological fronts. Exchanges of momentum, energy and water at the air-sea interface are amplified to first order by the impact of these phenomena on the near-surface wind, often leading to an intensification of these exchanges by more than 10% (and up to a factor of 10 in some cases) compared to estimates that ignore these impacts. Such an effect is currently not taken into account in climate models. The database of several months of AROME forecasts allows us to build a robust parameterization, combining both physical (choice of predictors) and statistical (objective predictors selection, statistical modeling) bases.

The parameterization is performing well and will be implemented and tested in the CNRM climate model (ARPEGE-climat). The objective is to increase the realism of the fluxes at the air-sea interface, which will probably have impacts on the performance of the model (climatology, variability).

**Reference:**

Blein, S., R. Roehrig, and A. Voldoire, 2022: Parameterizing the mesoscale enhancement of oceanic surface turbulent fluxes: a physical-statistical approach. *Quarterly Journal of the Royal Meteorological Society*. https://doi.org/10.1002/qj.4273

Blein, S., R. Roehrig, A. Voldoire and G. Faure, 2020: Meso-scale contributions to air-sea fluxes at GCM-scale. *Quarterly Journal of the Meteorological Society*, 146(730), 2466-2495. https://doi.org/10.1002/qj.3804

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## Future evolution of extreme sea levels events along the European coasts

A. Chaigneau, A. Voldoire, A. Melet, G. Reffray, S. Law-Chune, L. Aouf

Studies based on global climate models show that sea level events that occurred once a century over the 20th century will happen once every two years by the end of 21st century over many regions. Such studies are based on relatively coarse models that do not represent all processes contributing to the sea level evolution: at best they take into account the large-scale ocean circulation evolution, the cryosphere melting and the ocean thermal expansion. However, to properly estimate the evolution of mean sea level and its extremes over the western European coasts, more processes have to be considered such as tides, storm surges, waves and their interactions. To this aim, a specific model framework has been built up in cooperation between Météo-France and Mercator Ocean. This framework consists in a regional configuration at 6 km resolution of the NEMO ocean model designed at Mercator Ocean and called IBI-CCS (Chaigneau et al., 2022a), and in a regional configuration at 10km of the MF-WAM wave model developed at Météo-France and called IBI-CCS-WAV (Chaigneau et al., 2022b). Based on global climate projections produced with the CNRM-CM6-1-HR model, this new tool has shown that including all these processes is necessary to properly estimate the change in mean and extreme sea level at the European scale. More specifically, it has been highlighted that past sea level variability was well estimated only if all processes are considered. A proper estimation of sea level variability is also key to assess the amplification of extreme sea level events over the 21st century.

**Reference:**

Chaigneau A., G. Reffray, A. Voldoire, and A. Melet, 2022a, IBI-CCS : a regional high-resolution model to evaluate western Europe sea level changes, *Geosci. Model Dev.,* 15, 2035–2062, DOI:10.5194/gmd-15-2035-2022.

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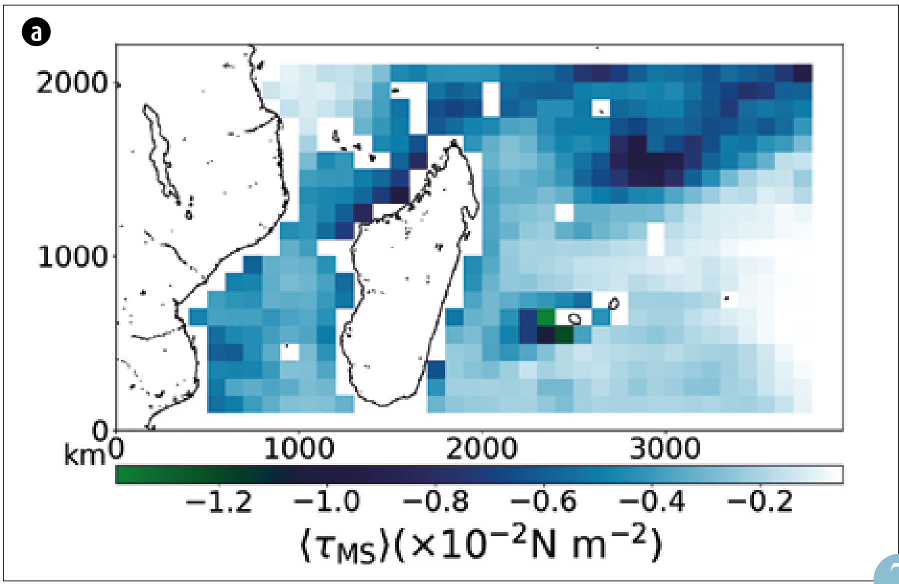


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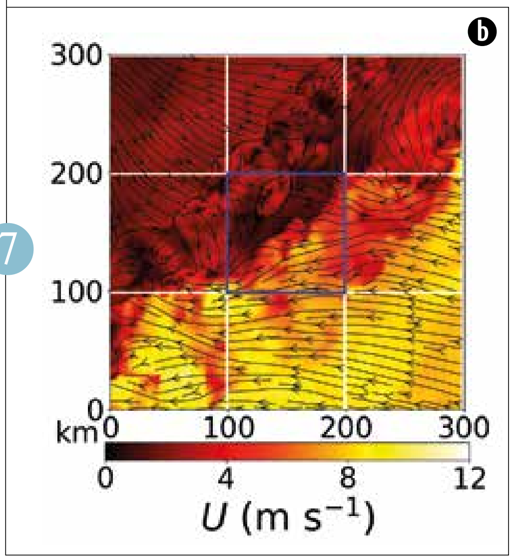
(a) Quantification of the effect of mesoscale variability (subgrid) on the momentum flux at the air-sea interface averaged over one month, at a horizontal resolution of 100 km.
(b) Fine-resolution visualization (2.5 km horizontal resolution) by the AROME weather forecast model of the near-surface wind over an illustrative event (meteorological front).

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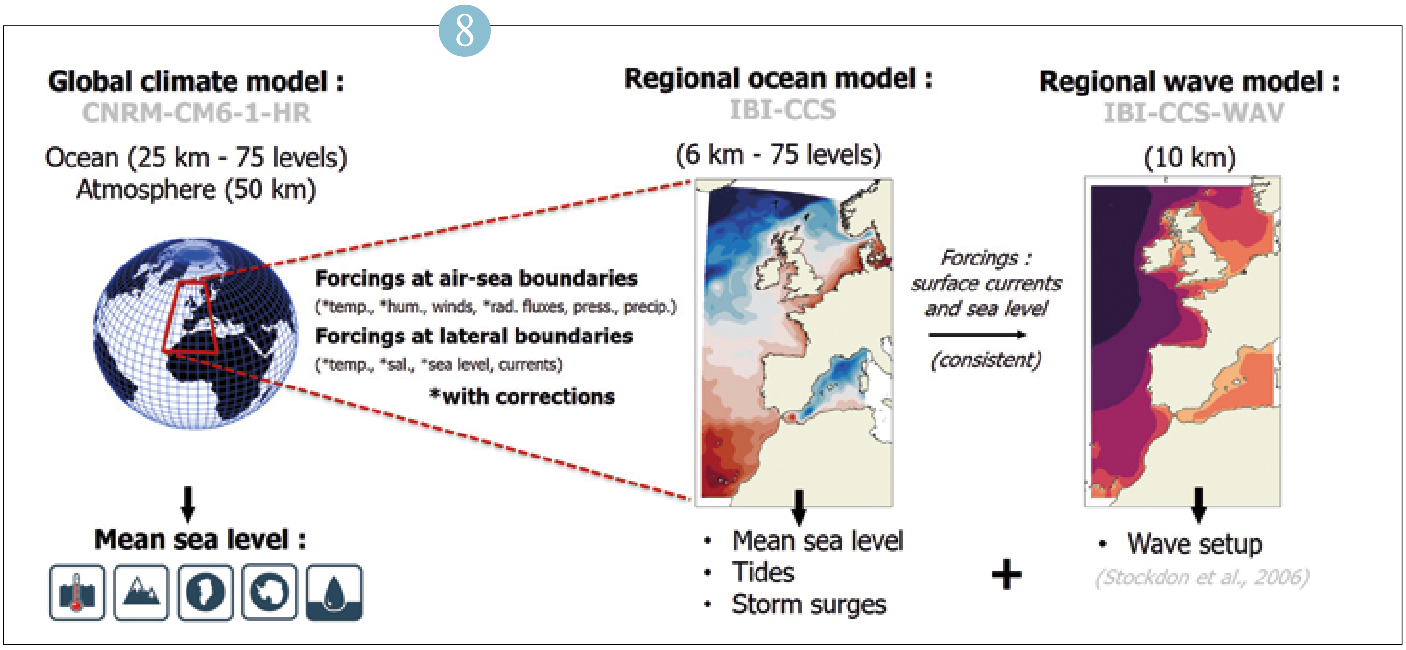


Modeling framework developed to produce regional-scale sea level information, combining output from the IBI-CCS regional ocean model and the IBI-CCS-WAV regional wave model.

# Evolution of meteorological and agricultural droughts in France with climate change

J.-M. Soubeyroux, A. Drouin, F. Rousset

The 6th IPCC report highlighted the worsening of droughts in connection with climate change in many regions of the world. In France, soil droughts have become twice as likely today as in the 1960s and the year 2022 has set new historical records for soil moisture deficits. The link with climate change has been demonstrated in a number of studies, including the ClimSec project in 2011, which is specifically dedicated to the topic of soil drought.
In 2020, a new set of regionalized climate projections, DRIAS-2020, was produced for France based on the EuroCordex ensemble. Within the framework of a national project on water futures (Explore2), these simulations were used as input to the SIM2 hydrological model to determine the evolution of water resources in France, and in particular the soil moisture component.
From these DRIAS-2020 and DRIAS-2020-SIM2 datasets, standardised drought indicators on precipitation (SPI) and soil moisture (SSWI) were calculated for 12 GCM/RCM pairs and three climate scenarios (RCP8.5, RCP4.5, RCP2.6).
Excluding RCP2.6, the results confirm a worsening of meteorological droughts in the future climate, especially in summer, and of soil droughts throughout the year, as well as of a north-south contrast over the country. In RCP8.5 for end of century horizon (figure attached), the median of the DRIAS-2020 ensemble indicates that a 10 years soil drought will be more than three times more likely than in recent climate (10-year occurrence over a 30-year horizon).

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# New climate simulations for the explore 2 project

Lola Corre, Agathe Drouin, Paola Marson and Jean-Michel Soubeyroux.

The Explore2 project aims to study the impact of future climate change on water resources in mainland France. It is based on hydroclimatic projections fed by high-resolution atmospheric data covering the period from 1976 to 2100.
The production of such data has been carried out previously in several countries with different methods.
For metropolitan France, the DRIAS portal proposes the DRIAS-2020 set of 30 climate projections covering 3 greenhouse gas and aerosol emission scenarios (RCP 2.6, RCP 4.5 and RCP 8.5). This set is based on a selection of 12 global/regional model pairs from the EURO-CORDEX ensemble. For the Explore2 project, DRIAS-2020 has been enriched with 7 new pairs. The simulations were projected onto an 8 km resolution grid, and bias corrected from the SAFRAN reanalysis using the ADAMONT ((Verfaillie et al., 2017) and R2D2 (Vrac 2018) methods.
The DRIAS-2020 and Explore2 selections cover the range of changes simulated by the EURO-CORDEX ensemble well. The addition of the new simulations in Explore2 has little impact on the range of future temperature and precipitation changes.
The impact of the corrections on future changes has also been quantified. Despite some differences, the changes projected by the two corrected sets are close. As a median over all simulations, they project annual warming of about 4°C over metropolitan France between the periods 1976-2006 and 2070-2099, for the RCP 8.5 scenario.

**Reference:**

Verfaillie, D., Déqué, M., Morin, S., and Lafaysse, M. 2017 : The method ADAMONT v1.0 for statistical adjustment of climate projections applicable to energy balance land surface models, Geosci. Model Dev., 10, 4257-4283, [https://doi.org/10.5194/gmd-10-4257-2017].

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11

# Heat wave evolution in future climate

A. Drouin, Lola Corre, Jean-Michel Soubeyroux, M. Schneider

France still remembers the exceptional heat wave of August 2003, which caused nearly 15,000 additional deaths. A new heat wave occurred in July 2006. Following these events, a method for identifying and characterizing heat waves using observed daily average temperatures has been developed and progressively enriched. This method allows today to compare the characteristics of historical heat wave episodes (date of occurrence, duration, maximum intensity and severity).
This method, applied to the climate simulations of the DRIAS 2020 set of climate projections for France, allows to estimate the evolution of heat waves in future climate according to the considered horizons and scenarios. For each simulation of the DRIAS 2020 set, heat waves have been identified for 3 future horizons: near future (2021-2050), medium future (2041-2070) and far future (2071-2100) and for the greenhouse gas emission trajectories: RCP4.5 and RCP8.5.
For each of the simulations, the number of heat waves and all their characteristics are strongly increasing. Some models simulate heat waves lasting more than two months in RCP8.5, while those simulated in the reference period hardly exceed three weeks, a duration very close to the observation itself. In general, the most severe heat waves observed in the past will be seen in the future climate as minor events. This study shows how the frequency, duration, intensity, severity and calendar period of heat wave events are increasing in a worrying way in the future climate.

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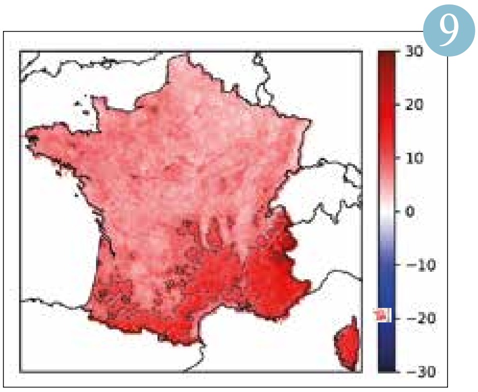
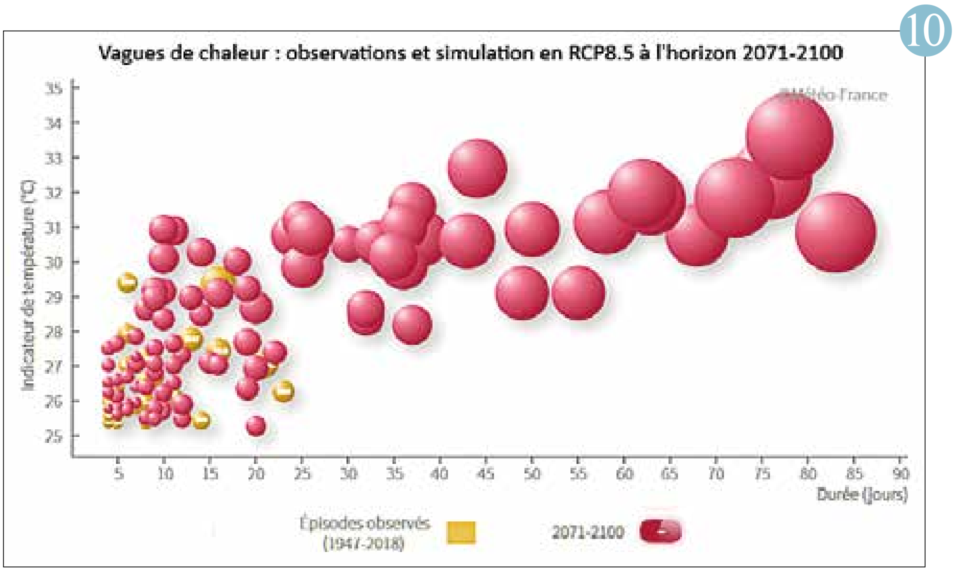
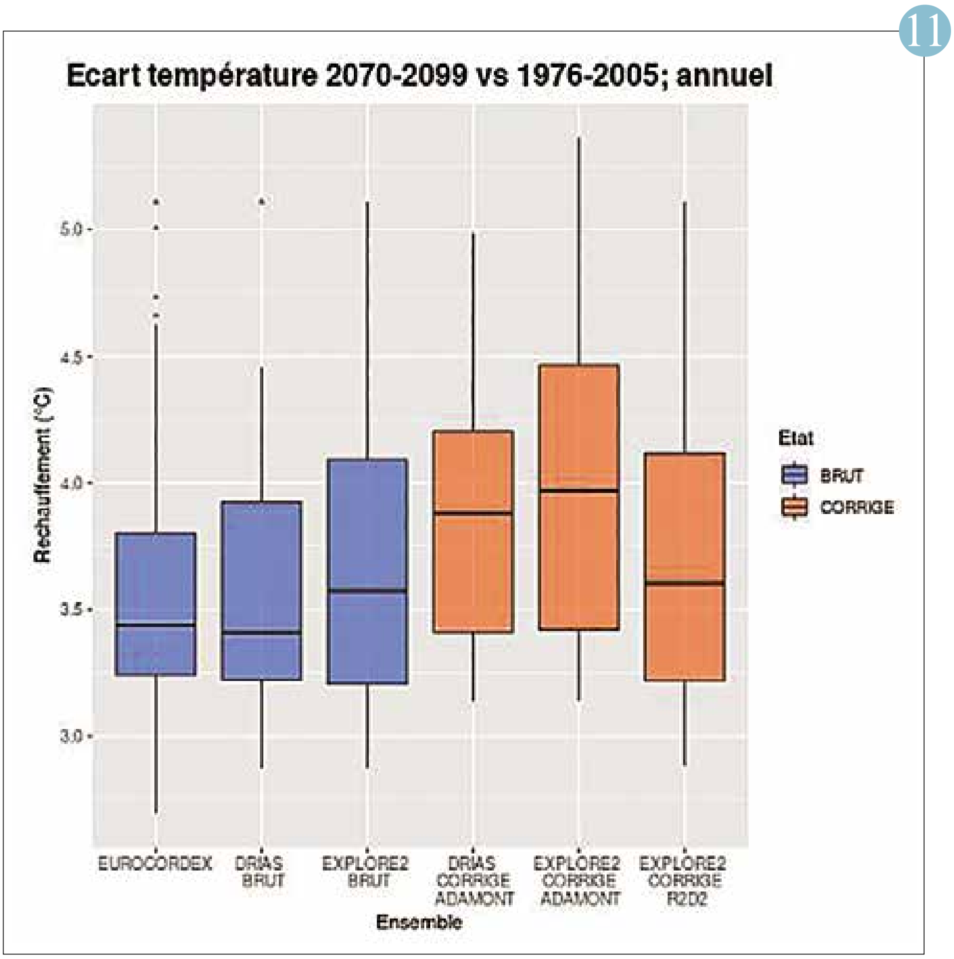



Median of the DRIAS-2020 ensemble under RCP8.5 f
or the end-of-century horizon (2071-2100)
for time spent in 10 year soil drought.
The legend indicates the number of years over 30 years
of at least 10 years drought occurrence.




