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FRANÇAISE
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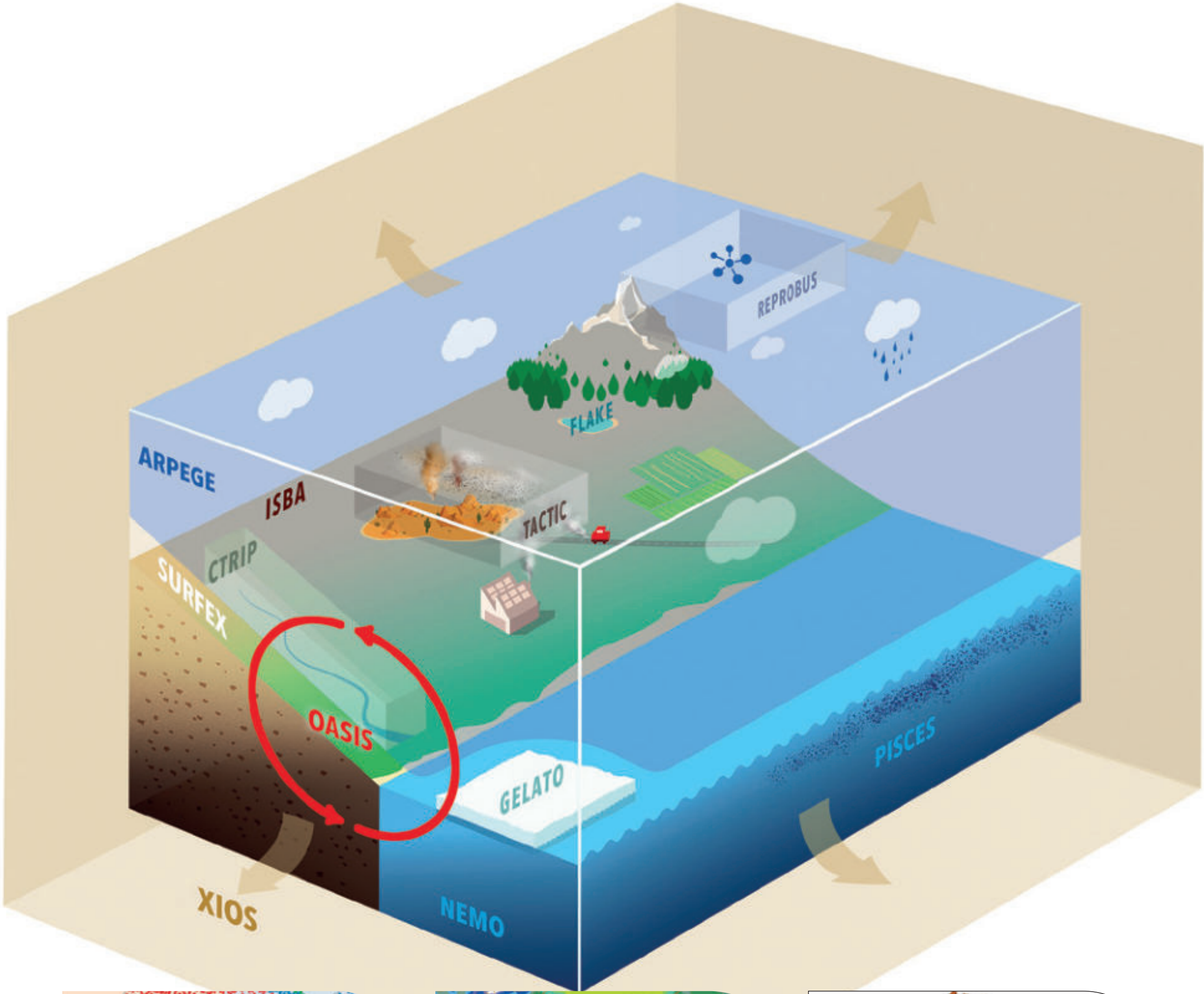

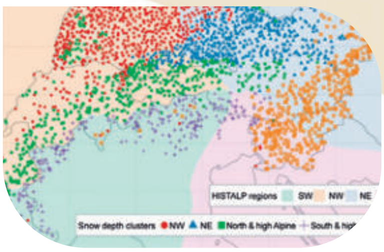

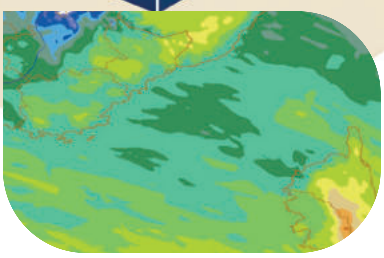

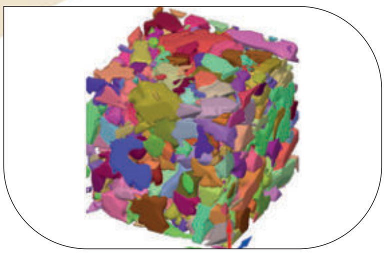

Research **Report**
2021

Research report 2021

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In 2021, Météo-France finalised a new Contract of Objectives and Performance (COP) with the State for the period 2022 to 2026. It has been built in line with the 2020-2030 Scientific Strategy, approved in 2020. Research occupies a privileged place in it, as it supports all the institution's missions. It is the source of the progress that is then implemented in terms of observation, modelling, numerical weather forecasting and climate studies. It enables the establishment to constantly improve the quality of its operational products and services and to open up new areas to meet the expectations of society and public authorities.

In 2021, the two new supercomputers became operational in February, bringing an increase in power by a factor of 5.5. The operational numerical weather prediction suite have been installed identically, but above all the first major evolutions of this suite have been tested since mid-2021. For the first time, the ensemble forecasting systems AROME-France and ARPEGE will have the same resolution as the deterministic versions. ARPEGE also benefits from a major evolution of its physics with a new deep convection scheme. The resolution of the AROME overseas systems will be reduced from 2.5 km to 1.3 km, which will particularly benefit the realism of precipitation. This new suit will be installed in operation by mid-2022 and will bring significant progress in both global and regional forecasts. The details of this next operational suit are the subject of one of the three main topics highlighted in this report.

The 2021 research report, as agreed with the new management of the CNRM (Samuel Morin and Nadia Fourrié), now separated from the research management of Météo-France, highlights three major topics this year. In addition to a description of the scientific features of the future version of the operational numerical weather prediction suite, the report highlights several contributions from Météo-France to the 6th IPCC report. The CNRM, in association with CERFACS, has made a major contribution to the Sixth Coupled Model Intercomparison Project (CMIP6), producing 35,000 years of simulations, using around 300 million hours of computing time provided by the Météo-France HPC centre between 2016 and 2021. CNRM's CMIP6 simulations were the first to be distributed in the summer of 2018, which contributed to their massive use in numerous publications and for the 6th IPCC report. Many CNRM researchers and engineers contributed to this sixth exercise, and it is worth noting the huge investment of a CNRM researcher who coordinated the chapter on water cycle changes in the IPCC Group I assessment report.

The third topic highlighted concerns future satellite instruments, which herald "a new revolution for meteorology and climate". Satellite observations play a key role in the initialization and evaluation of numerical weather prediction systems, air quality and atmospheric composition, as well as in the study of processes and climate. The next two major EUMETSAT missions will bring new decisive observations, in particular for AROME-France. These are the geostationary satellites Meteosat Third Generation with its "imager" and "sounder" instruments and the low-orbiting satellites METOP Second Generation with a new generation of the hyperspectral sounder IASI.

In the field of forecasting, the efforts and progress expected in assimilation are focused on the development of EnVar assimilation schemes. The first encouraging results obtained with the 3DEnVar scheme

applied to AROME are a first step towards the 4DEnVar objective. This new scheme will allow AROME-France to assimilate more observations, in greater detail, and in a better way, thus enabling regular improvements in metropolitan forecasts, over the duration of the new Météo-France COP.

The other works and results are presented by main themes in relation to the priority research areas of Météo-France. Process studies, measurement campaigns, overseas territories, hectometric resolution, cities and their heat islands, climate, seasonal forecasting, atmospheric composition, snow and mountains are not left out. All this work contributes to the continuous improvement of knowledge and forecasting of phenomena, which are the task of the Institute to monitor and forecast. They are all on the menu of this Research Report 2021 ...

In order to pursue these advances, the research entities of Météo-France are involved in numerous national and international (especially European) research projects. Of particular note in 2021 is the success of the OneWater, a *Programme et Equipements Prioritaires de Recherche* (PEPR), which focuses on the issue of water, a common good, and in which Météo-France is a partner. Other PEPRs, notably concerning climate modelling, climate services (TRACCS), risk studies (IRIMA) and the study of the Indian Ocean (BRIDGE) have been prepared for 2021 and are awaiting the results of the selection process. Météo-France, with its numerous partners in the research world, has had three projects selected as part of the Equipex+ *Équipements Structurants pour la Recherche*. The first is GAIA DATA, which aims to facilitate access to Earth system data, in particular by supporting the Data Terra Research Infrastructures, CLIMERI-France and the PNDB (biodiversity), and is organized around data centers (Atmosphere, Ocean, Continental Surfaces, Solid Earth) and climate and biodiversity databases and simulations, bringing together a total of thirty or so Data and Services Centers (DSCs). Then comes OBS4CLIM, which is a joint effort for innovation and synergy of the three French components of the European Research Infrastructures ACTRIS, IAGOS, ICOS in the atmospheric domain in order to meet the new challenges posed to Earth observation and to provide their users with qualified and relevant data sets. The third success is ANVOLE, a project that supports the acquisition of a new high-altitude scientific laboratory aircraft operated by SAFIRE, the Unit associating Météo-France, CNRS and CNES, for the understanding of atmospheric processes, climate change and natural hazards, space observation of the Earth and civil and military aviation.

At the Toulouse level, Météo-France has joined the ISAE dynamic to create the Toulouse Sustainable Aviation Institute, with two Toulouse universities, ENAC, Cerfacs, the Toulouse School of Economics and the Toulouse Business School. The objective is to structure the scientific approach to the issue of air transport sustainability, to stimulate interdisciplinary research and to better respond to this major regional, national and European issue, at the crossroads of societal, economic and technological challenges. Météo-France continues to support the structuring of higher education and research in Toulouse by participating in the TIRIS project "Toulouse Initiative for Research's Impact on Society" as part of the "Excellence in all its forms" call for proposals.

It remains to mention the start of the new ACCORD consortium, which brings together the regional NWP activities of 26 European and North African countries around the AROME system, under the leadership of a Météo-France scientist. The work plan is now defined and aims to address all the issues of tomorrow, including dynamic cores, the adaptation of codes to different hpc architectures and high-resolution physics with its 3D effects.

« Bonne lecture »

Marc Pontaud
Director of Higher Education and Research

Météo-France's contribution to the IPCC 6th assessment report

The Summary for Policymakers of the contribution of Working Group I to the IPCC (Intergovernmental Panel on Climate Change) 6th Assessment Report, approved on 6 August 2021, provides the main conclusions of a comprehensive assessment of the physical basis of past, present and future climate change. The contribution of Working Group II (Impacts, Adaptation and Vulnerability) to IPCC AR6 was published at the end of February, that of Working Group III (Mitigation of Climate Change) at the beginning of April, and the synthesis report is expected in September 2022.

The 6th assessment report of Working Group I was prepared by 234 authors (including many French scientists, some of them from CNRM and CERFACS) from 65 countries, and took just over three years to complete due to the Covid-19 pandemics. The full report is structured in 12 chapters (including the one on water cycle changes, coordinated by Hervé Douville, CNRM), is nearly 4,000 pages long and is based on the evaluation of 14,000 scientific papers, including many papers produced by CNRM researchers.

The report also relies heavily on new data from the climate simulations of CMIP6 (Coupled Model Intercomparison Project phase 6), to which the CNRM made a major contribution, in association with CERFACS. In total, CNRM has produced 35,000 years of simulations, generating about 1.3 PB of data. For this, about 300 million hours of computing time provided by the Météo-France High-Performance Computing Centre have been used over 2016-2021. Produced to the standards required by CMIP6 , these simulations are distributed in open access via CNRM's ESGF (Earth System Grid Federation) node. Thanks to the commitment of CNRM engineers and researchers and in collaboration with CERFACS and IPSL, the CMIP6 simulations produced by CNRM were the first to be distributed in the summer of 2018, which explains why they have been massively used in numerous scientific papers and for the IPCC 6th assessment report.

The report is complemented by an online interactive atlas accessible online (interactive-atlas.ipcc.ch), which makes it possible to visualise the evolution of different variables characterising the climate (temperature, precipitation, etc.) for a given region, socio-economic scenario and time horizon. This atlas is based on the global climate simulations of CMIP5 and CMIP6, but also on the regional simulation exercise CORDEX, in which the CNRM was also heavily involved.

D. Salas y Melia

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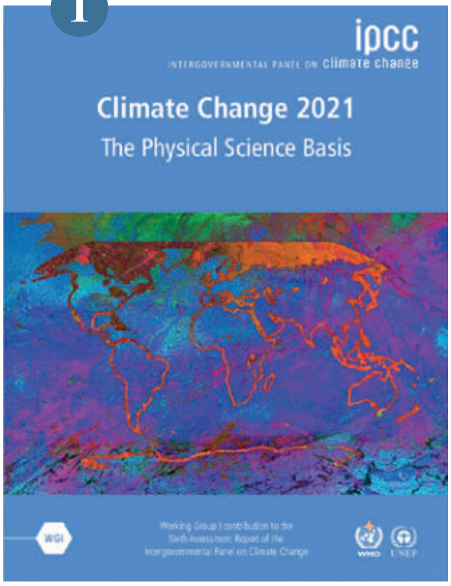

Cover of the IPCC Group I 6th assessment report: "Changing" (Alisa Singer)

Some key points from the IPCC 6th report

H. Douville

According to the IPCC 6th Assessment Report (AR6), global mean surface temperature will continue to rise for at least two to three decades, whatever greenhouse gas (GHG) emission scenario is considered, and many of the changes due to past and future GHG emissions are irreversible for centuries or even millennia, particularly changes in ocean temperature, acidity and oxygenation, ice caps and sea levels. From a physical perspective, human-induced global warming can only be limited to a certain level if we achieve zero net carbon dioxide (CO_2) emissions and deep reductions in other GHG emissions. Following on from the Special Report SR1.5 published in 2018, this is partly what the IPCC experts are stressing: since emissions cannot be stopped immediately, the planet is committed to further climate change until 2050, but the longer-term future is still in our hands. But the time frame for stabilising the climate over the 21st century is even shorter, and the effort to be made to do so is even greater than previously estimated, due to an upward revision of the lower bound of 'climate sensitivity': 2.5-4°C for a doubling of atmospheric CO_2 according to AR6, compared to 1.5-4.5°C according to AR5.

Other key messages from AR6 include the 'unequivocal' contribution of human activities to observed global warming (+1.09°C in 2011-2020 relative to 1850-1900) but also, with a high level of confidence, to many other observed facets of global climate change (notwithstanding, for example, the competing effects of GHGs and atmospheric aerosols on the water cycle). The scale of these recent changes is unprecedented over several centuries to several thousand years. As global warming continues, all regions will be affected by climate change, and many extreme events with high potential impact, such as heat waves, heavy precipitation and droughts, will become more frequent and intense. Global surface temperatures will continue to rise until at least mid-century under most emission scenarios. Unless immediate, deep and sustained reductions in CO_2 and other GHG emissions are made, the +1.5°C and +2°C thresholds envisaged in the Paris agreement will be exceeded during the 21st century (as early as 2050 for the +2°C threshold in the intermediate scenario, which is closest to current emission trajectories). While ambitious mitigation policies can curb global warming in about 20 years from now, their effects will only be felt much later at the regional level. Hence the need, in order to reduce the magnitude of future climate risks, to pursue in parallel policies of adaptation to ongoing changes, avoiding the maladaptation that consists in particular in temporarily limiting the consequences of global warming while reinforcing its causes and its increase in the medium and long term.

Références :

Douville, H., K.Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panelon Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055–1210, doi:10.1017/9781009157896.010.

Development of the CNRM coupled global climate models and contribution to CMIP6

D. Salas y Melia, A. Voldoire, D. Saint-Martin, B. Decharme et R. Séférian

As part of the CMIP6 intercomparison exercise whose model output was used in the 6th IPCC report, the CNRM developed and produced simulations with three versions of its CNRM-CM model: (1) the standard 100 km resolution model (Voldoire *et al.*, 2019), (2) the high resolution model (50 km) and (3) the Earth system model based on the standard version with the addition of the representation of the full carbon cycle, land use, stratospheric ozone chemistry as well as the activation of the interactive aerosol scheme (Séférian *et al.*, 2019).

All three versions are derived from a common base and their calibration is identical. This coherent set of models has allowed an objective study of the impact of complexity versus spatial resolution on the representation of the 20th century climate and on future projections. Within these three models, version 6 of the ARPEGE-Climat atmosphere model (Roehrig *et al.*, 2020), developed in synergy with Météo-France's ARPEGE numerical weather prediction model, is coupled with the SURFEX-CTRIP continental surface platform (Decharme *et al.*, 2019) and the NEMO-Gelato ocean-sea ice model. The new version of ARPEGE-Climat capitalizes on numerous developments initiated since the mid-2000s, and which involved the various departments of CNRM: the new convection scheme, coupled with detailed cloud microphysics, deals continuously with deep and shallow convection; the new turbulence scheme improves the representation of boundary layers; a non-orographic gravity wave scheme allows to take into account sources related to deep convection and frontogenesis; SURFEX-CTRIP describes the processes related to aquifers and floodplains.

References:

Decharme, B., Delire, C., Minvielle, M., Colin, J., Vergnes, J.-P., et al. (2019). Recent Changes in the ISBA-CTRIP Land Surface System for Use in the CNRM-CM6 Climate Model and in Global Off-Line Hydrological Applications. *Journal of Advances in Modeling Earth Systems*, 11(5), 1207-1252. https://doi.org/10.1029/2018ms001545

Roehrig, R., Beau, I., Saint-Martin, D., et al. (2020). The CNRM global atmosphere model ARPEGE-climat 6.3: Description and evaluation. *Journal of Advances in Modeling Earth Systems*, 12, e2020MS002075. https://doi.org/10.1029/2020MS002075

Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voldoire, et al. (2019) Evaluation of CNRM earth system model, CNRM-ESM2-1: role of earth system processes in present-day and future climate. *Journal of Advances in Modeling Earth Systems*, 11(12), 4182– 4227. http://dx.doi.org/10.1029/2019ms001791.

Voldoire, A., D. Saint-Martin, S. Sénési, B. Decharme, *et al.* (2019). Evaluation of CMIP6 DECK experiments with CNRM-CM6-1, Journal of Advances in Modeling Earth Systems.

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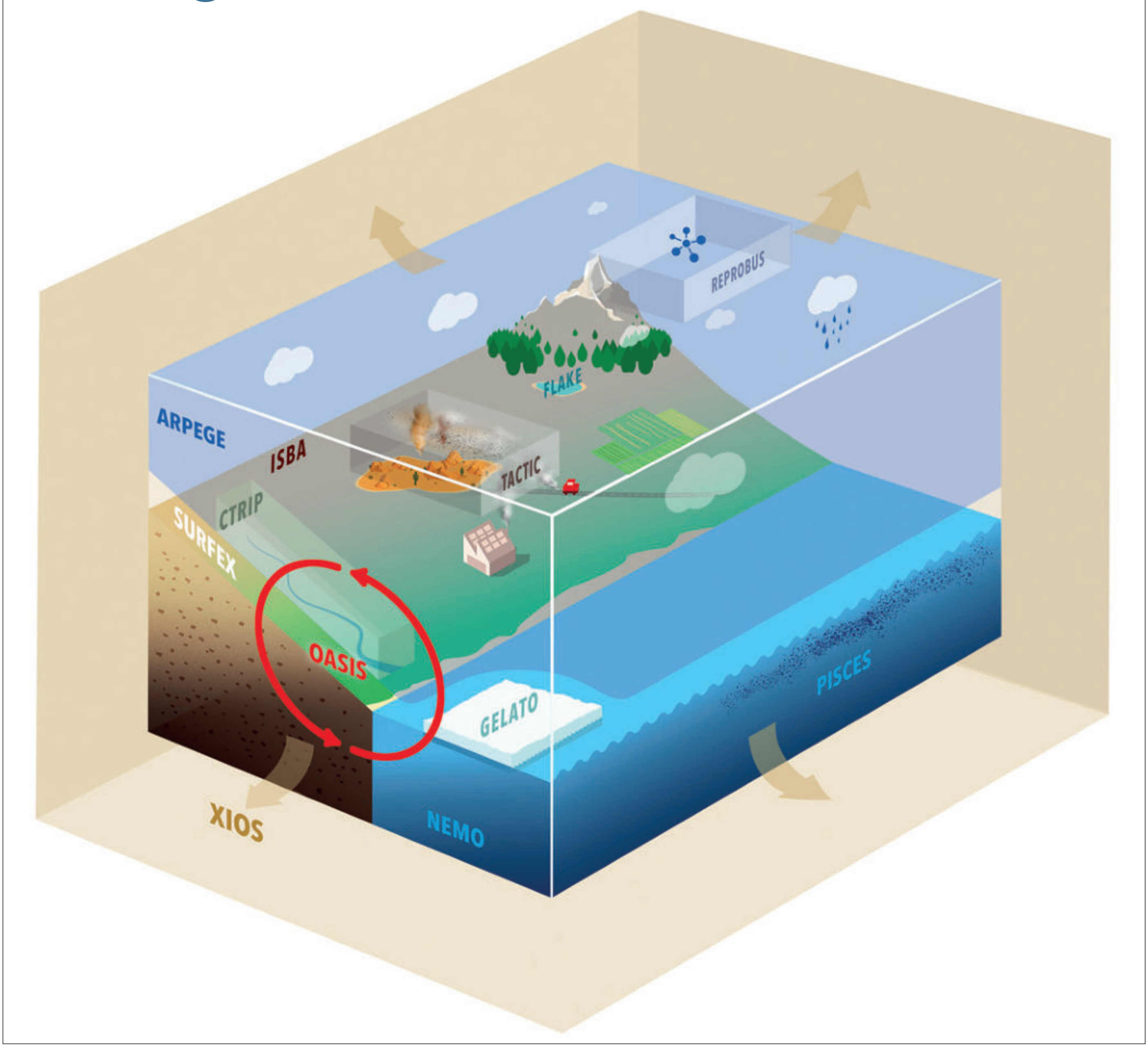

Design of the Earth system version of the CNRM-CM6 climate model.

New climate projections combining modelling and observations

A. Ribes

The scientific community regularly produces climate projections with the aim of quantifying the expected climate changes in the 21st century and beyond. These projections have so far been based on climate model simulations. However, at the beginning of the 21st century, warming is increasing and observations are becoming increasingly informative about the magnitude of past and future climate change.

Using a new statistical method, we adjusted the expected global warming during the 21st century by combining the latest climate simulations (CMIP6 exercise) with observations since 1850. Our results suggest that the uncertainty arising from climate simulations is significantly reduced by taking into account the observations, by about a factor of three in the short term (before 2050), and by a factor of 2 in the long term (end of the 21st century). The expected warming in 2100 compared to the period 1850-1900 is about +2°C (+/-0.6°C) for a strong mitigation scenario (SSP1-2.6), +3°C (+/-0.6°C) for a scenario with intermediate greenhouse gases emissions (SSP2-4.5), and +5°C (+/-0.6°C) for a scenario with very high emissions (SSP5-8.5).

This method was used by the authors of the 6th report of the IPCC Working Group I to adjust the global average temperature projections. In addition to the interest of these results for adaptation and mitigation strategies, many other applications of the proposed method are envisaged in order to refine climate projections at regional or local scales, and/or for variables other than temperature.

Shared Socio-economic Pathways. This new generation of scenarios has been considered for CMIP6 and the IPCC 6th Assessment Report, and replaces the RCP (Representative Concentration Pathways) used so far.

Référence :

Ribes, A., S. Qasmi, and N.P. Gillett, 2021: Making climate projections conditional on historical observations. Science Advances, 7(4), eabc0671, doi:10.1126/sciadv.abc0671.

3

Quantifying the decline in snow cover in the European Alps since 1971

S. Morin

Until now, studies of snow cover trends have been limited to small areas of the Alpine region and have been based on data from no more than a few hundred measuring stations. Published in 2021, for the first time, a study coordinated by Eurac Research and involving researchers from the CNRM and the Direction de la Climatologie et des Services Climatiques of Météo-France has systematically collected and analyzed snow data from more than 2,000 measuring stations in Italy, Austria, Slovenia, Germany, Switzerland and France. The results provided a reliable description of snow cover trends up to 2000 m elevation. Above, there are not enough measuring stations to be able to extract reliable information for the entire Alpine region. This coherent data set spans five decades and was created through the collaboration of more than 30 scientists from each of the Alpine states.

The data, covering the period 1971-2019, show that snow is unevenly distributed and does not decrease everywhere to the same extent, but the decadal variability is similar throughout the Alpine region. The 1970s and 1980s were generally snowy, followed by a period of scarce winter snow in the late 1980s and early 1990s. Since then, although snow depth has again increased to some extent at high elevation, it has not reached the level of the 1970s. The duration of snow cover has decreased from 22 to 34 days over the past 50 years, particularly at low and medium altitudes. Snow cover tends to build up later in winter and, at all altitudes, to disappear earlier in spring, a direct consequence of climate change.

Beyond the intrinsic results of this study, this complete and unified data collection is a particularly valuable tool, and most of the data have been made available to the scientific community. This article, documenting in a very complete way the past evolution of mountain snow cover in the European Alps, has been taken into account in Chapter 9 "Ocean, Cryosphere and Sea Level Change" of the IPCC Working Group I report, published in August 2021

Reference:

Matiu et al. Observed snow depth trends in the European Alps: 1971 to 2019, The Cryosphere, 15, 1343-1382, 2021. https://doi.org/10.5194/tc-15-1343-2021

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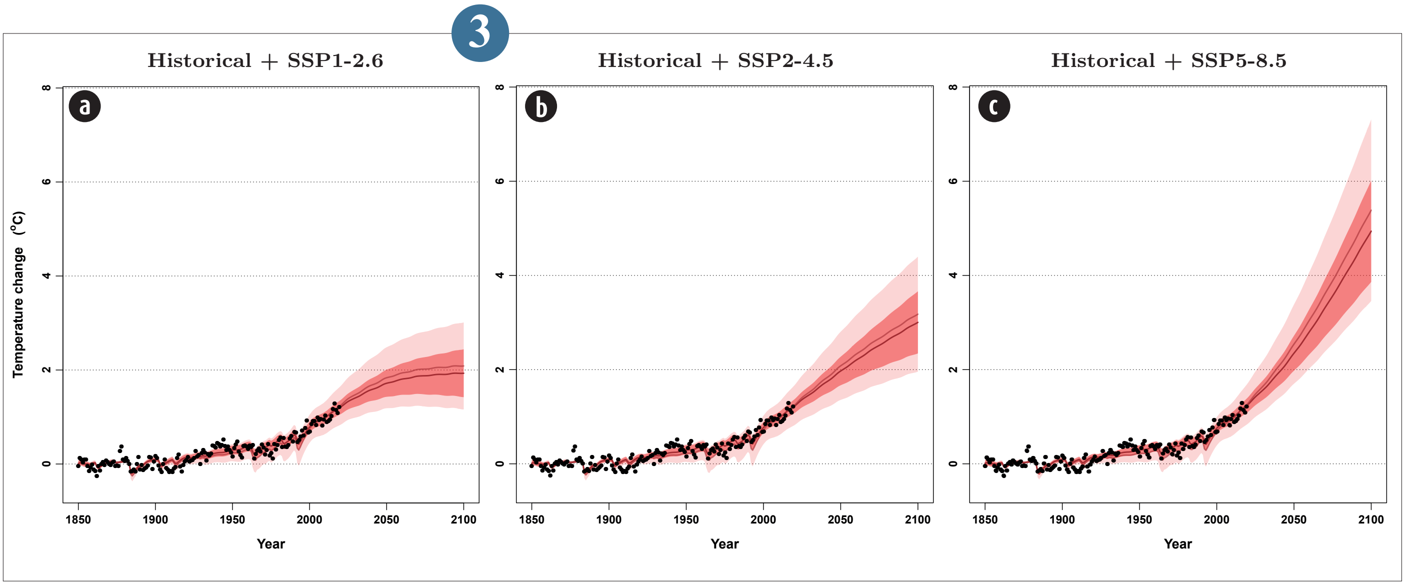
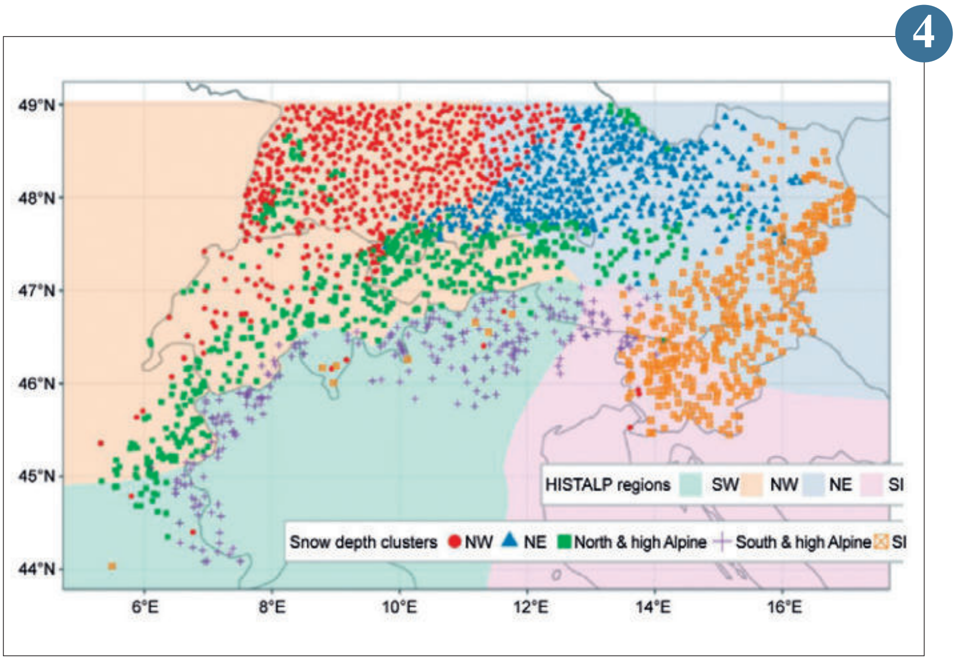


▲
Global mean temperature warming projections and associated uncertainties (5-95% confidence intervals) obtained from climate simulations alone (pink interval), and with observations taken into account (red interval). The calculation is based on 22 CMIP6 climate models, for three emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5). Observed annual global mean temperature values are indicated by black dots. All temperatures are anomalies with respect to the period 1850-1900, used as a reference.



◀
Classification of the snow depth stations used in this study, grouped according to their commonality in snow characteristics. The colored areas correspond to the climatological regions identified in a previous study (HISTALP, Auer et al., 2007) based on temperature, precipitation, air pressure, sunshine and cloud cover data.

EURO-CORDEX: a very large ensemble of high-resolution climate projections for climate change studies and adaptation in Europe

L. Corre, S. Somot

Adaptation to climate change is essentially carried out on a national or even sub-national scale. It therefore requires high-resolution climate data able to represent local weather phenomena and to cover the uncertainties inherent in any projection.
The international EURO-CORDEX initiative launched in 2009 aims to meet this demand at the European scale by producing regional climate simulations at 12 km spatial resolution, forced by global climate models from the CMIP5 initiative. The set available today includes 137 simulations of the 21st century based on 13 regional models, 10 global models and 3 socio-economic scenarios (RCP8.5: 78 simulations, RCP4.5: 26, RCP2.6: 33). This is undoubtedly the largest set of regional simulations ever carried out in the world. The Météo-France contribution, resulting from a collaboration between the research laboratory and the department for climatology and climate services, consists of 9 simulations carried out with the ALADIN regional climate model.
This large ensemble has been evaluated by the scientific community and is now available on an open database (ESGF). It increases the reliability of studies to better understand regional climate phenomena, their variability and evolution. It also serves as a basis for many European and national climate services, including the recent version of the « DRIAS - Futures of climate » portal, which provides reference climate projections for metropolitan France.
EURO-CORDEX data and studies based on this dataset have also made a substantial contribution to the latest IPCC reports, notably the report on the physical basis of climate change (WG1, published in August 2021), whose regional dimension relies heavily on climate modelling carried out at this scale.
Currently, the EURO-CORDEX community is preparing the next generation of this ensemble with regional models reaching the kilometer scale and the use of the new CMIP6 forcings.