Heat waves as simulated by an Regional Climate Model (Aladin model from Météo-France) from the far future period 2071-2100 for RCP8.5 compared to observed haet waves between 1947 and 2018.




Temperature changes between the periods 1976-2005 and 2070-2099 (RCP 8. 5), averaged over metropolitan France for the EURO-CORDEX set (67 uncorrected simulations), the raw DRIAS-2020 selection (12 uncorrected simulations), the raw Explore2 selection (19 uncorrected simulations), the DRIAS-2020 set (12 ADAMONT-corrected simulations), the Explore2-ADAMONT set (19 ADAMONT-corrected simulations), the Explore2-R2D2 set (19 R2D2-corrected simulations).

# Seasonal forecast

## Seasonal scenarios of temperature and precipitation over Europe

D. Specq

Seasonal predictions are designed to forecast the climate for the upcoming season, for instance the average temperature anomalies over the next quarter. Such forecasts are issued by Météo-France every month through integration of the coupled climate model CNRM-CM with proper real-time initialization, and perturbations to generate an ensemble of forecasts accounting for the wide range of possible changes in the atmosphere. These forecasts are also provided to the European program Copernicus Climate Change Services (C3S).

Seasonal forecast information is commonly summarized with the ensemble mean or tercile probabilities. CNRM has investigated an approach to extract seasonal scenarios within the ensemble forecasts, so as to concisely diagnose the various trajectories the atmosphere may follow. The scenarios are determined through a hierarchical clustering algorithm of the members, based on the seasonal-mean temperature maps over Europe. Consistent temperature and precipitation scenarios are then described through a composite analysis over the clusters. These scenarios are currently being experimented in the preparation of the Météo-France operational seasonal forecast bulletins. As illustrated in the figure, the less likely scenario may sometimes turn out to better predict the actual seasonal outcome. Ongoing work includes diagnostics to relate each scenario and large-scale phenomena, as well as extending the clustering methodology to the Copernicus C3S multimodel to increase robustness.

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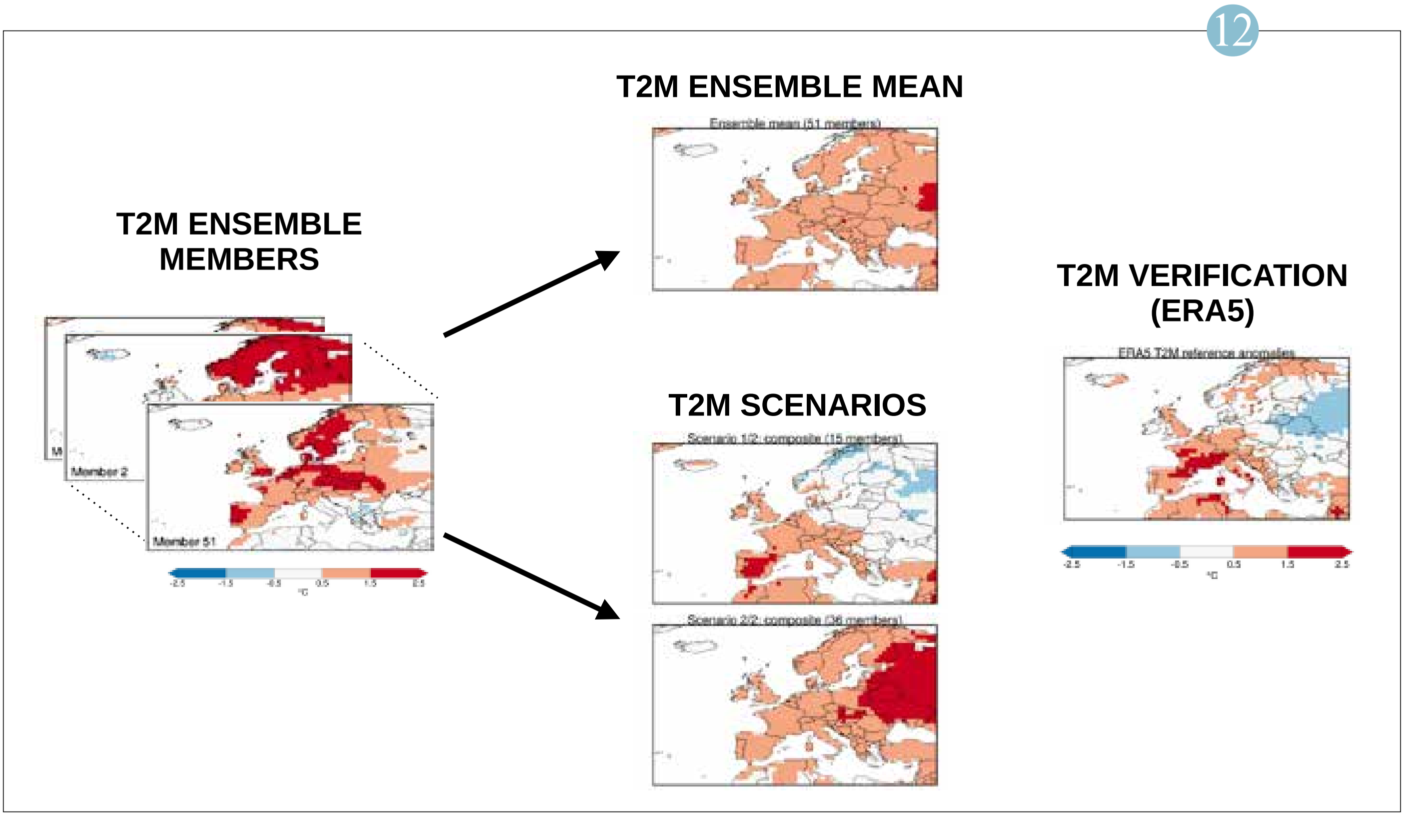


Surface temperature anomalies (T2M) in April-May-June 2022.
Left: 51 members of the Météo-France seasonal forecasts issued in March 2022. Middle, top: Ensemble mean of the 51 members.
Middle, bottom: Composites on the 2 scenarios retained.
Right: Verification in ERA5 reanalysis.
The minority scenario #1 (15 members out of 51) better captures the actual spatial patterns of temperature anomalies.

# Chemistry, aerosols and air quality

**On 14 and 15 January 2022, the Hunga Tonga-Hunga Ha'apai volcano (Tonga archipelago) experienced a major eruption, which was atypical in several ways. The expelled magma interacted with seawater, producing a series of particularly violent explosions and projecting large quantities of water vapour into the atmosphere (thus increasing the greenhouse effect). The oxidation of the emitted SO2 was particularly rapid and led to an increase of the stratospheric sulphate burden. During intense volcanic eruptions, the latter effect usually dominates, resulting in a slight cooling of the climate for 1-3 years. But the Hunga Tonga eruption was an exception, as its combined effects produced a radiative forcing of about +0.2 W/m² (about 7% of the total human impact on the climate), and thus a slight global warming, which has never been observed before after a volcanic eruption. In addition, the eruption was so intense that gases were injected up to 57 km in altitude, reaching the mesosphere, much higher than the Pinatubo eruption in 1991 (35 km). Finally, the eruption resulted in the propagation of infrasound waves, described as a 'meteotsunami', which was still detectable more than 13 days after the eruption using a combination of satellite imagery, ground station networks and airborne platforms. Plumes emitted during volcanic eruptions can disrupt air traffic but also affect human health, hence the importance of forecasting the evolution of these events. Météo-France is in charge of the Toulouse Volcanic Ash Advisory Centre (VAAC) covering a vast area including southern and eastern Europe, western Asia and Africa. One of the tasks of the VAAC is to issue air traffic safety warnings. During the eruption of Hunga Tonga, the operational and research teams were once again mobilised to best predict the dispersion of the volcanic plumes of ash and sulphur dioxide (SO2). In order to be used operationally, Mocage Accident was adapted to the very atypical conditions of the eruption, with in particular the particularly high injection altitude taken into account. A version of Mocage Air Quality with assimilation of the SO2 column from S5P was also implemented. This model configuration made it possible to provide air quality forecasts up to 4 days in advance, and to anticipate that the risks to human health would be very low, which was confirmed by the observations. The year 2022 has seen a wealth of developments for the advancement of knowledge of atmospheric chemistry and for future operational applications, but let us mention two that concern ozone. The first one concerns the understanding and representation of the evolution of ozone in the lower layers of the atmosphere, and therefore its impact on air quality. This is an important issue, both on short time scales and in relation to long-term climate change. At this level of the atmosphere, ozone reacts chemically with nitrogen oxides and volatile organic compounds. The latter, linked to the type and state of vegetation, are rarely taken into account for climate projections. To this end, the SURFEX surface model platform, which manages the emissions and deposition of chemical species, has been coupled with MEGAN (Model of Emissions of Gases and Aerosols from Nature). This may lead to new applications with MOCAGE but also with the CNRM-ESM Earth system model, which are planned in the framework of the national TRACCS programme on climate modelling for climate services (https://climeri-france.fr/pepr-traccs/). The second development was aimed at describing the stratosphere in MOCAGE in greater detail by increasing the vertical resolution. The implementation of this new version has enabled a better representation of the total ozone column and its temporal variability, and the production of new simulations of the shrinking of the ozone hole over Antarctica.w**

1

## Assessment of biogenic emissions by MEGAN-SURFEX

Joaquim Arteta, Safae Oumami

The prediction of air quality and its evolution in the context of climate change is an important health and societal issue. This is particularly the case for ozone pollution episodes.

Ozone formation is governed by chemical reactions involving nitrogen oxides, mostly of human origin, and volatile organic compounds (VOCs), almost 90% of which originate in nature in the presence of strong solar radiation. Climate projections of air quality, if they take into account the evolution of meteorology and emissions linked to human activities, rarely take into account the evolution of biogenic compound emissions linked to the impact of climate change on ecosystems.

In order to carry out climate projections of air quality taking into account the evolution of biogenic emissions, the MEGAN biogenic flux calculation model, in its version 2.1, has been coupled to the Météo-France soil model, SURFEX. In order to validate this coupling, global emissions of isoprene, the main biogenic VOC, were calculated with the SURFEX-MEGAN model with several meteorological forcings (operational IFS, ERA5 and MERRA) for the year 2019, as shown in Figure 1, and compared with existing emission inventories. The results obtained show a global balance ranging from 341 Tg to 436 Tg depending on the meteorological forcing used. Current global inventories show global isoprene emissions between 310 Tg and 627 Tg (see Figure 2). The results obtained with SURFEX-MEGAN are within the range of previously published balances.

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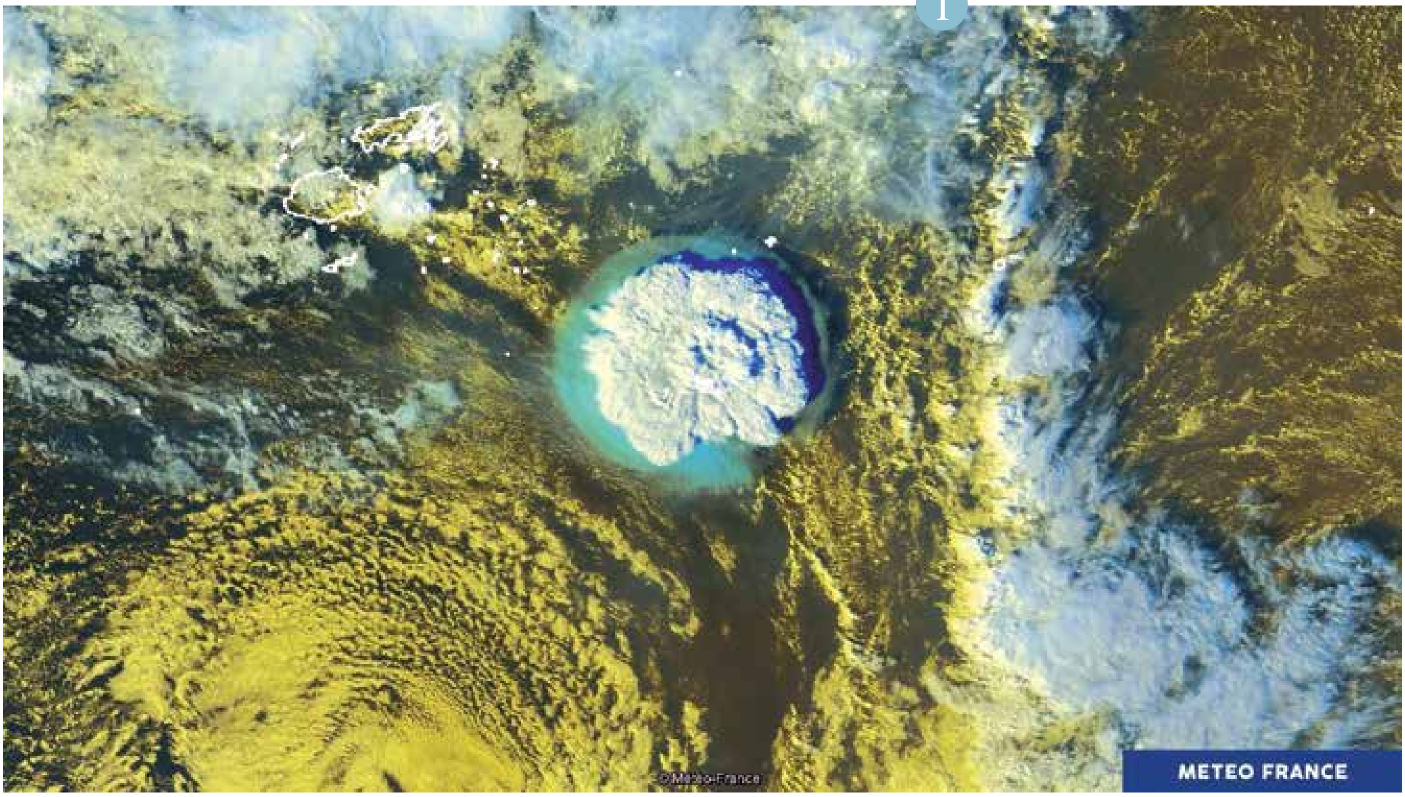
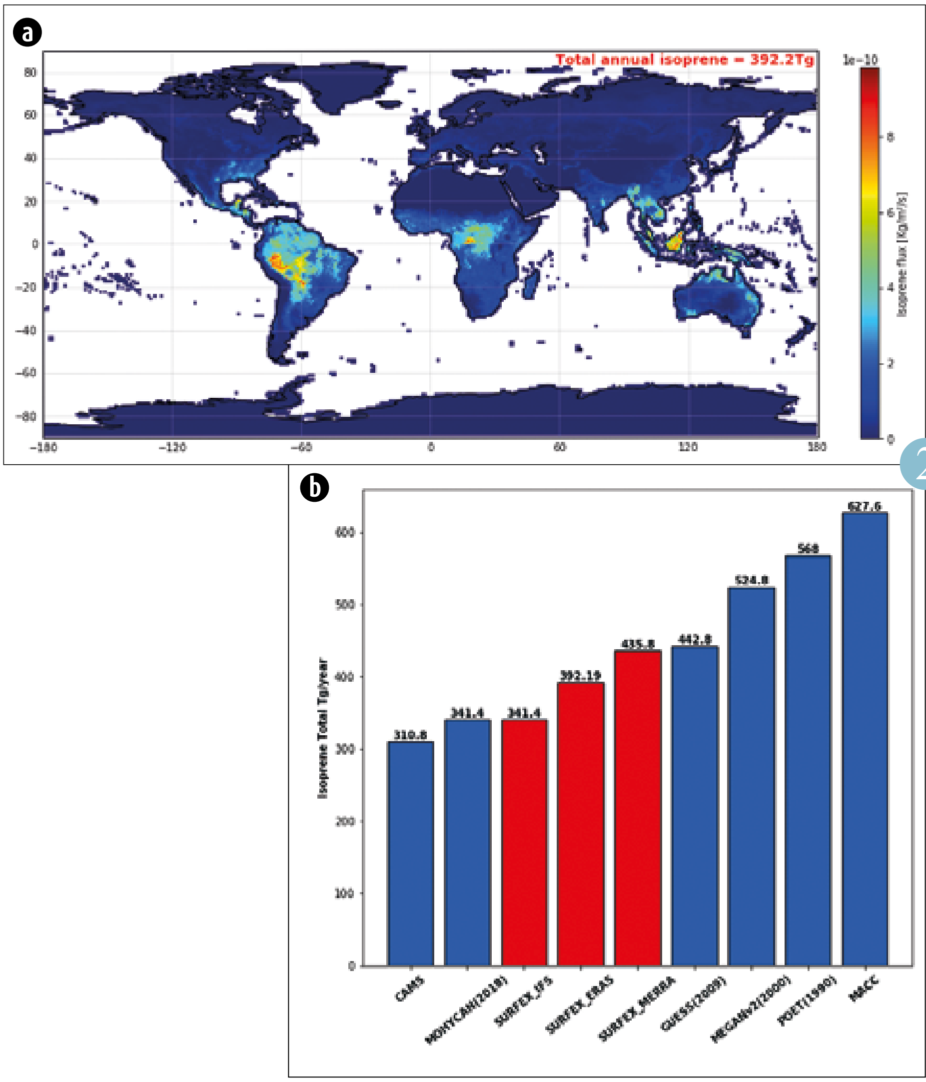



HIMAWARI8 satellite image from 15/01/2022 at 05:00 UTC. 50 minutes after the beginning of its eruption, the Hunga Tonga-Hunga Ha'apai volcano has released a huge amount of ash into the atmosphere, and the plume already reaches 400 km in diameter. © Météo-France.




(a) Global annual isoprene emissions modelled with the SURFEX-MEGAN model forced by ERA5
(b) Comparison of the results obtained with the main existing emission inventories.

# Mineral aerosols in AROME-dust, evaluation over the Sahel region

Jonathan Guth, Vincent Guidard

Desert dust emission and transport events have an impact on weather forecast, especially temperature and visibility. It is therefore critical to be able to predict these events.

The representation of desert dust aerosols can be integrated in the fine scale numerical weather prediction model AROME. In this upgraded version of AROME, desert dust emissions are computed by the surface model SURFEX[1]. The effect of desert dust aerosols is taken into account in the radiation scheme and allows a more realistic description of the temperature in the troposphere among other impacts.

Evaluation and characterization of the AROME model ability to simulate the uplift and transport of desert dust aerosols have been made over a Sahelian domain that includes Chad and Niger, in order to encompass a certain number of desert dust emitting areas.

A five month long simulation on the Sahelian domain, compared to in-situ and satellite aerosols optical thickness observations, shows very encouraging results. The displayed figure illustrate the good match of the desert dust over Chad and the South of Algeria.

This new version of the AROME model is intended to enhance desert dust forecasts which impact can be significant especially for military forces and aeronautic sector.

*1. SURFEX : Surface Externalisée*

3

# Assimilation of european ceilometers to improve air quality forecasts

Mickaël Bacles

Aerosols are particles suspended in the air, at different altitudes, having a natural origin (deserts, forest fires, volcanic eruptions), or anthropic (industries, heating, road transport). Close to the surface, aerosols can reduce visibility and even have an impact on our health. It is therefore important to anticipate these fine particle pollution episodes. However, aerosol forecasting involves many uncertainties that can be reduced by assimilating profiles observed by lidars and ceilometers of the E-PROFILE network, whose location is shown in figure a. The contribution of the assimilation of these instruments was evaluated during a particular episode, between 1st March 2022 and 19th March 2022, in the MOCAGE chemistry-transport model and was compared with independent observations from the European Environment Agency. The following maps represent median PM10 concentrations observed at the surface (figure b) and simulated without assimilation (figure c) and with assimilation of the E-PROFILE network instruments (figure D). We notice that for this period, the model underestimates the PM10 concentration at the surface. However, the assimilation allows to increase the PM10 concentration at the surface and thus to get closer to the observed values at the surface, especially where the E-PROFILE network is dense.

For the moment, the assimilation of ceilometers and lidars only allows to modify the total aerosol mass. However, aerosols behave differently depending on their type and size. One way to improve aerosol forecasting would therefore be to know the size and type of aerosol and then assimilate them into the model..

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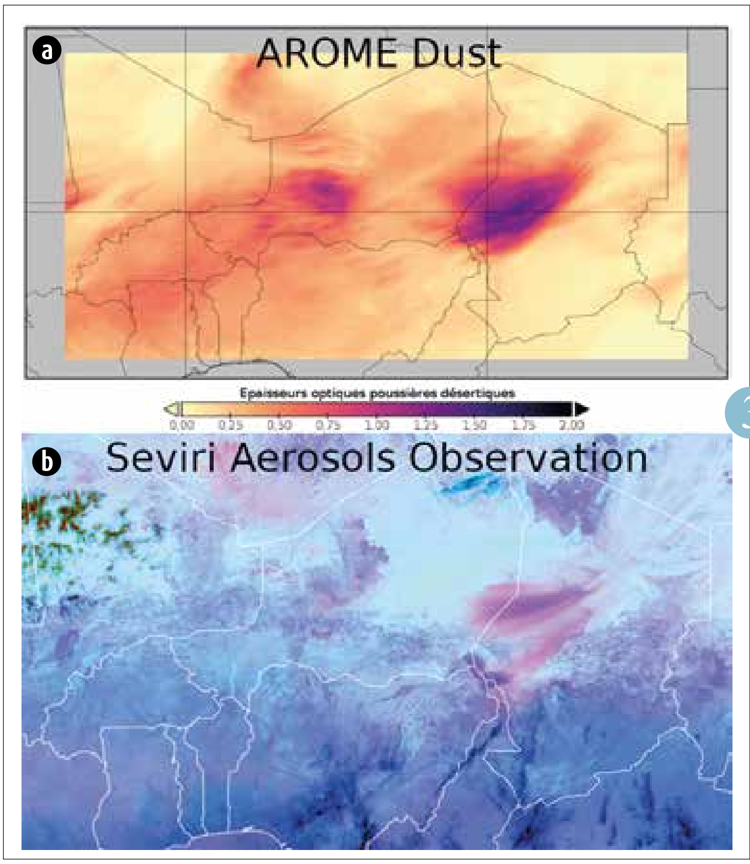


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Desert dust aerosol optical depth simulated by AROME (a) and aerosols images from Seviri observations (satellite Meteosat-11,
(b) for February the 10th 2022 at 14h.

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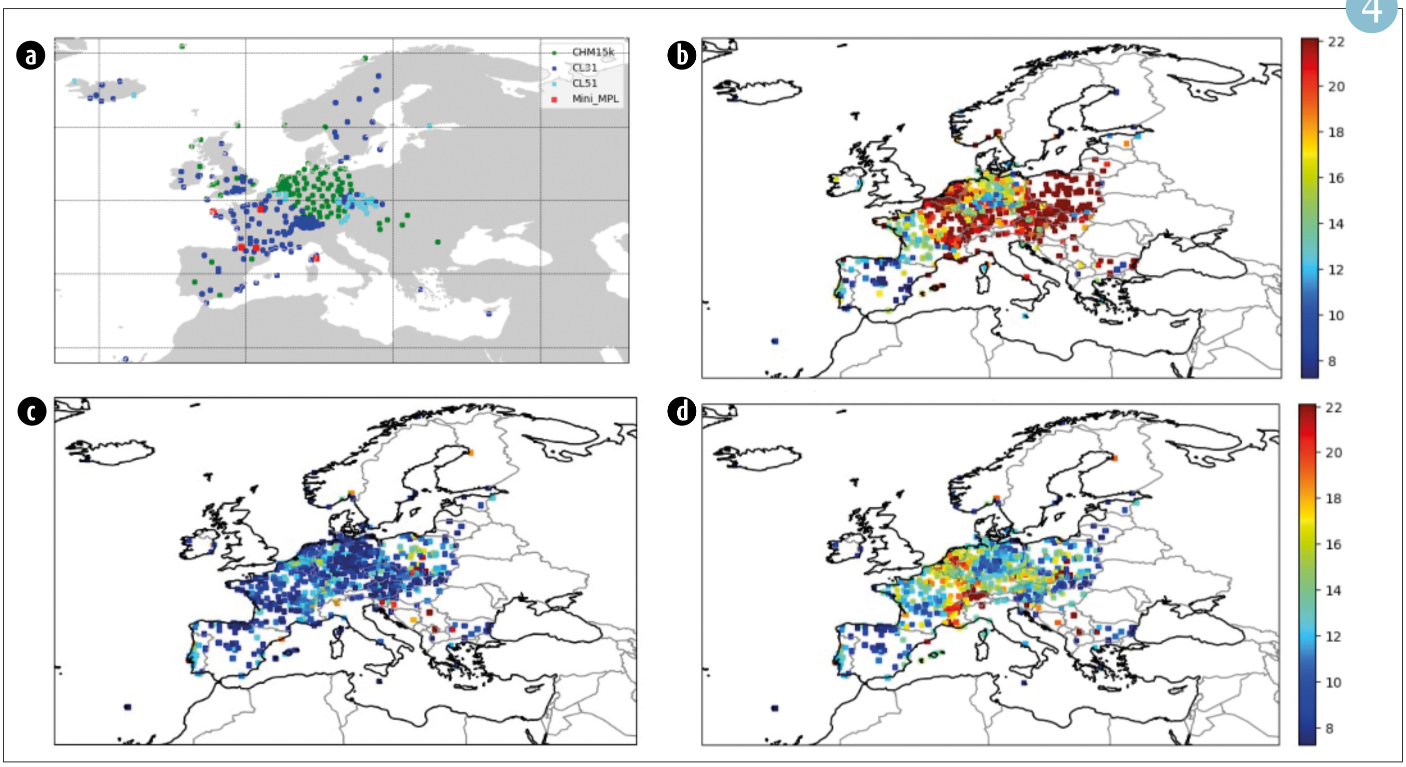


Location of the E-PROFILE lidars and ceilometers network instruments (figure a) and PM10 concentration observed by the EEA network (figure b) and simulated by MOCAGE without assimilation (figure C) and with assimilation of lidars and ceilometers (figure d).

# Participation in Phase 2 of the Chemistry-Climate Model Initiative (CCM-I project)

Béatrice Josse and Françoise Chéroux

In order to support the activity of the WMO (World Meteorological Organization) and UNEP (United Nations Environment Programme) on the scientific assessment of ozone depletion, the international Chemistry Climate Model Initiative (CCM-I, https://blogs.reading.ac.uk/ccmi) asked the different modeling groups to perform a series of simulations, with the aim of intercomparison of the results.

The MOCAGE model was used to represent the past evolution (1960-2020), the supposed future evolution (until 2100) of the chemical composition of the atmosphere, as well as 'geo-engineering' simulations (until 2100), for which a massive injection of sulphate aerosols in the stratosphere is assumed. For these 3 types of simulations, a mini-set of 4 simulations has been performed in order to propose a variability estimate. For this exercise, the meteorological forcings are from the CNRM-CM climate model. The version of the MOCAGE model used has a vertical extension up to 0.1hPa, i.e. about 60km, whose stability over very long periods has been demonstrated.

The first analyses of the MOCAGE results are very satisfactory. Indeed, the past evolution of the ozone layer is well represented compared to the observations, both in chronology and in intensity. The future evolution, and in particular the date at which the ozone layer should return to the 1980 level, are in full agreement with the other models. This date is estimated only around 2050 (see associated figure), as the impact of CFC emissions is long-lasting, since their ban was ratified by the Montreal Protocol in 1987.

The inter-comparison of the results of the different models is in progress and will continue in 2023.

5

# A new version of MOCAGE, up to 0.1 hPa

Béatrice Josse
and the transverse structure MOCAGE

A new version of the MOCAGE model, the Chemistry-Transport model developed at Météo-France, has been elaborated. Its vertical extension has been increased from 47 levels, with a peak at 5hPa, i.e. about 35km, to 60 levels, with a peak at 0.1 hPa, i.e. about 60km.

This allows to better describe the chemical phenomena of the stratosphere, in particular the evolution of the ozone layer and the nitrogen oxides, very present in the upper stratosphere. The presence of these nitrogen oxides at these altitudes is at the center of the chemical system of the area and required long development works to obtain a seamless description of the chemical system over the whole troposphere and the stratosphere.

The results obtained are of several kinds. On the one hand, the chemical system as such is better described over the whole globe. In particular, on the associated figure, which represents the daily evolution over one year of the total ozone column above the Antarctic station of Dumont d'Urville, we notice a better representation of the chronology of the sudden ozone variations linked to the positioning of the stratospheric vortex and the associated ozone hole.

On the other hand, this also has consequences on the representation of the air quality at the surface, since the chemical system at any point strongly depends on the photodissociation reactions, themselves modulated by the amount of ozone above this point. Finally, this vertical extension corresponding to the one of the numerical weather prediction model ARPEGE will allow to provide the latter with relevant ozone information in real time. Thus, the operational transition of this version to 60 levels is planned for the year 2023.

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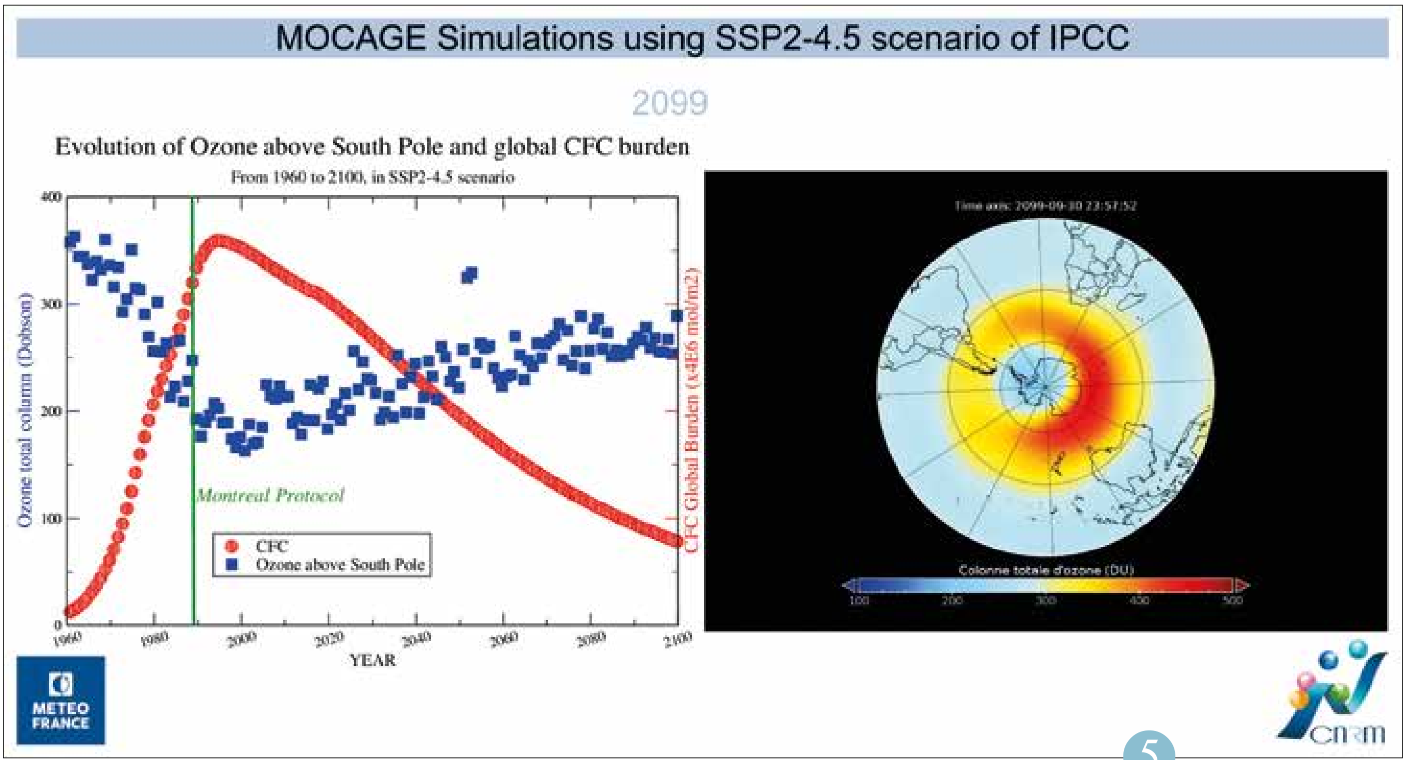


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Left: According to MOCAGE, temporal evolution from 1960 to 2100 for the months of October of the global amount of CFCs (in red) and of the total ozone column over the South Pole (in blue). Green is the date of signature of the Montreal Protocol.
Right: According to MOCAGE, total ozone column over the South Pole in October 2099. The 'ozone hole' is no longer perceptible: the values at the heart and outside of the vortex are again equivalent.

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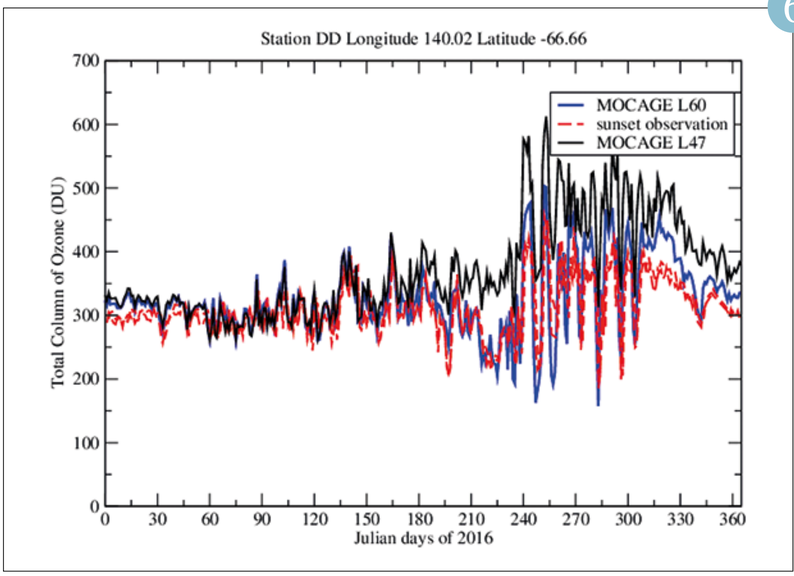


Daily evolution over the year 2016 of the total ozone column above the Antarctic station of Dumont d'Urville. In red, according to the observations of the in-situ measurement network SAOZ (http://saoz.obs.uvsq.fr/). In black, according to MOCAGE in its 47-level version. In blue, according to MOCAGE in its 60-level version.