References:

Coppola E., et al. (2020) Assessment of the European Climate Projections as Simulated by the Large EURO-CORDEX Regional and Global Climate Model Ensemble. Journal of Geophysical Research – Atmospheres, http://doi.org/10.1029/2019JD032356

Vautard R., et al. (2021) Evaluation of the large EURO-CORDEX regional climate model ensemble. Journal of Geophysical Research – Atmospheres, https://doi.org/10.1029/2019JD032344

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The climate response to emissions reductions due to COVID-19

R. Séférian

In 2020, the Covid-19 pandemic forced many countries to curb their industrial and economic activities and impose severe travel restrictions. These restrictions resulted in a temporary but very significant reduction in greenhouse gas (GHG) emissions, primarily carbon dioxide (CO_2), as well as air pollutants such as ozone and aerosol precursors. Although emission reductions were concentrated in a few months of the year, human CO_2 emissions in 2020 were about 6% lower than in 2019 (a decrease of 2.2 billion tonnes).
In order to assess the climatic impact of this reduction in human emissions, an international group (including researchers from CNRM and CERFACS) set up a coordinated climate simulation exercise in the spring of 2020. This scientific cooperation allowed (1) the construction of a GHG and aerosol emission inventory consistent with the emission reductions observed at the beginning of 2020 and taking into account the projections for the years 2021 and 2022; (2) the implementation of a simple and quasi-operational multi-model climate simulation protocol and (3) the analysis of the first results of these simulations.
The authors of the study present the first conclusions, based on sets of simulations carried out with 12 Earth system models, including the CNRM-ESM2-1 model developed by CNRM and CERFACS. This represents a total of more than 300 simulations covering the period 2020-2024, making it possible to quantify as well as possible the influence of the sanitary crisis on climate, while estimating the various sources of uncertainty, linked to both modelling and initial conditions.
This first analysis, included in the IPCC sixth assessment report, showed that the reduction in anthropogenic emissions linked to the health crisis led to a decrease in tropospheric aerosol concentrations, resulting in an increase in incoming solar radiation, particularly over southern and eastern Asia, which are the regions most affected. However, the reduction in GHG and aerosol emissions was too limited in time and space to have a significant global impact on temperature and precipitation. Smaller-scale regional and dynamical analyses, as well as an analysis of extremes, are needed to further exploit these initial results. This study confirms that one-off fluctuations in greenhouse gas emissions have a very limited impact on long-term climate change.

Reference :

Jones, C. D., Hickman, J. E., Rumbold, S. T., Walton, J., Lamboll, R. D., Skeie, R. B., et al. (2021). The Climate Response to Emissions Reductions due to COVID 19: Initial Results from CovidMIP. Geophysical Research Letters, 48, e2020GL091883. https://doi.org/10.1029/2020GL091883

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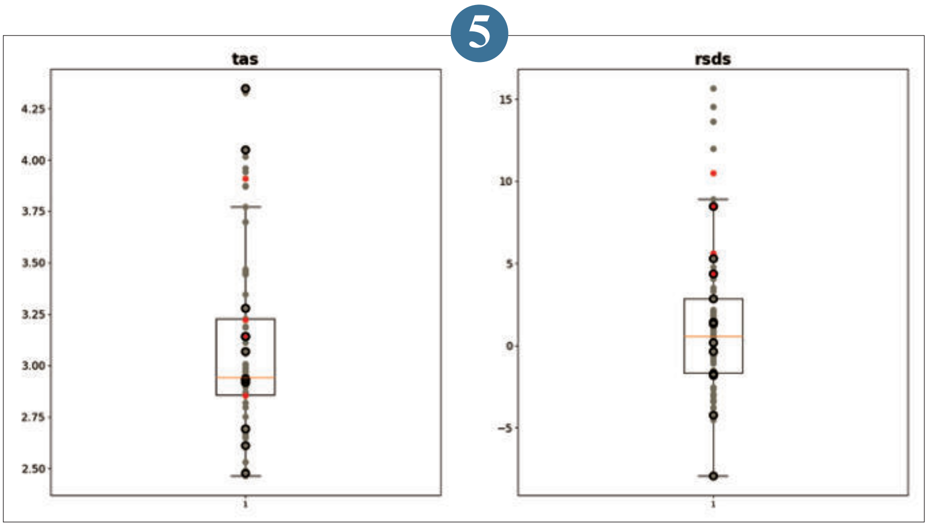
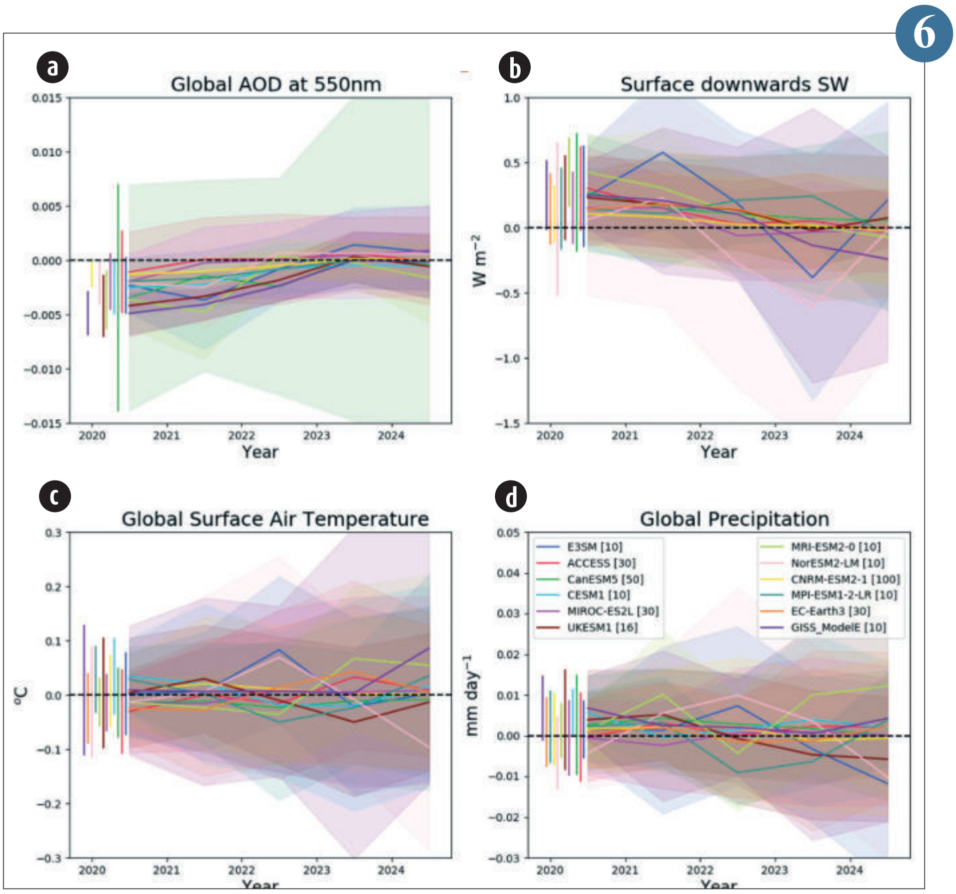


Change for surface temperature (left, °C) and for surface solar radiation (right, $W.m^{-2}$) between the periods 1981-2010 and 2070-2099 averaged over France for the different simulations of the EURO-CORDEX ensemble at 12 km resolution (grey dots), including the simulations carried out with the ALADIN model by Météo-France (red dots) and the simulations selected for the DRIAS national climate service portal implemented by Météo-France (black circles). The box plots show the median, interquartile range and the range of the EURO-CORDEX ensemble.



Each plot shows the annual and global average of the multi-model simulated anomaly between the simulations with COVID-19 emission reductions (SSP2-4.5-Covid) and the SSP2-4.5 reference simulations (moderate greenhouse gas emissions, continuing recent trends).
(a) Aerosol optical thickness at 550 nm;
(b) surface downwelling solar radiation;
(c) near-surface air temperature;
(d) precipitation. For each model, the coloured lines and the plumes show respectively the mean of the ensemble produced with each model, and the dispersion of the ensemble (defined as ±1 standard deviation).
The vertical bars on the left of each graph show t he change for the first year (2020) simulated by each model (mean ±1 standard deviation).

Preparation of a new version of the operational numerical weather prediction systems

2021 will have marked a new stage at Météo-France for numerical numerical weather prediction forecasting models. Declared operational in February 2021, the new ATOS high performance computing system Bull Sequana XH2000, offering five times more computing power than the previous computer, has made it possible to prepare major developments in AROME regional and ARPEGE global forecasts. The new numerical forecasting chain prepared in 2021 has been running has en experimental suite since summer 2021.
It marks an unprecedented turning point for the ensemble forecasting systems AROME and ARPEGE, since, for the first time since their implementation, their vertical and horizontal resolutions will be the same as those of the associated deterministic forecasting system. The ensemble forecasts thus become fully representative of the uncertainty of the AROME and ARPEGE forecasts. In addition, the uncertainties of the modelling in ARPEGE are represented by a new algorithm.
This chain also benefits from a major evolution of the ARPEGE physics, with notably a redesign of the parameterisation of convection, a key component of the model. As a result, ARPEGE's forecasting scores have improved significantly, both over the globe and over Europe. AROME-France also sees significant improvements and in particular better precipitation forecasts in diurnal convection conditions without synoptic forcing. The AROME Overseas, for their part, see their resolution improving from 2.5km to 1.3km, which is particularly beneficial to the realism of precipitation.
The observation assimilation system has also undergone numerous developments that contribute to the improvement of forecasts. In particular, the development of satellite microwave data assimilation in cloudy conditions, the assimilation of a new radar data processing channel, the revision of observation screening algorithms, as well as the assimilation of assimilation of new satellite sensors and downward radiosonde data.
The following articles describe some important aspects of this new forecast chain, which is expected to become fully operational by mid-2022.

F. Bouyssel

Physical modifications of ARPEGE and AROME

Y. Bouteloup, Y. Seity

Major evolutions of the physical parameterizations of ARPEGE and AROME models have implemented in the new version of the numerical weather prediction chain that has been developed in 2021.

For ARPEGE, four fundamental elements of the physical parameterizations have been changed. First, the deep convection scheme used since the origins of the model, with some evolution, has been replaced by the one of the IFS model, developed by the ECMWF. This parameterization is also used by the DWD's ICON model. The resulting model improvement in the inter-tropical area is significant.

The second element is an evolution of the CNRM (ECUME) fluxes parameterization at the ocean interface. A new adjusting technique of he coefficients to the observations from the measurement sea campaigns allows a much better forecast of these fluxes. The resulting model improvement is significant at all latitudes.

The third element is the replacement of the old short wave radiation code by the RRTM scheme, this allows the activation of the McIca solver which calculates more precisely the overlapping effects of the different cloud layers. This change, and especially the resulting model adjustments, is a first step towards the use of the EcRad modular radiation code, shared by a large number of numerical weather prediction models.

The latest development concerns the activation of the 1d sea ice model GELATO, integrated in the SURFEX surface modeling platform. The sea ice surface temperature is now a model variable that evolves with the forecasts. Previously, it was derived from old climatology and remained constant during the forecast. The variability of surface temperatures is now more important both spatially and temporally. this is illustrated in figure 1 where the temperature measured by the drifting boat "polarstern" is plotted as well as the corresponding forecasts of the operational model Arpege and a release using the GELATO parameterization.

These modifications have significantly improved the ARPEGE model as shown in Figure 2.

The main modification of AROME-France is a response to reports by forecasters, since 2016, of an underestimation of precipitation in situations of diurnal summer convection without synoptic forcing. Studies were conducted in 2018 showing the sensitivity of these situations to the numerical diffusion settings applied to the AROME cloud fields. Unfortunately, this work did not result in a new setting that could be used in an operational configuration (the improvement of these cases leading to a deterioration of others). By performing semi-idealized simulations, we were able to go back to the real source of the problem. This one was located in the AROME transport scheme, and more precisely in the choice of the method used to interpolate the model fields in this process. Semi-academic tests have indeed shown that the transport scheme was behind a cloud fields mass artificial creation (naturally much less 'smooth' than a wind or temperature field, or even quite binary in the case of small convective cells). This flaw was present since the origins of AROME in 2008, but was 'hidden' by the settings we had applied to the numerical diffusion of the cloud fields. This diffusion having been settled following the switch of AROME horizontal resolution to 1.3km in 2016, the default has become more visible than in the previous version of the model (AROME 2,5km). The choice of a new interpolator having different properties, and in particular a mass preservation, have allowed to consider new settings of the model (by jointly suppressing the numerical diffusion applied on the cloud fields). Tests have shown that the model was greatly improved in the problematic situations reported by the forecasters (Figure 3), without being degraded in the general case. In addition to these new settings, the new version of AROME benefits, as ARPEGE, from the new version of the ECUME ocean fluxes parameterization.

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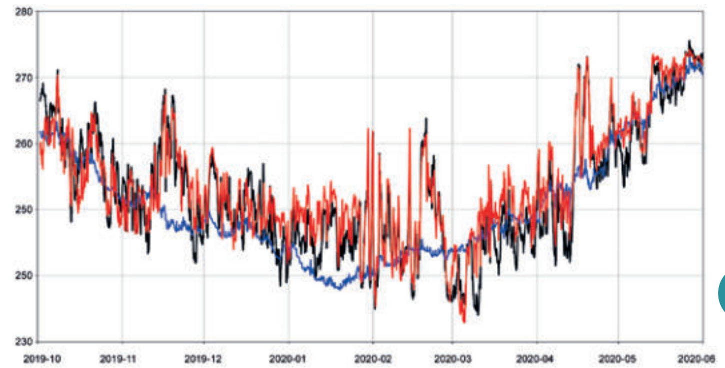
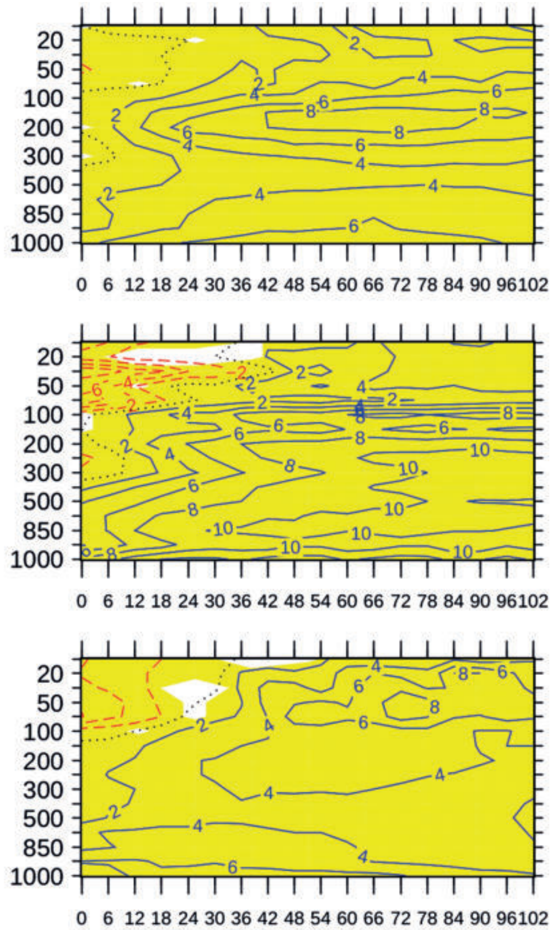


Observed and predicted temperatures along the trajectory
of the drifting boat "polarstern In black the observations made by the boat,
in blue the temperatures predicted by the operational ARPEGE
and in red those predicted by an ARPEGE with the GELATO parameterization.



Normalized wind scores (in %) of the ARPEGE e-suite
(release cy46t1_op1) compared to the operational model
over the North20 (top), Tropic (middle)
and South20 (bottom) domains.

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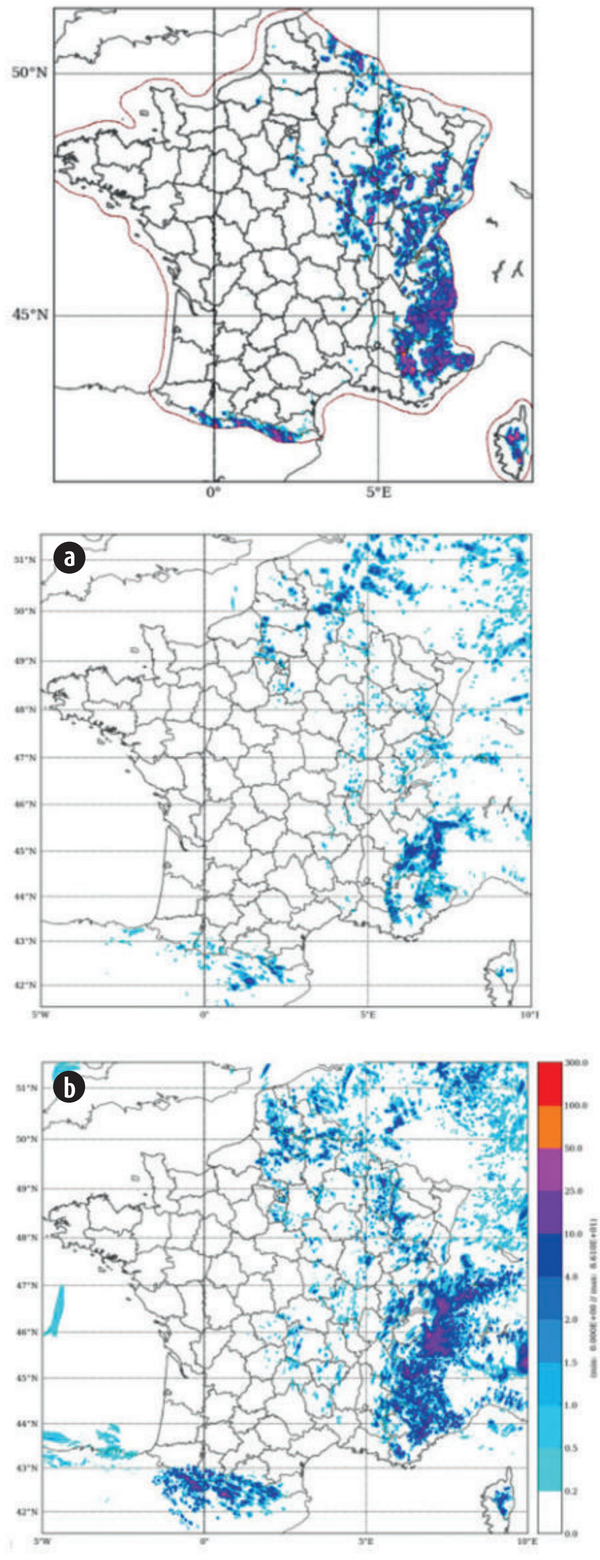

24-hour rainfall accumulation for the day of July 25, 2018.
Top Observations, center AROME operational,
bottom AROME e-suite.

The global ensemble prediction system PEARP

L. Descamps, C. Labadie, P. Cébron

In 2022, the global ensemble prediction ARPEGE (PEARP) will be increased in horizontal resolution, which translates into an accuracy of 5 km over France and 24.5 km in the antipodes, and a modelling of atmospheric movements from 10 m to 65 km altitude. The PEARP perturbed forecasts will thus be at the same resolution as the ARPEGE forecast. The ensemble prediction becomes fully representative of the uncertainty of the forecast process and the ARPEGE forecast will be integrated into the ensemble.
The physical modelling of the processes in the ensemble forecasting system will also progress. Half of the forecasts will adopt a new deep convection scheme, Tiedtke-Bechtold, as ARPEGE, offering a significant improvement for the global numerical forecast process. The remaining forecasts will be based on an already used convection scheme, PCMT. In addition, the philosophy of the modelling error representation will evolve: the set of ten physical packages used so far will be replaced by a more comprehensive approach using stochastic perturbations of several parameters of the parameterisation schemes. Each forecast will therefore randomly use a slightly different setting, sampling the possible values of the physical parameters of the model.
An eight-month evaluation of this new PEARP configuration shows a clear improvement over the operational one on most of the scores, for several domains and weather variables. This figure shows the relative contribution of the future ensemble prediction system compared to the current operational system in percentage for six representative variables of the state of the atmosphere (mid-atmosphere geopotential (Z500), temperature and wind in the lower layers (T850 and FF850), mean sea level pressure (PMER), 10 meters wind (FF10m) and 24-hour rainfall, (RR24). This input is measured over a wide area encompassing the North Atlantic Ocean and Western Europe.

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2

The regional ensemble prediction system PEARO

L. Raynaud

The Arome ensemble prediction system (PEARO), operational at Météo-France since fall 2016, provides a probabilistic information in addition to the deterministic forecast. For that purpose, different sources of uncertainty are represented, regarding the initial conditions, the surface, the lateral boundary conditions (LBCs) and the model.
In 2022, the horizontal resolution of PEARO will increase from 2,5km to 1,3km. This convergence toward the deterministic system also allows for an increase of ensemble size from 16 to 17 members, including 16 perturbed members and a control member provided by the deterministic forecast. Moreover, PEARO benefits from the upgrades of the other NWP systems, with improved initial conditions, a new Arome physics package and enhanced high-resolution PEARP LBCs. The new aviation and convective diagnostics are also computed for each member.
The performances of this high-resolution PEARO have been evaluated over several months and show significant improvements, in particular for 10-meter wind and precipitation forecasts. The analysis of several cases of heavy precipitating events also indicate a more accurate prediction of rainfall intensity (Figure).

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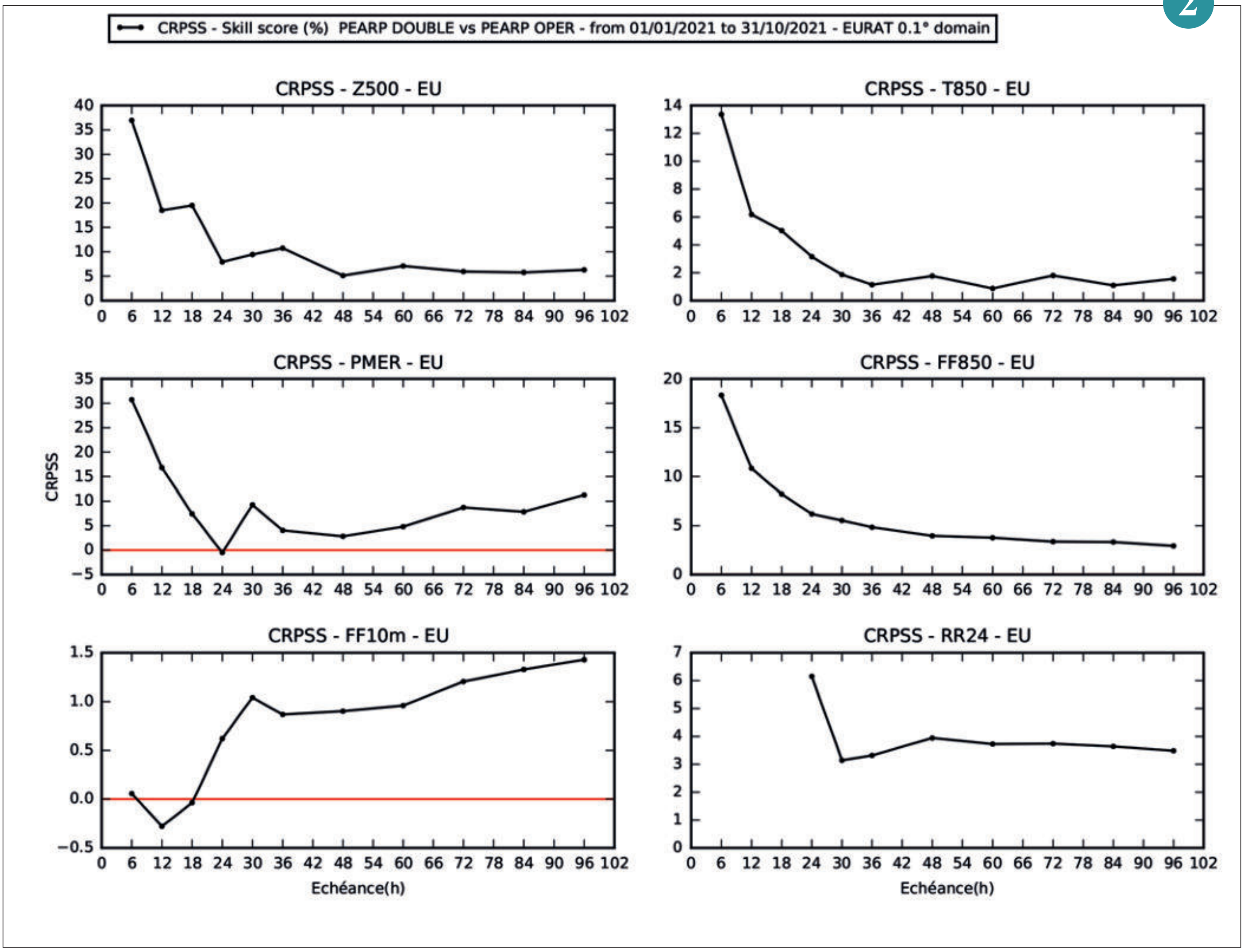

Relative contribution of the future ensemble prediction system compared to the current operational system in percentage for six variables (500hPa geopotential height (Z500), temperature and wind speed at 850hPa (T850 and FF850), mean sea level pressure (PMER), 10 meters wind speed (FF10m) and 24-hour rainfall, (RR24).
The scores have been computed over a wide area encompassing western part of the North Atlantic Ocean and Western Europe.

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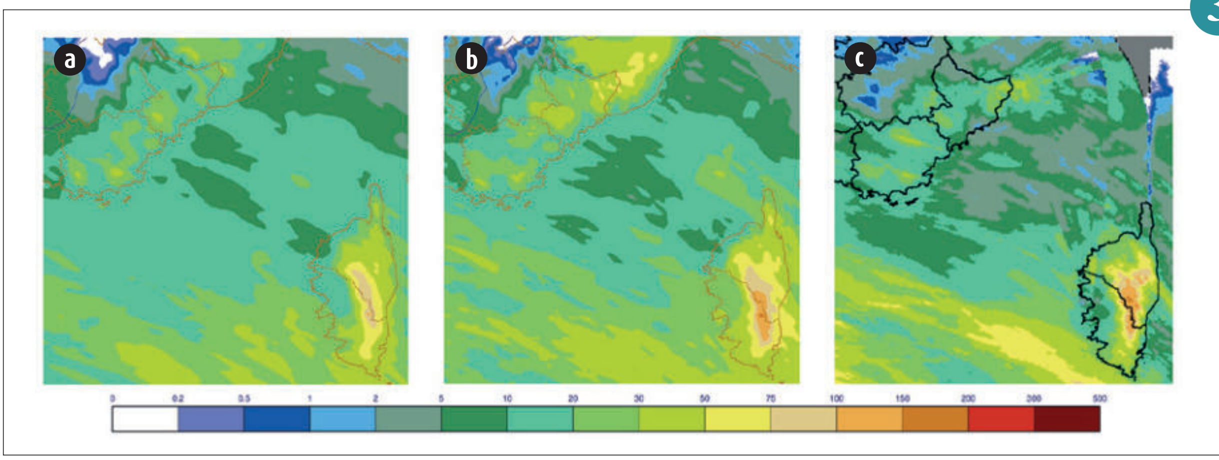

24h-accumulated precipitation valid on 11/11/2021 at 00 UTC (unit: mm). Percentile 75 predicted by (a) the operational PEARO and (b) the future high-resolution PEARO, launched on 08/11/2021 at 21 UTC. (c) Antilope observations.

Arome Overseas

G. Faure, O. Nuissier

The French overseas territories (the West Indies, French Guiana, New Caledonia, French Polynesia and the territories located in the southwest Indian Ocean) have benefited since 2016 from Arome deterministic forecasts at a horizontal resolution of 2.5 km. This has led to forecast improvements in these tropical areas where, in addition to cyclones, convection often combines with significant relief to produce very intense rainfall episodes.

The arrival of a new supercomputer at Météo-France, as well as major optimisations of the computation cost of the Arome model, have made it possible to improve these forecasting systems along two lines. The first, which will be deployed in operation during 2022, consists in improving the realism of the existing deterministic simulations, with the use of the same horizontal resolution as in mainland France (1.3 km), all other things being equal. Figure 1 shows an example of this realism improvement during a rainy episode over Guadeloupe in February 2021. The persistent nature of this intense rainfall episode, which is very unusual during this season, was simulated much more realistically by the 1.3 km model, both in extent and intensity.

The second improvement will take place one year later, with the implementation of Arome ensemble forecasts for these 5 overseas domains. In concrete terms, twice a day, 16 Arome forecasts at 2.5 km will be run simultaneously, each one containing different perturbations which will ultimately allow to assess the uncertainty of the day's situation.

The numerical forecasting tools for the overseas territories will therefore undergo a major evolution in the coming years, which will enable forecasters in these territories to respond even better to the needs of their users.

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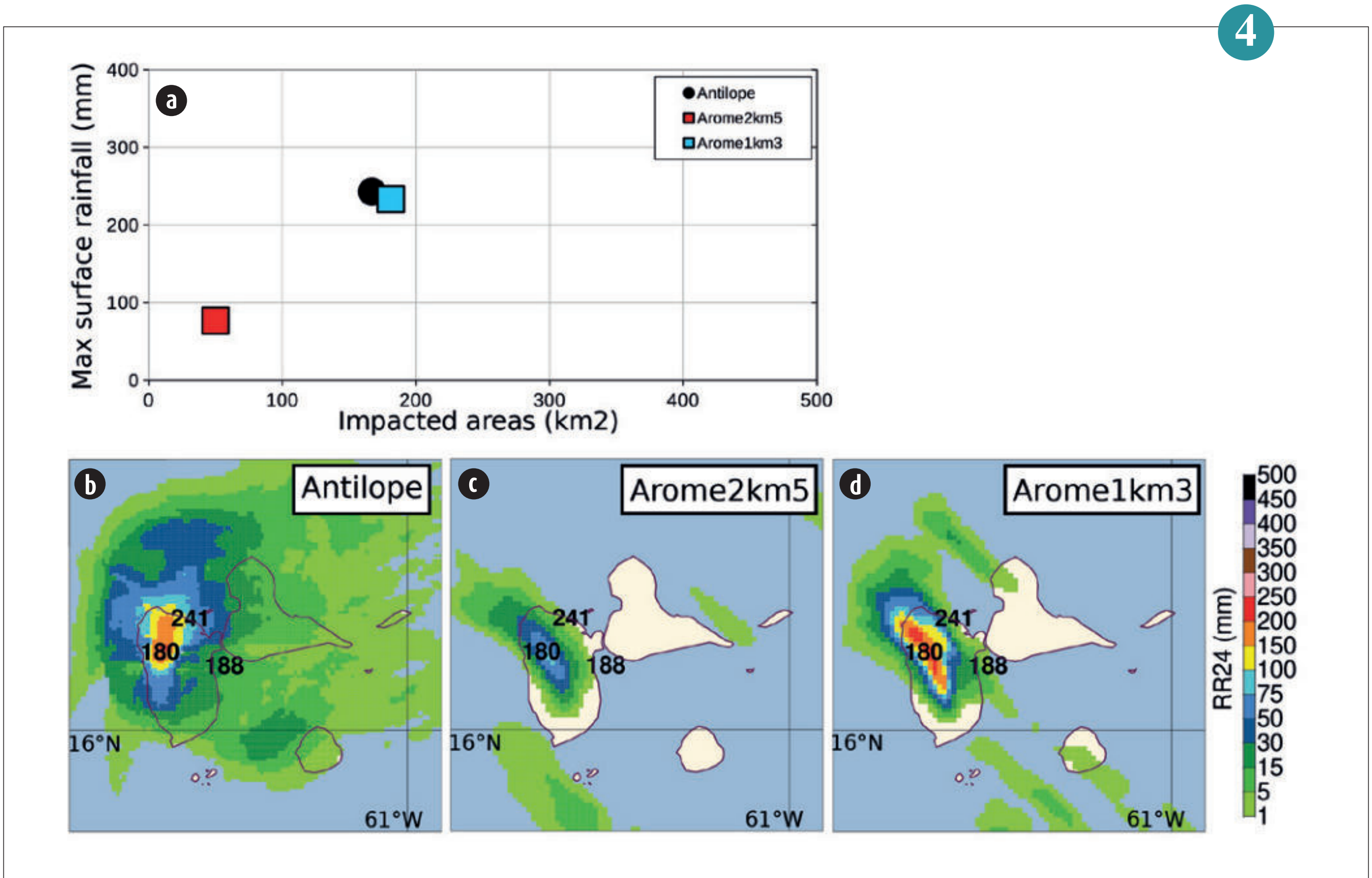

(a) Maximum surface rainfall for the 24h-period (03 February 2021 06 UTC to 04 February 2021 06 UTC), as a function of areas impacted by precipitation greater than 100 mm, observed from Antilope (black circle, radar and raingauge estimation product), and simulated by Arome oper 2km5 (red square), and Arome e-suite 1km3 (blue square), respectively. Spatial distribution of surface precipitation over the same period represented for (b) Antilope, (c) Arome oper 2km5 and (d) Arome e-suite 1km3. The numbers stand for some significant raingauge observations for three locations Sainte-Rose, Petit-Bourg and Pointe-Noire, respectively.

Future satellite instruments, a new revolution for meteorology and climate

Satellite observations play an essential role in the initialisation and the evaluation of the weather forecast systems, the atmospheric composition and the air quality models, but also for the study of processes and climate.
Among future satellites, two major missions of the European agency for meteorological satellites (EUMETSAT) will transform the *landscape* in the coming years. The geostationary Meteosat Third Generation mission will comprise two types of satellites. The first one, Meteosat Third Generation Imager, is dedicated to imagery for weather forecasting, continental surfaces, aerosols and lightning detection, while the second, with the IRS (InfraRed Sounder) on board, will represent a revolution in terms of information available for the AROME kilometre-scale forecast model. The instrument will also be used to study air quality and atmospheric composition. The European Polar Satellite Second Generation mission launched in 2024 will also provide new observations with, among others, the IASI New Generation hyperspectral sounder and data in the microwave spectrum.
The CNRM (research laboratory joined between Meteo-France and CNRS) is involved in many satellite missions in cooperation with space agencies. Scientists may be involved in the design and definition of space instruments or later, in the preparation and exploitation of data in the forecasting models operated by Météo-France. Concerning their exploitation, the use of satellite data is based on the development of radiative transfer models that allow the realistic simulation of observations based on atmospheric model variables and to deduce information from observations. The improvement of radiative transfer models, particularly in new observation range, makes it possible to use new observations. For example, the FORUM mission selected by the European Space Agency for a launch in the second half of the decade will complement the observation of the infrared electromagnetic spectrum already observed by the IASI-NG series of instruments and will thus enable the evaluation and improvement of atmospheric models.