# Snow and mountain

**A complex material in constant evolution, a mixture of air and ice whose white color fills winter stories, snow is a pillar of the Earth climate system. A climate regulator, water resources, a threat to humans, animals and infrastructures through avalanches, snow interacts with all the components of the cryosphere, glaciers, ice caps, permafrost, thus partly controlling the evolution of these different systems.**
**Météo-France, in particular the Centre d'Etudes de la Neige (CEN, Météo-France - CNRS, CNRM), conducts research to better understand the evolution of snow in the past and to predict its future evolution in the short and longer term as well as its contribution to current and future natural hazards.**
**In 2022, we have studied in detail the evolution of snow over the last 40 years, in particular in relation to the deposition of Saharan mineral dust and black carbon. We have also carried on numerous studies on climate change and snow in the mountains for different applications, from the operation of ski areas to the vulnerability of agropastoral systems. Machine learning combined with physical modeling has allowed us to open new perspectives of numerical tools for avalanche risk forecasting. Observation is also progressing at all scales, from satellite observation of avalanche deposits to better qualify avalanche activity, to micro-scale observations by X-ray tomography to better understand snow evolution under given temperature conditions.**

## Phase-field modeling of snow metamorphism and application o the evolution of its physical properties over time

L. Bouvet, N. Calonne, F. Flin

Once deposited on the ground, snow forms a complex porous material, made up of air, ice and sometimes liquid water. This material constantly changes over time, inducing a significant modification of its physical properties, with important consequences on the macroscopic evolution of the snowpack. As part of the ANR MiMESis-3D project, which focuses on the study of snow microstructure and its physical properties using 3D images, and which brings together the expertise of several laboratories (CNRM/CEN, 3SR, INRAE/ETNA, IGE, ICJ), we have recently been interested in the modeling of isothermal metamorphism (IM). Significantly active by very low thermal gradient, this metamorphism leads to a rounding and coarsening of the grains and plays a crucial role in the evolution of the snowpack. Based on the evaluation of the air-ice interface curvature, the "phase-field" model used makes it possible to reproduce, from images obtained by tomography, the characteristic evolution observed during IM. The description of this type of metamorphism is classically based on the condensation coefficient $\gamma$, a poorly constrained parameter, which controls the intensity of the evolution. The confrontation of this model with a time series obtained experimentally allowed us to estimate the value at −2°C of this parameter, and to validate it using an independent data set. This model now makes it possible to study the effect of IM at −2°C on all kinds of snow microstructures in order to, e.g. deduce its impact on the effective transport properties (thermal conductivity, diffusivity, permeability, etc.) using numerical simulation. This work will soon be extended to other types of metamorphism and other physical properties. It should thus provide particularly effective tools for improving snowpack models.

**Reference:**

Bouvet, L., N. Calonne, F. Flin and C. Geindreau, 2022. Snow equi-temperature metamorphism described by a phase-field model applicable on micro-tomographic images: Prediction of microstructural and transport properties, Journal of Advances in Modeling Earth Systems, 14(9), e2022MS002998, https://doi.org/10.1029/2022MS002998

Projet ANR MiMESis-3D : https://anr.fr/Project-ANR-19-CE01-0009

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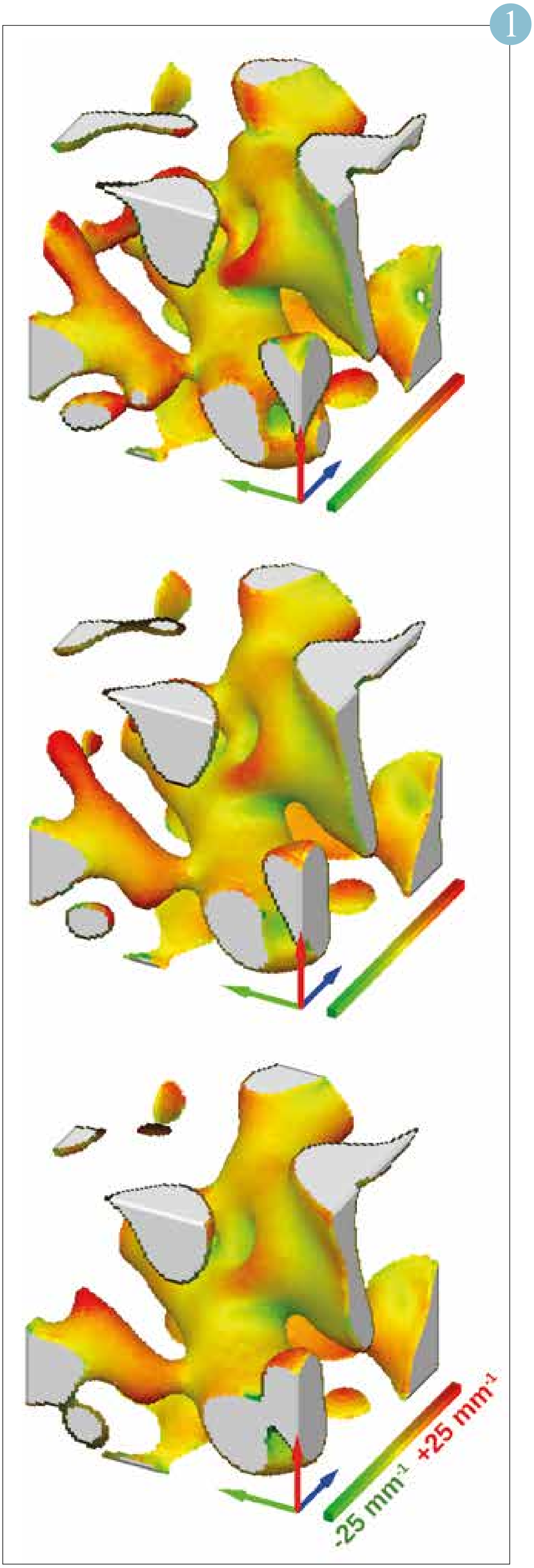


3D representation of a sample of recent snow subjected to isothermal metamorphism. The phase-field model applied here makes it possible to obtain, from the initial tomographic image (on the left), the evolution at -2°C of the microstructure after 8 and 16 days. Convex surfaces, shown in red, sublimate, while concave surfaces, in green, correspond to areas of vapor deposition. The flat areas, in yellow, change relatively little over time. The colored scale bar measures 0.7 mm. The blue, green and red arrows indicate the x, y and z directions, z pointing upward.

## Towars distributed indicators of avalanche activity using Sentinel-1

A. Karas, F. Karbou

Sentinel-1 SAR observations have a great potential to detect avalanche deposit areas in mountains, and standard methods used in the literature are simple thresholding methods with/without some explicit expert indicators. The complexity of the interaction of the radar signal with the snow environment and the mountain topography calls for the implementation of advanced statistical methods to better handle the large data flow and to link the information content of the observations with changes in the snow environment. Links between satellite observations and the presence of avalanche debris are rather complex and require knowledge of several parameters including atmospheric conditions influencing the state of the snow (freezing/thawing, presence of water, etc.), precipitating events, snow and soil conditions, terrain characteristics, ... that are hard to accurately define everywhere. Beyond the identification of pixels associated with avalanche debris, the challenge is to derive new spatialized indicators of avalanche activity at the scale of mountain ranges. A novel segmentation method has been developed to automatically detect avalanche debris areas from Sentinel-1 20m measurements (Karas et al. 2022a-b). Debris estimates were successfully evaluated using an independent database from SPOT-6 optical observations. Following this, spatialized indicators of avalanche activity at the scale of an area of interest (corridor scale and massif scale) were derived (Karas et al. 2022c). These debris lines were analyzed and evaluated using in situ observational data and were found to be relevant for monitoring avalanche activity at regional scale, which complements in situ data and avalanche hazard bulletins.

2

## Climate change and the mountain snow cover

Samuel Morin, Raphaëlle Samacoïts, Diego Monteiro, Jean-Michel Soubeyroux

The effects of climate change on mountain territories are multiple and often heavy with consequences locally and around these regions. Research is conducted through the prism of the evolution of snow cover in the mountains, and its effects on natural hazards (avalanches), ecosystems, water resources and socio-economic activities (winter sports). In 2022, the results included the publication of a synthesis of climate projections of the EURO-CORDEX ensemble on temperature, precipitation and snow conditions in the Alps (Kotlarski et al., 2022). This work was lead by researchers from Meteo-Swiss and the Austrian Meteorological Service (ZAMG). It includes a case study on the Mont Blanc massif, obtained by applying the ADAMONT adjustment method to EURO-CORDEX projections using the SAFRAN reanalysis as a baseline. This work illustrates the effect of altitude on the magnitude of the effects of climate change on winter snow cover, particularly pronounced at low and medium altitudes (see Figure). An updated version of these climate projections has been posted on the Drias website, with an extended set of climate simulations used and the extension to mid-altitude massifs (http://www.drias-climat.fr/accompagnement/sections/341). In addition, work is in progress to analyse the added value of simulations carried out with the AROME model in climate configuration, which show a gain in realism for some variables while displaying weaknesses in the representation of some processes over the French Alps, for example concerning the modelling of snow cover (Monteiro et al., 2022).

This research is also part of an interdisciplinary framework and upstream of the development of climate services such as the ClimSnow service. For example, work has been carried out in collaboration with INRAE on the evolution of hydroclimatic and snow conditions in alpine pastures in the Alps, making it possible to better appreciate the vulnerability of agropastoral systems to climate change (Deléglise et al., 2022). In the field of winter tourism, the work carried out as part of Lucas Berard-Chenu's thesis, co-supervised by INRAE Grenoble and CEN, has made it possible to quantify past changes in snow cover in 16 resorts in Savoie, taking into account changes in their snowmaking equipment fractional coverage. This work highlights the great heterogeneity of equipment and the effect of snowmaking on the operating conditions of ski areas (Berard-Chenu et al., 2022a). This work contributes to reflections on transitions in mountain areas in the context of climate change, including the risks of maladaptation (Berard-Chenu et al., 2022b).

3

**Reference:**


Berard-Chenu, L., François, H., George, E., and Morin, S. : Past changes in natural and managed snow reliability of French Alps ski resorts from 1961 to 2019, *The Cryosphere*, 16, 863–881, https://doi.org/10.5194/tc-16-863-2022, 2022a.

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Kotlarski, S., Gobiet, A., Morin, S., Olefs, M., Rajczak, J. and Samacoïts, R., 21st Century alpine climate change, *Clim Dyn.*, https://doi.org/10.1007/s00382-022-06303-3, 2022.

Monteiro, D., Caillaud, C., Samacoïts, R., Lafaysse, M., and Morin, S., Potential and limitations of convection-permitting CNRM-AROME climate modelling in the French *Alps, Int. J. Climatol.*, https://doi.org/10.1002/joc.7637, 2022.


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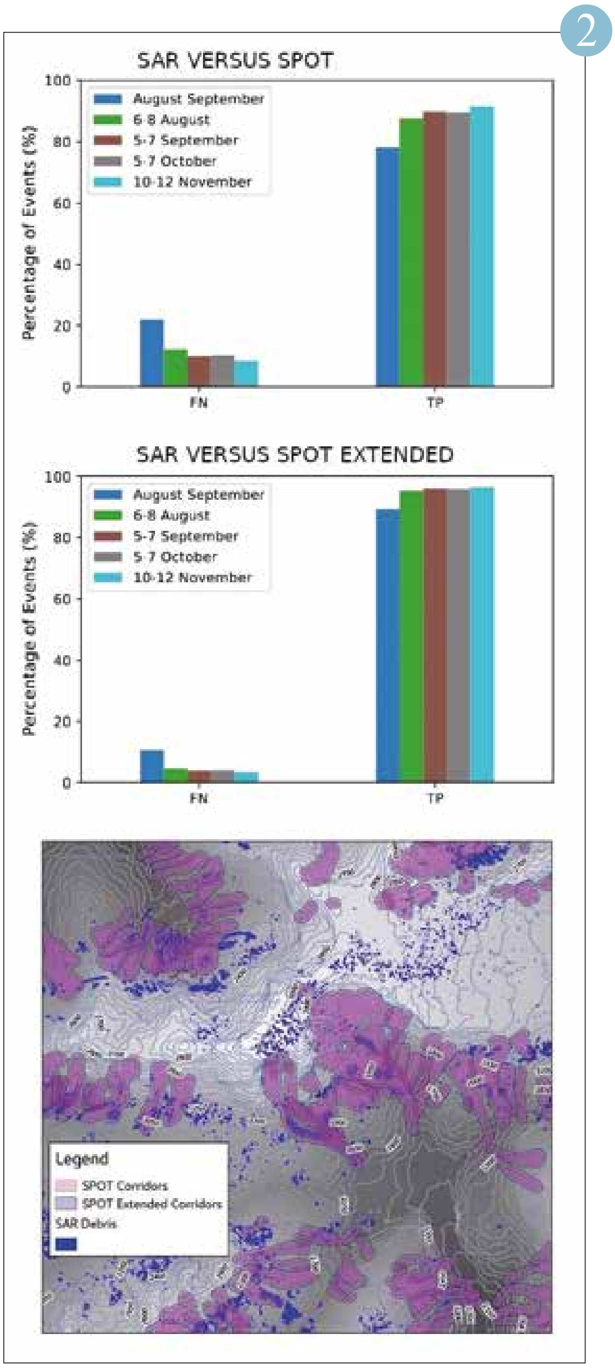
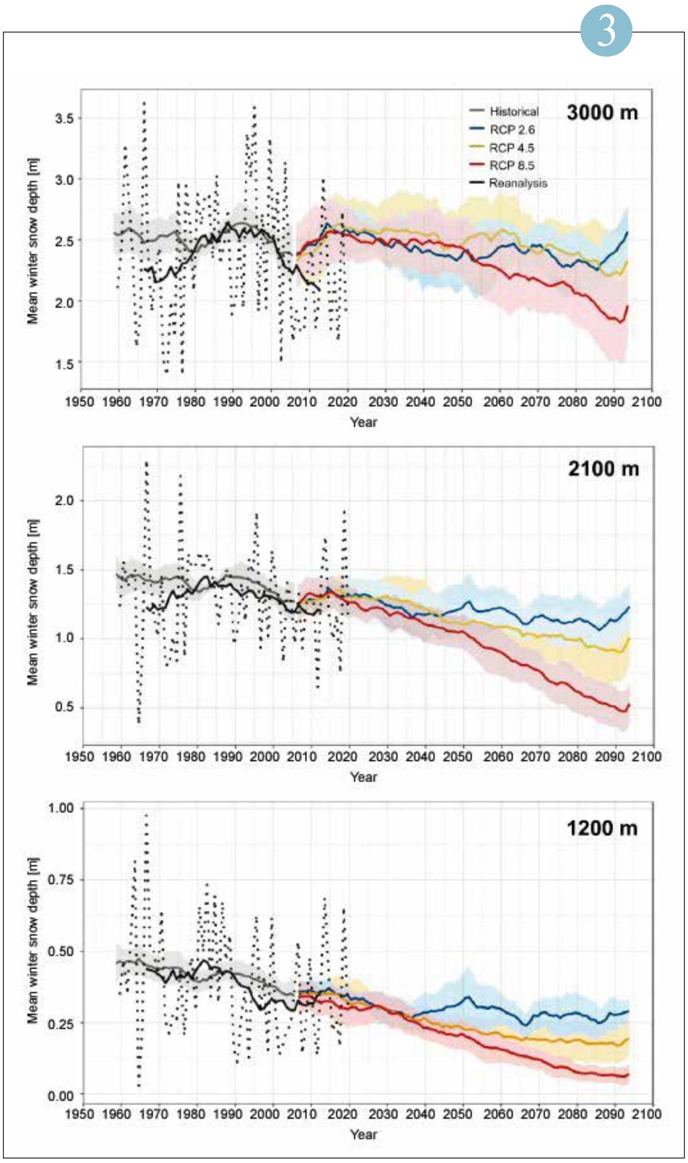



Percentage of TP detection (True Positive: SAR detection corresponds to an event observed in the SPOT image) and FN detection (False Negative: no SAR detection in SPOT). Detections have been performed using the January 2018 SAR ascending orbit over part of Switzerland (using different detection method settings by varying the reference dates). TN and TP values are calculated with respect to SPOT mapped avalanches (Hafner et al. 2021) (left) and with the addition of a 50m buffer zone around SPOT corridors (right). The map illustrate an example of avalanche corridors from SPOT and SAR detections .




Snow cover changes in the Mont-Blanc region at three elevations (3000 m, 2100 m and 1200 m above mean sea level), from 1950 to 2100. The dotted line corresponds to annual values of the mean winter (Nov.-Apr.) snow depth.
The black continuous line shows the corresponding 15-years moving average.
Grey (historical) and colored (future projections) lines correspond to the multimodel mean (surrounded by 1 standard deviation) of 15-years multi-annual values from all available GCM/RCM pairs for each RCP.

# Black carbon and dust alter the response of mountain snow cover under climate change

Marie Dumont and Marion Réveillet

Particles such as black carbon (combustion residues) and Saharan dust darken the snowpack when deposited on its surface. As a result, a greater proportion of the solar radiation is absorbed by the snow, accelerating its melting in the spring. However, the role of these depositions on seasonal snowpack evolution and climatic trends in snow duration is still poorly understood. By combining in-situ observations of the snowpack, satellite observations, and detailed snowpack modeling, we have quantified this effect on the duration of snow cover in the French Alps and Pyrenees for the last 40 years. The results show that black carbon and Saharan dust depositions advance the end date of the annual snow cover period by an average of 17 days.

Although these particles accelerate melting and decrease the seasonal snow cover duration, black carbon deposition is less important today and therefore accelerates the annual melting less than in the 1980s. Conversely, the decrease in snow cover is more pronounced today than it was 40 years ago, mainly due to the increase in temperature associated with climate change. Thus, the decrease in black carbon deposition over the past 40 years partially offsets the effect of climate change on snow duration. The shortening of snow duration due to current climate change would therefore be even more pronounced without the decrease in soot carbon deposition since the 1980s. In contrast, although dust deposition influences annual snowpack duration, it also has no detectable effect on the long-term trend in snowpack duration.