N. Fourrié

Towards to use of IASI-NG in Numerical Weather Prediction: selection of information

F. Vittorioso, V. Guidard

In the framework of the EUMETSAT Polar System–Second Generation (EPS-SG) preparation, a new generation of the Infrared Atmospheric Sounding Inter-ferometer (IASI) instrument has been designed. The IASI-New Generation (IASI-NG) will measure radiances at a doubled spectral resolution compared to its predecessor and with a signal-to-noise ratio improved by a factor of 2. This instrument will provide a very large amount of measured radiances that will be thus not directly exploitable in operational numerical weather prediction (NWP) contexts. For these reasons, an appropriate IASI-NG channel selection in needed. Several methodologies can be applied in order to select the most informative data to be exploited for the aforementioned purpose. The one we decided to use relies on evaluating the impact of the addition of one channel at a time on a scalar figure of merit reflecting the improvement of the analysis error over the background error. Through this process, a total of 500 channels have been chosen to serve as a basis for future channel selections to be provided to NWP centres – 277 temperature, 23 surface-sensitive and 200 water vapour channels (Vittosioso et al, 2021). One-dimensional variational (1D-Var) assimilation experiments realised from the Andrey-Andres et al 2018 atmospheric database show that using this selected set of channels leads to a reduction of the standard deviation of the error in temperature (up to 30%) and water vapour (up to 50%) profiles with respect to the a priori information.

References:

Vittorioso, F., Guidard, V. & Fourrié, N. (2021) An Infrared Atmospheric Sounding Interferometer – New Generation (IASI-NG) channel selection for numerical weather prediction. Quarterly Journal of the Royal Meteorological Society, 147(739), 3297–3317. Available from: https://doi.org/10.1002/qj.4129

Andrey-Andrés J., Fourrié N., Guidard V., Armante R., Brunel P., Crevoisier C. and Tournier B. (2018) : « An Observing-system simulation experiment to assess the impact of IASI-NG hyperspectral infrared sounder », Atmos. Meas. Tech., 11, 803-818, https://doi.org/10.5194/amt-11-803-2018

1

Hyperspectral infrared measurement from the geostationary orbit: benefits for the atmospheric composition

F. Vittorioso, V. Guidard

Météo-France contributes to the operational Air Quality forecasting system with the MOCAGE chemistry-transport model. In this context, research studies have been undertaken on the assimilation of satellite observations to provide information on chemical composition or aerosols. Monitoring pollutants through polar orbiting satellites allows to follow the transport over large distances and to identify the pollution sources, the emissions, and the variability of the tropospheric composition. However, satellite observations should have enough temporal repetitiveness and spatial resolution to monitor the variability of pollutants. One solution to this problem is the use of sounders located on a geostationary platform. Data acquired from geostationary satellites could be very valuable because of their extensive geographic coverage and of the time acquisition frequencies of 30 minutes over Europe. The Infrared Sounder (IRS) on board the Meteosat Third Generation series will acquire data in two spectral bands (679-1210 and 1600-2250 cm^{-1}) sensitiv to many species, among which Ozone and Carbon Monoxide. These characteristics are essential in deducing information about the atmospheric pollution. Sensitivity studies have already been performed to test the response of the instrument itself. Observing System Simulation Experiments (OSSEs) are being undertaken in order to produce simulated realistic observations to be assimilated in MOCAGE. This step will be essential in deducing the impact of these observations in a chemistry transport model.

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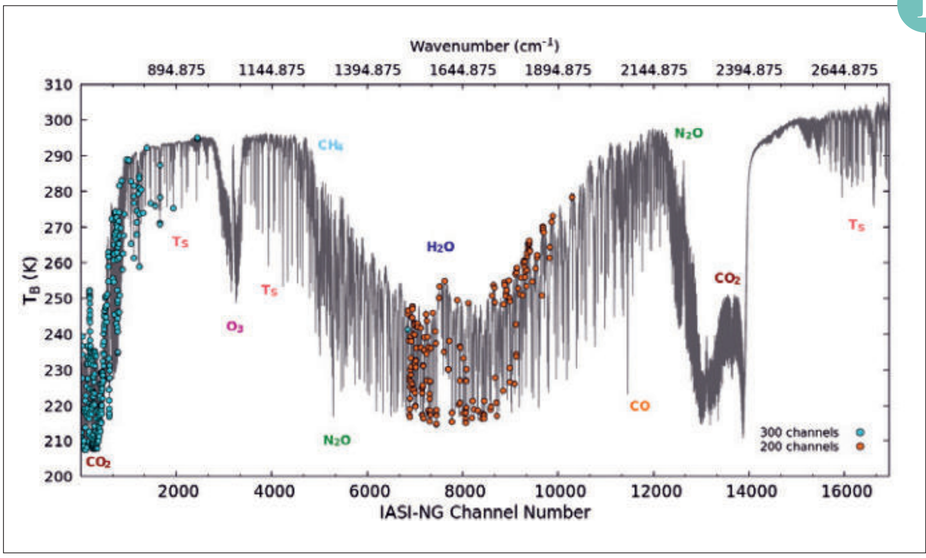

Spectral location of the 500 selected channels over a typical IASI-NG spectrum: 300 in the CO_2 band (cyan dots) and 200 in the water vapour band (orange dots).

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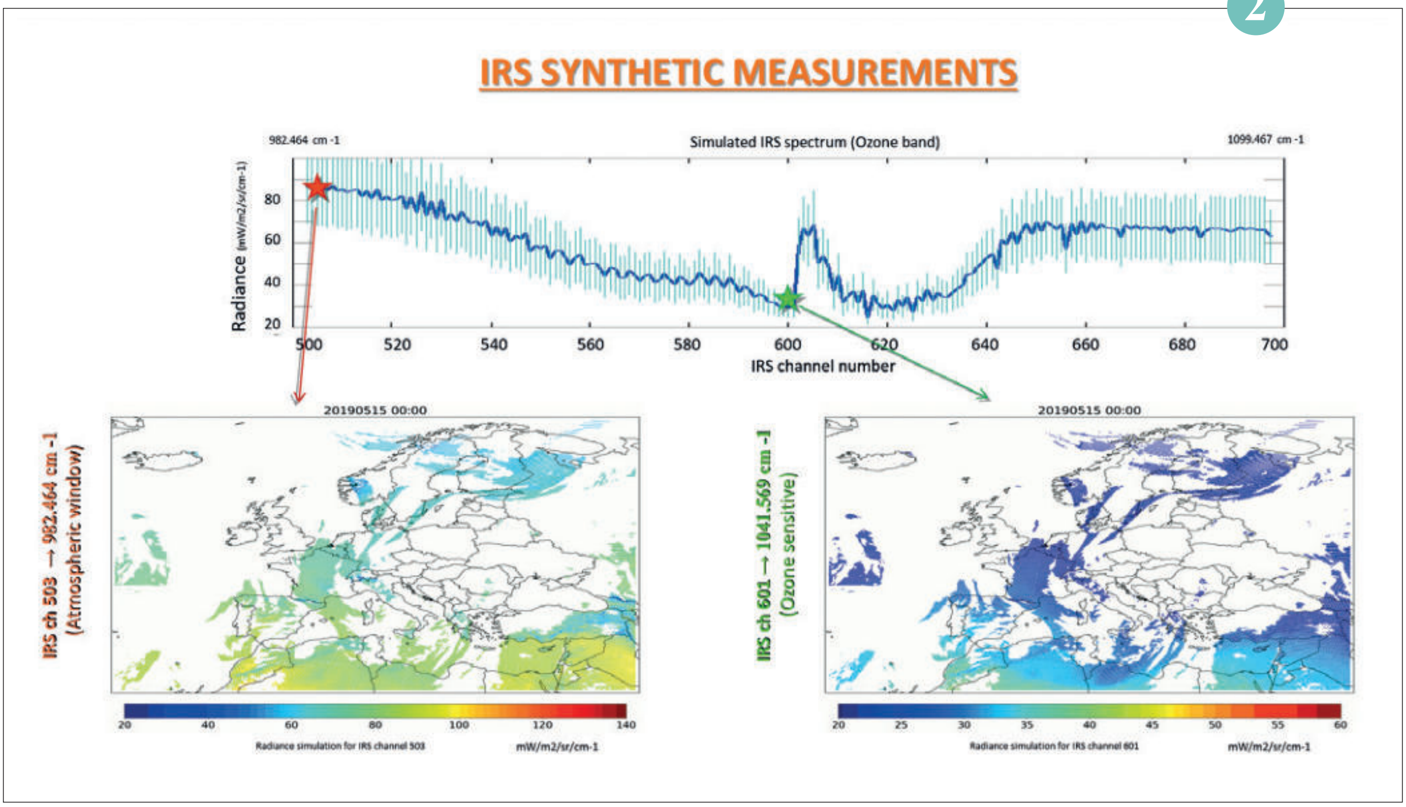

Synthetic IRS measurements simulated to evaluate their impact in MOCAGE.

IASI-NG and FORUM, new infrared sounders to improve numerical weather prediction and climate modeling

Q. Libois, J. Vidot, L. Leonarski

The Earth emits infrared radiation to space in the spectral range 100-2500 cm^{-1}. While the total amount of outgoing radiation is a fundamental quantity for the climate system, its spectral distribution contains much information on the atmosphe. The operational spaceborne instrument IASI, launched in 2006, measures the Earth emission spectrum at 0.5 cm^{-1} resolution in the range 645-2760 cm^{-1}, which corresponds to the thermal infrared. IASI has quickly become key for numerical weather prediction due to its unprecedented sensitivity to vertical profiles of temperature and humidity. The follow-on mission of IASI, IASI-NG (Crevoisier et al., 2014), will be launched in 2025. It will cover the same spectral range as IASI, but at twice finer resolution and with an instrumental noise reduce by a factor of two. In the last few years, more and more climate studies have been using IASI observations, taking advantage of the long time series available. However the thermal infrared only encompasses half of the total infrared energy radiated by the Earth, the remaining energy originating from the far infrared (667-100 cm^{-1}). The aim of the FORUM mission (Libois et al., 2020), selected to become the 9th Earth Explorer of the European Space Agency, is to measure this complementary part of the spectrum. FORUM should be launched in 2027 and will cover the range 100-1600 cm^{-1} at 0.5 cm^{-1} resolution. It will fly less than a minute behind IASI-NG, and the combination of both instruments will provide for the first time the measurement of the full emission spectrum of the Earth (99 % of the radiated energy will be measured). These unique observations will greatly benefit to numerical weather prediction and air quality monitoring, but will also strongly participate to the evaluation and refinement of climate models.

References:

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3

Extension of RTTOV to UV/VIS/PIR hyperspectral instruments for atmospheric chemistry: the GOME-2 example

J. Vidot

The operational assimilation of radiances measured by satellites in the infrared and microwave spectral domains in NWP models has been realized for about 30 years using the RTTOV fast radiative transfer model. More recently, the possibility to simulate radiances measured in the solar, far infrared and even sub-millimeter domains has been made possible by extending the spectral range of the different compartments of the model (parameterization of atmospheric transmittance, scattering by aerosols and/or clouds, optical properties of surfaces, etc...). In the same continuity and in order to cover the whole electromagnetic spectrum related to meteorological applications, the RTTOV model has been extended to the ultraviolet domain.

Thus, we could for the first time simulate clear sky observations for the GOME-2 instrument on board Metop-C which covers the range 240-790 nm at spectral resolutions between 0.2 and 0.5 nm. Figure XX represents the reflectance spectrum simulated by RTTOV-13. This spectrum faithfully reflects the absorption bands of the main absorbing molecules in these ranges: from ozone under 300 nm to oxygen around 760 nm.

The next step of this work will be to test the scattering by aerosols and to introduce a reflectance model of the land surfaces for the UV. Finally, an intercomparison exercise with the KNMI DAK radiative transfer model is planned. The final objective will be to simulate the observations of the future generations of satellites (Sentinel 4 and 5) in order to foresee the assimilation of their observations in meteorological/chemical models.

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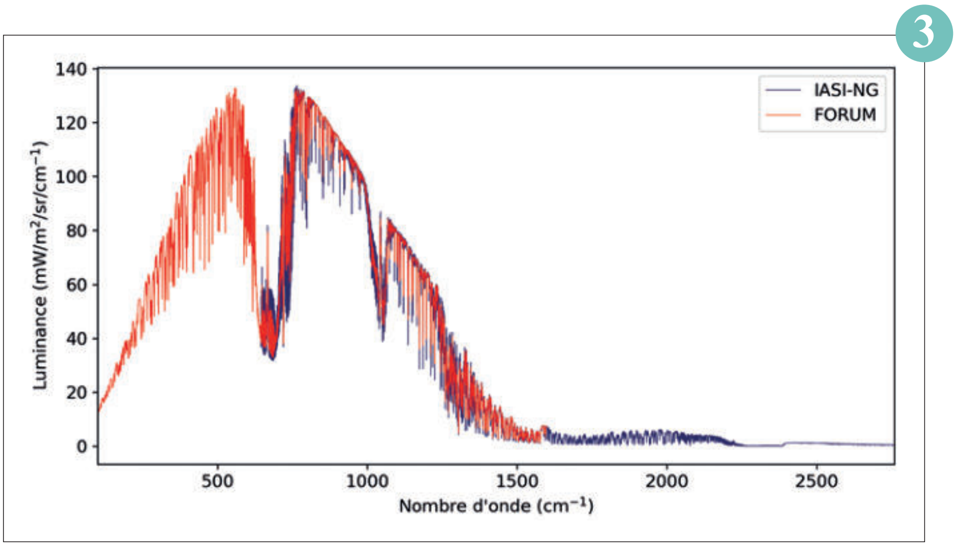
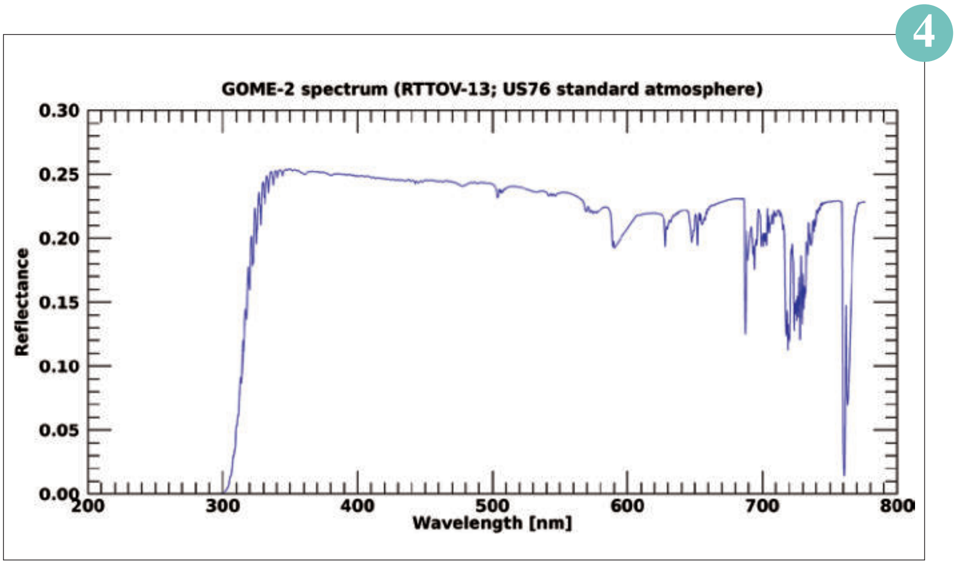


Nadir radiance spectra for IASI-NG and FORUM as simulated by the radiative transfer code RTTOV for a tropical atmosphere over the ocean.



RTTOV-13 simulated reflectance spectrum for the GOME-2 instrument in clear sky over ocean for a standard US76 atmosphere.

The assimilation of future IRS observations, a new step in the improvement of the weather forecasts for the AROME regional model

O. Coopmann, N. Fourrié

A major step forward in the improvement of Numerical Weather Prediction model performances, and particularly for fine-scale models such as AROME, will be taken with the coming of new generations of meteorological satellite sounders. One of them will be on board the future European geostationary satellite, Meteosat Third Generation (MTG), scheduled for launch in 2024. This is the IRS infrared sounder, which will provide a unique 4D view of the atmosphere. It will measure the Earth's disc with a very high spatial frequency of 4 km over Africa and a temporal frequency of 30 minutes over Europe. It will be able to observe this region of the Earth system using wavelengths sensitive to atmospheric temperature and humidity, clouds, surfaces, chemical composition and many other parameters. Figure (a) illustrates these sensitivities based on an accurate assessment of IRS observations, for temperature, water vapour, skin temperature and ozone on the left hand graph and for CO_2, CH_4, CO, N_2O and SO_2 on the right hand graph (Coopmann et al, 2022).

The volume of data generated by the IRS represents a challenge for meteorological centres. It is therefore essential to prepare for the arrival of such an instrument. For this purpose, we are using a method which, starting from a realistic state of the atmosphere, simulates all the observations that can be assimilated into the AROME 3D-Var assimilation system. The main objective is to evaluate the real impact of IRS observations on weather forecasts in addition to the observation system currently assimilated for AROME, including conventional, satellite and radar data. The first step was to simulate the IRS observations in the different wavelengths. Figure (b) shows that these data will allow the monitoring of different atmospheric and terrestrial conditions in near real time with a very fine resolution. The first assimilation tests of the IRS observations are currently in progress, as well as the first evaluations of the weather forecasts from AROME.

Reference :

O. Coopmann, N. Fourrié and V. Guidard (2022): Analysis of MTG-IRS observations and general channel selection for Numerical Weather Prediction models. In revision in Q.J.R.M.S.

5

AOS mission : Towards improved aerosol lidar products from space

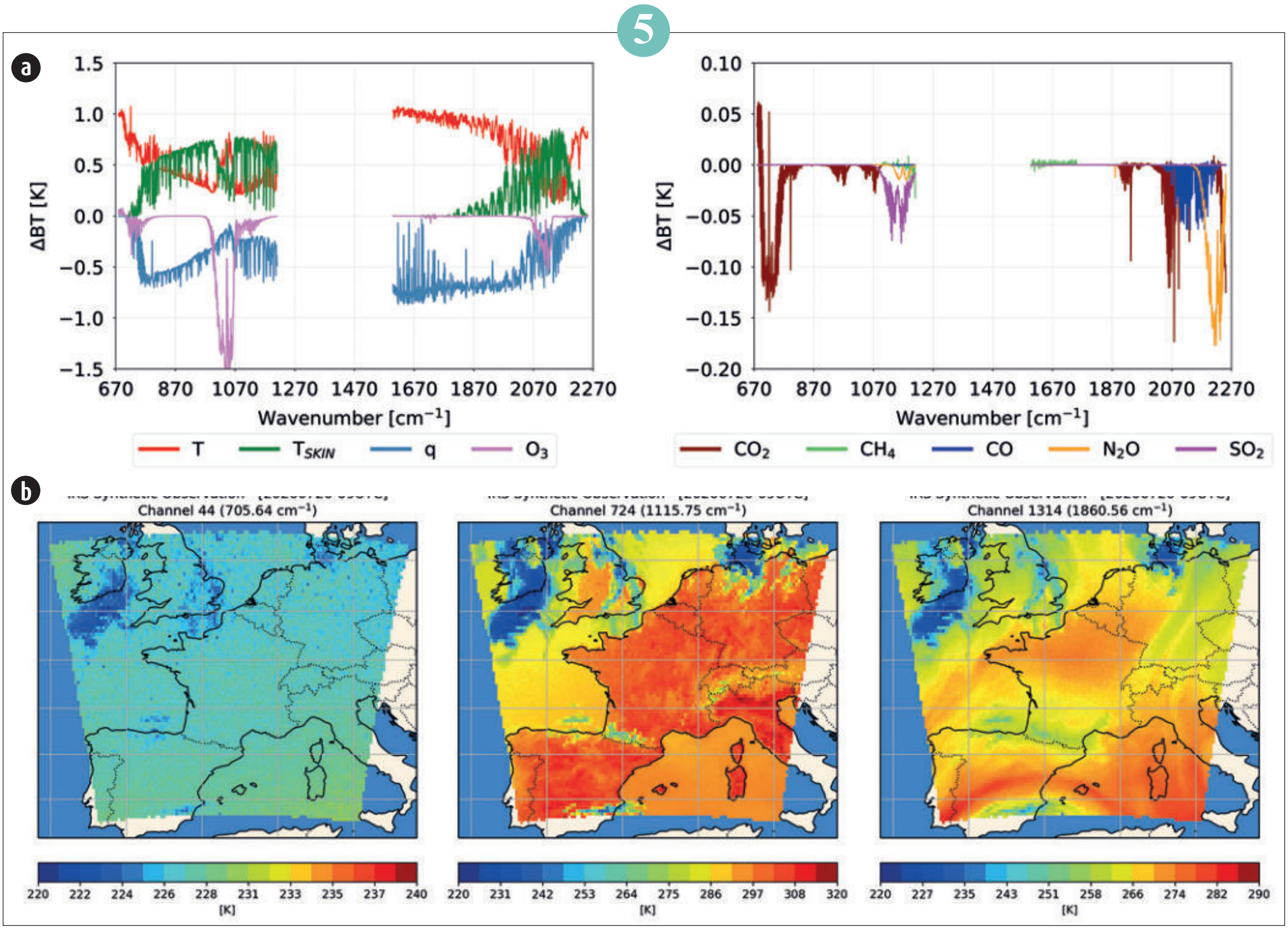
F. Cornut, L. El Amraoui

The AOS (Atmosphere Observing System) mission is a collaborative project between several space agencies (NASA, CNES, JAXA, CSA, DLR) which consists in designing a lidar (CLIO) on board a space platform. The AOS project aims to better understand the transformation processes of aerosol particles and their consequences on air quality, climate and the environment. Our knowledge of aerosols, their distribution, speciation, interactions with clouds and precipitation and their contribution to air quality phenomena will be improved. The main innovation of the AOS CLIO lidar is the presence of a HSRL (High Spectral Resolution Lidar) filter on the visible channel (532 nm) allowing the separation of the signal of the molecules from the signal of aerosol particles.

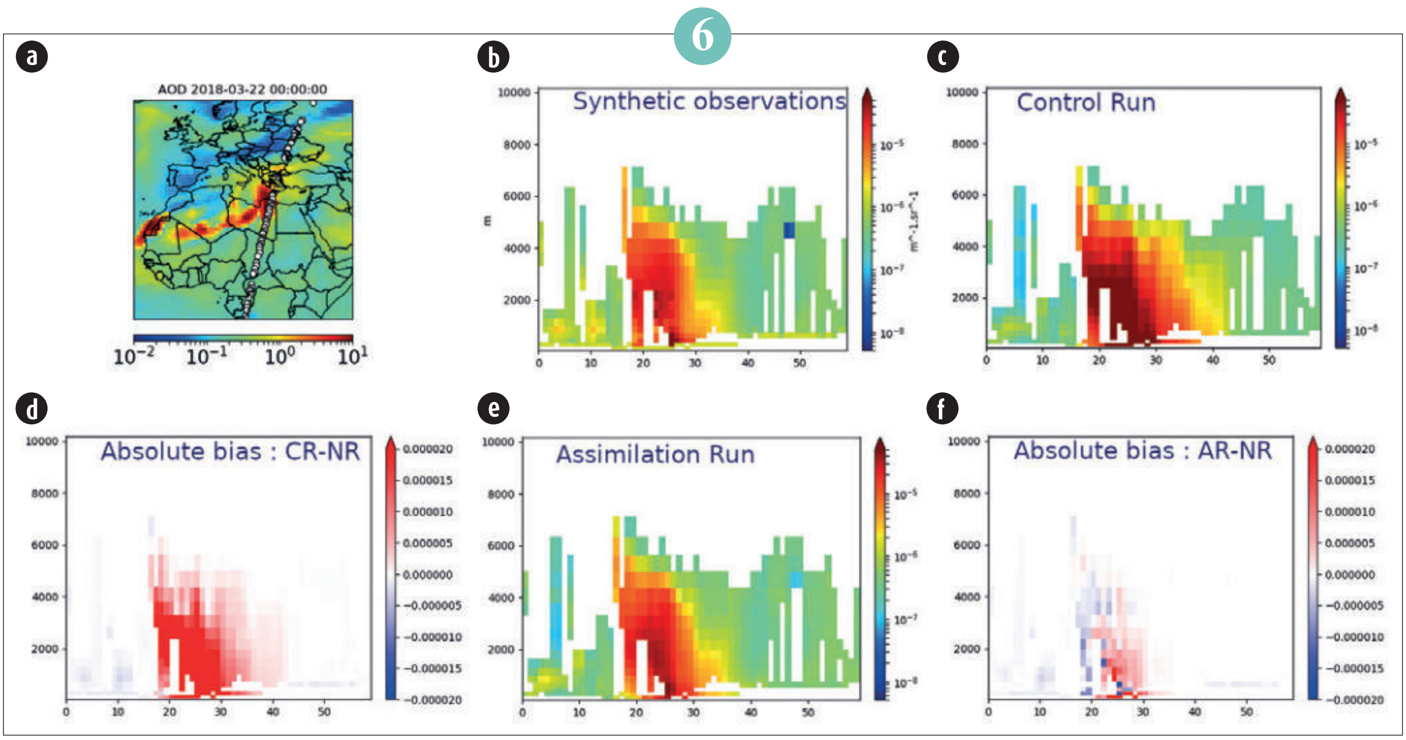
Within AOS, we evaluate the capacity of the CLIO lidar to detect and characterize the different types of aerosols by using a range of Observing System Simulation Experiments (OSSE) with the MOCAGE model. The principle of the OSSE is to define a nature run (NR) considered as the reality from which synthetic observations (SO) of the lidar are extracted. These SOs are then assimilated into a control run model (CR). The objective is to quantify the ability of these SOs to constrain the model analysis. Figure(a) shows a NR representing a desert dust outbreak through which SOs are sampled. Figure (b) shows the lidar SOs in terms of backscatter coefficient. Figure (c) shows the CR in which the SOs are assimilated, and Figure (e) shows the assimilation run (AR). Figure (f) shows the 'AR-NR' differences which are globally lower than the 'CR-NR' deviation (Figure d) showing a positive impact of the lidar measurements on the model.

6

(a) Illustration of a nature run (NR) representing a desert dust transport event in terms of optical thickness over which CLIO lidar observations are sampled.
(b) shows the synthetic observations (SO) as measured by the CLIO lidar taking into account these instrumental characteristics.
(c) shows the control run (CR) in which the SOs are assimilated
(d) shows the 'CR-NR' differences.
(e) shows the assimilated field (AR) resulting from the integration of the SOs in the CR.
(f) shows the 'AR-NR' differences. The 'AR-NR' differences are globally lower than the 'CR-NR' ones which demonstrates a positive effect of the SOs on the MOCAGE model.



(a) Mean spectral difference of brightness temperatures from IRS observations for the sensitivity study in temperature (T), water vapour (q), surface temperature (Tskin) and ozone (O_3) on the left and in carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O) and sulphur dioxide (SO_2) on the right.
(b) Map of IRS observations on the AROME domain for channel 44 (temperature sensitive) on the left, 724 (surface sensitive) in the middle and 1314 (water vapour sensitive) on the right on 20 July 2020 at 09 UTC.



Towards an advanced characterization of aerosols and land surfaces with the upcoming FCI camera aboard MTG-I

X. Ceamanos, A. Georgeot

Meteorological satellites in geostationary orbit are a major tool in Earth observation. Their main advantage is their constant position above the same point of the surface, which allows the acquisition of a large number of images per day. This high temporal resolution enables the monitoring of the atmosphere and land surfaces on a fine time scale.

EUMETSAT has scheduled to launch at the end of 2022 the first Meteosat Third Generation-Imager (MTG-I) satellite. This new geostationary mission will replace the current Meteosat Second Generation (MSG) mission, which has been in orbit since 2002. MTG-I will be equipped with the Flexible Combined Imager (FCI), which will acquire images from the disk of the Earth to 0° longitude at a maximum resolution of 1km (3 times better than the Spinning Enhanced Visible and Infrared Imager, SEVIRI, on board MSG), in 16 spectral channels (5 more compared to SEVIRI, see Figure) and every 10 minutes (instead of 15 for SEVIRI). FCI will provide unprecedented observations of the Earth from space. For example, aerosol remote sensing will be improved with the addition of a spectral channel measuring blue light at 0.44 microns. This information will allow the detection of particles above bright surfaces such as deserts for which SEVIRI shows limitations (Ceamanos et al 2019). This characterization of aerosols will allow FCI to obtain high-quality measurements of land surfaces thanks to an improved compensation for atmospheric effects. Also, the greater number of FCI spectral channels will be used to estimate more precisely the broad-band radiative variables (defined over a wide spectral domain) that are commonly used to represent land surfaces in numerical weather prediction.

CNRM will carry out this work in collaboration with EUMETSAT within the framework of the LSA-SAF project and other projects to come.

Reference:

Ceamanos, X.; Moparthy, S.; Carrer, D.; Seidel, F.C. Assessing the Potential of Geostationary Satellites for Aerosol Remote Sensing Based on Critical Surface Albedo. Remote Sens. 2019, 11, 2958. https://doi.org/10.3390/rs11242958

7

The Monitoring Nitrous Oxide Sources (MIN_2OS) satellite project

P. Ricaud

Nitrous oxide (N_2O) is the third most important long-lived greenhouse gas. Global N_2O emissions increased by 0.25-0.30% yr^{-1} over 2007-2016 and the majority of socio-economic scenarios project their increase until 2100. Of the global total emission (~17 TgN yr^{-1}), ~57% is natural and ~43% is anthropogenic, dominated by agriculture (~52%). But the estimation of N_2O emissions suffers from large uncertainties.

The Monitoring Nitrous Oxide Sources (MIN_2OS, Ricaud et al 2021) satellite project (Figure) aims at monitoring global-scale nitrous oxide (N_2O) sources by retrieving N_2O surface fluxes from the inversion of space-borne N_2O measurements that are sensitive to the lowermost atmospheric layers under favourable conditions. A novel approach developed at CNRM is based on the development of: 1) a space-borne instrument operating in the Thermal InfraRed domain providing, in clear sky conditions, N_2O mixing ratio in the lowermost atmosphere (900 hPa) and 2) an atmospheric inversion framework to estimate N_2O surface fluxes from the atmospheric satellite observations. To implement it, a new thermal Infrared instrument has to be developed, centred at 1250-1330 cm^{-1}, with a resolution of 0.125 cm^{-1}, a Full Width at Half Maximum of 0.25 cm^{-1} and a swath of 300 km. The spectral noise can be decreased by at least a factor of 5 compared to the lowest noise accessible to date with the Infrared Atmospheric Sounding Interferometer-New Generation (IASI-NG) mission. The N_2O total error is expected to be less than ~1% (~3 ppbv) along the vertical.

The MIN_2OS project is the collaboration of French and international laboratories together with industrial partners. It has been submitted to the European Space Agency Earth Explorer 11 mission ideas in December 2020 but not selected. Reflections are underway to identify other opportunities to implement this project.

Reference:

Ricaud, P., J.-L. Attié, R. Chalinel, F. Pasternak, J. Léonard, I. Pison, E. Pattey, R. L. Thompson, Z. Zelinger, J. Lelieveld, J. Sciare, N. Saitoh, J. Warner, A. Fortems-Cheiney, H. Reynal, J. Vidot, L. Brooker, L. Berdeu, O. Saint-Pé, P. K. Patra, M. Dostál, J. Suchánek, V. Nevrlý, C. Groot Zwaaftink, The Monitoring Nitrous Oxide Sources (MIN2OS) satellite project, Remote Sensing of Environment, Volume 266, 2021. https://doi.org/10.1016/j.rse.2021.112688

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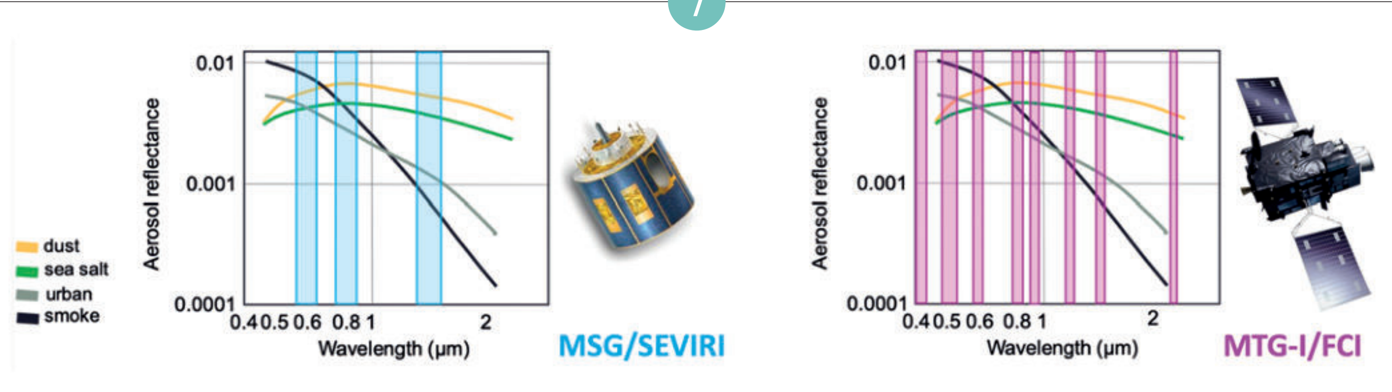

Comparison of spectral channels measuring light reflected from the Earth in the visible and near infrared domains for SEVIRI (left) and FCI (right).
The greater number of FCI channels will help to better distinguish between different types of aerosols.

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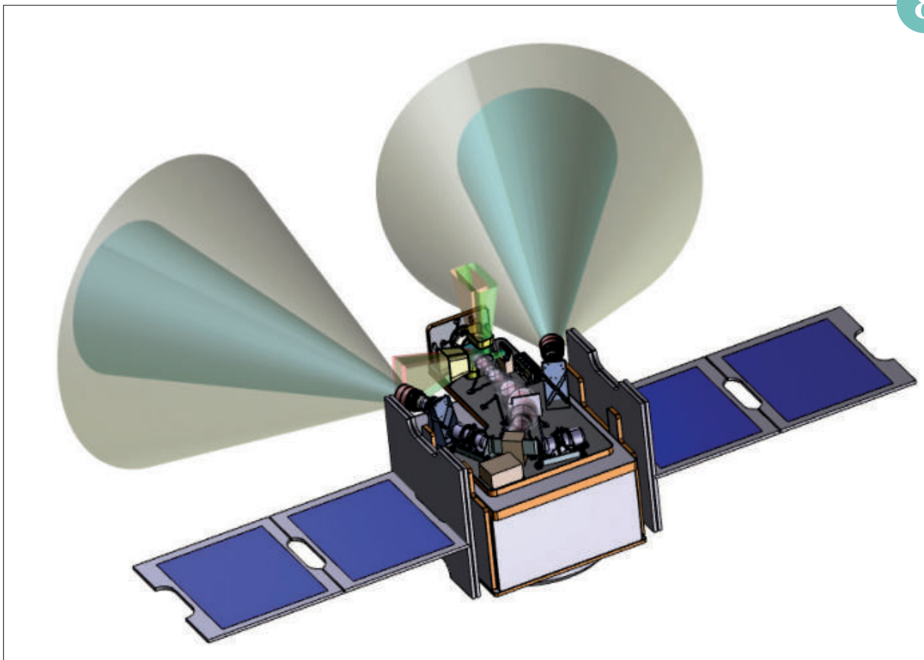

The MIN_2OS project: Imaging spectrometer instrument accommodation on the space platform.

A collection of results illustrating research advances in 2021

Numerical weather prediction and data assimilation

In addition to the major developments in the numerical weather prediction (NWP) chain, research activities have been carried out to prepare for longer-term developments of NWP systems. The assimilation into ARPEGE of balloon data from the experimental campaign Strateole-2 illustrates the contribution of this type of data in the tropics. An assimilation scheme, called "3DEnVar", combining the variational and ensemble approaches, is developed in AROME to represent more precisely the covariances of forecast error in real time and to take into account the temporal dimension in the "4DEnVar" version. The results of different methods to represent modelling uncertainties in the AROME ensemble forecast are also presented. Finally, several works highlight
how weather models, and in particular ensemble forecasts, can be processed in an automatic way to optimise their usefulness in different domains: wind and solar forecasts for renewable energies, hail risk forecasting, sea state modelling and monthly cyclone forecasting for emergency efforts in the Indian Ocean.

F. Bouyssel

Stratéole-2: ARPÈGE assimilates data from long-duration balloons drifting in the tropical lower stratosphere

A. Doerenbecher, V. Pourret

The Stratéole-2 scientific project aims to make progress on the understanding of physical processes in the lower tropical stratosphere and their influence on climate. This project is based on two long measurement campaigns involving balloon-borne instrumental platforms lifted at an altitude between 18 and 20 km with CNES super-pressurized balloons. These balloons have the capability to drift for several months at a constant density level. They have the capacity to circumnavigate the globe several times.
The first long campaign started in October 2021. 17 balloons were launched from the Seychelles over a period of two months. Météo-France commissioned two senior forecasters to help planning these launches. CNRM/GMAP receives near-real time data via the LMD which operates a high precision observation system (TSEN) on-board each balloon. These 10-minute frequency data are inserted into the Météo-France databases. ARPÈGE, Météo-France's global assimilation/forecasting system, is able to use these data. After three weeks of monitoring to assess their quality, the TSEN data entered the operational ARPÈGE system as well as the "double" system that prefigures the future system that will become operational in 2022. One and a half months after the start of the campaign, 11 balloons are still flying. The monitoring indicates that the data is of good quality. Quantifying the impact of these data on the quality of forecasts will be the subject of a study in 2022.
Specific developments are underway to make the most of these balloon data. After validation during this campaign, they could be used during the second Stratéole-2 campaign planned for 2024.

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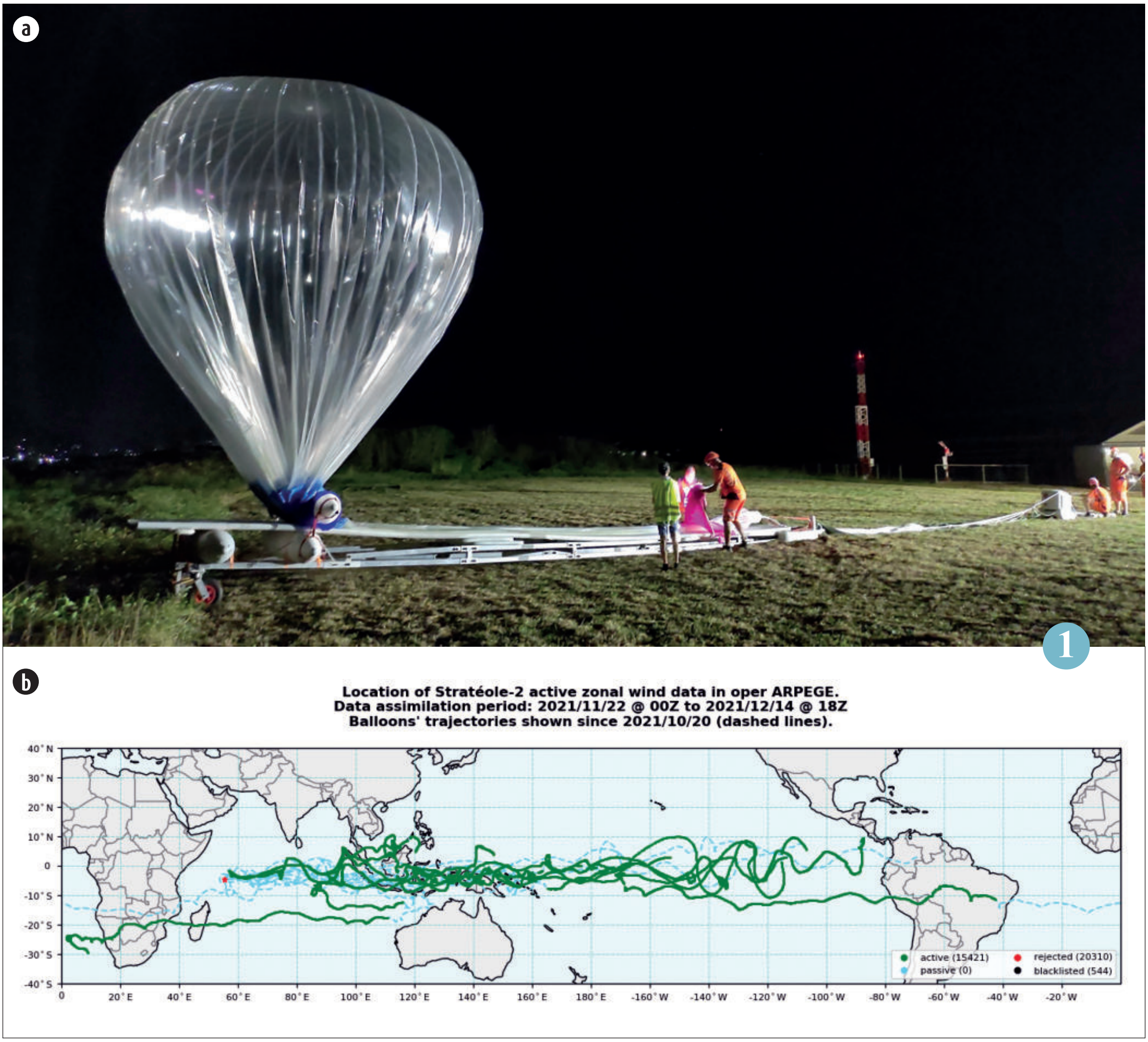
(a) Preparation of a 13 m balloon before its launch (at night). On the ground, the gas gathers at the top of the envelope, the lower part of which is lying on a pad. Once at the ceiling, the gas fills the whole envelope which is spherical and in super-pressurized with respect to the outside atmosphere. Payloads to be lifted in the stratosphere are visible on the right. Copyright: Albert Hertzog, IPSL/LMD.



(b) The dashed lines show the flown trajectories of the Stratéole-2 balloons launched at the Seychelles (red star). The green dots indicate the assimilated data.

First results of a long-term experimentation of a 3DEnVar assimilation scheme for Arome-France

V. Vogt, P. Brousseau

Since its implementation in 2008, the AROME-France 3DVar assimilation system has been using background error statistics modeled under many assumptions, such as spatial and temporal homogeneity. Another representation of these statistics, dependent on the meteorological situation, can be obtained by a scheme combining variational and ensemble techniques, called 3DEnVar, which uses the perturbations provided by an ensemble of data assimilations. Such a scheme, available in the OOPS software framework, is currently being evaluated in a long-term experimentation in order to be implemented for operations. About 30 experiments, based on a pre-operational configuration, have been run over a 3-month period covering the fall and winter of 2020, in order to tune a large number of parameters, such as the number of members of the ensemble, the localization or the hybridization of the background error covariances, which enable the filtering of the sampling noise.

Initial results show a significant advantage of the 3DEnVar scheme over the 3DVar scheme. The root mean square error of the 12-hour forecasts compared to the radiosondes is reduced by 13% for the temperature, and by 10% for the wind and humidity at 850hPa. The IP16 indicator, which measures the performance of the AROME NWP model in forecasting precipitation and wind gusts over 6 hours, has been improved by 3%, compared to the Meteo France target of an increase of 0.5% per year. This work is currently continuing with a validation on meteorological situations at stake in view of a future evolution of our operational sysems.

Reference:

Michel, Y., and Brousseau, P. (2021). A Square-Root, Dual-Resolution 3DEnVar for the Arome Model: Formulation and Evaluation on a Summertime Convective Period. Monthly Weather Review, 149(9), 3135-3153.

Montmerle, T., Michel, Y., Arbogast, E., Ménétrier, B., & Brousseau, P. (2018). A 3D ensemble variational data assimilation scheme for the limited area Arome model: Formulation and preliminary results. Quarterly Journal of the Royal Meteorological Society, 144(716), 2196-2215.

2

Model error representation in AROME-EPS using perturbed parameters approach

M. Wimmer, L. Raynaud, L. Descamps

Ensemble Prediction Systems aim to represent the different sources of uncertainty occurring in numerical weather forecasts, in particular the uncertainty due to model imperfection. The AROME-EPS operational at Météo-France currently represents model error by randomly perturbing the physical tendencies. However, this method has some disadvantages and an alternative approach, based on the perturbation of parameters involved in the physical part of the AROME model, has been developed and evaluated. Following advice of physics experts, 21 parameters whose values are uncertain have been selected. Sensitivity analyses allowed us to identify 8 parameters with the highest influence on AROME forecasts, and thus more likely to contribute to the model errors. These parameters thus occur in the representation of turbulence, microphysics, shallow convection, surface, radiation and numerical diffusion.

Several perturbed parameters techniques have then been set up and evaluated over long periods. Compared to the current approach used in AROME-EPS, they largely improve forecasts performances for most near-surface variables, including wind speed and accumulated precipitation (see Figure).

This method will next be evaluated in the forthcoming high-resolution AROME-EPS. The development of spatio-temporal parameters perturbations will also be investigated.

Reference:

Wimmer, M., L. Raynaud, L. Descamps, L. Berre and Y. Seity, 2021: Sensitivity analysis of the convective-scale AROME model to physical and dynamical parameters, Quart. Jour. Roy. Met. Soc, vol. 148, pp 920-942, doi :10.1002/qj.4239.

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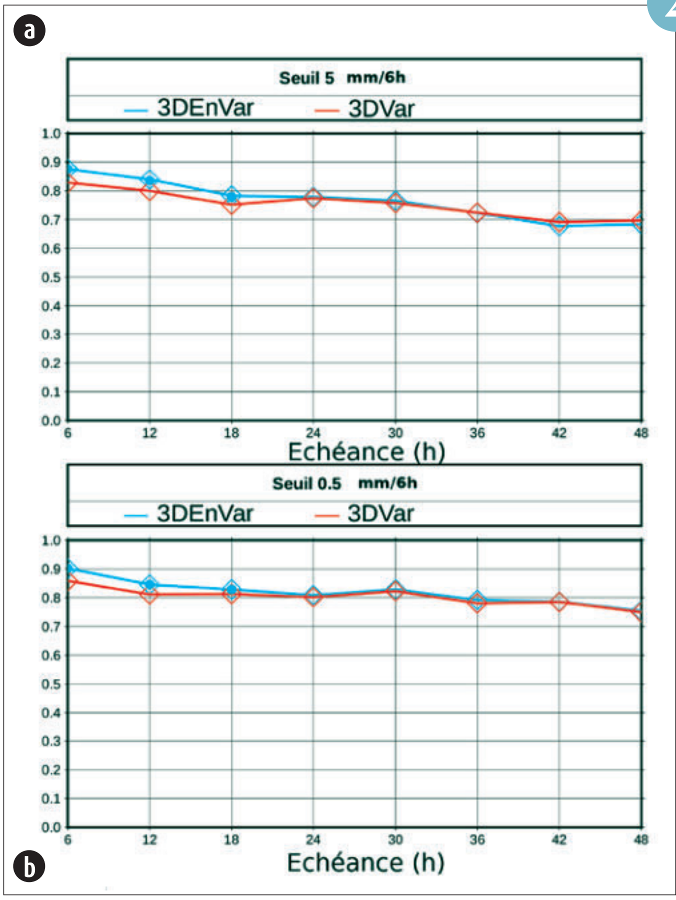

Evolution of the regional normalized Brier score computed over a 52.8km neighborhood for precipitation thresholds of 5mm/6h (a) and 0,5mm/6h (b) as a function of the forecast range (abscissa). Forecasts start at time 00 UTC. The red (resp. blue) curve represents the 3DVar (resp. 3DEnVar) configuration. Higher values indicate better performance, and the statistical significance of the differences between the two versions tested is indicated by the point inside the diamonds representing each threshold and forecast range.

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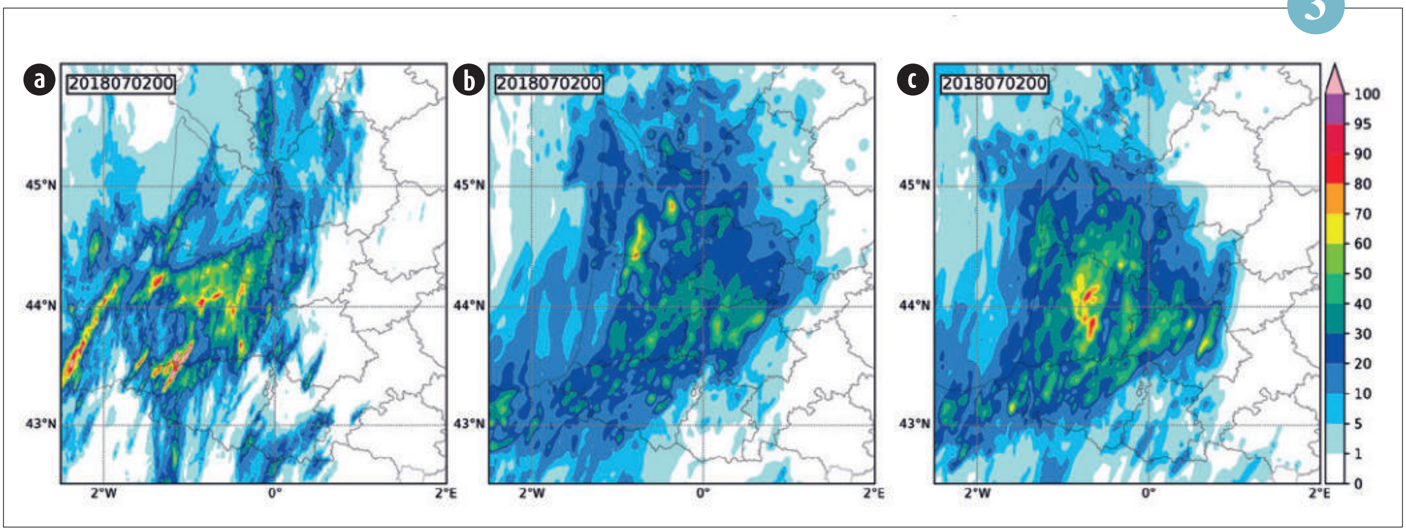

24h accumulated precipitation valid on 2 July 2018 at 00h UTC:
(a) Observations;
(b) Maximum percentile of AROME-EPS with current model error representation;
(c) Maximum percentile of AROME-EPS with new model error representation based on parameters perturbations.

AROME error prediction mechanisms in turbulent and convective flow

A. Fleury and F. Bouttier

The quantification of weather forecast uncertainty by ensemble prediction requires accounting for numerical model error. Current model error representations suffer from poor knowledge of the error characteristics, they are currently based on crude perturbation schemes of model equations or input parameters, which are tedious and expensive to tune.

A novel approach has been studied in the AROME numerical weather prediction model. Random fluctuations are introduced inside the model equations in accordance with the physical hypotheses that underpin the model design. For instance, numerical noise from turbulent eddies smaller than the AROME computational grid is introduced, which generates ensemble forecast spread on some weather parameters in turbulent weather regimes. Another example is convection, which is hypothesized in AROME to involve only one cloud structure per model column: a random pattern generator has been introduced to account for diversity in the cloud distribution. The statistics of these numerical noise generators have been tuned using a novel approach that relies on atmospheric models at very fine resolutions (LES: large eddy simulations). The forecast impact of the noise has been assessed in simulations of cumulus clouds, fog, etc. and compared with more traditional ensemble perturbation techniques. The conclusion is that physically-based uncertainties have a significant forecast impact in some weather situations. Thus, including them into the AROME ensemble prediction system is expected to improve probabilistic weather forecasts. These developments are being tested in real size experiments, and they are being extended to condensation, precipitation and radiation processes.

Reference:

Fleury, A., F. Bouttier, F. Couvreux, 2022: Process-oriented stochastic perturbations applied to the parametrization of turbulence and shallow convection for ensemble prediction. Quart. Jour. Roy. Met. Soc., https://doi.org/10.1002/qj.4242

4

SMART4RES Project: Valorization of ensemble forecasts for renewable energy predictions

B. Alonzo, I. Aleksovska

The European project Smart4RES aims at improving the short term forecasts of wind and solar renewable energy production in order to ease their integration in electrical systems. In this context, 4 months of Arome (PEARO) and Arpège (PEARP) ensemble forecasts at very high resolution have been produced, respectively composed of 25 Arome forecasts at 1.3km resolution with outputs available every 5 minutes, and of 35 Arpège forecasts at 5km resolution over France with outputs every 4 minutes. These very high spatial and temporal resolutions should allow to meet energy partners requirements.

In addition to the raw ensemble outputs, several innovative post-processing methods have been developed. The first one consists in a deterministic synthesis of PEARO. Different methods have been assessed for 100m wind speed forecasts, in particular the use of an optimized percentile, a weighted mean and the identification of a main scenario. The results show a clear advantage for the optimized percentile, which provides a performance improvement of around 15% over the deterministic AROME forecast, and 10% over the ensemble mean for winter 2020 (Figure a).

The second post-processing aims at designing "seamless" ensemble wind forecasts up to 4 days ahead, by cleverly connecting the AROME and ARPEGE ensemble forecasts to ensure temporal continuity (Figure b).

The methods developed for wind will then be applied to solar radiation. The benefit of high resolution ensemble forecasts and post-processing methods to energy production will also be evaluated by the project partners.

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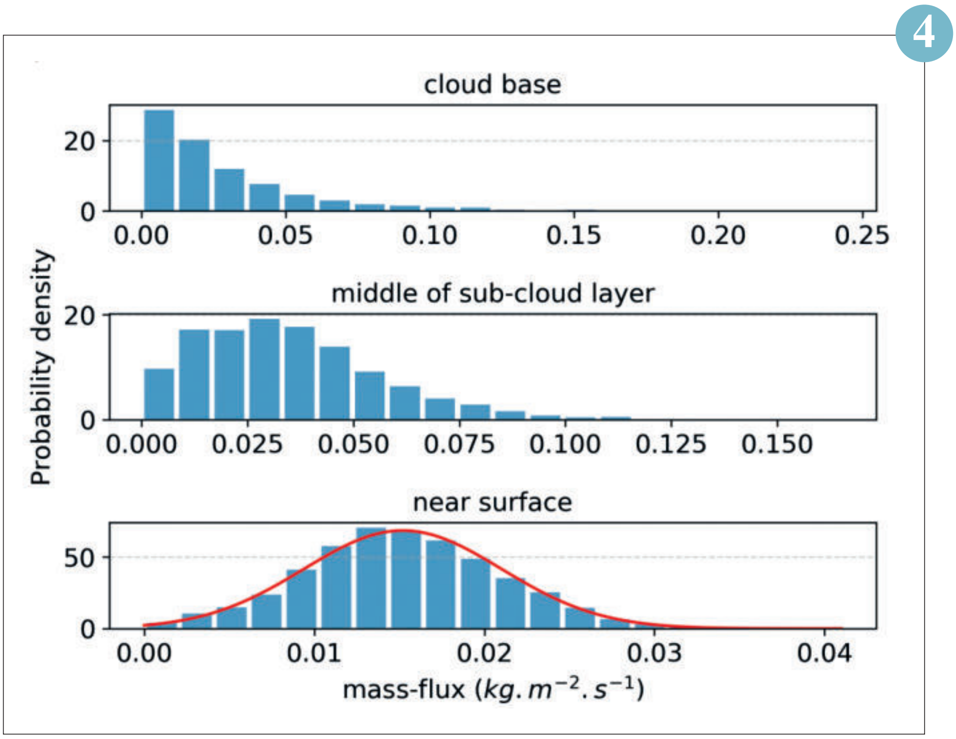
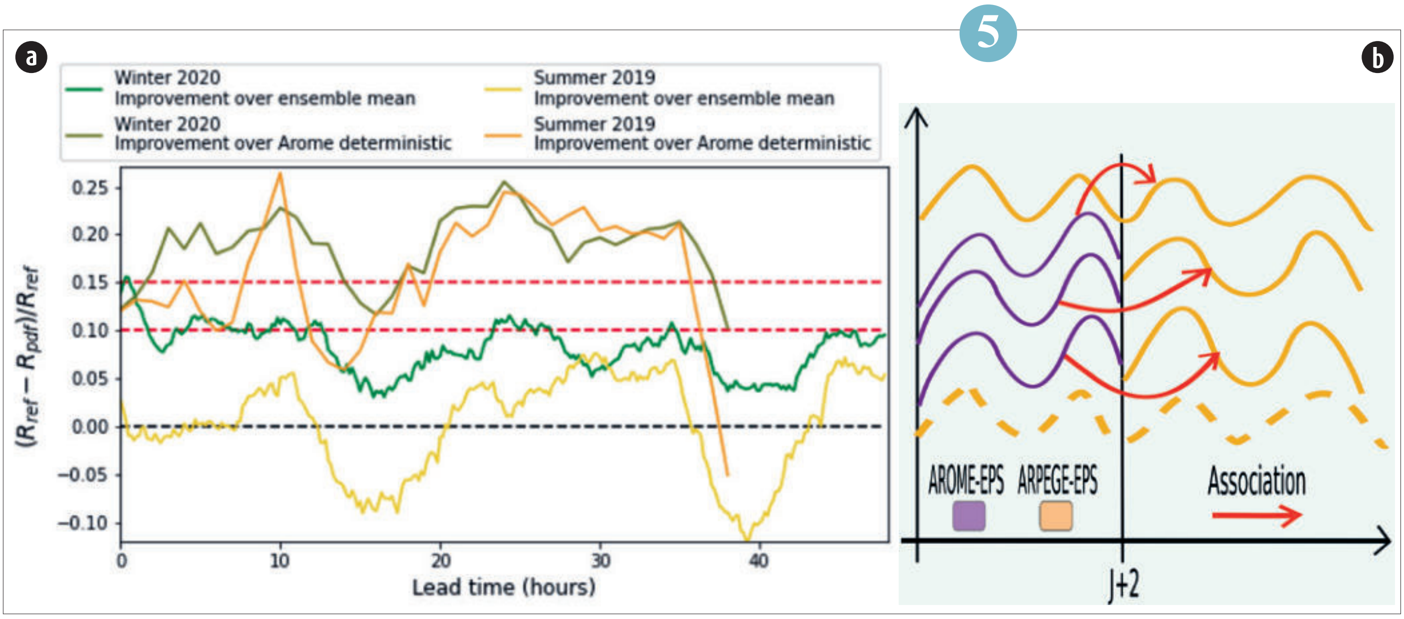


Intensity histograms of upward fluxes in a column that contains a stratocumulus cloud, in a high resolution numerical simulation. Top to bottom: flux at cloud base, below cloud base, and near the surface.
These plots indicate the random number distributions to apply for uncertainty representation in the AROME convection scheme.



(a) RMSE improvement with respect to the Arome deterministic forecast and the ensemble mean forecast obtained with the optimized percentile.
(b) Schematic representation of the seamless ensemble design between PEARO and PEARP. Each Arome member is connected at 51 hours to an Arpège member, chosen to minimize temporal discontinuities.

Towards automated hail forecasts

F. Bouttier and H. Marchal
in cooperation with the ALPHA project

Hailstorms can cause considerable damage, but they are hard to predict because of their physical complexity and low predictability. The location and timing of hail events is highly uncertain in forecasts beyond a few hours, at which time the information in raw numerical prediction model fields is worthless. A probabilistic approach that extracts the predictable scales is necessary. To this end, a novel hail postprocessing procedure has been developed. It is a machine learning algorithm driven by the graupel diagnostic in the AROME numerical ensemble prediction system. The spatial filtering and intensity thresholds used in the algorithm has been trained over summer 2020 and 2021. Verification against radar-derived hail observations (see figure) over long periods is used to evaluate the hail product: at forecast ranges from 12 to 36 hours, the forecasted hail probabilities have demonstrable predictive value if one is ready to accept more false alarms than non-detection of hail events. High detection is normally preferred by users who are greatly impacted by hail.
This forecast procedure is under evaluation for possible operational use in the ALPHA forecast project. The forecast quality is still limited, but it will improve in 2022 thanks to planned AROME resolution upgrades, as well as in the longer term through ongoing research for improving hail observations and machine learning procedures.

6

Contribution of the Arome-IFS forcing for coastal wave forecasts in the Mediterranean sea

A. Dalphinet

Until 2021, over the Mediterranean sea, marine forecasters only worked with forecasts of high-resolution waves forced by Arpège or Arome wind. In situations with a marked divergence between Arpège and IFS, there was no coastal wave scenario forced by IFS or its fine-scale regional variation, Arome-IFS. A WW3 coastal model forced by Arome-IFS fills this gap and is now operated in real time.
The replay of extrem events have shown the strong interest of having this new model. Arome and Arome-IFS are indeed likely to differ and sometimes greatly. The case of Storm Adrian is the most striking recent example with a difference between the two wave simulations of more than 3 meters (see map). This large discrepancy is explained by a very different chronology of the storm between the Arome and Arome-IFS forcings. The validation against observations shows the better results of the simuation forced by Arome-IFS.
On average, the deviations remain measured, less than 30 cm on the height of the waves, and mainly concern the last time steps.
Average scores were calculated over the fall of 2020 against available buoys and altimeters. They show that the WW3 model forced by Arome-IFS turns out to present the same good quality as WW3 Arome. This validation led to the implementation of this new operational configuration.

7

PISSARO: Forecasting cyclonic activity in the southwestern Indian Ocean on a monthly scale

H. Vérèmes, S. Malardel

The INTERREG V project PISSARO (carried out by the LACy) focuses on subseasonal forecasting (from 2 weeks to 2 months) for applications in the SouthWestern Indian Ocean (SWIO) basin. Its objective is to evaluate, improve and valorize the forecast on a monthly scale. This valorization includes the development of forecasting products adapted to different types of users for the anticipation of the cyclonic risk on a monthly scale in the SWIO.
The first step was to establish a mutual understanding between the researchers and the operational partners of the project (notably DIROI and PIROI). This was facilitated by several actions: the animation of a monthly experimental briefing on cyclonic activity and weather patterns in the SWIO and the participation in conferences in the humanitarian field.
In response to the urgent need for disaster risk reduction, a tropical cyclone occurrence probability product has been adapted to be interpretable by non-meteorological users and restricted to populated areas. In parallel, a tropical cyclone track classification study targets the development of future S2S-derived forecast products to provide potential track scenario probabilities potentially useful to forecasters (see figure). The products will be available on the project website http://pissaro.re.
In 2022, the work on cyclone forecasting will be extended to other weather phenomena (intertropical convergence zone, extreme rainfall) in collaboration with other users (in particular the *SMA*, a partner of the PISSARO project).

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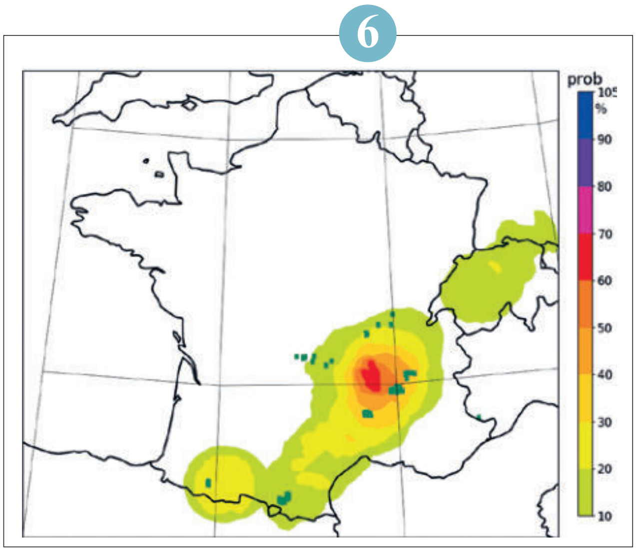
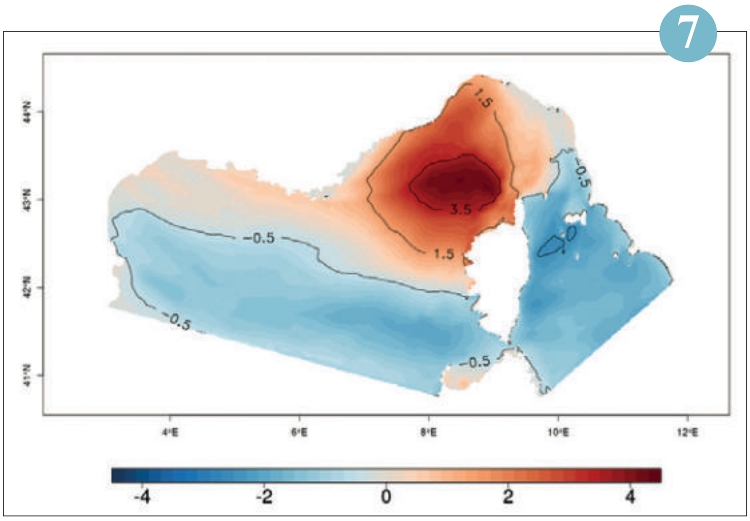
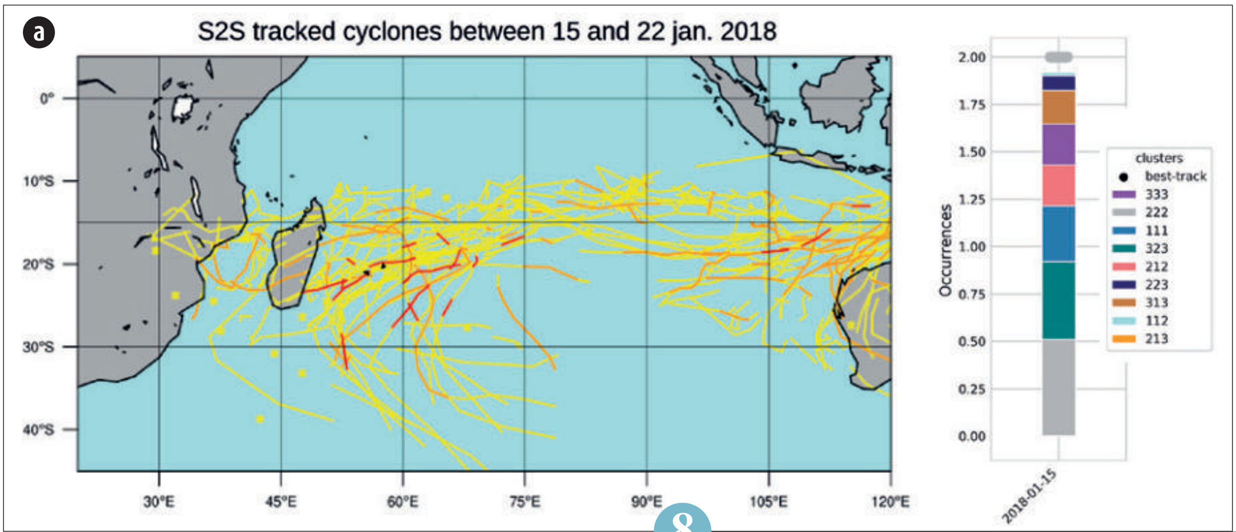


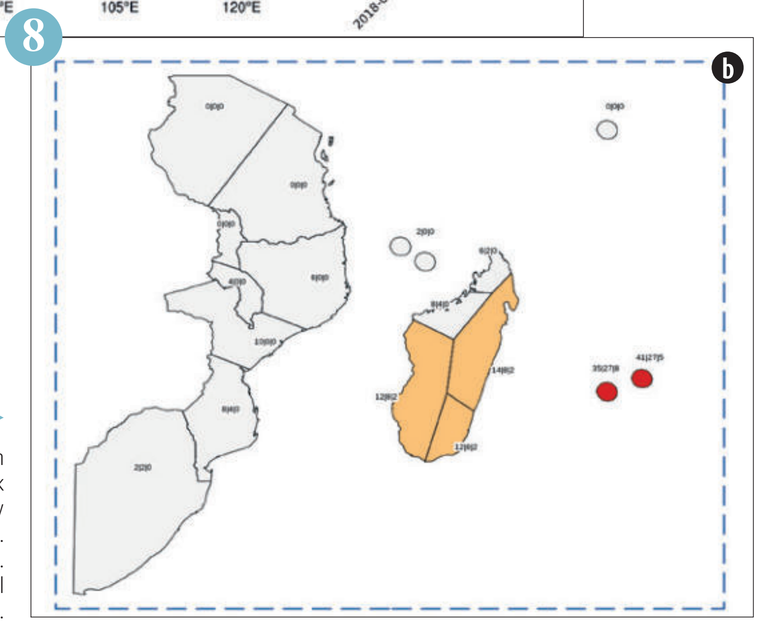
Sample hail prediction valid on 22 July, 2020 at 17h. Dark green symbols show radar observations of hail events. Colour shading indicate probability levels postprocessed from the AROME ensemble prediction issued the night before. An optimal deterministic hail prediction is obtained by thresholding probabilities around 10%.