Future changes in soot carbon deposition related to human activities should therefore be considered when assessing the evolution of snow cover in the coming decades

**Reference:**

Réveillet, M., Dumont, M., Gascoin, S. et al. Black carbon and dust alter the response of mountain snow cover under climate change. Nat Commun 13, 5279 (2022) https://doi.org/10.1038/s41467-022-32501-y

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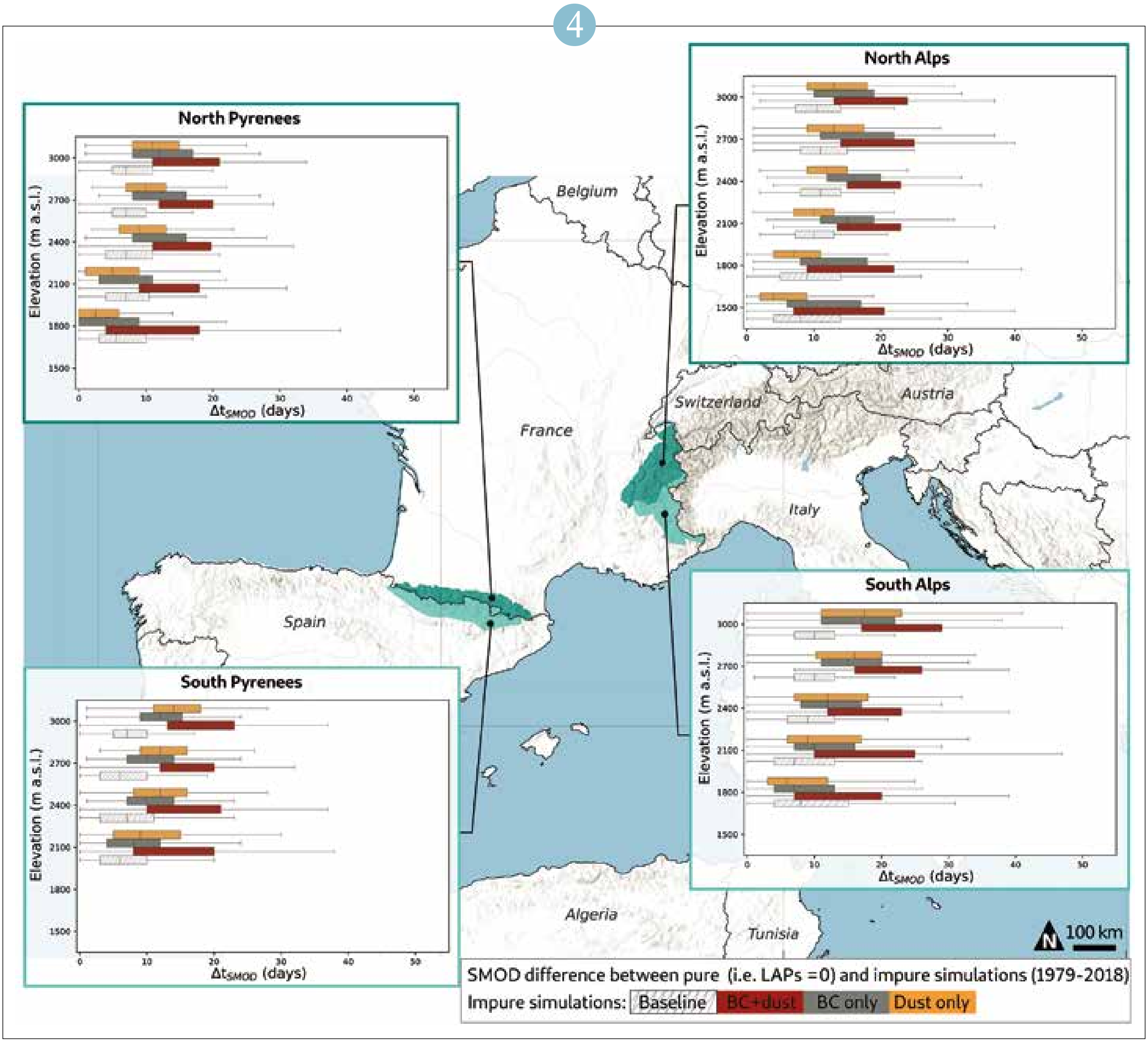


Shortening of snow cover duration due to black carbon and mineral dust deposition for various regions and elevations (SMOD: snow melt out date)

# Avalanche activity forecast with mechanical stability analysis and machine learning

Léo Viallon-Galinier, Pascal Hagenmuller, Benjamin Reuter

Avalanches are a major concern in mountain regions as they threaten recreationists, infrastructures and urbanized areas. In order to help reducing the associated risk reduce the associated risk, Météo-France produces avalanche bulletins and warnings to authorities and the population. Forecasters rely on different observation networks and snow stratigraphy modelled by models developed at Centre d'Études de la Neige (CNRM, Grenoble, France). The interpretation of snowpack stability from these simulations and the synthesis in terms of expected avalanche activity remain challenging.

Based on our knowledge of mechanical processes leading to avalanches, we introduce a new method for the snowpack stability analysis. This analysis allows to synthesiseand exploit in detail the information produced by snow cover models. In a first step, different stability indices are produced, each one representative of one or several processes of avalanche formation. A forecast of expected avalanche activity is then performed with a machine learning algorithm (Random Forests), calibrated with past observed avalanche activity from Meteo-France observer networks and Enquête Permanente Avalanche (EPA, from ONF and INRAE). This forecast is conducted at high spatial resolution decomposed in elevation bands and aspect ranges.

The model evaluation installs confidence in the statistical model to represent avalanche activity, with a probability of correct identification of avalanche situations of 75% and a probability of correct identification of non-avalanche situations of 76%. Compared to more conventional snow and meteorological variables, the added value of the stability indices selected also have been demonstrated. Whereas the study was initially conducted on the Haute-Maurienne area, the extension of the methodology to different areas of the French Alps and Pyrenees is in progress.

This work opens perspectives for new decision support tools for forecasters in mountain regions for avalanche bulletins or civil weather watch.

**Reference:**

Léo Viallon-Galinier, Pascal Hagenmuller, Benjamin Reuter et Nicolas Eckert. Modelling snowpack stability from simulated snow stratigraphy: Summary and implementation examples. *Cold Regions Science and Technology*, 201, pp. 103596, 2022. doi: 10.1016/j.coldregions.2022.103596.

Léo Viallon-Galinier. 2022. Combining physical modeling and machine learning to improve avalanche risk forecasting, PhD thesis, Université Toulouse III - Paul Sabatier. https://www.theses.fr/s295176

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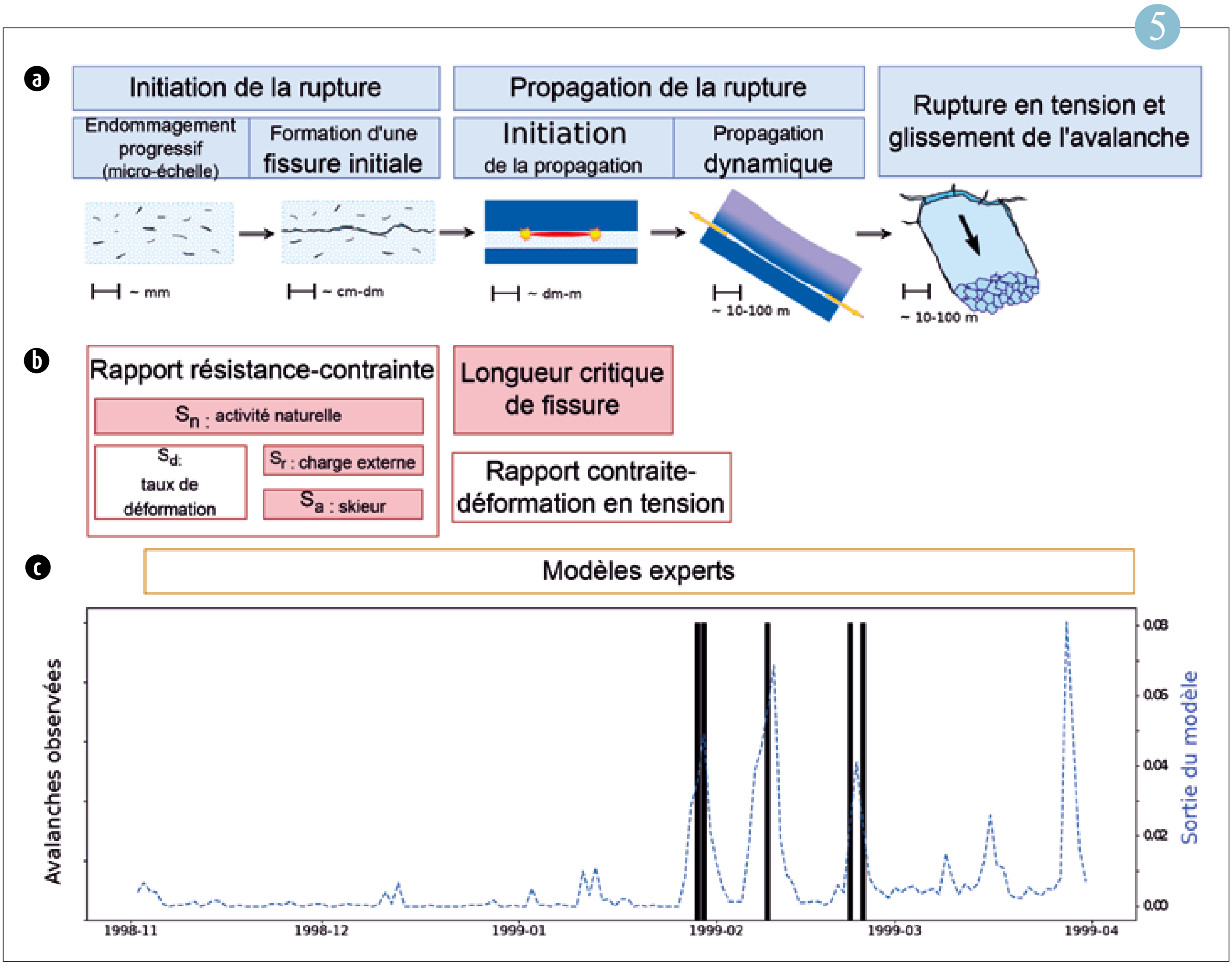


(a) Processes of avalanche formation and (b) associated stability indices. The highlighted stability indices are used in the machine learning algorithm.
(c) Results of the Random Forest model for the Haute-Maurienne area, 2400m, NW aspect and season 1998-1999.
The model output is compared to the avalanche observations (black bars) from Enquête Permanente Avalanche.

# Engineering, campaigns and observation products

**The PANAME campaign, largely detailed in the first chapter of this report, was at the heart of Météo-France activities during the Summer of 2022. Actually the last year as a whole was very rich in terms of observational research activites. For SAFIRE[1] it was the Arctic year. The ATR 42 indeed flew twice at high latitudes, first to characterize air masses via the isotopic composition of water vapor, then to study Arctic cyclones and their interactions with sea ice. Further South 2022 was also a record-breaking Summer in terms of temperature. The Mediterranean was no exception, with an unprecedented marine heatwave, that was characterized in detail by satellite observations. Non-conventional data also continue to receive much attention at Météo-France, for example with the commercial microwave links from telephone operators that are used to estimate the intensity of precipitation. More conventional, the radars from the ARAMIS[2] network, in addition to precipitation, can estimate wind speed. However, this estimation becomes uncertain for high wind speeds, hence a new method has been developed to improve the quality of the retrievals in such conditions. Finally, radars are not only sensitive to weather conditions. Birds also reflect the signal, which allows to follow the main migration routes, and will perhaps help in the future to anticipate these movements and reduce the impact of human activities on these bird populations.**

*1. Service des avions français instrumentés pour la recherche en environnement*
*2. Application Radar à la Météorologie Infra-Synoptique*

## Météo-France ATR42: a flying laboratory on the Arctic research service

Jean-Christophe Canonici, Aurélien Bourdon

From 21 March to 10 April, the ISLAS[1] campaign funded by the ERC[2] aimed to better describe the water cycle on the scale of a northern region by characterising water vapour by its isotopic composition, in order to improve its representation in climate models and better forecasting of future climate. Météo-France's ATR42, based in Kiruna, Sweden, was the main investigative tool for tracing the journey of water molecules from their evaporation over the Arctic Ocean to their precipitation on the ice pack. From 4 to 26 August, the THINICE campaign, financed by ONR[3], Cnes[4], CNRS[5] and Nerc[6], tracked Arctic lows and associated cloud processes as well as their interaction with the ice pack. In particular, it carried the RALI remote sensing platform, which includes a cloud Doppler radar and a high-resolution lidar, as well as an infrared radiometer. The representation of these key phenomena for the melting of sea ice in summer should be improved. The Safire team operated the ATR42 from Svalbard. These two campaigns mobilised the Safire unit's resources beyond the Arctic Circle. These projections from an operational base several thousand kilometres away, sometimes very harsh weather conditions and a specific aeronautical environment required careful preparation and great rigour in the execution of the missions.

*1. Responsable scientifique : H. Sodemann, Univ. Bergen*
*2. European Reserch Council*
*3. Office of Naval Research, USA*
*4. Centre national d'études spatiales, France*
*5. Centre national de le recherche scientifique, programme LEFE de l'Institut national des sciences de l'Univers, France, projet Cyclonice*
*6. Natural Environmental Research Council, Royaume-Uni*

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# Analysis of the marine heatwave in the Mediterranean during the summer of 2022 based on satellite observations

T.Guinaldo, F.Vergneault, S.Somot, S.Saux Picart, H.Roquet

The Mediterranean Sea experienced a particularly intense oceanic heat wave during the summer of 2022. Within the framework of the OSI SAF project led by Météo France and funded by EUMETSAT, techniques are being developed to estimate sea surface temperatures (SSTs) from satellite data. In order to identify the influence that the exceptional synoptic conditions of the summer had on SSTs, a study has been carried out to analyse the behaviour of these SSTs around various French coastlines with a particular focus on the Mediterranean Sea.
The analysis of SSTs in the Mediterranean Sea (Figure 1) shows an average seasonal anomaly, between June and August, of 2°C warmer than the climatology over the period 1982-2011 with a maximum temperature of 30.8°C on the 4th of August 2022 in the Gulf of Lion. This prolonged sequence of warmer than usual sea surface temperatures was marked by daily anomalies about 3°C above climatology and the occurrence of marine heatwaves.

Marine heatwaves are well known and have been regularly observed in the Mediterranean Sea for many years. However, the 2022 marine heatwave, which started on June 25th 2022, is exceptional due to its average intensity (+2.8°C). It is also an absolute record in terms of duration (59 days), maximum intensity (+4.4°C) and the strong impact, already reported, that this event had on coastal marine ecosystems.
The response of ocean surfaces to these heatwaves demonstrates the need for developing coupled ocean-atmosphere systems that continuously integrate satellite measurements in order to anticipate the changes threatening oceans and marine ecosystems within the context of climate change

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# Quantify and anticipate bird migration using radar measurements to limit mortality induced by wind farms

T. Désert, J. Figueras i Ventura, T. Nicolau

In order to reduce the loss of biodiversity in a globally expanding wind energy sector, the de-risking of wind farm projects is a major issue. Billions of birds fly across France every year on their way to optimal habitats depending on the season. These migratory movements are very complex to trace, even more over ocean than on land.
Thus, an accurate tool for bird detection is a strategic issue for project planning and the issuance of alerts of imminent passage of migratory birds. Weather radars capture any target backscattering its electromagnetic pulse: from precipitations to migrating birds. A network of weather radars therefore offers the possibility to study and quantify biomass over long periods.
The SEMAFOR project brings together the institutions: France Energie Marine, Météo-France, Biotope and Swiss Ornithological Institute. Its ambition is to develop a real-time observatory of migratory birds at high resolution from the French weather radar network, and to propose a tool to forecast migratory passages.
Firstly, existing algorithms for bird detection will be adapted to raw data from the weather radar network operated by Météo-France and calibrated with the ornithological radars from Biotope. Once the algorithm validated, the spatial location and temporal evolution of migratory movements will be studied on a national scale during a complete life cycle. Secondly, a predictive model for the probability of passage of migratory birds will be developed by the Swiss Ornithological Institute. The model will take into account real time measurements from weather radars, but also local meteorological and environmental parameters and orographic obstacles, as well as knowledge of the main migration routes.

4

# Commercial Microwave Links used to estimate rainfall at Météo-France

Dominique Faure

This project named Raincell is developed in the framework of Météo-France's actions to use opportunistic sensing, in order to complete the existing standard measurement networks, and to improve existing data fusion products.
The possibility of estimating rainfall from the disturbances recorded by the microwave networks of telecommunication operators has been demonstrated by various international research teams. The method is based on the estimation of the signal attenuation between two relay antennas which constitute a commercial microwave link (CML). Since the attenuation is related to the precipitation rate encountered by the signal during its path between the two antennas, it is possible to estimate the average rainfall rate along this link from the total attenuation over the length of the link.
In 2022, Météo-France finalised the signature of a contract with Orange, and a collaboration contract with the Institut de Recherche pour le Développement (IRD), in order to collect and process in near real time data from more than 4200 Orange CML links available in metropolitan France and overseas territories. A dedicated data hub has been developed by Orange, and a real time data flow was established between Orange facilities and Météo-France at the end of November 2022.
In 2023, the activity will be focused on the development and validation of a software to process the data in near real time, in order to obtain usable rainfall estimates from raw attenuation measurements, benefiting from the experience acquired by IRD in this scientific field.

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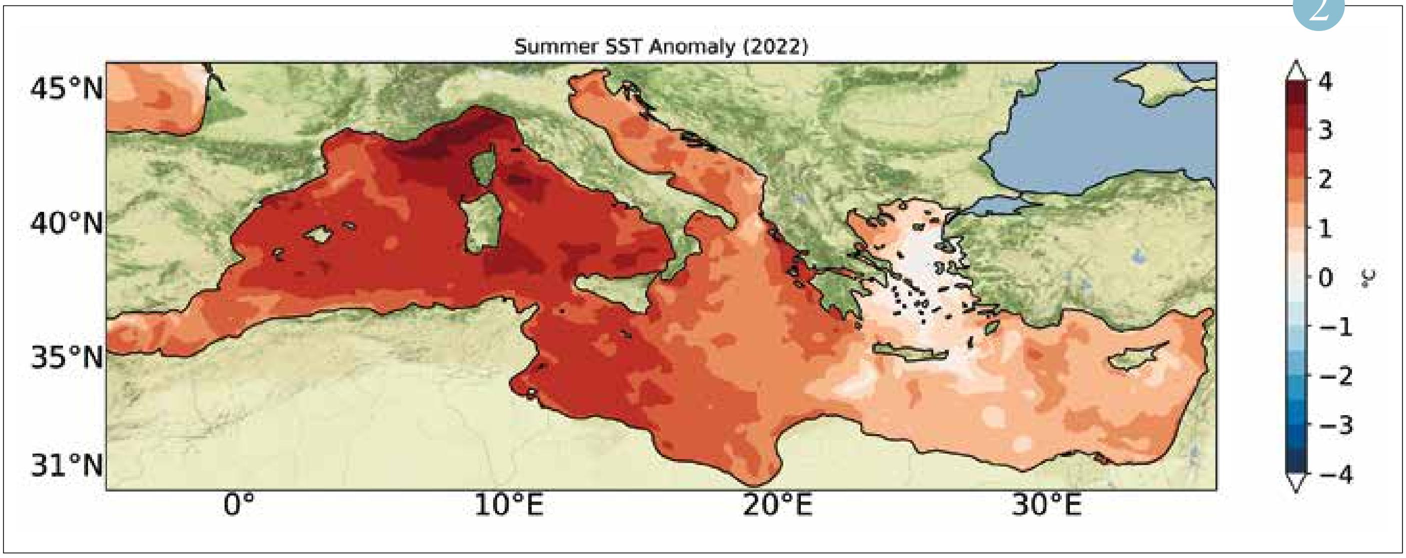


Seasonal sea surface temperatures (SST) anomalies over the Mediterranean Sea for the June-August 2022 period. Seasonal climatology is calculated based on the 1982-2011 period.

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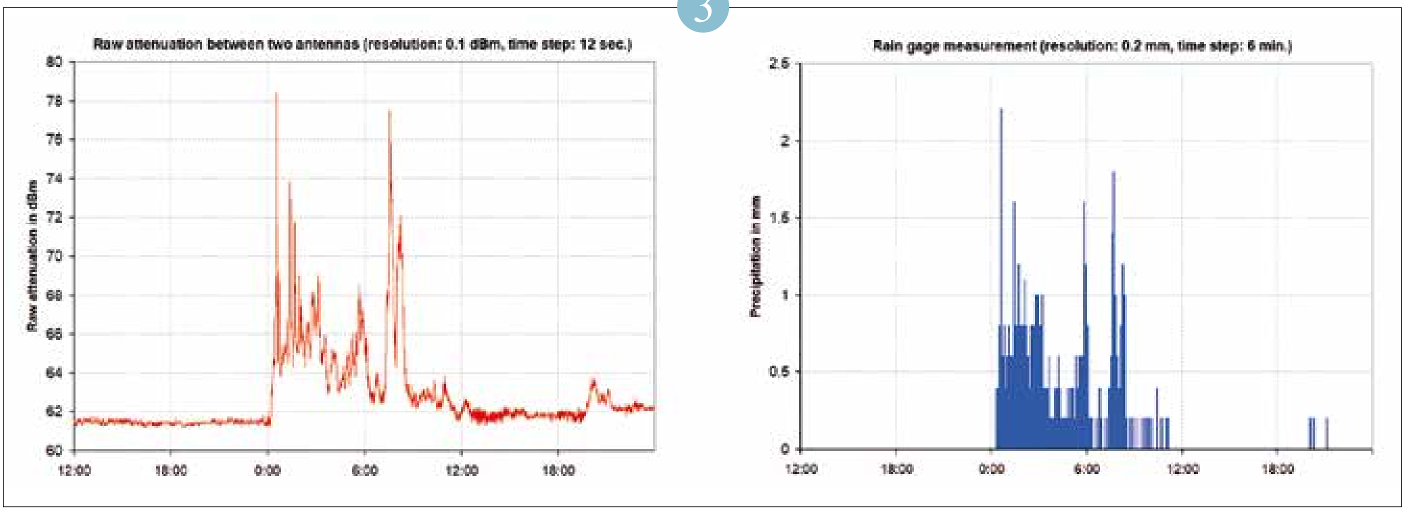


Comparison for a rain event the 23 and 24 of october, 2022. Top, raw attenuation measured for a 23 GHz CML link, 4 km long, with an accuracy of 0.1 dBm, and a 12 seconds measurement step. Bottom, measurement of a rain gauge located near the centre of the link, accuracy 0.2 mm, 6 minutes time step.

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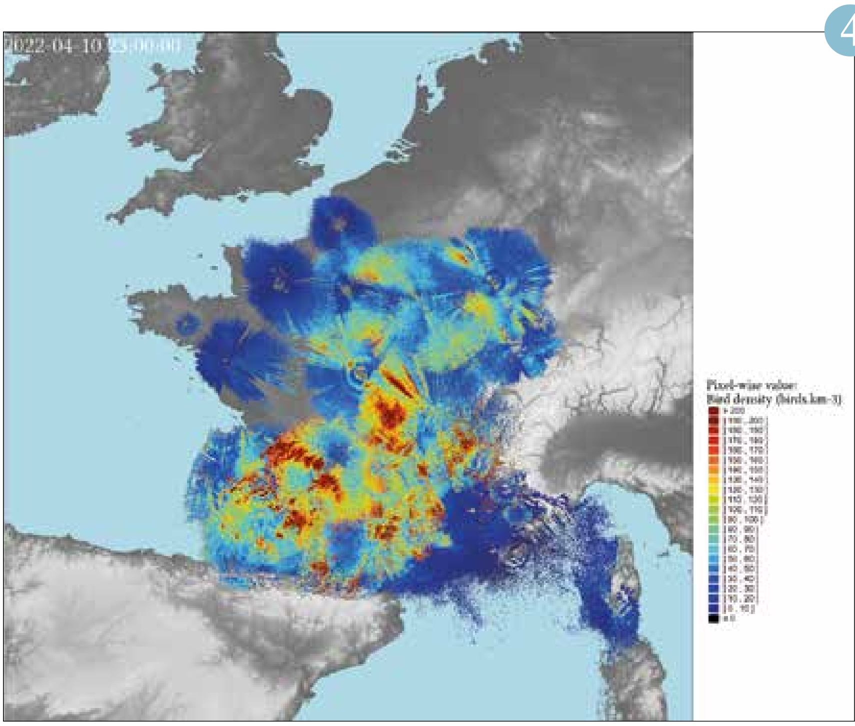


Mosaic of radar measurements of a night of very high migration (night from 2022/04/10 to 2022/04/11).
The pixels are colored by the estimated density of birds per km³, each pixel represents a 1kmx1km area at ground level.

# Improvement of Doppler data quality by correcting dealiasing errors

Tony Le Bastard

The Doppler velocity is estimated by measuring the phase shift between two successive radar pulses. Since the maximum phase shift between two waves is ±ϖ, the maximum directly measurable velocity cannot exceed ±VN, the Nyquist velocity (approximately 3 to 8 m.s-1 for the radars in the ARAMIS network). For higher observed velocities, the measured velocity will therefore be "aliased" into the ±VN interval.
To "dealiase" the measured velocity and thus recover the real velocity, Météo-France uses a triple-PRT scheme (Tabary et al., 2006). The use of three interleaved emission frequencies, each with its own Nyquist velocity, makes it possible to obtain three distinct measurements. By testing the different possible aliasings of one of the measured velocities and exploiting the other two measurements, it is possible to reproduce velocities up to ±60 m.s-1. However, aliasing errors can occur, mainly due to noise in the 3 measured velocities.
To deal with these errors, a new method has been developed. The errors are first identified by comparing the values at each pixel with a set of medians calculated from the neighbouring pixels. If the pixel deviates too far from these medians, it is considered to be affected by an error. Then, knowing that the error is a multiple of 2VN, the value is corrected until it is as close as possible to the neighbourhood median.
This correction method makes it possible to obtain a much less noisy field while maintaining a good level of detail compared to the application of a simple median filter (figure). It will be deployed operationally in a new version of SERVAL during 2023.

**Reference:**

Tabary, P., Guibert, F., Perier, L., & Parent-du-Chatelet, J. (2006). An operational triple-PRT Doppler scheme for the French radar network. *Journal of Atmospheric and Oceanic Technology*, 23(12), 1645-1656.

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# Analysis of the exceptional volcanic eruption of Hunga Tonga on January 15, 2022

Jean-Marie Lalande, Jérome Vidot, Samuel Morin

The explosive eruption of the underwater volcano Hunga Tonga, January 15, 2022 has generated several exceptional atmospheric and geophysical phenomena. This is what an international study conducted by a team of 76 scientists from 17 countries, in which two researchers from CNRM (Centre d'Etudes en Météorologie Satellitaire, Lannion) participated, reveals.
The work, compiled in a very short period of time, details the magnitude of the waves from the eruption, which, according to the authors, are comparable to those of Krakatoa (Indonesia), which occurred in 1883, over a century ago. The data provide a resolution and coverage of the evolving wave field that is unmatched by what was available at the time. The paper, published in the journal Science, was the first comprehensive account of the atmospheric waves generated by the eruption.This extensive study analyzes the volcanic explosion, the most powerful recorded since the last century, using various networks of ground and space-based instruments: seismometers, microbarometers, hydrophones, GNSS (Global Navigation Satellite System), DART buoys, and weather satellites.
Initial evidence suggests that an eruption on January 14 lowered the main vent of the volcano below sea level, initiating the massive explosion that occurred the next day. The January 15 eruption generated a wide variety of atmospheric waves, including bangs heard 10,000 km away in Alaska. It also created a pulse that caused the unusual occurrence of a tsunami-like disturbance an hour before the onset of the actual seismic tsunami.
Scientists have been interested in the waves generated by this major flare, among others: sound and infrasound waves, Lamb waves, etc. The ionospheric signatures of most of these waves were also observed using GNSS satellites. The published results exploit the synergy between different measurement technologies to study rarely observed phenomena (in particular the Lamb wave). The analysis of the dynamic coupling of the waves generated at the ocean-land-atmosphere interfaces allows to better characterize the eruptive source of Hunga as well as the impulse response of the planetary fluid envelope to an eruption of exceptional intensity. This study also highlights new geophysical investigation methods and their combined contributions to characterize the mechanism and short-term consequences of the eruption of this volcano.
The CNRM also participated in the coordination and writing of a synthesis of the scientific lessons learned from this eruption, in the form of an inter-agency note produced by the "Atmosphere" Thematic Group of AllEnvi, published at the end of 2022: https://www.allenvi.fr/note-inter-organismes-sur-leruption-explosive-du-volcan-hunga-tonga/

**Référence :**

Matoza et al., Atmospheric waves and global seismoacoustic observations of the January 2022 Hunga eruption, Tonga, Science, https://doi.org/10.1126/science.abo7063, 2022.

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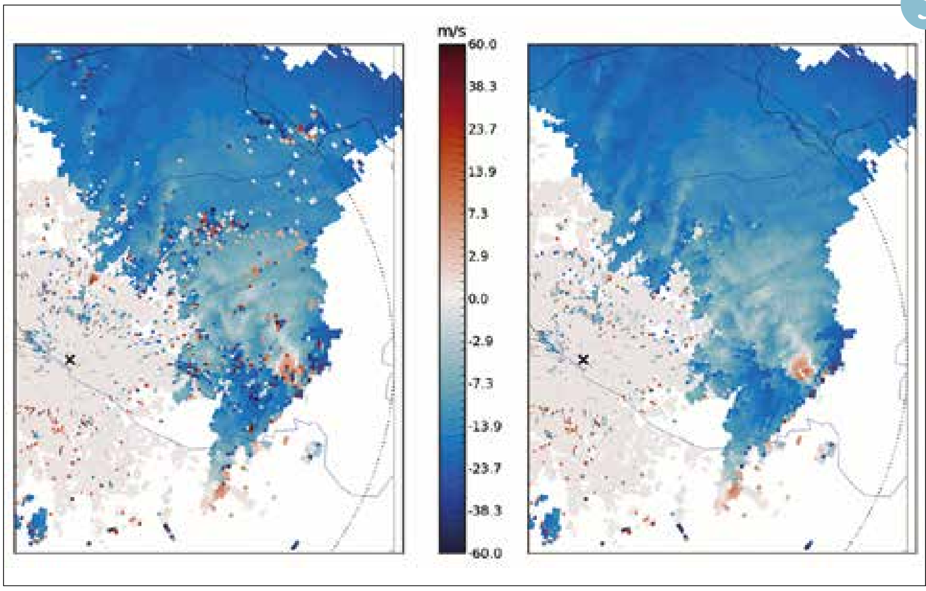


Radial velocities before and after correction of aliasing errors during the passage of a tornado over Bihucourt on 23/10/2022 at 16:15 UTC. Abbeville radar at elevation 0.4°.

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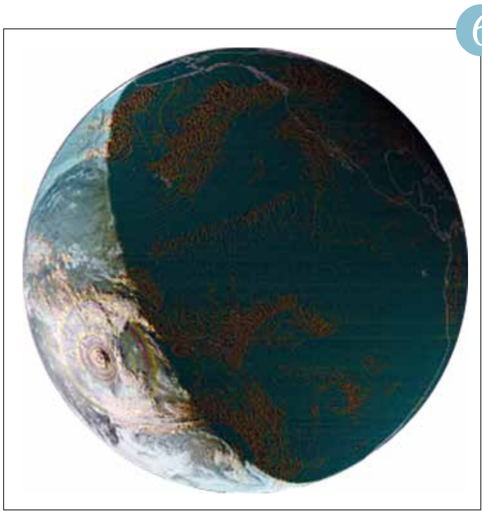

Waves generated by the eruption of Hunga Tonga superimposed on the true color composition seen by the geostationary satellite GOES-17

# Open Science, scientific ethics, scientific mediation

**Open science, scientific ethics and scientific mediation are important issues for the research activities conducted at Météo-France. Open science is the idea that the results of scientific research should be freely available and easily accessible to all, without restriction or financial barrier. The research entities of Météo-France are increasingly implementing the principles of open science, whether it is to promote access to scientific publications through a new policy of scientific publications (open access principles), access to research data according to the FAIR (« Findable, Accessible, Interoperable, Reusable ») principles, and the collaborative development of computer codes. These principles underlie the 2nd National Open Science Plan 2021-2024 and are increasingly applied in research organizations including Météo-France.**
**In addition, in 2022, Météo-France has introduced a scientific integrity referent, in accordance with the provisions of the research programming law for the years 2021 to 2030. This law contains a new article concerning the requirements of scientific integrity, which aim to guarantee the honest and scientifically rigorous nature of public research activities, and to consolidate the bond of trust with society. They apply to all public institutions contributing to the public research service, including Météo-France. These requirements concern in particular the training and awareness-raising of personnel, the promotion of open science practices in terms of scientific publications and the availability of data and source codes associated with research results, the prevention and detection of breaches of these requirements, as well as the investigation of reports received.**
**Finally, the scientific mediation of Météo-France's research activities is essential, aiming at making the results of its research accessible to the general public and promoting scientific culture. In 2022, the staff of the research entities of Météo-France participated in several communication and awareness-raising events, notably the « Nuit européenne des chercheurs » in September 2022, but also the « Fête de la science », the « Festival Toulouse Innovante et Durable », etc. On another note, Météo-France staff participated in the book "Tout comprendre, ou presque, sur le climat" (Understanding almost everything about climate), published in March 2022. This graphic work, coordinated by the CNRS, gives an account of what we really know about climate change, how this knowledge was established, and unravels some preconceived ideas.**

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## The new policy for scientific publications at Météo-France

S. Morin

In 2022, Météo-France adopted a policy for its scientific publications. Scientific publications play an essential role in the dissemination of scientific knowledge resulting from research or technical developments and are governed by a virtuous process of peer review and robust description of the methods and results obtained. Météo-France's policy stipulates that scientific publications must meet the requirements of open access, in accordance with the objectives of the National Plan for Open Science and in coherence with the Law for a Digital Republic. Two options are possible: to publish in journals giving direct free access to the content of the articles ("Gold Open Access") or to publish in traditional journals with paid access to the articles or hybrids, and to place the text of the accepted article (not edited by the journal) on a deposit site ("Green Open Access"). The procedure stipulates that the principle adopted in the first instance is to give priority to publications in natively Gold Open Access journals, or failing that to use the Green Open Access approach. The repository site chosen for all Météo-France publications is the multidisciplinary open archive HAL (https://hal.science/), which has a specific sub-domain for Météo-France productions (http://hal-meteofrance.archives-ouvertes.fr/). This open archive gathers all the publications of national scientific organizations and allows direct access to publications co-authored by a member of an entity dependent on Météo-France, through its dedicated portal.

1

# Météo-France contribution to data dissemination activities (Data Terra, Gaïa Data, SAFIRE+)

Hervé Roquet

Within the framework of the new French research planning law, the provision of data resulting from research activities is now an obligation for all public institutions contributing to research public service, and is an integral element of Open Science policy. Since more than 10 years, Météo-France is contributing actively to the development and functioning of data and services centres for research, not only by providing data resulting from its research activities, but also data from its operational observation networks to meet the needs of the scientific community. Moreover, it directly supports the AERIS centre (htpps://www.aeris-data.fr), dedicated to atmospheric observation data, by assigning an agent at OMP. AERIS is also hosting the SAFIRE+ data base and its access portal to measurements performed by research aircraft of the SAFIRE Unit, which is operated jointly by Météo-France, CNRS and CNES.

Today, the four data and services centres for earth system (AERIS, THEIA, ODATIS and FORMATER) are federated within the national Research Infrastructure Data Terra, which allowed to strengthen their funding, to pool many development activities, and to unify data access portals and catalogues. Furthermore, Data Terra is today carrying the Gaïa Data project, funded by the national Research Agency (ANR) for 8 years, and which Météo-France is a partner of. The objective of the project is make interoperable data bases of Data Terra, of the national data centre for biodiversity (PNDB) and of CLIMERI (national Research Infrastructure for climate modelling), and to develop new services, including the on-demand access to computing resources for massive data processing.