Map of the difference in wave height (m) between WW3 Arome IFS and WW3 Arome (WW3 Arome IFS - WW3 Arome), at 33h time step of the 12h UTC run on 10/28/2018. Validity date: 10/29/2018 at 21h UTC, storm Adrian.



(a) Left: set of potential trajectories for the week of 15 January 2018 forecasted 2 weeks earlier. Yellow indicates a low-pressure system level, orange a storm level, and red a cyclone level.
Right: average occurrences of these trajectories by class as defined by the classification developed at the DIROI.
One of the challenges of the PISSARO project is to extract information from the S2S subseasonal forecast data that is close to the observations and directly exploitable in a cyclone risk anticipation framework. The classification of the forecasted trajectories shows a higher probability of occurrence of 222 type trajectory (grey color, i.e. trajectory located between 50°E and 70°E) which effectively corresponds to the class of the observed trajectory of cyclone Berguitta.



(b) Experimental product of probability level of the passage of a tropical cyclone on the territories of the SWIO basin, developed in the framework of the PISSARO project. The redder the color, the higher the probability of risk occurrence. This product will be calibrated and evaluated in 2022. Example with the 1st January 2018 forecast for the week of 15 January. The areas for which the forecast predicted the highest probability level (i.e., Reunion and Mauritius) were actually exposed.

Process studies and modelling

Research process studies aim to improve the understanding of phenomena in order to better represent these processes in numerical weather and climate prediction models, and to design relevant weather and climate services.
Process studies are generally based on a complementary approach between observation and modelling: fine-scale numerical simulations, evaluated with observations, provide a detailed description that allows better characterisation of the processes, in order to better represent them in larger-scale models. Research work is based on the development and the use of physical parameterisations, mesoscale data assimilation, ensemble forecasting methods and impact models.
In the troposphere, clouds have a radiative impact that modulates the Earth radiative budget, essential for climate modeling and numerical weather forecasts. This is based on parameterisations of the radiative properties of clouds using simplifying assumptions about the microphysics of hydrometeors. The uncertainty related to these assumptions could be assessed and appears significant.
In the field of storm studies, the NAWDEX measurement campaign sought to better understand the role played by cloud processes on mid-latitude atmospheric disturbances and on the formation of errors in forecast models and biases in climate models. Through a combination of observation and modelling, various cloud processes have been identified as influencing the upper air dynamics, driving the intensity of these storms on the ground.
Further down in the troposphere, interactions with the surface processes also drive atmospheric phenomena, and the coupled modelling approach between atmosphere and surface is therefore essential. Over oceanic surfaces, ocean-atmosphere coupling is a central issue for the representation of tropical cyclones or Mediterranean heavy precipitation events. At the kilometre scale, the AROME-NEMO coupled system constitutes the reference, and can be evaluated with innovative float measurements on the paths of cyclones. Over continental vegetation surface, modelling requires a realistic representation of the soil-plant system. Recent work relies on machine learning techniques to make better use of satellite data assimilation in the representation of vegetation and soil moisture. Cities, where most of the world's population, activities and infrastructures are located, also present important issues for hectometric forecasting and adaptation to climate change. The urban-atmosphere coupled modelling has reached an advanced degree of realism, allowing the representation of morphologically heterogeneous cities, such as Hong Kong, and the evaluation of the impact of urban adaptation strategies. Multidisciplinary research has led to the inclusion of vegetation and hydrological processes in the urban surface model, paving the way for studies on urban cooling and water management in cities, and nature-based land-use planning strategies.

C. Lac

Improving the representation of cloud optical properties in atmospheric models

E. Jahangir, Q. Libois

Cloud radiative forcing characterises how clouds affect the Earth radiative budget. It is a key quantity, both for climate modeling and numerical weather forecasts. The radiative properties of clouds depend on their physical properties at the microscopic scale, in particular they are very sensitive to the size of the cloud particles. In atmospheric models a characteristic size is diagnosed from the water content. For liquid clouds this diagnosis is based on empirical relations derived from very specific observations, and assumes a constant shape of the droplet size distribution. Similarly, the estimation of the cloud optical properties from the characteristic droplet size requires an assumption on the shape of the distribution. In practice, a single distribution is used for all clouds, whereas a large variety of distributions are observed in nature. It is therefore important to quantify the uncertainty on the radiative forcing of clouds induced by this approximation. To answer this question we have developed diagnostics of the characteristic size and optical properties estimates assuming different distribution shapes. For a given cloud characterized by its liquid water content we have calculated different radiative forcing for different distributions. Applying these tools to five years of simulations performed with the CNRM-CM6 climate model, we showed that the global radiative forcing of clouds (in the shortwave and near infrared ranges) simulated by the model could vary by more than 6 W m^{-2}, which is about 13% of the best observational estimate (Jahangir et al., 2021). This highlights the importance of refining the representation of cloud microphysical properties in atmospheric models to properly represent their radiative impact.

Reference:
Jahangir, E., Libois, Q., Couvreux, F., Vié, B., & Saint Martin, D. (2021). Uncertainty of SW cloud radiative effect in atmospheric models due to the parameterization of liquid cloud optical properties. *Journal of Advances in Modeling Earth Systems*, 13(12), e2021MS002742. https://doi.org/10.1029/2021MS002742

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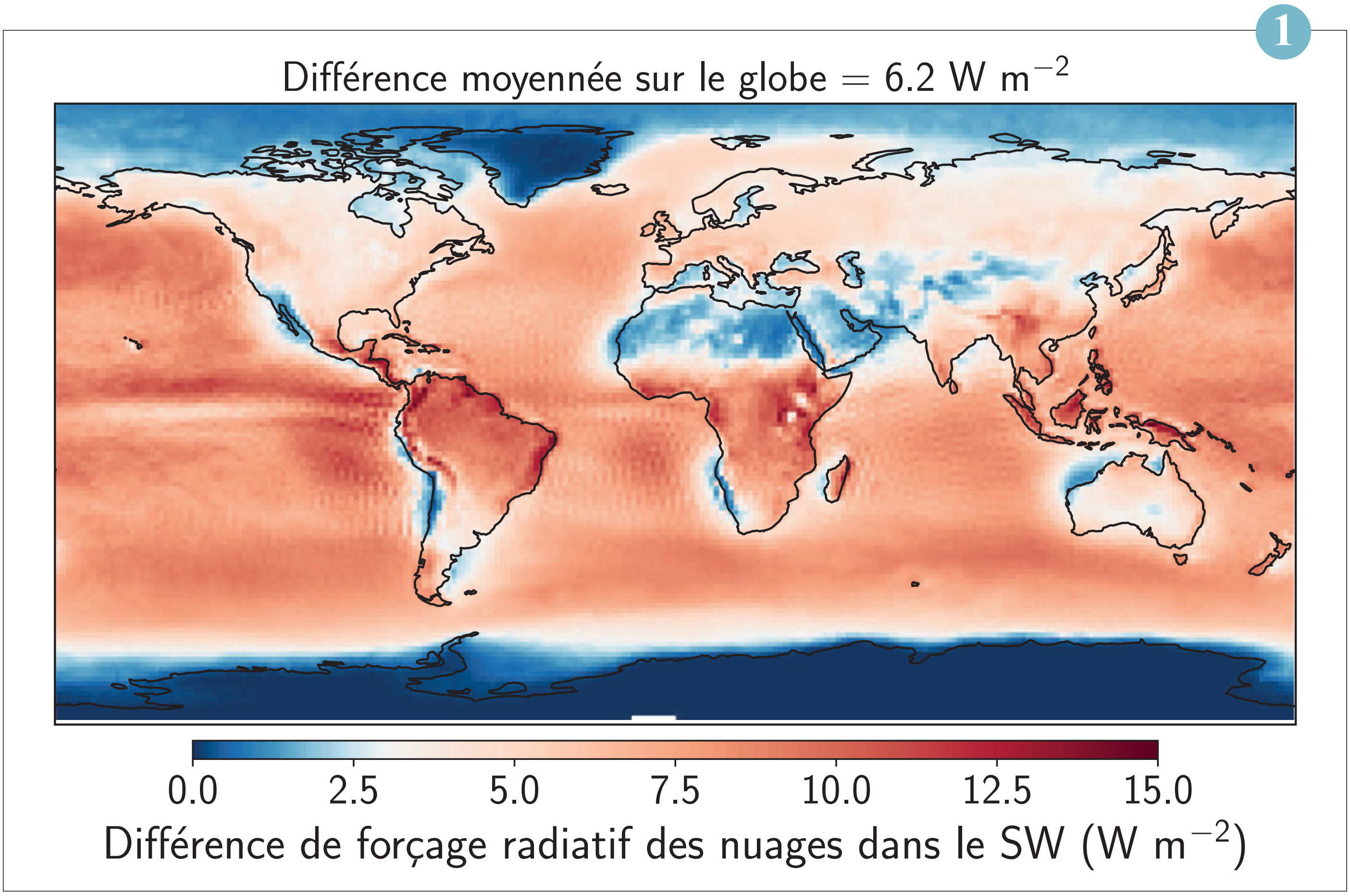

Differences in shortwave cloud radiative forcing computed from five years of CNRM-CM6 simulations, using two distinct droplet size distributions. The distributions are lognormal distributions with σ parameters equal to 0.2 and 0.65.

Impact of microphysics parameterization on warm conveyor belts and upper-tropospheric dynamics

M. Mazoyer

The intensity and sinuosity of the jet stream over the North Atlantic Ocean at an altitude of about ten kilometers are decisive for the formation of meteorological events that can affect Western Europe. Thus, the warm conveyer belts (WCB) associated with storms have an impact on the upper air dynamics. Processes inducing heat exchange within clouds forming in WCBs reinforce the anticyclonic circulation in the upper troposphere. By simulating with the Meso-NH research model several storms observed during the NAWDEX (North Atlantic Waveguide and Downstream Impact Experiment) airborne campaign deployed over North Atlantic in 2016, some microphysical processes were found to be particularly impacting on the upper ridge building:

– water vapor deposition on ice and water droplets,

– the rate of auto-conversion from primary ice to snow.

Since the representation of these processes is subject to uncertainties, comparisons with NAWDEX measurements from the French aircraft through released dropsondes and the remote sensing platform RALI composed of a doppler cloud radar, a high-resolution backscatter lidar and an infrared radiometer. allowed us to evaluate the microphysical schemes. In particular, two different options for water vapor deposition on the hydrometeor species have been tested: the first one (S) distributes the excess water vapor on the ice and droplets according to their proportion, for the second one (T40) this distribution depends only on the temperature. The figure shows the different phases (liquid, iced and mixed) of the hydrometeors inside the clouds, the first option produces a mixed phase only at the interface between liquid and ice in the melting zone, while the second option manages to produce supercooled water at the top of the icy clouds, as observed. This research work underlines the strong impact of radiative and microphysical processes associated with clouds in ice or mixed phase (ice and liquid) on the intensification of the upper ridge (Mazoyer et al., 2021).

Reference:

Mazoyer, M., D. Ricard, G. Rivière, J. Delanoë, P. Arbogast, B. Vié, C. Lac, Q. Cazenave, and J. Pelon, Microphysics impacts on the warm conveyor belt and ridge building of the NAWDEX IOP6 cyclone, *Mon. Weather Rev.*, 149, 3961-3980, 2021. https://doi.org/10.1175/MWR-D-21-0061.1

2

Added value of machine learning in the assimilation of satellite data into a land surface model

T. Corchia, B. Bonan, G. Colas, J.-C. Calvet

CNRM has developed a Land Data Assimilation System (LDAS) called LDAS-Monde. It is able to jointly assimilate satellite-derived observations of surface soil moisture and Leaf Area Index (LAI) in the ISBA land surface model, with the objective of better representing vegetation and root-zone soil moisture. These quantities can be used to initialize weather forecast and seasonal prediction models, or water resource monitoring models. Surface soil moisture is produced by EUMETSAT from the ASCAT radar. LAI is produced by the Copernicus Global Land Service (CGLS). The radar backscatter coefficients (σ^0) observed by the ASCAT instrument on the Metop satellites contain information on both surface soil moisture and vegetation. With that in mind, a key question is how to integrate the complete information contained in ASCAT σ^0 values in the ISBA model, including the part related to vegetation? To that end, two observation operators were developed: a neural network and a semi-empirical model (Water Cloud Model). Both allow ISBA to simulate the ASCAT σ^0 observations. Their performances were evaluated over 12 weather stations in southwestern France equipped with soil moisture sensors (SMOSMANIA network). After a learning phase over the 2007-2012 time period based on variables simulated by ISBA and on CGLS satellite-derived LAI, the assimilation of the ASCAT σ^0 was evaluated over 2013-2017. Contrary to the Water Cloud Model, the neural network allows the assimilation of ASCAT σ^0 to update the simulated LAI very efficiently. Comparisons with in situ observations of soil moisture show that the simulated soil moisture is improved as well.

This work paves the way towards the assimilation of data that are closer to the physical observations made by spaceborne sensors.

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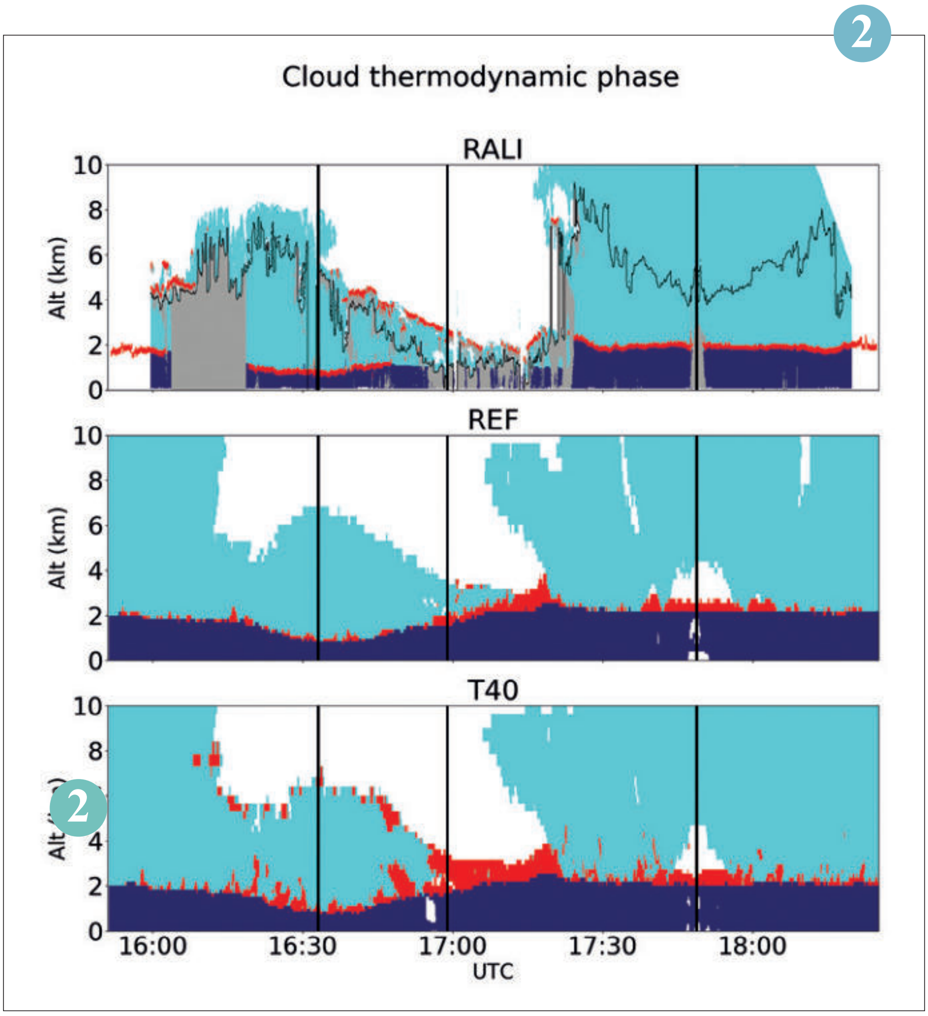
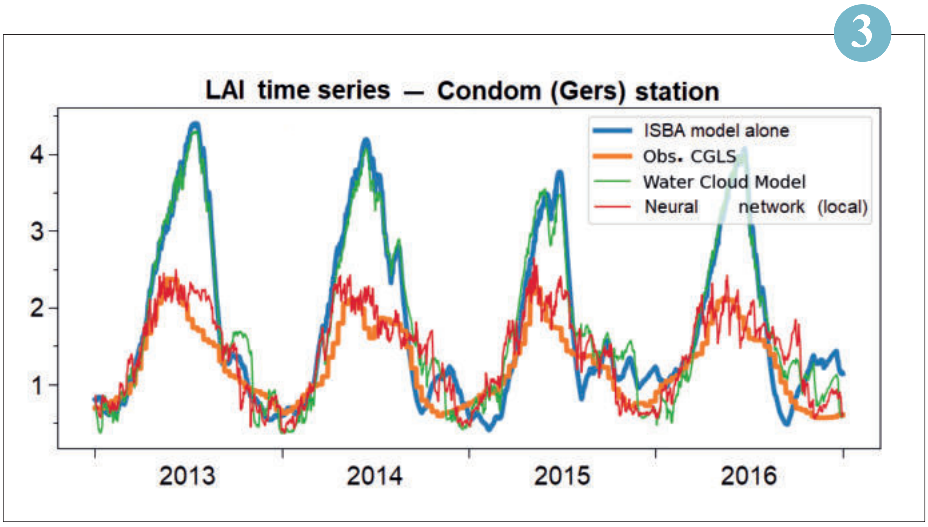


Comparison of thermodynamic phases (liquid in marine blue, ice in cyan, mixed in red) in a Warm Conveyor Belt case on October 12, 2016 detected by the RALI product (RADAR + LIDAR onboard the Falcon) (top) and simulated by Meso-NH using the ICE3 microphysics scheme with the S reference option (center) or the T40 option (bottom). Uncertain areas are in grey and non-cloudy areas are in white, while the black line in the observations represents the limit of the bottom detection of the lidar.



Leaf Area Index (LAI) over the Condom weather station in Gers. The ISBA model alone (blue line) markedly overestimates LAI at summertime with respect to the CGLS satellite observations (orange line) because ISBA does not represent agricultural practices. Integrating ASCAT σ^0 in ISBA using the Water Cloud Model as an observation operator has little impact on the LAI simulation. On the other hand, using a neural network very efficiently corrects LAI.

First results of the ocean-atmosphere AROME-NEMO coupled model over Metropolitan France

C. Lebeaupin-Brossier, J. Pianezze

To improve high-resolution numerical environmental predictions, it is essential to represent ocean-atmosphere (OA) interactions properly, which is generally not the case in current operational regional forecasting systems. A new forecast-oriented coupled OA system that covers Western Europe was recently build between CNRM and Mercator Ocean International. This system uses the high-resolution numerical weather prediction (NWP) model AROME and the 3D ocean model NEMO with a horizontal resolution of 2.5 km for both c omponents.

A sensitivity study was carried out using 7-day simulations, from 12 to 19 October 2018, characterised by extreme weather events (Callum winter storm, Leslie tropical cyclone and the Aude heavy precipitation event) in the area of interest (Pianezze et al., 2021). Comparisons with in-situ and satellite observations show that the fully coupled simulation reproduces quantitatively well the spatial and temporal evolution of the sea surface temperature (SST) and the 10 m-wind speed. The sensitivity analysis to OA coupling shows that the use of an interactive SST modifies the atmospheric circulation and the location of heavy precipitation, in contrast to the use of a fixed SST as currently done in NWP. When compared to the operational-like ocean forecast, simulated oceanic fields show a large sensitivity to the OA coupling. Forced ocean simulations highlight that this sensitivity is mainly controlled by the change in the atmospheric model used to drive NEMO (AROME vs. ECMWF IFS operational forecast). In particular, the ocean mixed layer depths can vary by more than 40% locally between the two ocean-only sensitivity simulations. This impact is amplified by the interactive coupling due to a positive feedback loop between sea surface cooling and evaporation.

Research studies using the AROME-NEMO coupled system aim now to further apprehend OA interactions at kilometer scale for more applications.

Reference:

Pianezze, J., Beuvier, J., Lebeaupin Brossier, C., Samson, G., Faure, G., and Garric, G.: Development of a forecast-oriented km-resolution ocean-atmosphere coupled system for Western Europe and sensitivity study for a severe weather situation, Nat. Hazards Earth Syst. Sci., in press

4

Oceanic evaluation of the AROME-NEMO coupled system by ALAMO float measurements: Case of cyclone FLORENCE

G. Hoarau, S. Malardel

The coupled atmosphere-ocean system AROME Overseas-NEMO is under development at LACy since 2020. The initial configuration on the Indian Ocean operational domain has been adapted in 2021 to a large Atlantic domain in order to validate the oceanic response of the coupled system to the passage of cyclones thanks to a set of ALAMO (Air-Launched Autonomous Micro Observer) float measurements (Sanabia and Jayne, 2020). These floats are released by reconnaissance aircraft from the United States near the path of Atlantic cyclones and can then drift for several weeks. They sample the temperature and salinity of the ocean to a depth of up to 1000 m depending on the configuration. The measurements are transmitted by satellite each time they come to the surface. The data is then processed and made available by the Naval Research Laboratory which is part of the US Meteorological and Oceanographic Service (NOAA). This work is part of an intercomparison exercise that started in 2021 to evaluate coupled NWP systems at ECMWF, the Met. Office and LACy. Figure (a) shows the evolution of temperature profiles for the top 300 metres of the ocean measured by one of the ALAMO buoys released on 11/09/2018 just before the passage of tropical cyclone Florence, which was then at its maximum intensity. We find in AROME-NEMO the signature of the quasi-inertial waves generated by the passage of the cyclone over the ocean with an amplitude and a wavelength very similar to those of the observations (Figure (b)). In IFS-NEMO, the oscillations are less intense (Figure (c)), probably due to the lower resolution of the models in this configuration (IFS-NEMO: 9km-1/4°, AROME-NEMO: 2.5 km-1/12°). These results were confirmed by a comparison of frequency analyses of ALAMO and model data. The good behaviour of the AROME-NEMO model will have to be confirmed with other case studies for which ALAMO measurements are available (cyclones IRMA in 2017, TEDDY in 2020...). In parallel, the evaluation of the coupled AROME-NEMO system is continuing over the Indian Ocean basin, which unfortunately has fewer observations.

Reference:

Sanabia, E., R., and Jayne, S., R. (2020). Ocean observation under two major hurricanes : Evolution of the response across the storm wakes. AGU Advances, 1, e2019AV000161. https://doi.org/10.1029/2019AV000161

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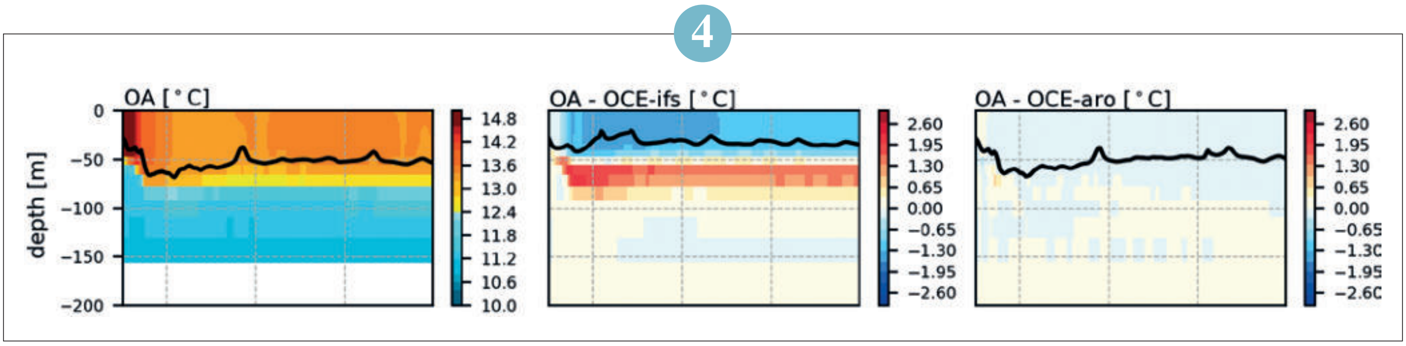
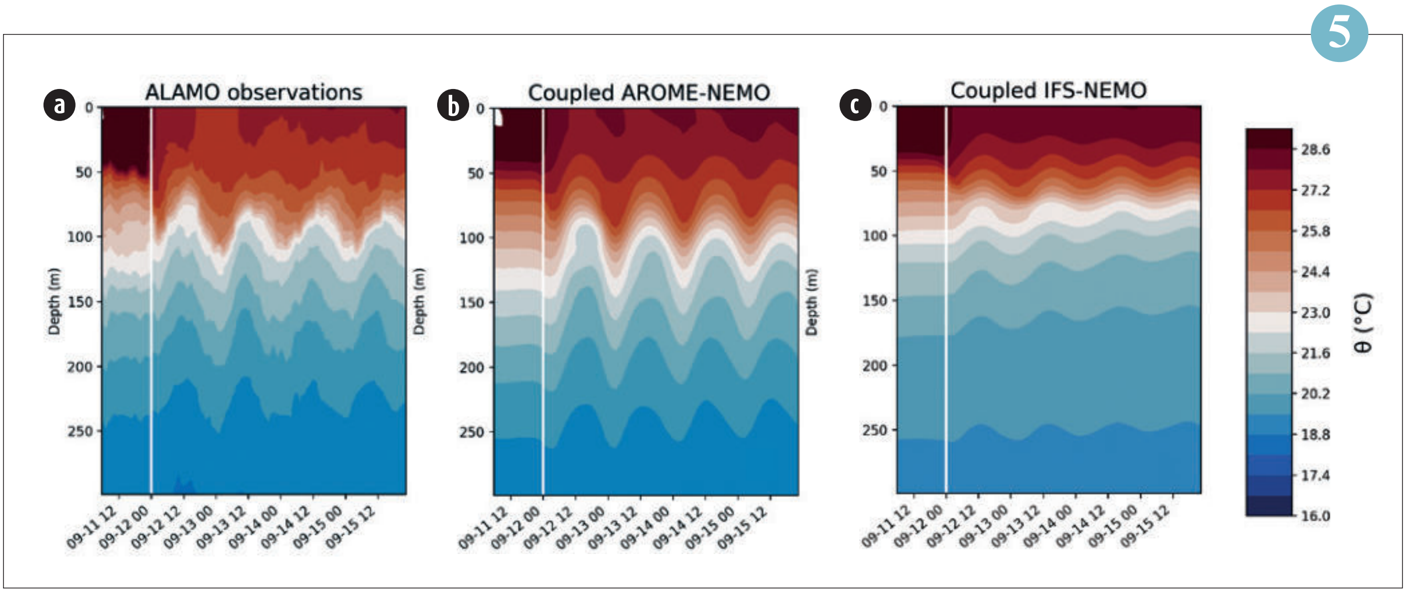


Time-series of the ocean temperature (°C) vertical profile in the Celtic Sea for the coupled simulation (OA) and differences with two ocean-only simulations (OCE-ifs for the experiment driven by the IFS forecast and OCE-aro for the one driven by AROME fields). The black line indicates the simulated mixed layer depth in OA (left), OCE-ifs (middle) and OCE-aro (right).



Temporal evolution of (a) temperature profiles measured by the ALAMO float between the ocean surface and 300m depth; (b)-(c) temperature profiles simulated by AROME-NEMO (b) and by ECMWF's operational deterministic system, IFS-NEMO (c).

Urban climate and adaptation for a coastal high-rise city: Modelling the extreme case of Hong Kong

R. Schoetter, C. de Munck

Urban climate models are not well suited for numerical weather prediction and the study of climate change adaptation for high-rise and strongly heterogeneous cities. Numerical modelling of high-rise cities requires a paradigm shift in the coupling between atmospheric and land surface models. The single-layer coupling used until now treats the city as a surface below the atmosphere without representing the effect of buildings on the wind field, temperature and humidity at the different atmospheric levels intersecting with the buildings (Figure a).

The city of Hong Kong, characterised by a strong landscape heterogeneity (coast, steep mountains, high-rise buildings, forests) and a network of meteorological stations suited for model evaluation has been used to test a newly developed multi-layer coupling between the atmospheric model Meso-NH and the land surface model SURFEX which includes the urban climate model TEB (Town Energy Balance). Evaluation reveals that, during heat wave conditions, the multi-layer coupling leads to a strong improvement of daytime air temperature and humidity in the urban canopy layer, compared to the traditional approach. Wind speed is also slightly improved.

These developments allow one to analyse in a more realistic way the effect of urban morphology changes made to adapt cities to climate change. The simulation of ventilation corridors on an urban scale has highlighted the importance of urban porosity beyond these corridors for the improvement of night-time thermal comfort (Figure b)

References :

Schoetter R, Kwok YT, de Munck C, Lau K, Wong WK, Masson V. 2020. Multi-layer coupling between SURFEX-TEB-V9.0 and Meso-NH-v5.3 for modelling the urban climate of high-rise cities. *Geoscientific Model Development* 13(11): 5609–5643. URL : https://doi.org/10.5194/gmd-13-5609-2020

Kwok, YT, de Munck C, Lau K, Ng E. 2021. To what extent can urban ventilation features cool a compact built-up environment during a prolonged heatwave? A mesoscale numerical modelling study for Hong Kong. *Sustainable cities and society, Special issue: the Creation of Cool Cities and Communities. Volume 77. February 2022*. URL: https://doi.org/10.1016/j.scs.2021.103541

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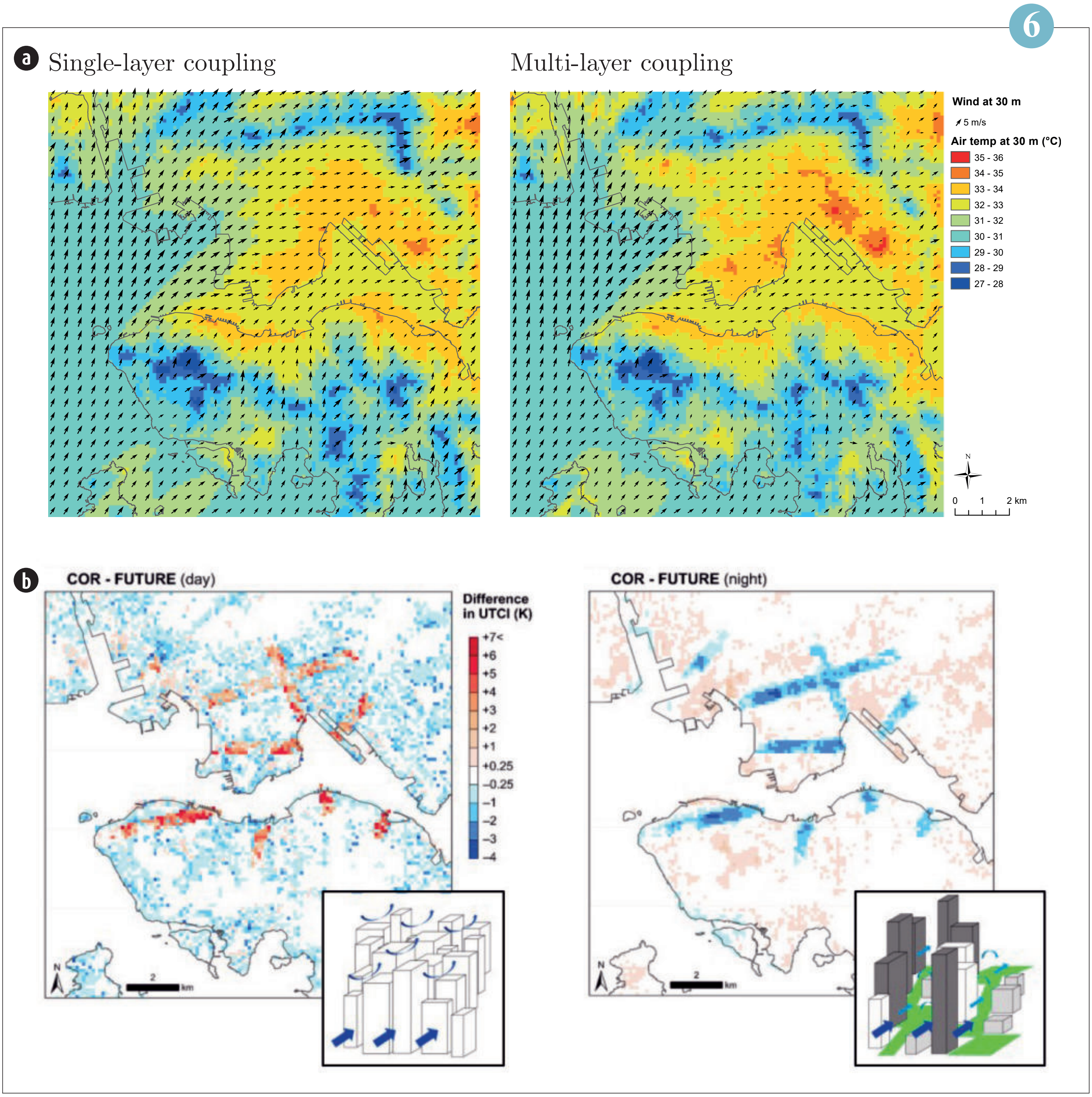

(a) Wind field at 30 m above ground level for the dense high-rise districts of Hong Kong Island and Kowloon.
The buildings influence the wind field more for the multi-layer than for the single-layer coupling.
(b) Average difference of human thermal comfort indicator UTCI (Universal Thermal Climate Index) simulated for a district of Hong Kong during a heat wave with and without vegetated ventilation corridors
at daytime (left) and at nighttime (right).

Improved consideration of vegetation and hydrological processes in the TEB urban surface model

É. Bernard, C. de Munck

Urban adaptation issues require a multidisciplinary research approach to better understand the interacting processes within urban environments. This makes it possible, for example, to address issues related to urban cooling and water management in cities.
Consequently, work has been carried out on the surface model describing urban territories, TEB, to combine the integration of urban trees on the one hand, and of a subsoil and an urban drainage network on the other (Figure a). The region of Paris and its inner suburbs was chosen for this pioneering study, due to its stakes and the unique existence of data for the coupled study of hydro-climatic processes. Thanks to complementary databases and a close collaboration with the Gustave Eiffel University (Laboratoire Eau et Environnement), the artificial and vegetated surfaces of the region, as well as the sewerage network, were mapped in detail. The new model has made it possible to simulate the response of the territory to the meteorological conditions of 2001-2017, translated on Figure b in terms of hydrological (overflows), micro-climatic (urban heat island, thermal stress) and coupled (hydric stress) vulnerabilities.
These developments will now enable to study urban planning strategies that rely on Nature Based Solutions (NBS), and to extend this type of study in a context of climate change or to other urban territories.

References:

Bernard Émilie. 2021. Réponse hydroclimatique de Paris et sa petite couronne. Thèse de doctorat, Université Toulouse III - Paul Sabatier, France. http://www.theses.fr/s294526

Bernard E, de Munck C, Chancibault K, Mosset A & Lemonsu A. 2021. Hydro-climatic response of Paris metropolitan area through TEB-Hydro model simulation: multi-catchment calibration and model evaluation. Presented at : *15th international conference on urban drainage [ICUD]*, Melbourne (online), Australia, 25-28 October 2021.

7

Characterization of ice particles forming in aviation fuels

F. Flin, I. Haffar, P. Latil

Icing in jet fuels is a serious threat to the safety of air travel. A CIFRE doctoral program was recently carried out at CEN, in collaboration with IFTS and the 3SR laboratory, in order to characterize, in an icing loop developed by IFTS, the ice particles forming in kerosene at low temperature.
The development of appropriate sampling protocols first allowed the development of a new method of characterization based on X-ray tomography, the thermal stability of the samples during scans being ensured by a specific cold cell. This approach made it possible to access the geometric properties of ice particles in 3D and thus assess the impact of a wide range of process parameters such as the concentration of injected water, the interfacial tension, the recirculation time and temperature, on the size and shape distributions of the particles produced.
A high-speed imaging technique was then implemented to characterize, online and in real time, the ice particles moving in the IFTS injection loop. Image processing and analysis algorithms were then developed to identify and characterize the ice particles. Finally, a comparison of 3D and 2D results was performed in a wide range of process parameters.
The consistency of the results obtained showed the relevance of the 2D method proposed for characterizing ice particles for low concentrations. The developed tools will be particularly valuable for the sizing of aeronautical filters and offer new perspectives for the study of fuel icing.

Références :

Haffar, I., P. Latil, F. Flin, C. Geindreau, F. Bonnel, N. Petillon, P.-C. Gervais, V. Edery, Characterization of ice particles in jet fuel at low temperature: 3D X-ray tomography vs. 2D high-speed imaging, Powder Technology, 397, 2022. https://doi.org/10.1016/j.powtec.2021.11.039

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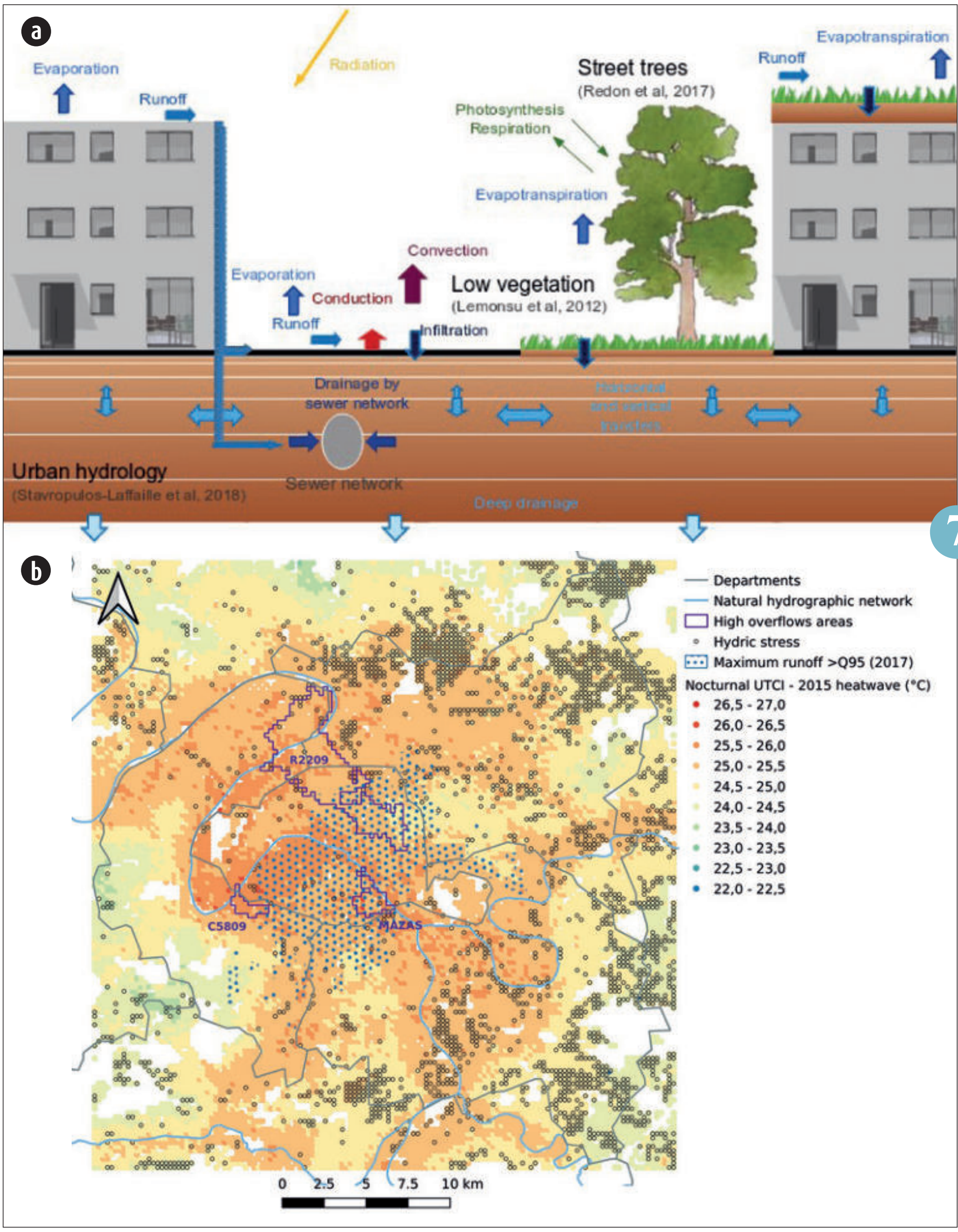
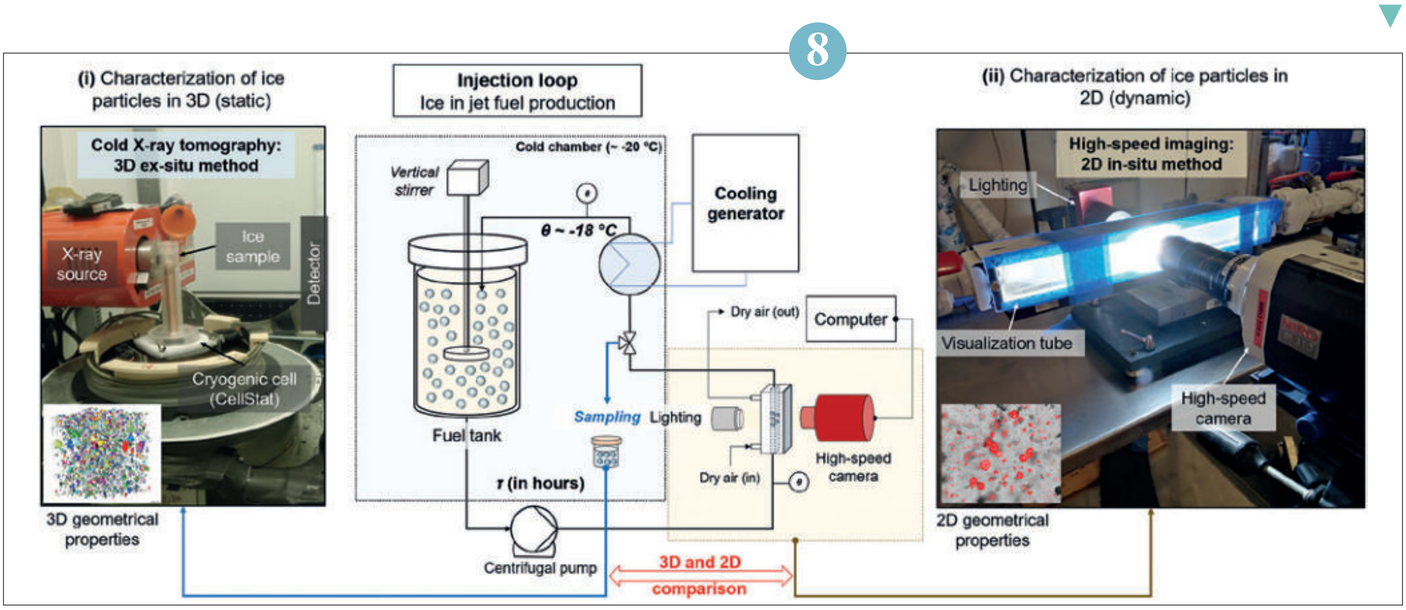


(a) The TEB model now makes it possible to describe in a coupled and detailed way the interactions between buildings and vegetation and the hydrological transfers in cities.
(b) Combined mapping of the most vulnerable areas between 2001 and 2017, to night-time heat stress (UTCI, background map), water stress (black circles), surface runoff (blue dotted lines) and combined sewer overflows volumes and frequencies (purple).

The ice particle characterization methods developed as part of Iheb Haffar's CIFRE doctoral program: the 3D ex-situ method (i), and the 2D in-situ method (ii).



Climate

The year 2021 was marked by an exceptional heat wave and devastating forest fires in the northwest of America at the end of June, and around the Mediterranean in August, and by exceptional floods in Germany and Belgium in July. Although human influence on the climate contributes to the multiplication of such events, global warming does not prevent the occurrence of some remarkable cold or snow spells, as was the case in Spain or the eastern United States at the beginning of the year, or over northern Europe, Siberia and Alaska in late November and early December. Extreme events are already having a severe impact on human and natural systems, and the next two decades will be crucial in limiting the escalation of climate risks, as recent IPCC reports have reminded us.

Among the range of tools contributing to define solutions to the climate issue, whether to limit warming (mitigation) or its impacts (adaptation), climate services are central, and can address various time scales. Flooding risks related to extreme rainfall, especially in the French Mediterranean, but also drought risks over a large part of France are among the matters of concern for the coming decades, and have been a theme of work in 2021, based on the new DRIAS-2020 data. The potential of seasonal forecasts to feed climate services has also been highlighted, especially for catchment areas with a large snow stock. The new Seasonal Forecasting System 8, which is based both on recent progress in initialisation and on a global climate model as close as possible to the one used to produce simulations in advance of the IPCC sixth assessment report, already offers prospects for improved forecasts, and ultimately more useful for various socio-economic sectors.

Whatever the time scale, numerical climate models are essential tools for understanding and anticipating climate impacts and risks. It is therefore essential to improve them scientifically and technically. In 2021, in addition to the continuation of long-term activities on the improvement of the physical part of our climate models, new work has allowed to better characterize the absorption of solar radiation by aerosols generated by biomass fires. This should allow to better take into account their properties in global and regional climate models, with the prospect of better representing low clouds and precipitation during large biomass fires.

D. Salas y Melia

1

Climate modelling

Aerosol transport from biomass fires over the South-East Atlantic: radiative effects difficult to model

M. Mallet

Recently, the South-East Atlantic region has been the focus of several field campaigns aimed at understanding the role of aerosols from biomass burning in Central Africa between June and September on the radiative budget and climate in the tropics. Contrary to sulphate particles which scatter most of solar radiation, these biomass burning aerosol plumes have the particularity of absorbing a large proportion of it. However, these different campaigns, in agreement with recent space observations, have clearly highlighted the highly absorbent nature of these aerosols, which is stronger than previously thought. These optical properties are crucial for understanding the aerosol-radiation-cloud interactions and thus quantify the impact of these plumes on the climate of this region.

The CNRM study shows that most of the latest generation global climate models that participated in the CMIP6 intercomparison exercise underestimate on average the absorption of radiation by biomass burning aerosols transported over the ocean. This bias, combined with recurrent model difficulties in representing marine stratocumulus over this region, leads many models to simulate a negative radiative forcing (cooling) at the top of the atmosphere, which is contrary to recent estimates. The magnitude of the solar warming induced by these aerosols is thus underestimated by these models, which could lead to an erroneous representation of the response of low clouds and precipitation to the radiative forcing of these aerosols in the tropics.

Références :

Mallet, M., P. Nabat, B. Johnson, M. Michou, J. M. Haywood, C. Chen and O. Dubovik, Climate models generally underrepresent the warming by Central Africa biomass-burning aerosols over the Southeast Atlantic., *Sci. Adv.*, *7*, 2021, doi.org/10.1126/sciadv.abg9998.

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Wildfire near the village of Limni (Greece), August 6, 2021. © REUTERS/Nicolas Economou

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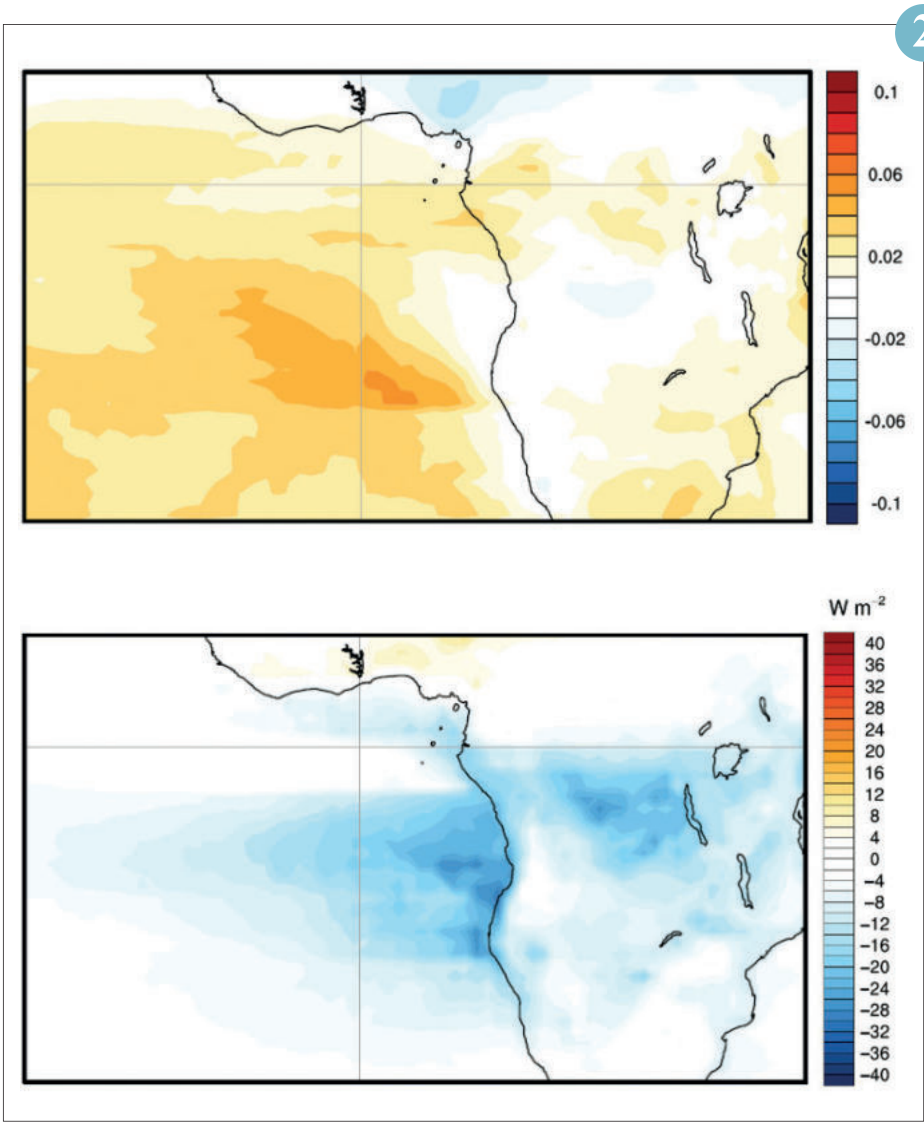

Average bias of CMIP6 models on aerosol scattering albedo (left, positive values indicate over-scattering aerosols, bias computed with respect to MACv2 climatology), and solar radiation absorption (right, bias computed with respect to CERES satellite product).

A comprehensive quantification of global nitrous oxide sources and sinks

S. Berthet, R. Séférian

Nitrous oxide (N_2O), like carbon dioxide, is a long-lived greenhouse gas that accumulates in the atmosphere. Over the past 150 years, increasing atmospheric N_2O concentrations have contributed to stratospheric ozone depletion and climate change, with the current rate of increase estimated at 2% per decade.

An international group of researchers from the Global Carbon Project and the International Nitrogen Initiative (https://www.globalcarbonproject.org/nitrousoxidebudget/) has performed the first N_2O inventory giving a full picture of N_2O emissions, by incorporating both natural and anthropogenic sources. This budget considers all compartments of the Earth System (atmosphere, land and ocean) and accounts for the interaction between nitrogen additions and the biochemical processes that control N_2O emissions. This budget allows to establish that global N_2O emission rate increased by 10% since 1980 to reach 17 TgN/year (teragrams of nitrogen per year) between 2007 and 2016.

Oceanographers from CNRM participated in the estimation of the oceanic N_2O flux. The N_2O flux produced by the ocean has been evaluated to 3.4 TgN/year (minimum-maximum estimates: 2.5-4.34) over the 2007-2016 decade. The tropical area (30°S-30°N) is the main ocean source area (53%): the upwelling regions of the equatorial Pacific, Indian and tropical Atlantic provide considerable sources of N_2O. The southern ocean region is the second largest contributor (31%), with emissions around twice as high as those from the northern oceans (17%). However global human-induced emissions are dominated by nitrogen additions to croplands and increased by 30% over the past four decades to 7.3 (4.2–11.4) TgN/year. This increase was mainly responsible for the growth in the atmospheric burden. The recent growth in N_2O emissions exceeds some of the highest projected emission scenarios, highlighting the urgent need to mitigate N_2O emissions.

Reference :
Tian, H., Xu, R., Canadell, J.G., R. L. Thompson, W. Winiwarter, P. Suntharalingam, E. A. Davidson, P. Ciais, R. B. Jackson, G. Janssens-Maenhout, M. J. Prather, P. Regnier, N. Pan, S. Pan, G. Peters, H. Shi, F. N. Tubiello, S. Zaehle, F. Zhou, A. Arneth, G. Battaglia, S. Berthet, et al. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* 586, 248–256. https://doi.org/10.1038/s41586-020-2780-0.

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Quantification of Chaotic Intrinsic Variability of sea-air CO_2 Fluxes at Interannual Timescales

S. Berthet, R. Séférian

Sea-air carbon dioxide (CO_2) fluxes undergo substantial regional and interannual fluctuations. These fluctuations are mostly forced by changes in large-scale atmospheric patterns, but ocean internal dynamics could also contribute to them. A group of oceanographers from LSCE, CNRM, IPSL and IGE has quantified these two sources of variability and their contributions to fluctuations of sea-air CO_2 fluxes over large oceanic regions. This study relies on the analyses of three ocean numerical simulations driven by the same atmospheric forcing but starting from small differences in initial conditions, and including a simplified representation of marine ecosystems. Simulations are run at a horizontal resolution allowing to model part of the effect of ocean mesoscale activity on physical and chemical tracers. Results show that interannual fluctuations of sea-air CO_2 fluxes are mostly controlled by the atmosphere in many regions, but that they are significantly impacted by non-linear chaotic oceanic processes where mesoscale activity is large. We demonstrate that non-linear oceanic processes drive fluctuations of sea-air CO_2 fluxes at interannual timescales that are inherently random. This result is of particular interest as this chaotic year-to-year evolution may hinder the predictability of sea-air CO_2 fluxes. The magnitude of these fluctuations is substantial over areas of high kinetic energy (e.g. the mid-latitude Southern Ocean, see Figure 1) and locally exceeds 76% of the total interannual variance of sea-air CO_2 fluxes.

References:
Gehlen, M., S. Berthet, R. Séférian, Ch. Ethé, and T. Penduff (2020). Quantification of Chaotic Intrinsic Variability of sea-air CO_2 Fluxes at Interannual Timescales. *Geophysical Research Letter*. https://doi.org/10.1029/2020GL088304

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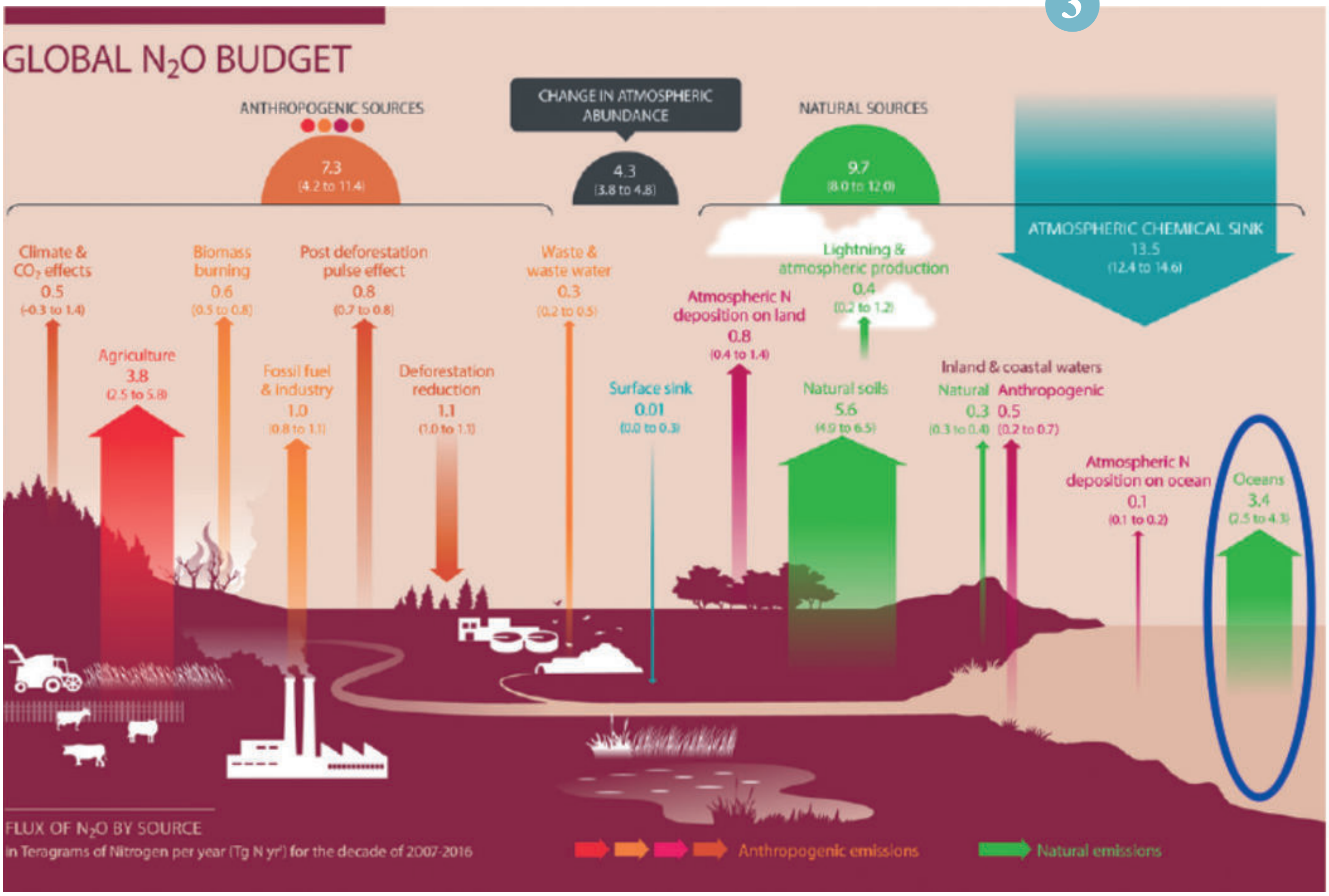

Global N_2O budget for 2007–2016. The coloured arrows represent N_2O fluxes (in TgN/year for 2007–2016) as follows:
red, direct emissions from nitrogen additions in the agricultural sector; orange, emissions from other direct anthropogenic sources; maroon, indirect emissions from anthropogenic nitrogen additions; brown, perturbed fluxes from changes in climate, CO_2 or land cover;
green, emissions from natural sources. The anthropogenic and natural N_2O sources are derived from bottom-up estimates.
The blue arrows represent the surface sink and the observed atmospheric chemical sink, of which about 1% occurs in the troposphere.
The total budget (sources + sinks) does not exactly match the observed atmospheric accumulation, because each of the terms has been derived independently and we do not force top-down agreement by rescaling the terms. This imbalance readily falls within the overall uncertainty in closing the N_2O budget, as reflected in each of the terms. The N_2O sources and sinks are given in TgN/year. © The Global Carbon Project.

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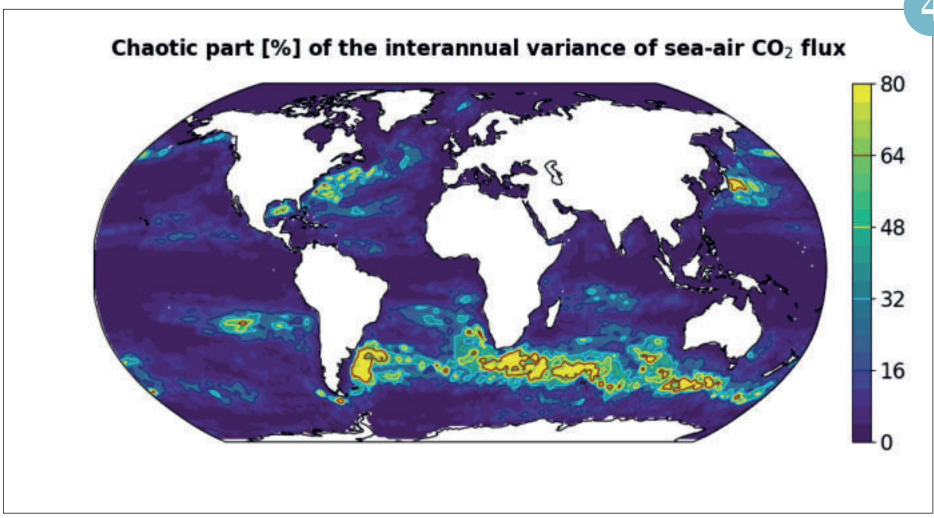

Chaotic interannual variability of sea-air CO_2 flux. Yellow to green colors highlight regions where variability is governed by chaotic unpredictable year-to-year variability.

Evolution of extreme precipitation in the Mediterranean regions

Results of the FlAude project

J.-M. Soubeyroux

The FlAude project (https://www.spaceclimateobservatory.org/fr/flaude-aude), supported as a Copernicus Climate Change Service (C3S) Use Case and labelled by the Space Climate Observatory (SCO), aims to strengthen the adaptation of territories to flood risks through the use of space data (provided by the CNES) and climate data (Météo-France and C3S).
The experimental area is the Aude department with a view to replicating it in the Occitanie region, the rest of France and Europe. The work carried out by Météo-France from June 2020 to June 2021 aimed to qualify C3S data sets for the analysis of extreme rainfall events in the Aude department, to define operational indicators for characterising episodes with the users involved, and to analyse past trends and future developments in extreme rainfall in this territory.
For the past climate, the use of the PRESCILIA daily rainfall dataset with a resolution of 1km available from 1960 to 2018 made it possible to obtain diagnoses in line with those of Ribes et al. (2019) for the Mediterranean region based on reference observations. The diagnoses produced highlighted an increase in the annual maximum daily precipitation of +15% (confidence interval of +2% to +30%) over the Mediterranean regions, +6% (-10%; +24%) over Languedoc Roussillon and +8% (-18%; +43%) over Aude. The surface area and precipitation volumes of extreme events over one day also show significant increases (see figure).
In the future climate, the diagnosis based on the DRIAS-2020 set has also highlighted an expected increase of +10% to +20% in extreme precipitation over this area.
This work is to be extended to other French regions in 2022.

Reference:
Ribes, A., Thao, S., Vautard, V., Dubuisson, B., Somot, S., et al., 2019. Observed increase in extreme daily rainfall in the French Mediterranean. *Climate Dynamics*, Springer Verlag, 52 (1-2), pp.1095-1114. https://doi.org/10.1007/s00382-018-4179-2

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Impact of climate change on Potential Evapotranspiration (PET)

S. Bernus

The impact of global warming on the agricultural sector is, today, a major concern. Among the existing indicators in this field, the Potential Evapotranspiration is used here to quantify the expected impacts and implement adaptation measures. In 2020, a new set of climate indicators based on corrected regional climate projections over France was produced and published on the French national climate data portal DRIAS. The climate projections are based on the EURO-CORDEX ensemble and corrected with the ADAMONT method according to the SAFRAN reference data set. The PET is calculated from this new dataset. Several calculation methods are used and compared. First, the PET is calculated upstream and downstream of the ADAMONT method. Then, different calculation procedures are tested for the formula recommended by the FAO called Penman-Montheith. One of them uses the average specific humidity instead of the minimum and maximum daily relative humidity, which are not available in all the selected models. The PET is also calculated using the Hargreaves approximation which replaces visible radiation with a function of temperature and a tuning coefficient. These different PETs are analyzed in order to quantify the influence of the calculation method on the resulting estimated trends. Overall, it is found that the PET tends to increase between 1976-2005 and 2071-2100 (+6 to +29% on average over France).