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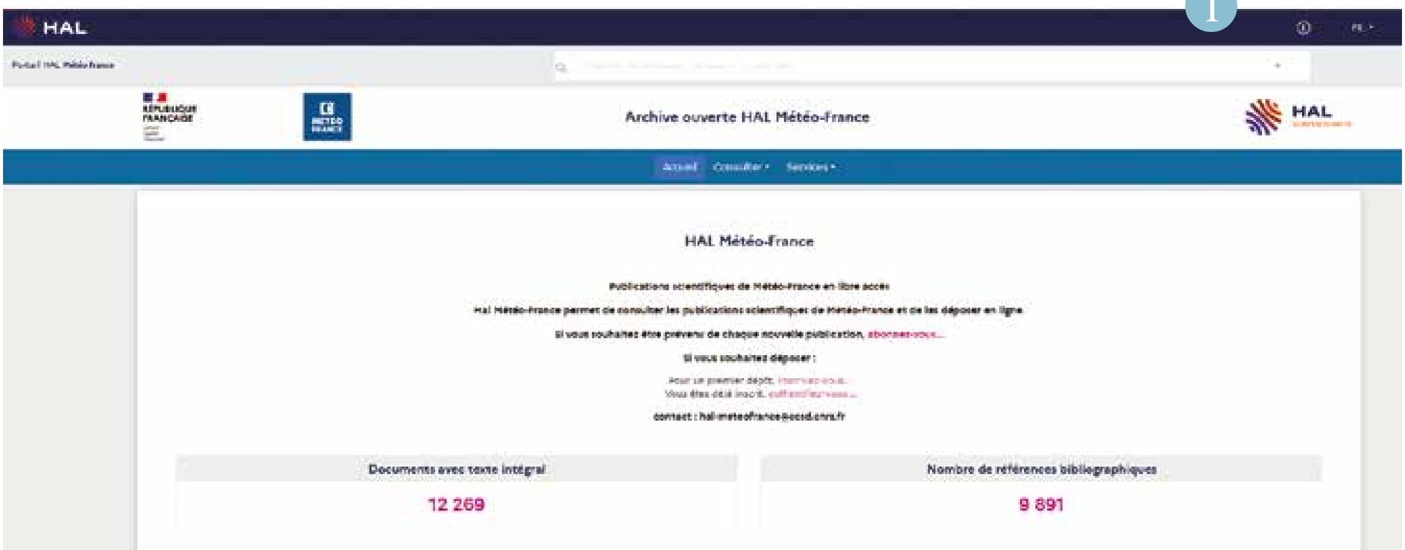


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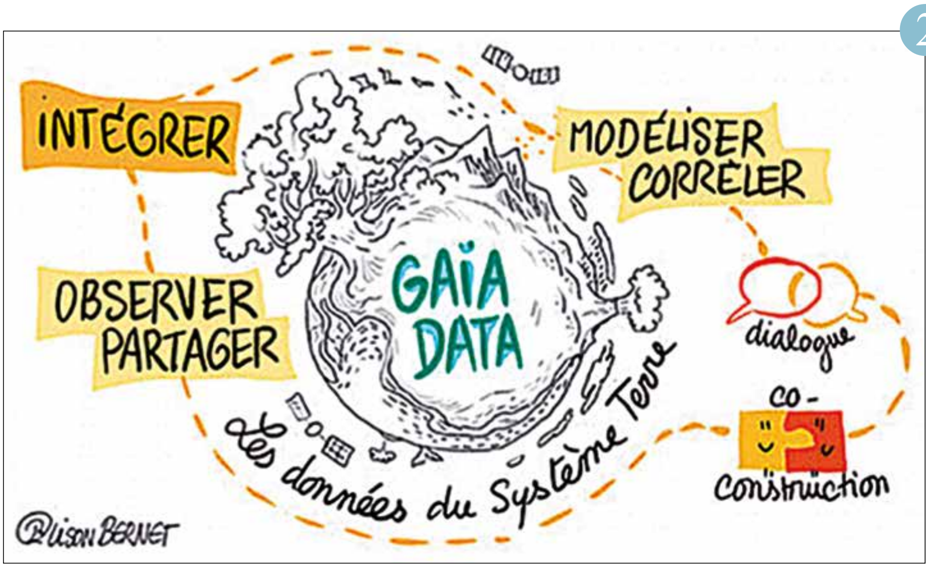


◄ ASrtist's view of Gaïa Data project and its objectives.

# « Data papers », a new approach supporting open science

S. Morin

One of the challenges of open science is to facilitate access to research data. In this context, in order to implement the FAIR (*Findable, Accessible, Interoperable, Reusable*) principles for datasets, the last few years have seen the emergence of a new type of scientific publication, the "data papers". These publications are subject to the same principles of peer review and published in specialized journals, such as *Earth System Science Data, Scientific Data, Data in Brief* etc. The evaluation criteria are broadly similar to those of traditional publications, while focusing on the methods of production, evaluation and availability of the data described. In many cases, the data in question are first deposited on specialized data portals, notably, in France, those implemented by the DataTerra research infrastructure (AERIS, Theia, Form@ter, Odatis). The SEDOO department of the Midi Pyrénées Observatory participates in these efforts. These datasets are equipped with a permanent DOI (*digital objective identifier*) allowing them to be referred to without ambiguity. In 2022, several data papers were published by Météo-France research entities. They facilitate the reuse of original datasets in the international scientific community and can be included in the Data Management Plan of the corresponding research projects.

**Reference:**


Martinet, P., et al, A dataset of temperature, humidity, and liquid water path retrievals from a network of ground-based microwave radiometers dedicated to fog investigation. *Bull. of Atmos. Sci.& Technol.,* https://doi.org/10.1007/s42865-022-00049-w, 2022. This paper describes an original dataset of data collected by a network of microwave radiometers deployed during the SOFOG3D campaign in 2019 and 2020 to investigate fog and model performance on it. These data are released on the AERIS data platform.

Vernay M., et al, The S2M meteorological and snow cover reanalysis over the French mountainous areas: description and evaluation (1958-2021). *Earth System Science Data*, https://doi.org/10.5194/essd-14-1707-2022, 2022. This paper describes the S2M meteorological and snow cover reanalysis over the French mountainous areas since 1958. The data from this reanalysis are disseminated via the AERIS data platform.

Munier S. and B. Decharme. River network and hydro-geomorphological parameters at 1/12° resolution for global hydrological and climate studies. *Earth System Science Data*, https://doi.org/10.5194/essd-14-2239-2022, 2022. This available dataset facilitates the implementation of global-scale hydrological modeling systems.

Bony et al, EUREC4A observations from the SAFIRE ATR42 aircraft, *Earth System Science Data*, https://doi.org/10.5194/essd-14-2021-2022, 2022. This study describes the data acquired aboard the SAFIRE ATR42 research aircraft during the 2020 EUREC4A campaign in Barbados, including the processing applied to these raw data

Finally, note the annual production of reference data on the global carbon cycle, with the participation of CNRM research staff in the emblematic data paper that is the annual study of the Global Carbon Project, also published in *Earth System Science Data*: Friedlingstein P., et al., Global Carbon Budget 2022, *Earth Syst. Sci. Data*, https://doi.org/10.5194/essd-14-4811-2022, 2022.


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# Ethics and scientific integrity

Hervé Roquet, Jean-Marcel Piriou

Scientific integrity is at the heart of every research activity : establishing honest, proven and reproducible knowledge, at the same time respecting actors (citation, acknowledgement), and more and more sharing not only publications, but also data and related algorithms (open science). This need for integrity is justified and motivated by an ethical reflection, which is a broader and upstream process aiming at determining which actions should be encouraged or discouraged. This ethical reflection must so underpin the writing of every constitution, law, as well as professional deontology, which scientific integrity is part of.

In 2022, Météo-France decided to implement an explicit policy with regard to scientific integrity. A reference person for scientific integrity has been nominated, and the Institute has acceded to the French chart of deontology in research professions : https://www.hceres.fr/sites/default/files/media/downloads/2015_Charte_nationale_déontologie_190613.pdf

This chart is applicable to every Météo-France's employee, holding a permanent position or not, who is contributing to research activity. Reflections have started as regards awareness raising and training actions which must be conducted on ethics and scientific integrity at Météo-France, as well as the procedure for collecting and processing alerts concerning scientific integrity. Their implementation is planned from 2023 onwards.

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Bulletin of Atmospheric Science and Technology (2022) 3:6
https://doi.org/10.1007/s42865-022-00049-w

RESEARCH ARTICLE

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## A dataset of temperature, humidity, and liquid water path retrievals from a network of ground-based microwave radiometers dedicated to fog investigation

Pauline Martinet[1] · Vinciane Unger[1] · Frédéric Burnet[1] · Jean-François Georgis[2] · Maxime Hervo[3] · Thierry Huet[4] · Ulrich Löhnert[5] · Eugene Miller[6] · Emiliano Orlandi[7] · Jeremy Price[8] · Mathias Schröder[9] · Guillaume Thomas[1,10,11]

Earth Syst. Sci. Data, 14, 2021–2064, 2022
https://doi.org/10.5194/essd-14-2021-2022


Open Access Earth System Science Data

## EUREC$^4$A observations from the SAFIRE ATR42 aircraft

Sandrine Bony[1], Marie Lothon[2], Julien Delanoë[3], Pierre Coutris[4], Jean-Claude Etienne[5], Franziska Aemisegger[6], Anna Lea Albright[1], Thierry André[8], Hubert Bellec[8], Alexandre Baron[7], Jean-François Bourdinot[8], Pierre-Etienne Brilouet[2,5], Aurélien Bourdon[8], Jean-Christophe Canonici[8], Christophe Caudoux[3], Patrick Chazette[7], Michel Cluzeau[8], Céline Cornet[9], Jean-Philippe Desbios[8], Dominique Duchanoy[8], Cyrille Flamant[10], Benjamin Fildier[11], Christophe Gourbeyre[4], Laurent Guiraud[8], Tetyana Jiang[8], Claude Lainard[8], Christophe Le Gac[3], Christian Lendroit[8], Julien Lernould[8], Thierry Perrin[8], Frédéric Pouvesle[8], Pascal Richard[8], Nicolas Rochetin[11], Kevin Salaün[8], Alfons Schwarzenboeck[4], Guillaume Seurat[8], Bjorn Stevens[12], Julien Totems[7], Ludovic Touzé-Peiffer[1], Gilles Vergez[8], Jessica Vial[1], Leonie Villiger[6], and Raphaela Vogel[1]

Earth Syst. Sci. Data, 14, 1707–1733, 2022
https://doi.org/10.5194/essd-14-1707-2022


Open Access Earth System Science Data

## The S2M meteorological and snow cover reanalysis over the French mountainous areas: description and evaluation (1958–2021)

Matthieu Vernay[1], Matthieu Lafaysse[1], Diego Monteiro[1], Pascal Hagenmuller[1], Rafife Nheili[1], Raphaëlle Samacoïts[1,2], Deborah Verfaillie[1], and Samuel Morin[1]

Earth Syst. Sci. Data, 14, 2239–2258, 2022
https://doi.org/10.5194/essd-14-2239-2022


Open Access Earth System Science Data

## River network and hydro-geomorphological parameters at 1/12° resolution for global hydrological and climate studies

Simon Munier and Bertrand Decharme
CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France

Earth Syst. Sci. Data, 14, 4811–4900, 2022
https://doi.org/10.5194/essd-14-4811-2022


Open Access Earth System Science Data

## Global Carbon Budget 2022

Pierre Friedlingstein[1,2], Michael O'Sullivan[1], Matthew W. Jones[3], Robbie M. Andrew[4], Luke Gregor[5], Judith Hauck[6], Corinne Le Quéré[3], Ingrid T. Luijkx[7], Are Olsen[8,9], Glen P. Peters[4], Wouter Peters[7,10], Julia Pongratz[11,12], Clemens Schwingshackl[11], Stephen Sitch[1], Josep G. Canadell[13], Philippe Ciais[14], Robert B. Jackson[15], Simone R. Alin[16], Ramdane Alkama[17], Almut Arneth[18], Vivek K. Arora[19], Nicholas R. Bates[20,21], Meike Becker[8,9], Nicolas Bellouin[22], Henry C. Bittig[23], Laurent Bopp[2], Frédéric Chevallier[14], Louise P. Chini[24], Margot Cronin[25], Wiley Evans[26], Stefanie Falk[11], Richard A. Feely[16], Thomas Gasser[27], Marion Gehlen[14], Thanos Gkritzalis[28], Lucas Gloege[29,30], Giacomo Grassi[17], Nicolas Gruber[5], Özgür Gürses[6], Ian Harris[31], Matthew Hefner[32,33], Richard A. Houghton[34], George C. Hurtt[24], Yosuke Iida[35], Tatiana Ilyina[12], Atul K. Jain[36], Annika Jersild[12], Koji Kadono[35], Etsushi Kato[37], Daniel Kennedy[38], Kees Klein Goldewijk[39], Jürgen Knauer[40,41], Jan Ivar Korsbakken[4], Peter Landschützer[12,28], Nathalie Lefèvre[42], Keith Lindsay[43], Junjie Liu[44], Zhu Liu[45], Gregg Marland[32,33], Nicolas Mayot[3], Matthew J. McGrath[14], Nicolas Metzl[42], Natalie M. Monacci[46], David R. Munro[47,48], Shin-Ichiro Nakaoka[49], Yosuke Niwa[49,50], Kevin O'Brien[51,16], Tsuneo Ono[52], Paul I. Palmer[53,54], Naiqing Pan[55,56], Denis Pierrot[57], Katie Pocock[26], Benjamin Poulter[58], Laure Resplandy[59], Eddy Robertson[60], Christian Rödenbeck[61], Carmen Rodriguez[62], Thais M. Rosan[1], Jörg Schwinger[63,9], Roland Séférian[64], Jamie D. Shutler[1], Ingunn Skjelvan[63,9], Tobias Steinhoff[65], Qing Sun[66], Adrienne J. Sutton[16], Colm Sweeney[48], Shintaro Takao[49], Toste Tanhua[65], Pieter P. Tans[67,68], Xiangjun Tian[69], Hanqin Tian[56], Bronte Tilbrook[70,71], Hiroyuki Tsujino[72], Francesco Tubiello[73], Guido R. van der Werf[73], Anthony P. Walker[74], Rik Wanninkhof[57], Chris Whitehead[75], Anna Willstrand Wranne[76], Rebecca Wright[3], Wenping Yuan[77], Chao Yue[78], Xu Yue[79], Sönke Zaehle[61], Jiye Zeng[49], and Bo Zheng[80]

# European Researchers Night 2022

N. Boullot, C. Labadie, M. Marquillie, J.-M. Piriou, H. Pierre[1]

The 2022 edition of the European Researchers' Night was held on 30 September around the national theme "Les imprévus". This annual event takes place simultaneously in more than 200 cities in Europe, including 16 cities in mainland France. It is an opportunity for the public to meet and exchange with scientists from all disciplines, to discover their work and to share their passion for research. The University of Toulouse, its establishments and its partners organised this 18yedition on the sites of Toulouse and Albi. In Toulouse, the *Cité de l'espace* hosted the event this year, with an increased public attendance up to 3150 visitors, 900 more than in 2019, the last 100% face-to-face edition. The CNRM has long been involved in this event.

The evening was punctuated by several formats of activities. The « grand labo » included activities in which the young public could participate. The « ice-cream vendor » stand run by P. Cébron, L. Descamps and C. Labadie from the CNRM welcomed an amused audience from all generations. It is a game that helps to understand the notion of probabilistic weather forecasting, and shows the richness of this type of forecasting. The objective can be measured when the players change their strategy advantageously during the game. For more information, see https://lameteorologie.fr/issues/2017/96/meteo_2017_96_21

Speed-Searching allowed a small group of visitors to meet and talk with researchers during a 10-minute one-to-one session about an object. For the CNRM, J.-M. Piriou, B. Balogh, C. Brochet, M.-A. Magnaldo and M. Marquillie shared their research on meteorology and climate. For Jean-Marcel Piriou, participating in Speed-Searching is always an enriching experience. Each person is different. From the high school student, already passionate about weather, who asks which courses of study allow him to work at Météo-France, to the mathematics students who, mockingly, come to ask questions about our ability to efficiently integrate the Navier-Stokes equations, which are reputed to be difficult, into Météo-France's computers, and not forgetting the schoolgirl with her mother who asks if there have always been land masses or why there is wind, the variety of questions is exceptional. The curiosity and complicity of the public during these Researcher's Nights are an inexhaustible source of joy.

Maëva Marquillie, a doctoral student in meteorology, shares her taste for popularising science, which she believes "bridges the gap between science and the general public". "Faced with the challenges of adapting to climate change, we need, more than ever, researchers to do this work of mediation and popularisation, so that the message is accurate and understood by all", she says. During her Speed-Searching session, she noted a strong interest from the public in the application of the effects of climate change to meteorology in France, particularly via the recurring question on the potential link between climate change and the intensification of extreme weather phenomena.

The next edition will be held on 29 September 2023 at the "Cité de l'espace" for the Toulouse site around the national theme "Nos futurs".

1. *Toulouse University*

**Reference:**

https://nuitdeschercheurs-france.eu/?2022

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In the background, the Cité de l'espace in Toulouse.
Left medallion: Jean-Marcel Piriou during the Speed-Searching session @ photo Adrien Basse Cathalinat.
Middle inset: Clément Brochet at the Speed-Searching @ photo Université de Toulouse.
Right medallion: Pierrick Cébron and Carole Labadie animating the ice cream vendor game @ photo N. Boullot.