Référence :
Verfaillie, D., Déqué, M., Morin, S., and Lafaysse, M.: 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, 2017

Jean-Michel Soubeyroux, Sébastien Bernus, Lola Corre, Agathe Drouin, Brigitte Dubuisson, Pierre Etchevers, Viviane Gouget, Patrick Josse, Maryvonne Kerdoncuff, Raphaëlle Samacoits et Flore Tocquer. Avec l'appui scientifique de Christian Pagé (Cerfacs), Samuel Somot et Aurélien Ribes (CNRM) et Robert Vautard (IPSL). Le rapport DRIAS pour les données : LES NOUVELLES PROJECTIONS CLIMATIQUES DE RÉFÉRENCE DRIAS 2020 POUR LA MÉTROPOLE - METEO-FRANCE

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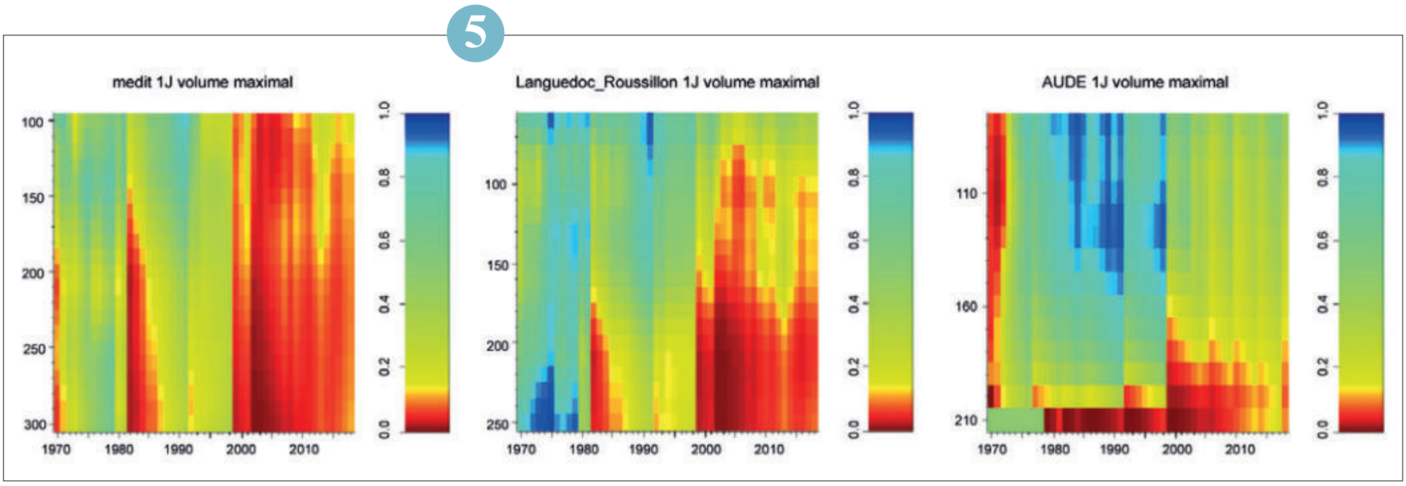
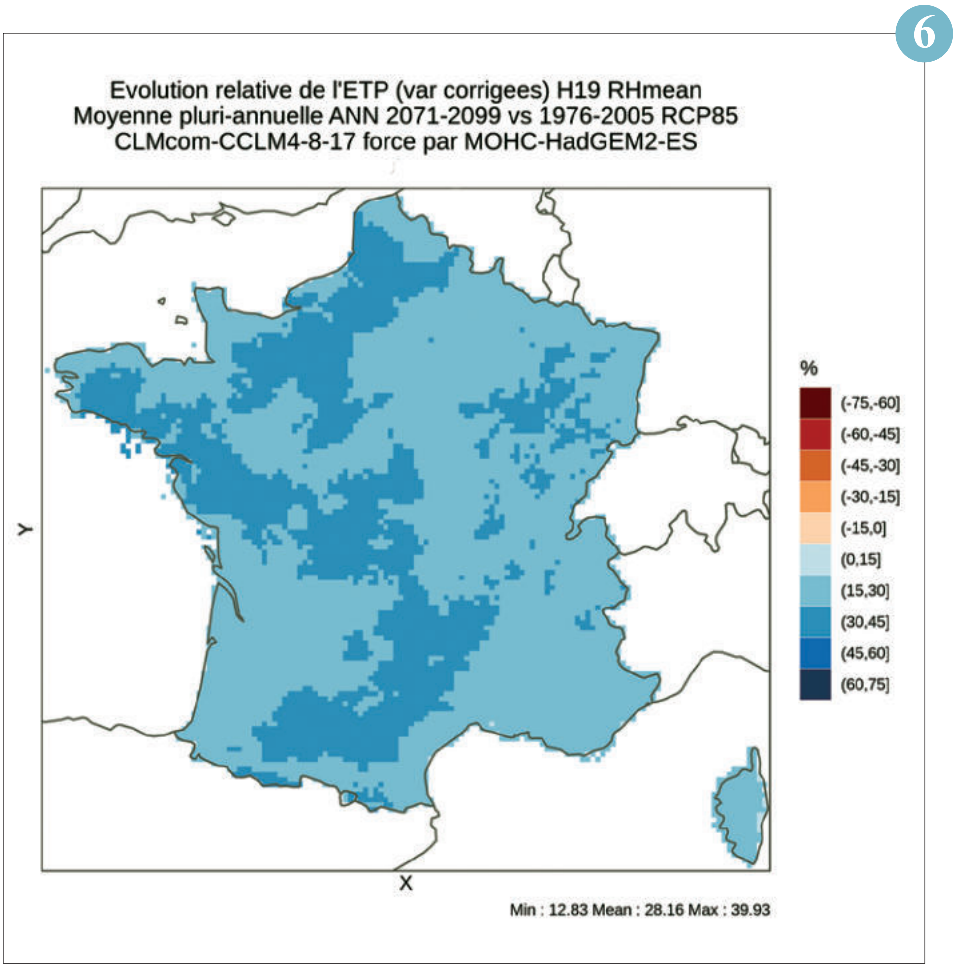


Estimated change of the maximum of rainfall volume during extreme precipitation event;
Statistical tests are applied for thresholds (Y axis) and for different time periods 1961-yyyy, (yyyy corresponding to the X axis).
Blue and red colors highlight significant decreasing and increasing trends.



Map showing the change in percentage (%) in Potential Evapotranspiration FAO with the Hargreaves approximation used with the single coefficient of 0.17 of the 2071-2100 multiannual means compared to those of 1976-2005 over France and for the regional climate model CLMcom-CCLM4-8-17 forced by the global climate model MOHC-HadGEM2-ES and for the RCP85 scenario.

Seasonal forecast

Flow dependence of wintertime subseasonal prediction skill over Europe

C. Ardilouze

Issuing skillful forecasts beyond the typical horizon of weather predictability remains a challenge actively addressed by the scientific community. Under certain conditions called “windows of opportunity”, subseasonal forecasts may perform quite well. In order to better identify and anticipate these conditions, wintertime subseasonal reforecasts delivered by the CNRM and ECMWF dynamical systems have been evaluated jointly. It has been found that the level of skill for predicting temperature in Europe 3 weeks ahead varies fairly consistently in both systems. In particular, forecasts initialized during positive North-Atlantic Oscillation (NAO) phases tend to be more skillful over Europe at a 3-week leadtime in both systems. Composite analyses performed in the ERA5 atmospheric reanalysis, a long-term pre-industrial climate simulation (piControl) and both forecast systems unveil very similar temperature (see figure) and sea-level pressure patterns three weeks after NAO conditions. Furthermore, regressing these fields onto the 3-week prior NAO index in a reanalysis shows consistent patterns over Europe but also other regions of the northern hemisphere extratropics, thereby suggesting a lagged teleconnection, either related to the persistence or recurrence of the positive and negative phases of the NAO. This teleconnection, conditioned to the intensity of the initial NAO phase, is well captured by forecast systems. As a result, it is a key mechanism for determining a priori confidence in the skill of wintertime subseasonal forecasts over Europe as well as other parts of the northern hemisphere. This study also demonstrates the benefit of using tools for weather forecasting, seasonal forecasting and climatic projections in a consistent manner, which is the case at CNRM.

Reference:
Ardilouze, C.,D. Specq,L. Batté,C. Cassou, 2021: Flow dependence of wintertime subseasonal prediction skill over Europe. Weather and Climate Dynamics, doi:10.5194/wcd-2-1033-2021

7

Introducing Météo-France seasonal prediction System 8

J.-F. Guérémy, L. Batté, C. Viel

The Météo-France Seasonal Forecasting System 8 (S8) has replaced System 7 (S7) in the Copernicus Climate Change Service (C3S) program multi-system since July 2021. It is based on a high-resolution version (55 km for the atmosphere and 28 km for the ocean) of the CNRM-CM coupled climate model.

Compared to S7, two main improvements have been implemented. An increased number of vertical levels in ARPEGE-Climate (from 91 to 137) allows a better vertical discretization, inducing an amplified convective activity and decreasing the positive biases of the 500hPa geopotential height in the tropics. In the stratosphere, the simulation of the quasi-biennial oscillation has been improved. The second axis consisted in modifying the initialization strategy of the coupled model. The objective is to increase the coherence between the initial states and those resulting from the integration of the coupled model, but also between the real-time forecasts and the reforecasts which are run to calibrate the forecasts and evaluate the predictive performance of the system. To this aim, S8 is initialized from model states derived from a CNRM-CM run relaxed to atmospheric (ERA5) and oceanic (Mercator Ocean International) reanalyses and analyses.

The area under the ROC curve score evaluates the discrimination capacity of a system for a probabilistic event. The figure taken from http://seasonal.meteo.fr shows this score for the 2m temperature in summer over the globe for S7 and S8 reforecasts, using ERA5 as reference. More generally, we find a slight improvement in T2m scores over most of the Northern Hemisphere in all main seasons and tropical precipitation in the equinox seasons (due to the vertical resolution of ARPEGE), as well as in the 500hPa geopotential height (due to the coupled initialization). This website also presents the scores for the European Centre for Medium-range Weather Forecasts (ECMWF) SEAS5, illustrating the state-of-the-art level of S8. S8 is planned to be operational until 2024.

Reference:
Batté, L., Dorel, L., Ardilouze, C. and Guérémy, J.-F., 2021. Documentation of the METEO-FRANCE seasonal forecasting system 8. Ref. C3S_D330_3.3.1, http://seasonal.meteo.fr/content/doc-modele

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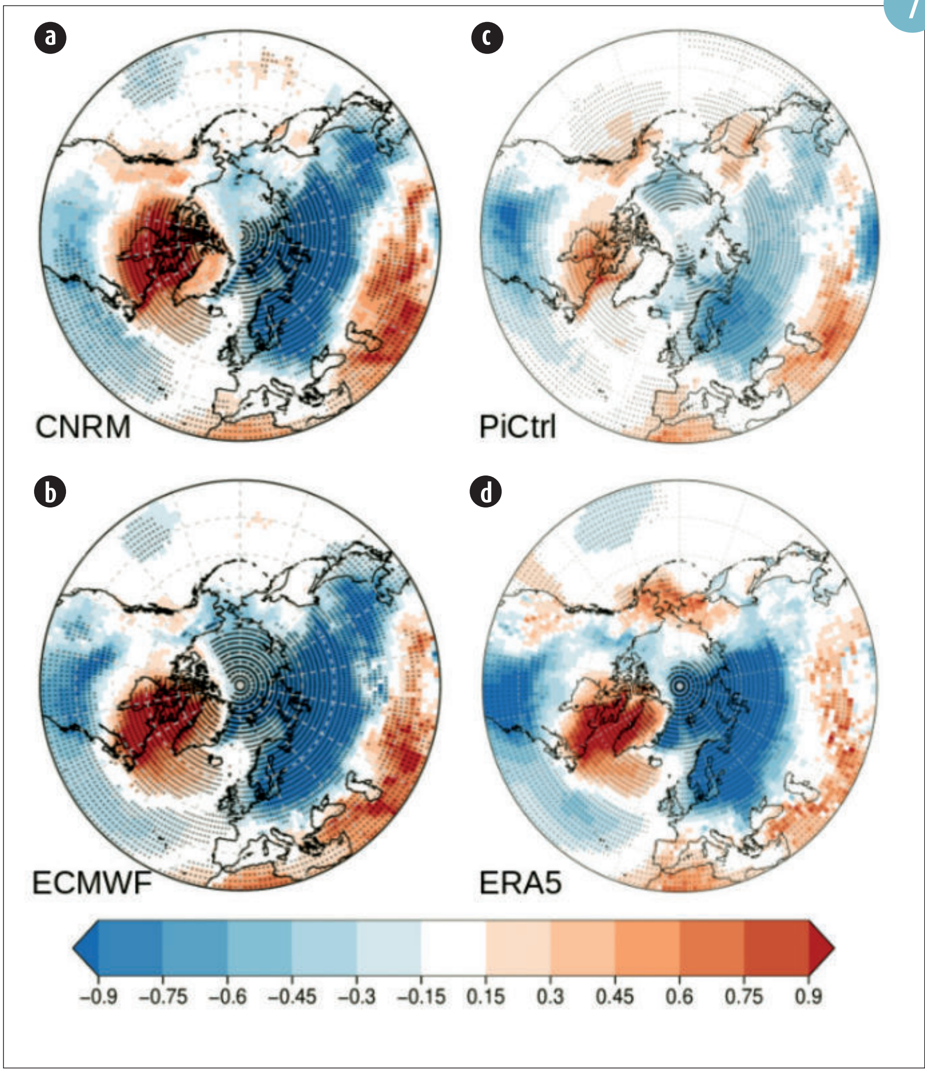

Composite anomaly of Week 3 2-meter temperature (in K) following NAO- initial conditions in
(a) CNRM subseasonal forecasts
(b) ECMWF subseasonal forecasts
(c) CNRM piControl simulation and
(d) ERA5 reanalysis.
Anomalies statistically significant at the 95% level are stippled.

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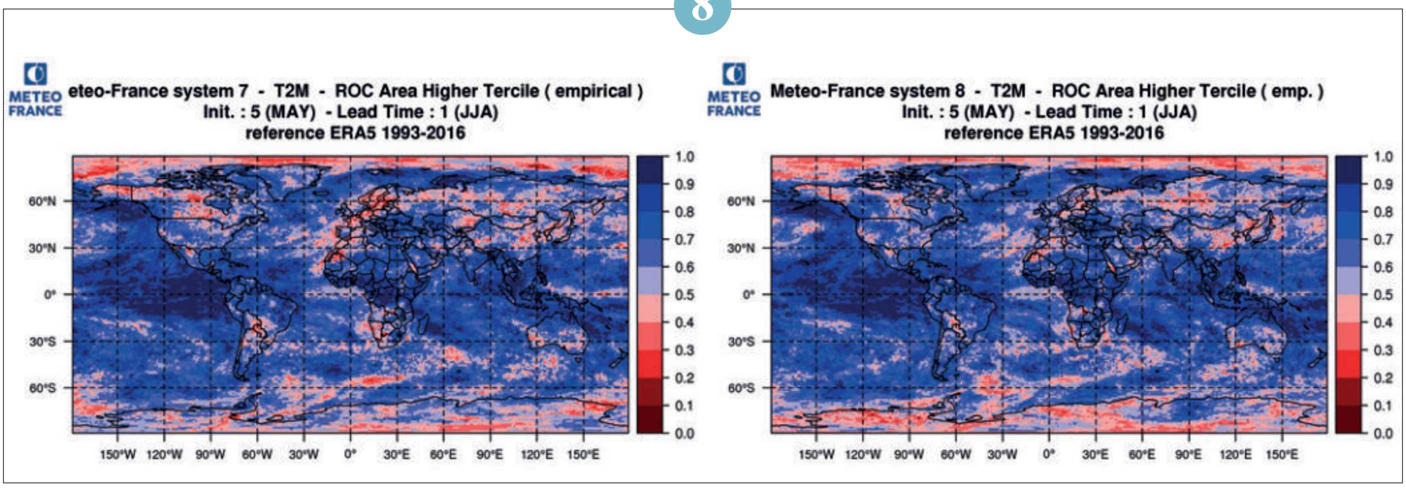

Area under the ROC curve for summer (June-July-August mean) 2m temperatures exceeding the upper tercile in re-forecasts initialized end of April – 1st May 1993-2016 with Météo-France seasonal forecasting systems S7 (left) and S8 (right).
Terciles are computed using the re-forecast period, and the reference is the ERA5 reanalysis.

Results of the MEDSCOPE project for seasonal climate services in the Mediterranean area

P. Etchevers, J.-M. Soubeyroux, C. Viel

One of the main objectives of the MEDSCOPE European project was to demonstrate the feasibility of developing climate services applied to hydrology in the Mediterranean area.
To this end, Météo-France has set up a hydro-meteorological modeling chain covering southern Europe and based on the Surfex-Ctrip model and the high-resolution reanalysis UERRA. The model is fed this with seasonal atmospheric forecasts downscaled with the ADAMONT method. A set of indicators was then developed from the modelling results for soil moisture, snow water equivalent and discharges over the Ebro, Rhône and Po river basins. These indicators were built in close collaboration with basin agencies in order to best meet their needs and to involve them in the results validation. The results, as well as the associated scores, are very encouraging (see figure). In particular, predictability is good in Spring for watersheds with a significant snow stock. This work is based entirely on open access tools and data from the C3S program. As shown by the set of recommendations issued at the end of the project, it paves the way for building operational tools for forecasting water resources on a seasonal scale over southern Europe.

Reference :
Batté, L., Rodríguez-Guisado, E., Rodríguez-Camino, E., Pérez-Zanón, N., Alvarez-Castro, C., Materia, S., Terzago, S. 2021. Recommendations for further improvements of operational seasonal forecasting systems (D.3.3, MEDSCOPE ERA4CS project). https://www.medscope-project.eu/wp-content/uploads/2021/06/D3.3_Recommendations_improvements.pdf

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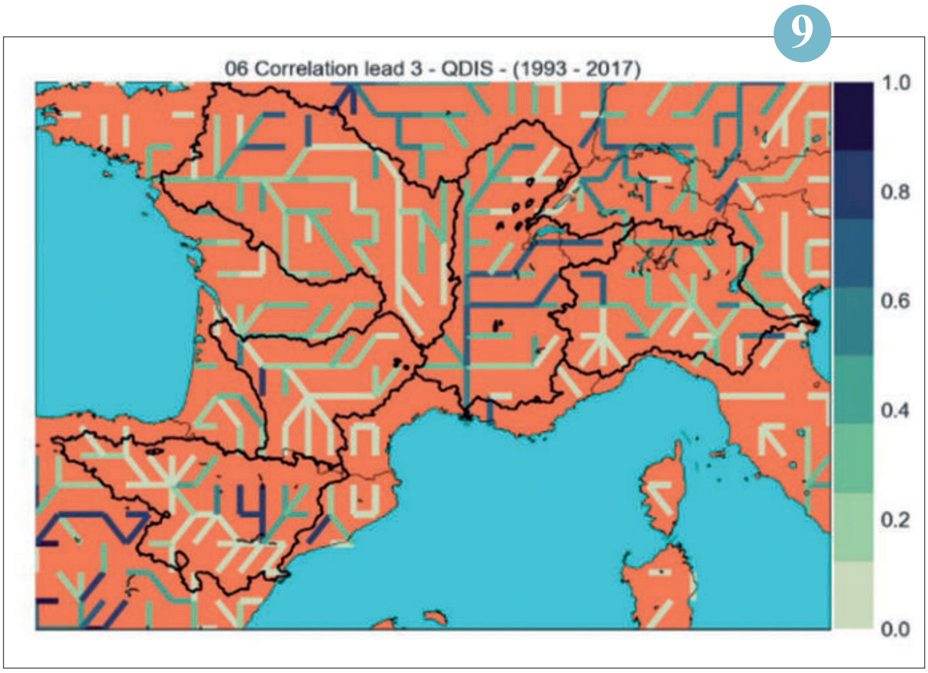

Correlation for monthly discharges between the UERRA reanalysis and the seasonal forecast initialized in March for the month of June (calculations made for the replay period of the forecast for the period 1993-2017).
It is noted that mountain watersheds generally have good predictability due to the presence of a large snow stock.

Chemistry, aerosols and air quality

The year 2021 was marked by several remarkable episodes of Saharan dust deposition over France. These particles can disrupt communications and air transport, reduce solar energy production, or affect human health by degrading air quality. They can, however, have a positive impact as they are an important source of nutrients for marine ecosystems or for forests such as the Amazon. They can also limit temperature increases by intercepting part of the solar radiation. Also, once deposited on a snowpack, the snow turns orange, absorbs more solar radiation and melts more quickly than 'clean' snow. During the episode of early February 2021, CNRM helped organise a participatory field campaign to collect samples of 'orange snow' in order to determine its concentration in sand dust. Such observations will help improve our knowledge of this type of event so that they can be better represented in air quality, numerical weather prediction and climate models.
Like desert dust, the plumes emitted during volcanic eruptions can disrupt air traffic but also affect human health, hence the importance of forecasting these events as well as possible. 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. This VAAC issued more than 700 advisories in 2021, which is a record, due to several volcanic eruptions (Cumbre Vieja in the Canaries, Nyiaragongo in the Democratic Republic of Congo, and Etna in Sicily). During each eruption, operational and research teams are mobilised in order to better predict the dispersion of volcanic plumes, composed in particular of ashes and sulphur dioxide (SO_2).
In order to better predict SO_2 plumes, new research work was carried out on the case study of the 2021 Soufrière Saint Vincent eruption by assimilating total columns from the TROPOMI instrument on board the Copernicus Sentinel-5 satellite. Other activities have led to a better understanding of the impact on ozone (for air quality) of halogenated species in volcanic plumes by studying the Etna eruption of Christmas 2018. Finally, activities on online chemistry (MOCAGE within IFS-Chemistry) continued, as well as the implementation of the complex secondary aerosol scheme (forming from precursors as a result of chemical reactions) SSH, for case studies but also for the calibration and validation of other simpler schemes that can be activated within the model.

D. Salas y Melia

1

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Saharan sand deposition on the snow at the Pyrenean ski resort of Ax 3 Domaines (Ariège) on 06/02/2021.
© Ludovic Bernède - Météo-France

Benefits of a mini-ensemble for air quality modeling at global scale

S. Pelletier-Belamari

Within the framework of the European air quality Copernicus Atmospheric Monitoring Service (CAMS) and the CAMS42 subcontract for global air quality modeling, a first study aiming at evaluating the benefits of a mini-ensemble for the global-scale forecast of surface concentrations of various air pollutants (ozone, nitrogen dioxide and sulphur dioxide) was conducted jointly by the CNRM, the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut, KNMI), the Max-Planck-Institute for Meteorology (MPI-M) and the Royal Belgian Institute for Space Aeronomy (BIRA-IASB). Three simulations were thus performed for the entire 2019-2020 period, in near-real time and without assimilation of observations related to the chemical composition of the atmosphere, using the three atmospheric chemistry configurations of the IFS model of the European Centre for Medium-Range Forecasting, namely the IFS(CB05), IFS(MOZART), and IFS(MOCAGE) models implemented by KNMI, MPI-M, and CNRM, respectively.

The performance of the three ensemble members as well as that of the median model constructed from them was evaluated through a comparison with surface observations from measurement networks for Europe, USA and China. The results indicate that the surface concentrations simulated by the different models are globally realistic. In particular, the dispersion simulated by the mini-ensemble is comparable to that of the observations. The performance of the median model indicates a benefit of using different chemical schemes for the prediction of ozone (secondary pollutant formed from chemical precursors), but not for nitrogen dioxide and sulfur dioxide which are directly emitted at the surface.

Therefore, in the future, this approach should be extended by increasing the size of the ensemble, using for example different parameterizations for dry and wet deposition processes and different emission sets, in order to improve the forecasting of air pollutants and to quantify more precisely the uncertainty in their representation.

2

Towards a more accurate modelling of secondary aerosols into the chemistry-transport model MOCAGE

J. Guth

The chemistry-transport model MOCAGE is used for daily air quality forecasts over Europe which is an important issue for our society. Among the pollutants affecting air quality are aerosols, including the secondary organic aerosols (SOA, formed in the atmosphere from precursors).

The multiplicity of molecules and reaction schemes makes it very difficult to represent the complexity of the physico-chemical phenomena involved in the formation of SOA. In the MOCAGE model, we have already developed two simplified schemes for modelling SOA. To go further, we are working on the integration of a module named SSH-Aerosols, jointly developed by CEREA and INERIS, and able to represent all the processes affecting SOA.

The figure shows the evolution over one day of two types of SOA, resulting from the same isoprene oxidation pattern, but having different physical properties. On one hand, the BIDER species is less volatile than BIPER showing then relative lower gas concentrations. On the other hand, BIPER can be degraded by solar radiation leading to a loss during the day.

The SSH-Aerosols module is too computationally expensive for use in an operational context. Thus, the use of the SSH-Aerosols module will allow case studies to be carried out, thus improving the general understanding of SOA. In addition, this tool will allow the calibration and validation of the other two representations of SOA.

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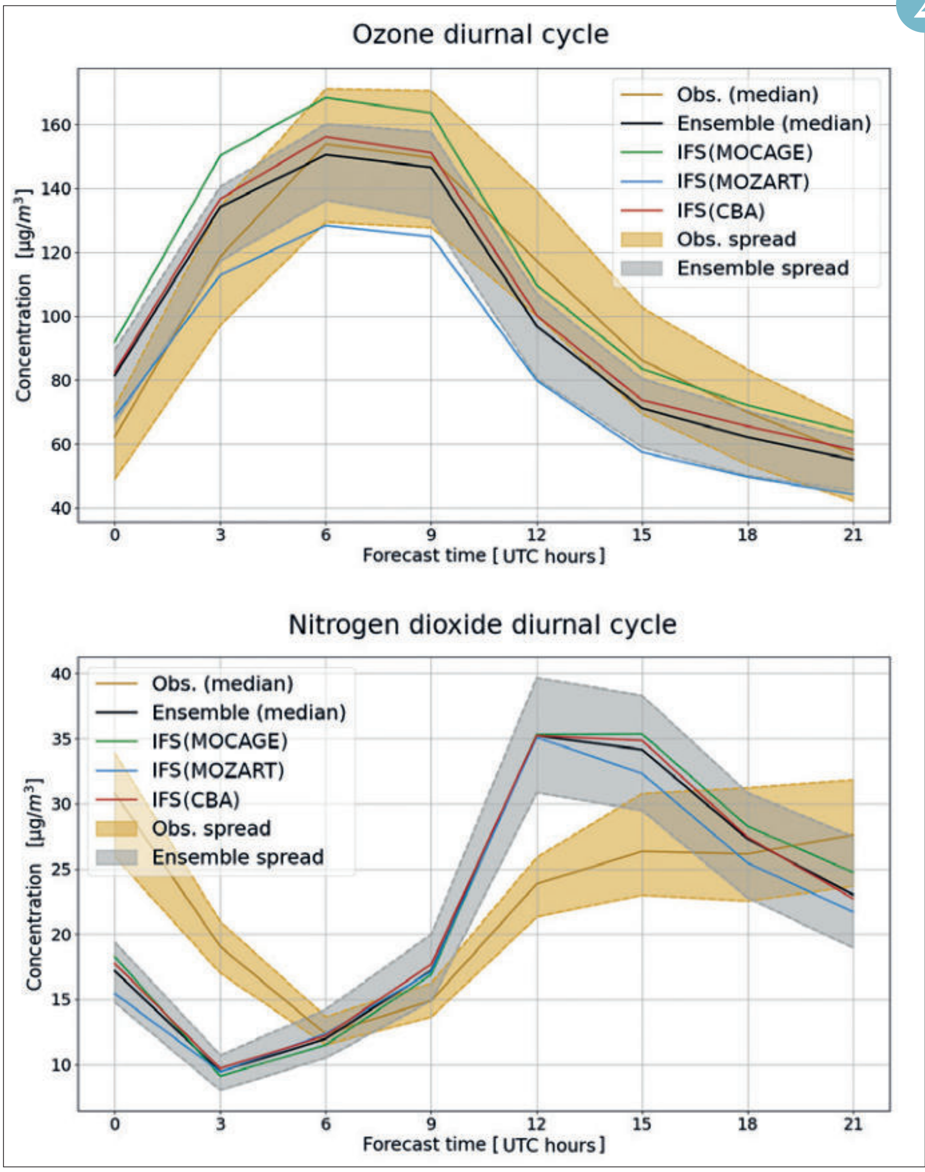

Mean diurnal cycle of ozone (top) and nitrogen dioxide (bottom) for June-August 2019 over northeast China simulated by the individual members of the ensemble IFS(MOCAGE), IFS(MOZART) and IFS(CBA) and by the median model. The median of the observations is represented by the bronze line. The shaded (bronze) area represents the dispersion (interquartile range) of the ensemble (observations).

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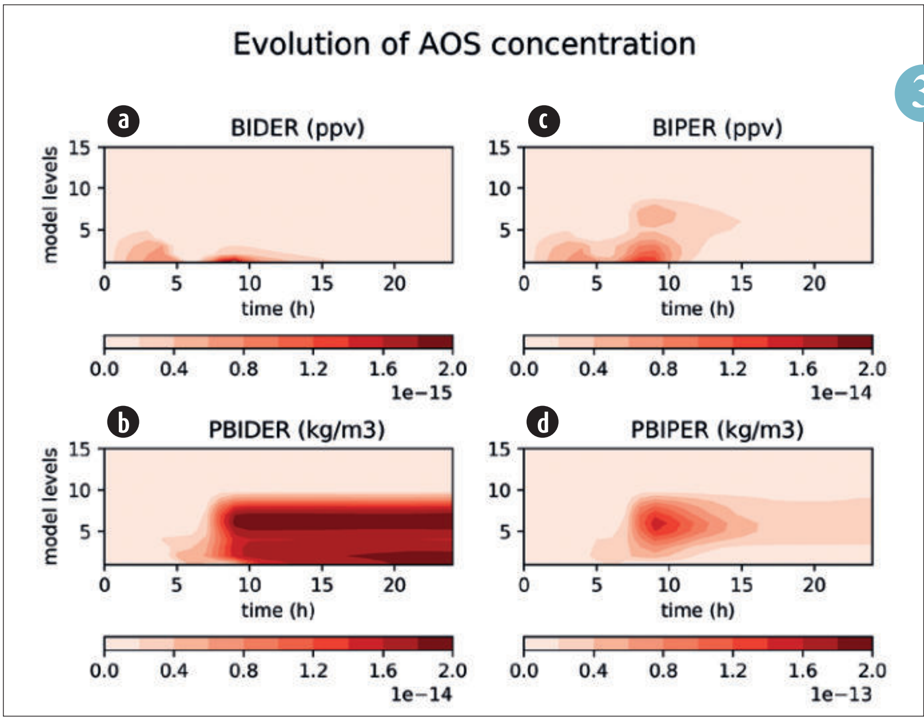

Evolution over one day of the concentration of gaseous(a) and aerosol (c) BIDER species and gaseous (b) and aerosol (d) BIPER species. These results are from a one-dimensional version of MOCAGE. BIDER and BIPER correspond to a grouping of molecules from the oxidation of isoprene in the SSH-Aerosols formalism.

MOCAGE simulations of volcanic halogens: the case study of the Mt Etna (Sicily, Italy) eruption on Christmas 2018

H. Narivelo, V. Marécal

The halogens emitted by volcanoes are in gaseous form and very soluble in water. For a long time, it was thought that their impact on the air composition was very limited because they are rapidly washed out by precipitation. It is only fairly recently that bromine was detected in non-soluble form in volcanic plumes, as bromine monoxide (BrO), and that the main chemical processes behind were subsequently identified. The presence of sulphur emitted by volcanoes in the plumes allows a very rapid and important production of BrO and a strong decrease of the ozone concentration.
The chemistry-transport model MOCAGE is used to study the impact of volcanic halogen emissions on tropospheric chemistry at the regional scale. The selected case study is the Etna's eruption of Christmas 2018. The numerical simulations cover the Mediterranean at a resolution of about 20 km and are performed over the period from 24/12/2018 to 31/12/2018. The analysis of these simulations shows that the SO_2 emitted on 24/12/2018 is transported by the volcanic plume crossing the Mediterranean as shown in figure (a). Strong increases in BrO concentrations are modelled all along the plume (figure (b)) and are associated with ozone depletion shown in figure (c). These results are consistent with the estimates of BrO and SO_2 from the TROPOMI satellite instrument.

4

TROPOMI data assimilation to describe volcanic sulphur dioxide plumes

M. Bacles, V. Guidard

During volcanic eruptions, sulphur dioxide (SO_2) is emitted in large amount and at high altitudes into the atmosphere, which can damage aircrafts as they pass through these plumes. As part of its responsibilities, the Toulouse Volcanic Ash Advisory Centre (VAAC) has to forecast the evolution of SO_2 plumes. Since no accurate real-time information on the amount of SO_2 emitted by the volcano is available, we assimilate total columns of SO_2 from the TROPOMI instrument, on board Sentinel 5 Precursor, into the MOCAGE model.
The assimilation of these observations has been tested for several eruptions and has shown an improvement of the SO_2 total column prediction. For the eruption of La Soufrière Saint Vincent volcano between 8 and 22 April 2021, the assimilation of SO_2 total columns from TROPOMI allowed the modelling of a SO_2 plume (c) that was not present in the simulation without assimilation (a). Independent observations of total SO_2 columns from IASI (b), on board the Metop B and C satellites, validate the contribution of the assimilation with a plume of the same shape as the one simulated (d). However, the assimilation of TROPOMI alone in MOCAGE results in structures that are not observed by IASI. This difference is explained by the fact that there are observations only once a day.
One way to improve the assimilation of volcanic SO_2 would be to assimilate other instruments to cover the temporal evolution. Taking into account the altitude of the plume is also a way to improve the assimilation of volcanic SO_2.