# Appendix

## 2022 Scientific papers list


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# Glossary

**3DEnVar** Schéma d'assimilation variationnel ensembliste tridimensionnel
**ABO** Aircraft Base Observation
**ACROSS-AO** Atmospheric Chemistry of the Suburban Forest : chimie atmosphérique des forêts suburbaines
**4DEnVar** Schéma associant l'approche variationnelle utilisée traditionnellement à Météo-France aux approches ensemblistes utilisées
**ADAMONT** Impacts du changement climatique et adaptation en territoire de montagne
**ADEME** Agence de l'Environnement et de la Maîtrise de l'Energie
**ADM** Atmospheric Dynamics Mission
**ADS-B** Antennes
**AEE** Agence Européenne de l'Environnement
**AEOLUS** Atmospheric Explorer Observations with a Lidar UV System
**AERIS** pôle de données et de service du système terre
**ALADIN** Aire Limitée Adaptation Dynamique et développement InterNational
**AMSR** Advanced Microwave Scanning Radiometer
**ANR** Agence Nationale de la Recherche
**AOS** Atmosphere Observing Systems
**ARAMIS** Application Radar à la Météorologie Infra-Synoptique
**AROME** Application de la Recherche à l'Opérationnel à Méso-Échelle
**AROME-PI** Configuration AROME Prévision Immédiate
**ARPEGE** Action de Recherche Petite Échelle Grande Échelle
**ARRA** ARome ReAnalysis
**ASCAT** Advanced SCATterometer
**AVHRR** Advanced Very High Resolution Radiometer
**BLAZE** Modèle de feu
**BRGM** Bureau de Recherche Géologique et Minière
**C3S** Copernicus Climate Change Service
**CALIPSO** Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
**CAMS** projet Européen Copernicus
**CART** Classification And Regression Trees
**CAT** Clear Air Turbulence, Turbulence en Air Clair
**CCM-I** Chemistry-Climate Model Initiative
**CCR** Caisse Centrale de Réassurance
**CDP** Cloud Droplet Probe
**Cedre** Centre de documentation, de recherche et d'expérimentations sur les pollutions accidentelles des eaux
**CEMS** Centre d'Etude en Météorologie Satellitaire
**CEN** Centre d'Etudes de la Neige
**CEPMMT** Centre Européen pour les Prévisions Météorologiques à Moyen Terme
**CERES** Satellite
**CERRA** Réanalyse en prévision
**CESBIO** Centre d'Etudes Spatiales de la Biosphère
**CGLS** Copernicus Global Land Service
**CLA** Couche Limite Atmosphérique
**CLIMERI** Infrastructure de Recherche nationale pour la modélisation du climat
**CLIMSNOW** Adaptation au changement climatique et projections de l'évolution de enneigement
**CLIO** Lidar
**CMCC** Centre euro-Méditerranéen sur le Changement Climatique (Italie)
**CMIM** Constellation de MIni sondeurs pour la Météorologie
**CMIP** Coupled Model Intercomparaison Project
**CMIP6** Climate Models Intercomparison Project n°6
**CML** lien micro-onde commercial
**CMO** Couche Limite Océanique
**CNES** Centre National d'Études Spatiales
**CNRM** Centre National de Recherches Météorologiques
**CNRM-CM6** Version 6 du Modèle de Climat du CNRM
**CNRM-RCSM6** sixième version du système couplé de modélisation régionale
**CNRS** Centre National de Recherches Scientifiques
**CNSA** Agence spatiale chinoise
**CO** Monoxyde de Carbone
**COMSI** Comité scientifique
**COP** COnférence des Parties
**COPERNICUS** European Earth observation system http://www.copernicus.eu/pages-principales/services/climate-change/
**CORDEX** COordinated Regional climate Downscaling EXperiment
**CROCUS** Modèle de simulation numérique du manteau neigeux développé par Météo-France.
**CTRIP** CNRM-Total Routing Integrated Pathway
**DATA TERRA** Infrastructure de Recherche nationale
**DCSC** Direction de la Climatologie et des Services Climatiques
**DCT** Diffraction Contrast Tomography
**DEAL** Direction de l'Environnement, de l'Aménagement et du Logement
**DESR** Direction de l'Enseignement Supérieur et de la Recherche
**DGPR** Direction Générale de la Prévention des Risques
**DIRAG** Direction Inter-Régionale Antilles Guyane
**DIROI** Direction InterRégionale Océan Indien
**DMSP** Defense Meteorological Satellite Program
**DRE** Effet radiatif direct
**DRIAS** Portail d'accès à des données climatiques
**DSM** Direction des Services Météorologiques
**DSO** Direction des Systèmes d'Observation
**DWD** service météorologique allemand
**E-PROFILE** Réseau d'instruments
**Eas** Echos Arqués
**ECMWF** European Centre for Medium-range Weather Forecasts
**ECOCLIMAP-SG** Base de données pour les caractéristiques végétation
**EDMF** Eddy-Diffusivity-Mass-Flux
**EDR** Eddy Dissipation Rate
**EMADDC** European Meteorological Aircraft Derived Data Center
**ENAC** Ecole Nationale Aviation Civile
**ENSO** El Nino Southern Oscillation
**EOF** Fonction Orthogonale Empirique
**EOM** Ecart quadratique moyen
**EPA** Enquête Permanente Avalanche
**EPS-SG** Système polaire de 2ème génération d'EUMETSAT
**ERA** European Re-Analysis
**ERC-IVORI** projet sur les transformations physiques du manteau neigeux
**ESA** European Space Agency
**ESGF** Earth System Grid Federation,
**ESPOIRS** projet collaboratif visant à l'obtention d'une meilleure connaissance de la variabilité, des propriétés statistiques et des mécanismes de formation des précipitations tropicales aux échelles régionale et locale.
**ETP** Évapotranspiration Potentielle
**EUMETNET** European Meteorological Network
**EUMETSAT** Organisation européenne pour l´exploitation de satellites météorologiques
**EUREC4A** Elucidating the role of clouds-circulation coupling in climate
**EUROCONTROL** Organisation européenne pour la sécurité de la navigation aérienne
**EUROCORDEX** Modèle régional de climat
**FCI** Flexible Combined Imager
**FN** False Negative : pas de détection SAR dans les couloirs SPOT
**FORMATER** pôle de données et de service du système terre
**FORUM** Sondeur Infrarouge
**FTP** File Transfert Protocol
**GAIA DATA** projet porté par Data Terra et financé par l'ANR

**GCM** Modèle de circulation Générale
**GELATO** Global Experimental Leads and ice for ATmosphere and Ocean
**GEO** Group on Earth Observations
**GET** laboratoire de Géosciences Environnement Toulouse
**GHG** Green House Gazes
**GIEC** Groupe Intergouvernemental d'experts sur l'Evolution du Climat
**GMAP** Groupe de Modélisation et d'Assimilation pour la Prévision
**GMEI** Groupe de Météorologie Expérimentale et Instrumentale
**GMI** Capteur micro-ondes
**GNSS** systèmes mondiaux de navigation par satellite
**GOES** Satellites météorologiques géostationnaires américains
**GPCP** Global Precipitation Climatology Project
**GTG** Graphical Turbulence Guidance
**HCERES** Haut Conseil de l'évaluation de la recherche et de l'enseignement supérieur
**HCL** Hauteur de Couche Limite
**HIRLAM** HIgh Resolution Limited Area Model
**HITRAN** HIgh-resolution TRANsmission molecular absorption database
**HOMONIM** Historique Observation MOdélisation des Niveaux Marins
**HRIR** High Resolution Infrared Radiometer
**HSRL** High Spectral Resolution Radar
**HYCOM** HYbrid Coordinate Ocean Model
**HyMeX** Hydrological cYcle in the Mediterranean EXperiment
**IAGOS** In-service Aircraft for Global Observing System
**IASI** Interféromètre Atmosphérique de Sondage Infrarouge
**IASI-NG** Interféromètre Atmosphérique de Sondage Infrarouge nouvelle génération
**ICE3** Schéma de nuages
**ICICLE** Campagne de mesures
**ICON** Modèle du DWD
**ICOS** Infrastructure de recherche qui observe les flux des gaz à effet de serre en Europe et dans les régions adjacentes
**Ifremer** Institut Francais de Recherche pour l'Exploitation de la MER
**IFS** Integrated Forecasting System
**IFTS** Institut de la Filtration et des Techniques Séparatives
**IGE** Institut des Géosciences de l'Environnement
**INRA** Institut National de la Recherche Agronomique
**INRAE** Institut National de Recherche pour l'Agriculture, l'alimentation et l'Environnement
**IODC** Indian Ocean Data Coverage
**IPCC** Intergovernmental Panel on Climate Change (Groupe d'experts intergouvernemental sur l'évolution du climat)
**IPSL** Institut Pierre Simon Laplace
**IR** Infra Rouge
**IR-ACTRIS** Infrastructure de Recherche
**IRD** Institut de Recherche pour le Dévelopement
**IRIS** InfraRed Interfometer Spectrometer
**IRS** InfraRed Sounder
**ISBA** Interaction Sol-Biosphère-Atmosphère
**ISOBAR** Projet pour l'amélioration des prévisions météorologiques du risque convectif
ISP Images Satellite Prévues
**JHU** John Hopkins University
**KNMI** Koninklijk Nederlands Meteorologisch Instituut
**LA** Laboratoire d'Aérologie
**LAAS** Laboratoire Analyse Architecture Systèmes
**LACY** Laboratoire de l'Atmosphère et des Cyclones – UMR 8105
**LAERO** Laboratoire d'Aérologie
**LAI** Leaf Area Index
**LAMP** Laboratoire de Météorologie Physique
**LARGE** Laboratoire de recherche en géosciences et énergie
**LATMOS** Laboratoire Atmosphères, Observations Spatiales
**LDAS** Land Data Assimilation System.
**LEFE** programme national « Les Enveloppes Fluides et l'Environnement »
**LES** Large Eddy Simulation
**LI** Lightning Imager
**LIAISE** Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment
**LIDAR** light detection and ranging
**LIMA** schémas microphysiques
**LISA** Laboratoire Interuniversitaire des Systèmes Atmosphériques
**LMD** Laboratoire de Météorologie Dynamique
**LMI** Lifetime Maximum Intensity
**LSA** Land Suface Analysis
**LSCE** Laboratoire des Sciences du Climat et de l'Environnement
**LVP** Low Visibility Procedure
**LWC** Liquid Water Content
**MAE** Erreur Moyenne Absolue
**MCT** Modèle de Chimie Transport
**MEB** Multi-Energy-Balance
**MEDSCOPE** Mediterranean Services Chain based On climate Predictions
**MEPRA** Modèle Expert d'Aide à la Prévision du Risque d'Avalanche
**MERCATOR-OCEAN** Société Civile Française d'océanographie opérationnelle
**MERRA** Modèle avec forçages météorologiques
**MESO-NH** Modèle à MESO-échelle Non Hydrostatique
**Met Office** Service national britannique de météorologie
**METAR** METeorological Aerodrome Report
**METEOSAT** Programme de collecte et de diffusion de données à des fins météorologiques reposant sur une famille de satellites spécifiques
**METOP** METeorological Operational Polar satellites
**MFWAM** Météo-France WAve Model
**MHS** Capteur micro-ondes
**MIMESIS-3D** Etude de la microstructure la neige et de ses propriétés physiques à l'aide d'images 3D
**MJO** Madden-Julian Oscillation
**MOCAGE** MOdélisation de la Chimie Atmosphérique de Grande Echelle (modélisation)
**MODCOU** MODèle hydrologique COUplé surface-souterrain
**MODIS** MODerate-resolution Imaging Spectro-radiometer (instrument)
**MOSAI** Model and Observation for Surface-Atmosphere Interactions
**MOTHY** Modèle Océanique de Transport d'HYdrocarbure
**MPI** Max Planck Institute
**MRIR** Medium Resolution Infrared Radiometer
**MSG** Météosat Seconde Génération
**MSU** Microwave Sounder Unit
**MTES** Ministère de la Transition Ecologique et Solidaire
**MTG** Météosat Troisième Génération
**MTG-I** Meteosat Third Generation – Imager
**MW** Micro Ondes
**MWHS2** Capteur micro-ondes
**MWR** radiomètre micro-ondes
**N2O** Protoxyde d'azote
**NAO** Oscillation Nord-Atlantique
**NAWDEX** North Atlantic Waveguide and Downstream Impact Experiment
**NCAR** National Center for Atmospheric Research
**NEMO** Nucleus for European Modelling of Ocean
**NERC** Natural Environmental Research Council
**NOAA** National Ocean and Atmosphere Administration
**NWC** Nowcasting (produit satellite)
**OACI** Organisation de l'Aviation Civile Internationale
**OAD** Outils d'Aide à la Décision
**ODATIS** pôle de données et de service du système terre
**OLCI** capteur satellitaire
**OMM** Organisation Météorologique Mondiale
**ONERA** Office national d'études et de recherches aérospatiales
**ONERC** Observatoire National sur les Effets du Réchauffement Climatique
**OOPS** object-oriented Prediction System restructuring the IFS
**OPAR** Observatoire de Physique de l'Atmosphère de la Réunion
**OPG** Orages Points de Grille
**OSSE** Simulations des Systèmes d'observation
**OSTIA** Operational Sea surface Temperature sea Ice Analysis
**OSUG** Observatoire des Sciences de l'Univers de Grenoble
**PANAME** PAris region urbaN Atmospheric observations and models for Multidisciplinary rEsearch
**PE** Prévision d'Ensemble
**PEARO** Prévision d'Ensemble Arome
**PEARP** Prévision d'Ensemble ARPège
**PI** Prévision Immédiate

**PIROI** Plateforme d'Intervention Régionale dans l'Océan Indien de la Croix-Rouge
**PKF** Filtre de Kalman paramétrique
**PM10** PM10 (particules aérosols de moins de 10 microns) ca
**PNDB** Pôle National de Données de Biodiversité
**PNRC** Parc Naturel Régional de Chartreuse
**PNT** Prévision Numérique du Temps
**POI** Période d'Observation Intensive
**PRESCILIA** jeu de données de pluie quotidienne
**PROSNOW** Provision of a prediction for Snow management
**RADOME** Réseau d'Acquisition de Données d'Observations Météorologiques Etendu
**RALI** RADAR + LIDAR embarqués
**RCM** Modèle de Climat Régional
**RCP** Representative Concentration Pathway
**RCP8.5** 8.5 W/m² Representative Concentration Pathway corresponding to a 8.5 W/m² radiative forcing at the end of the 21st century compared to preindustrial climate
**RDP** Projet modélisation du temps en ville
**RDT** Rapidly Developing Thunderstorm
**RGB** Red Green Blue (satellite)
**RHT** Relative Humidity Threshold
**RIS** Référent Intégrité Scientifique
**RTTOV** Radiative Transfer for TOVS
**S2S** Sub-seasonal to Seasonal
**SAF OSI** Satellite Application Facility for Ocean and Sea Ice
**SAFIRE** Service des Avions Français Instrumentés pour la Recherche en Environnement
**SAFRAN** Système d'Analyse Fournissant des Renseignements Atmosphériques pour la Neige
**SAR** Synthetic Aperture Radar
**SBG** Subgrid (phénomènes sous-grille)
**SCO** Spatial Climate Observatory
**SDI** Sahara Dust Index
**SEMAFOR** Observation et prédiction de la migration de l'avifaune à partir des radars météorologiques
**SESAR** Single European Sky ATM Research
**SEVIRI** Spinning Enhanced Visible and Infra-Red Imager
**Shom** Service Hydrographique et Océanographique de la Marine
**SIRS** Satellite InfraRed Spectrometer
**SIRTA** Site Instrumental de Recherche par Télédétection Atmosphérique.
**SMA** Seychelles Meteorological Authority
**Smart4RES** Projet d'amélioration de la prévision de production à court terme d'énergie renouvelable solaire et éolienne
**SMOD** Snow Melt Out Date
**SNO** Service National d'Observation
**SOFOG3D** SOuth westFOGs 3D (compréhension des processus de petites échelles pour améliorer les prévisions du brouillard)
**SOOI** Sud-Ouest Océan Indien
**SPOT 6** base de données indépendante issues d'observations optiques
**SREPS** Système de prévision d'ensemble
**SRON** Space Research Organisation Netherlands
**SSH-Aerosols** Module du modèle MOCAGE
**SSM** Special Sensor Microwave
**SSP** Shared Socio-economic Pathway
**SURFEX** code de SURFace EXternalisé
**SWI** Soil Wetness Index
**SWIM** Surface Wave Investigation and Monitoring
**SYNOP** Données d'observations issues des messages internationaux d'observation en surface
**TAF** Terminal Aerodrome Forecast
**TCCON** Total Carbon Column Observing Network
**TEB** Town Energy Balance
**TEMSI** TEMps Significatif (aéronautique)
**THEIA** pôle de données et de service du système terre
**THIR** Temperature-Humidity Infrared Radiometer
**TIROS** Television InfraRed Operational Sounder
**TP** True Positive : détection SAR correspond à un couloir observé dans l'image SPOT
**TSEN** système d'observation de haute précision sur ballon
**TSM** Températures de Surface de la Mer
**UCP** Université de Chieti-Pescara
**UERRA** Uncertainties in Ensembles of Regional Re-Analyses
**UK** United Kingdom
**UMR** Unité Mixte de Recherche
**UTC** Temps universel coordonné
**UTCI** Universal Thermal Climate Index
**UTLS** Haute Troposphère Basse Stratosphère
**VAAC** Volcanic Ash Advisory Centre
**VIIRS** Visible Infrared Imager Radiometer Suite
**WCB** Warm Convection Belts
**WIRE** Winter Risks for Energy
**WW3** Modèle de prévisions de vagues côtières
**ZAMG** service météorologique autrichien
**ZDR** réflectivité différentielle

# DESR: Management structure

October 1, 2022

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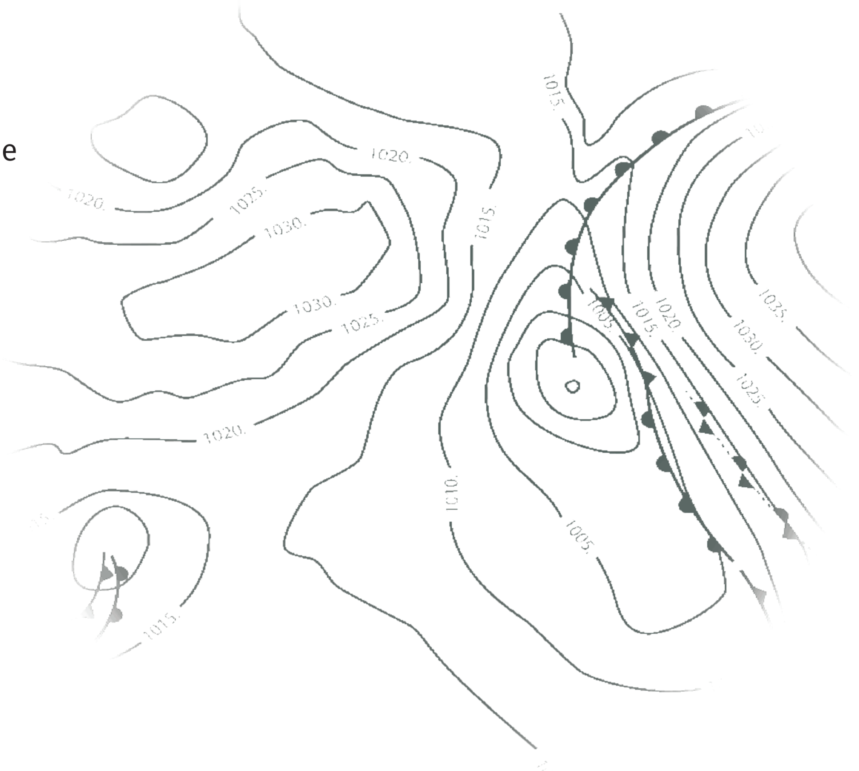

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