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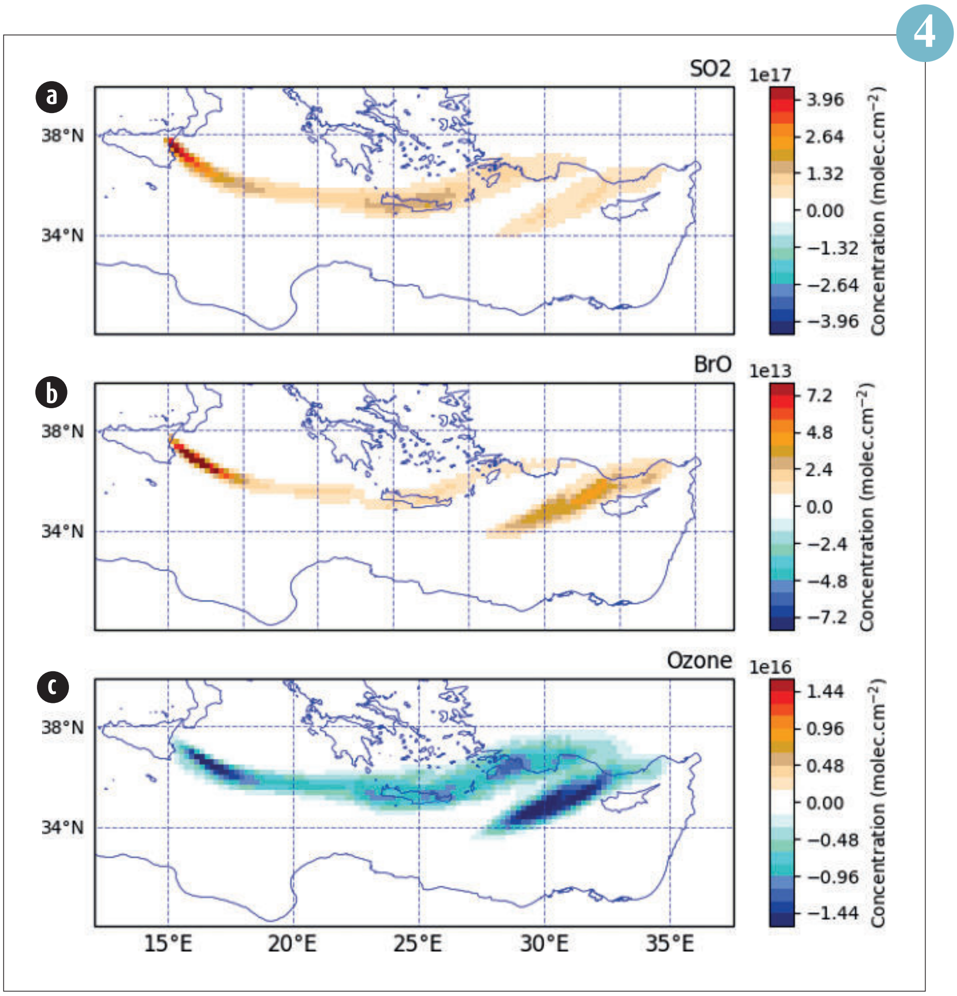
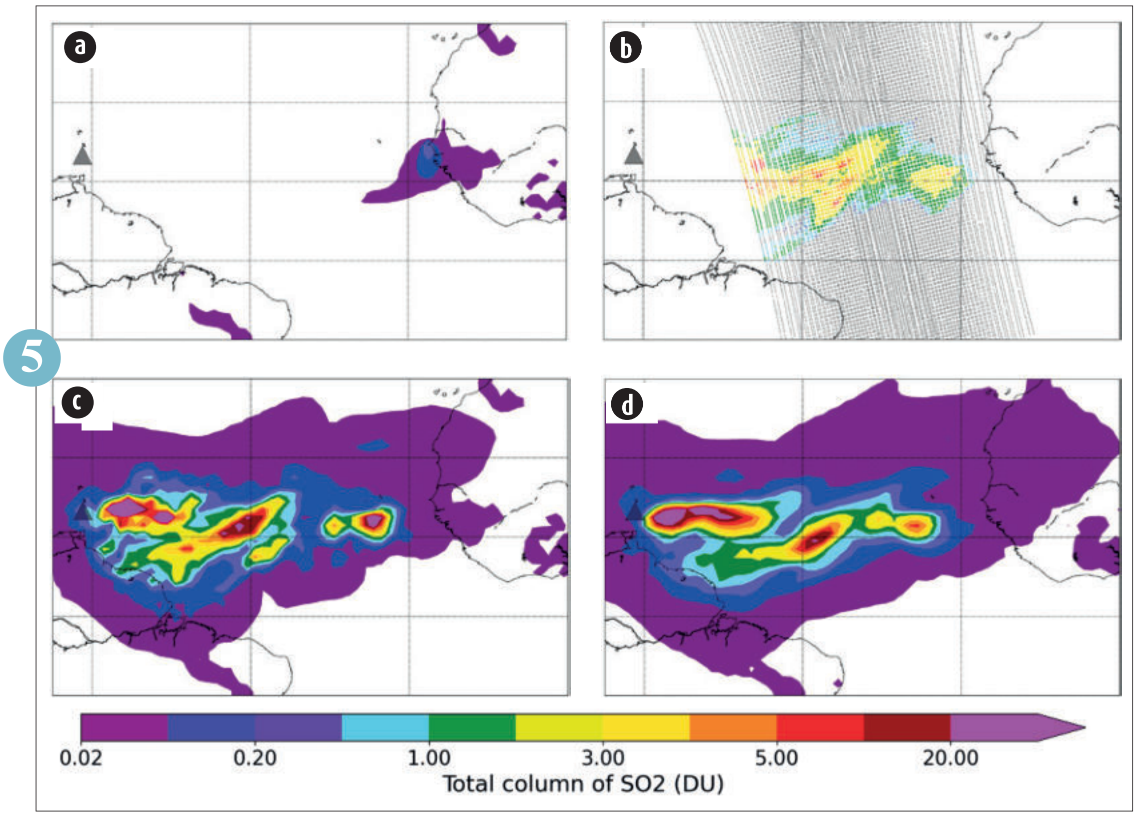


(a) Difference of the tropospheric column of SO_2 between the simulations with and without volcanic emissions in molec/cm² at 12:00 UTC on 25/12/2018.
(b) Difference of the tropospheric column of BrO between the simulations with and without volcanic emissions in molec/cm² at 12:00 UTC on 25/12/2018.
(c) Difference of the tropospheric column of ozone (O3) between the simulations with and without volcanic emissions in molec/cm² at 12:00 UTC on 25/12/2018.

Total columns of SO_2 simulated by MOCAGE with (c) and without (a) assimilation on 11th April 2021 at 5 pm, observed by IASI on 12th April 2021 between midnight and 1 am (b) and simulated by MOCAGE assimilating TROPOMI data on 12th April 2021 at 1 am (d).



From the Sahara to the Alps and Pyrenees

M. Dumont, B. Josse, M. Réveillet and F. Tuzet

At the beginning of February 2021, a vast plume of dust of Saharan origin was deposited over Europe giving a spectacular orange hue to the snowpack in the Alps and Pyrenees. This event was followed by other deposition events in February, March and April. In the emergency, a participatory science campaign was launched on social networks. This campaign aimed to collect orange snow samples to measure the mass of sand dust deposited on the ground (figure a). This campaign gathered 150 samples in the French and Swiss Alps, the French and Spanish Pyrenees and the Jura, covering an altitude range from 1000 to 3000 m (figure b). Analysis of the samples showed that the deposited masses varied between 0.2 and 60 g m^{-2}. The median values of the deposits are around 21.2 g m^{-2} for the Pyrenees, 7.2 g m^{-2} for the French Alps and 4.5 g m^{-2} for the Swiss Alps, i.e. several thousand tons deposited on the surface of the French Alps (figure b). The deposited mass thus decreases as a function of the distance to the source, the Sahara. These data are valuable because they allow us to better constrain atmospheric chemistry models but also to know precisely the impact of these deposition events on the snow cover. By changing the colour of snow, dust accelerates the melting of the snow cover. By combining data from the atmospheric models MOCAGE, ALADIN and the SAFRAN analysis with the detailed snowpack model, SURFEX-Crocus, we were able to estimate the impact of the event. This impact varies greatly depending on the location, due to variable snow conditions and deposition. A shortening of the snow season by several tens of days is attributed to the event for the most affected areas. The samples are still being analyzed in several laboratories to study, among other things, the granulometry, mineralogy and optical properties.

Reference:
Marion Réveillet, François Tuzet, Marie Dumont, Simon Gascoin, Laurent Arnaud, et al.. Dépôts massifs de poussières sahariennes sur le manteau neigeux dans les Alpes et les Pyrénées du 5 au 7 février 2021 : Contexte, enjeux et résultats préliminaires Version du 3 mai 2021. [Rapport Technique] CNRM, Université de Toulouse, Météo-France, CNRS. 2021. https://hal.archives-ouvertes.fr/hal-03216273

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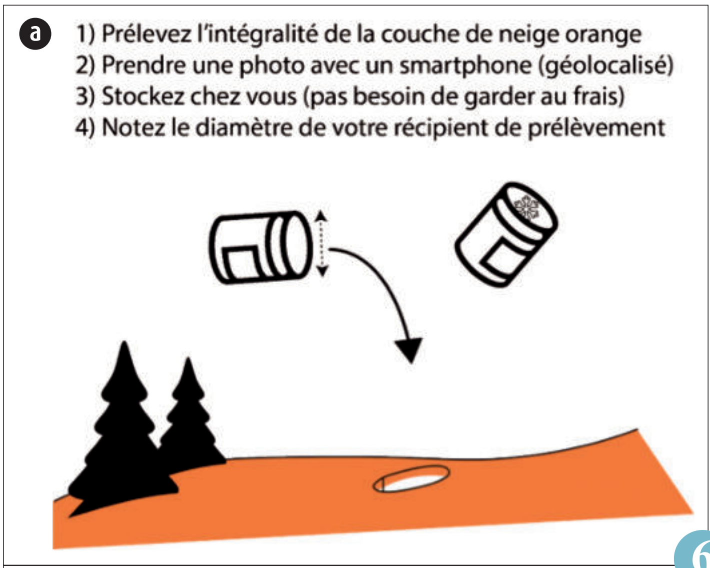

(a) Orange snow sampling measurement protocol sent on twitter by Simon Gascoin.

(b) Maps of orange snow samples collected, color indicates the mass of sand dust measured for each sample.

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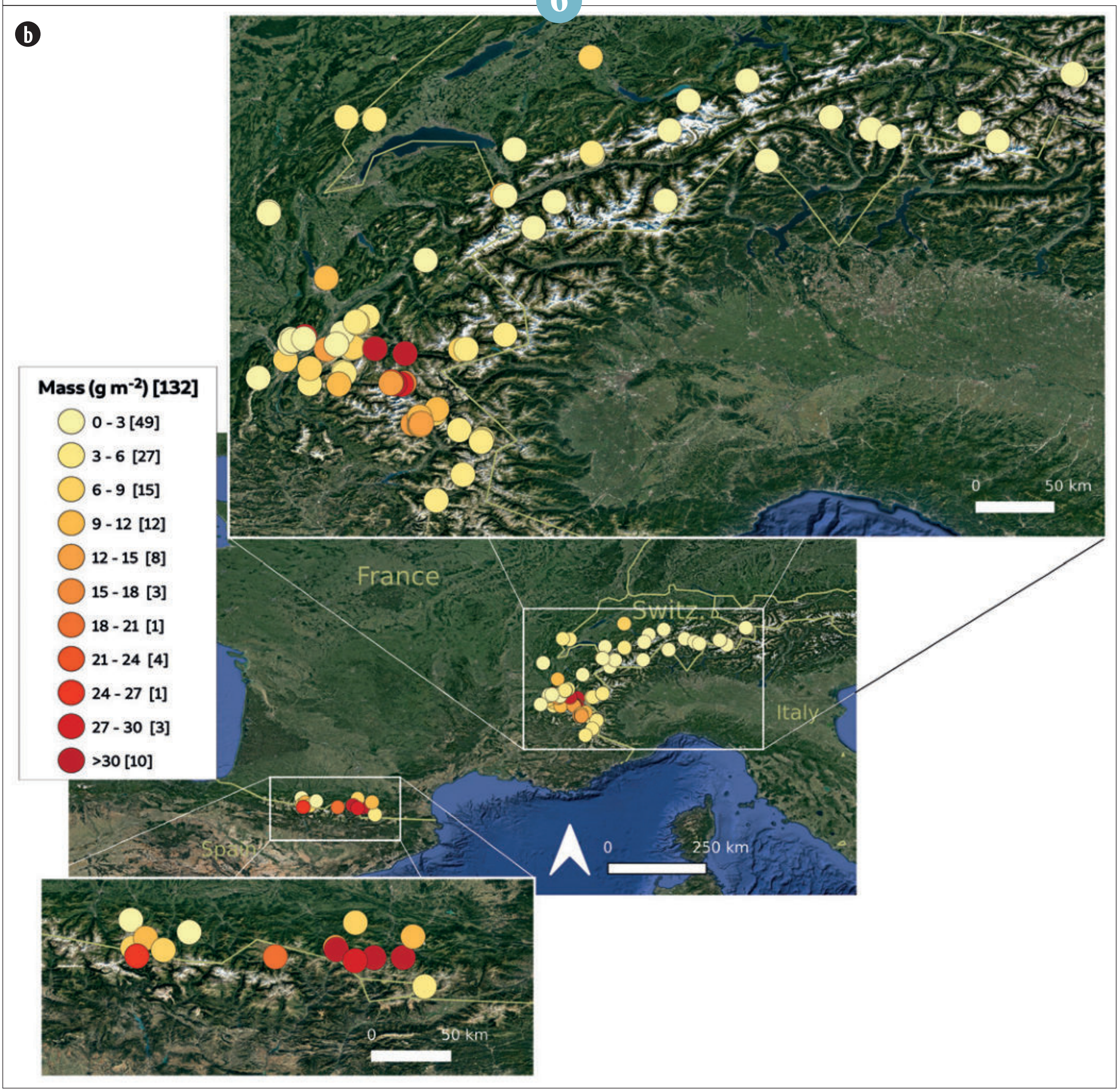

Snow and mountain

Snow is a pillar of our earth system. It plays an essential role for the Earth climate and for water resources. It covers all the components of the cryosphere, glaciers, ice caps, and permafrost, thus partly controlling the evolution of these different systems. It is also a key element for human societies and natural environments. Finally, snow is the source of natural risks such as avalanches. 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.

White, orange, windy, transported, at the scale of a micron or of the entire Alps, snow research topics were diverse. The development of a new snowpack modeling chain at 250 m resolution and with assimilation was continued efficiently, for instance by the development of an hectometric model for snow transport by wind. Following the major Saharan dust event in February, a participatory science campaign on orange snow was launched. The ERC IVORI project also started in February with, among other things, the first in situ X-ray tomography images on the Col de Porte site. Artificial intelligence methods have been applied for the downscaling of wind and the mechanical stability of the snowpack. The development of mountain climate services was carried on with the publication of a new reanalysis of snow and weather conditions in the mountains since 1958.

M. Dumont

High-altitude observatories as an asset to understand the biases of AROME in mountain terrain

I. Gouttevin

High-resolution numerical weather prediction systems have a great potential to provide meteorological information in alpine terrain, with key economic or societal value. However, they still suffer from biases which are highly detrimental for certain applications. For example, the AROME-France system exhibits a marked cold bias in surface and 2 m air temperatures in high altitude areas that limits its potential to model the snow cover and the associated risks.

To understand the possible origin of this bias, researchers from both the GMAP and CEN teams of CNRM and in collaboration with ECCC, have relied on modelling tools (SURFEX plateform) and high-altitude in situ observations acquired at two heavily instrumented sites from the French Alps, the Col du Lac Blanc and Col du Lautaret. These sites exhibit a unique instrumentation configuration for altitudes above 2000 m, enabling the retrieval of most of the components of the surface energy balance from observations.

Targeted numerical simulations revealed that errors in AROME screen-level fields, especially underestimations of wind speed and incoming longwave radiation, contribute to an average of 67 % of the AROME 2 m temperature bias. While this bias is not affected by the complexity of the snow scheme internal processes, it is sensitive to the formulation of turbulent fluxes in stable conditions, that tend to prevail over wintertime snow-covered terrain.

Evidence suggest that these findings could at least partially be generalized to the whole AROME-France alpine domain, but the lack of surface observations of infrared irradiance limits this evaluation. Actions are currently taken at the Department of Observation Systems (Meteo-France/DSO), with strong support from the CNRM, in order to set up an observational surface network for this variable in the near future.

Reference:
Arnould, Gabriel ; Dombrowski-Etchevers, Ingrid ; Gouttevin, Isabelle ; Seity, Yann. Améliorer la prévision de température en montagne par des descentes d'échelle. La Météorologie, 115, 37-44, 2021. 10.37053/lameteorologie-2021-0091

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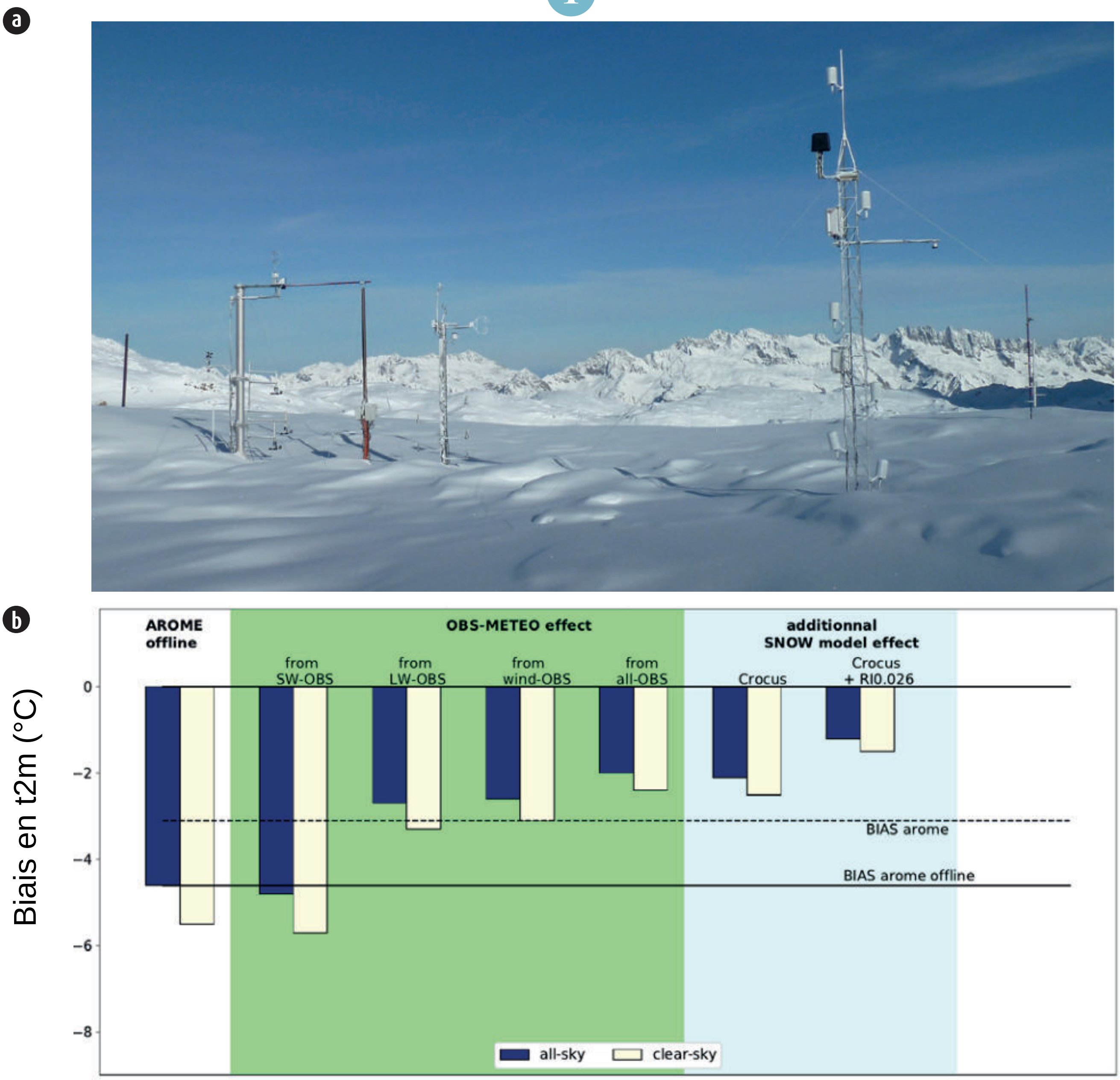

(a) The Col du Lac Blanc high-altitude site, operated at 2720 m a.s.l. by Meteo-France and INRAE
and (b) evolution of the 2 m temperature bias in a set of targetted offline simulations designed to quantify the contribution
to this bias of the meteorological forcing fields (green background),
and the additional contribution of the snow-scheme and surface coupling options (blue background).

Study of the temperature bias of the weather forecasting model, Arome, in the mountains

D. Préaux

The weather forecasting model, Arome, is an essential tool in mountain meteorology. However, its skills at temperature forecasting are altered by several temperature biases: (1) a cold bias at high altitude, (2) a low-altitude warm bias occurring in stably stratified layers and (3) a warm bias during snowfall situations.

Sensitivity tests (successive activation of some physical, assimilation and dynamic modifications) were carried out on the day of January 12, 2021, a problematic snowy situation in the Arve valley (Haute-Savoie).

The operational version of Arome has a mean absolute error (MAE) of 2.3°C in the valley over this period. The use of a new surface scheme associated with a more complex snowpack model allows to better forecast 2m temperature at the arrival of the warm front in the valley and reduces the error (1.8°C) whatever the altitude. The current surface scheme therefore seems too simplistic to correctly model soil-atmosphere interactions in the mountains for this situation. Forcing Arome with full-day data assimilation also reduces the bias in the valley (2.0°C). However, this experiment deteriorates the scores in the middle and high mountains. Although the increase of vertical resolution does not seem to improve the performance of the model in the valley, the MAE is nevertheless decreased from 1.4 to 1.1°C in the mid-mountain and from 1.5 to 1.2°C above 2000 m.

The results show that the warm bias during this snowy event has multiple origins. It will therefore be necessary to study other situations to confirm and correct them. Hence, a thesis entitled "Towards a sub-kilometer Arome for mountains meteorology and hazards modelling" will begin in May 2022.

2

Climate and snow cover variability and trends over the french mountains for the past 60 years

M. Vernay, D. Monteiro, M. Reveillet

Assessing past and future climate and snow conditions in mountainous areas is challenging due to their high spatial variability involved by the complex topography. The meteorological and snow cover reanalysis S2M* faces this challenge for the French mountains and spans the 1958-2020 period (Figure a). It is now freely available for the scientific community as an open access dataset, associated with an updated description of its main characteristics and limitations, especially the challenge to reproduce past climatological trends over a period that saw a dramatic increase of available observations (Figure b). As a result, an improvement of the quality of the simulation over time was emphasized. This complete and robust climatological dataset of past surface variables can be used as a reference for evaluating other climate simulations in mountain.

Thereby the S2M reanalysis has been recently used to assess the potentials and limitations of using the high resolution model AROME* for climate simulations in mountainous environments. Although AROME simulations exhibit a reduced cold bias compared to the coarser resolution regional model ALADIN, this cold bias is still significant especially above 2000 m elevation, associated with an unrealistic snow accumulation. Works in progress intend to fix this major issue, a necessary condition for climate change impact studies to take benefit from the added value of AROME high resolution and especially its promising ability to simulate the spatial variability of precipitation.

References :

Vernay, M., Lafaysse, M., Monteiro, D., Hagenmuller, P., Nheili, R., Samacoïts, R., Verfaillie, D., and Morin, S.: The S2M meteorological and snow cover reanalysis over the French mountainous areas, description and evaluation (1958–2020), Earth Syst. Sci. Data, https://doi.org/10.5194/essd-2021-249, sous presse.

Monteiro, Diego, Cécile Caillaud, Raphaëlle Samacoïts, Matthieu Lafaysse, Samuel Morin, Potential and limitations of convection-permitting CNRM-AROME climate modelling in the French Alps, Int. J. Climatol., sous presse.

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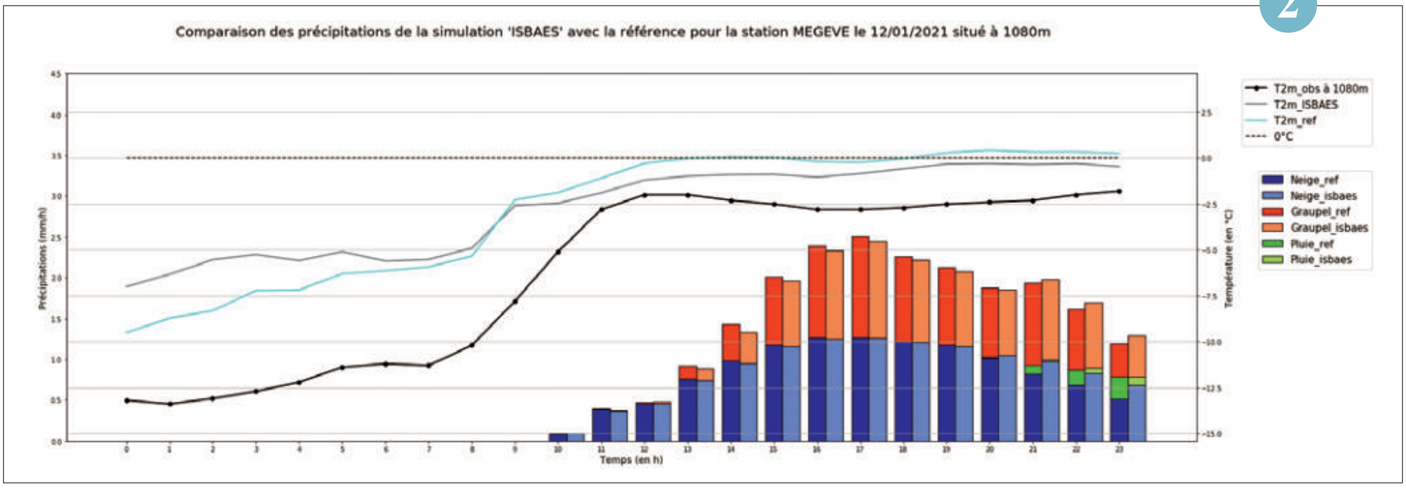
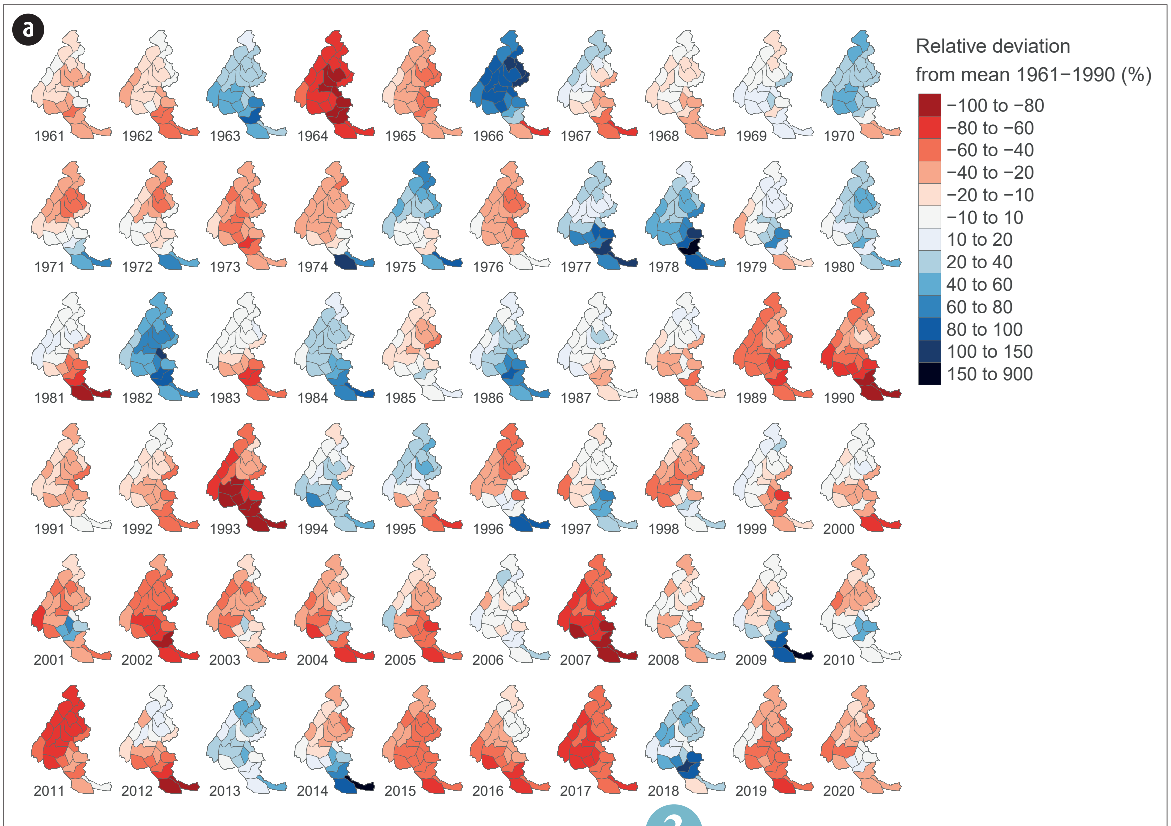
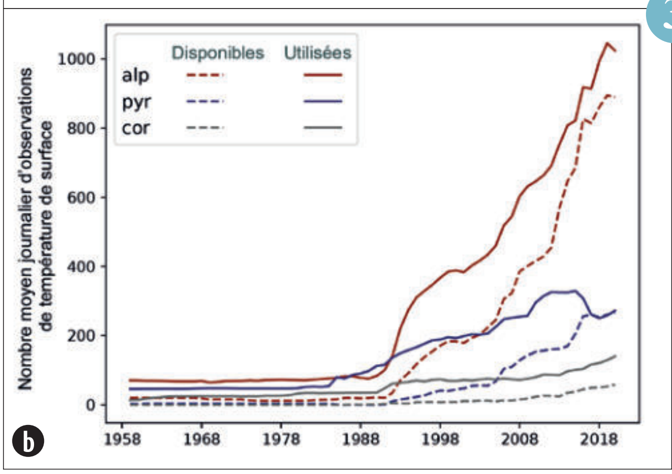


Simulated precipitation and simulated and observed temperature at 2 m in Megève. Snow is represented by a blue bar, graupel (corresponding here to wet snow) by a coral and rain by a green one. The darkest colours correspond to the operational and the lightest to the new snow scheme (ISBA_ES). The temperature is illustrated by black lines for the observations, cyan for the operational model and grey for the new snowpack scheme.





(a) Mean deviation of natural snow depth (in meters)from the mean snow depth of the period 1961-1990 in winter (from November to April) at 1800 m.

(b) Temporal evolution of the daily mean number of surface temperature observations available within the massifs limits (dashes) and effectively assimilated (solid lines) for each mountainous area over the period covered by the S2M reanalysis.

The Col de Porte snow and meteorological observatory: a historical witness of climate change in mountain areas

Y. Lejeune et al.

The Col de Porte observatory (alt. 1325 m), located near Grenoble in the heart of the Chartreuse massif, is with the Lac Blanc site (2720 m, Grandes Rousses massif) one of the two altitude sites for experimentation and observation of the CEN.
Its now 61 years of winter measurements provide a reliable and invaluable chronicle of the evolution of the mountain climate in France. Owing to its exceptional temporal depth and instrumental quality, this chronicle is now a reference for the monitoring of the snow cover in the Northern Alps, and more generally in mid-altitude mountain areas. Between the two 30-year normals (1960-1990 and 1990-2020) of winter variables (from 1 December to 30 April), it reveals a reduction of 37.7 cm in snow depth, jointly with a temperature increase of 1.01 ° C (see graph ONERC) and no significant trend in precipitation.
The observatory is an emblematic site for the study of snow at Météo-France, and a component of many observation structures for environmental experimentation and research at the local (OSUG), national (CryObsClim and GlacioClim, OZCAR), european and international (eLTER, WMO) scales. In addition, the observatory is today a perfectly acknowledged environmental reference for local mountain managers (PNRC, Grenoble-Alpes Métropole).

In addition to those of climatic nature, the activities on the observatory relate to:
- in-situ studies of the interactions between climatic conditions and the physical processes governing snowpack evolution (both in open and forested areas),
- tests of instrumentations and methods for the observation of the snow cover and the weather conditions above it,
- specific experimental campaigns.

The observatory is finally a privileged place for the transmission to all audiences of our knowledge on snow and climate.

Reference:

Lejeune, Y., Dumont, M., Panel, J.-M., Lafaysse, M., Lapalus, P., Le Gac, E., Lesaffre, B., and Morin, S. : 57 years (1960–2017) of snow and meteorological observations from a mid-altitude mountain site (Col de Porte, France, 1325 m of altitude), *Earth Syst. Sci. Data*, 11, 71-88, 2019. https://doi.org/10.17178/CRYOBSCLIM.CDP.2018

4

Monitoring the crystalline orientations of snow during temperature gradient metamorphism

F. Flin, R. Granger

Snow is a porous material made of air, vapor, ice, and sometimes liquid water. It transforms over time under the conditions imposed in the snow cover. In particular, a strong and constant temperature gradient leads to the formation of fragile faceted structures, often considered as a potential source of avalanches. We have recently studied the role of the crystalline orientation of grains constituting the snow in the metamorphism process. Each grain of ice has indeed its own crystalline orientation, resulting from the internal arrangement of water molecules and which can be revealed at the grain scale by typical faceted shapes, arranged in hexagonal prisms. For this study, we used "Diffraction Contrast Tomography" (DCT), a method allowing to obtain three-dimensional images of the snow structure as well as the crystalline orientation of each of its grains. This experiment was carried out at the Grenoble Synchrotron, by obtaining successive DCTs from a few mm-size snow sample, subjected to a temperature gradient of 52 °C/m. It made it possible to highlight a marked role of crystal orientation in the growth and sublimation of grains, the prismatic surfaces evolving faster than the basal surfaces, in the temperature range studied (-4 to -2°C). Growing surfaces have, however, shown a decrease in this phenomenon over time, probably linked to the immediate proximity of neighboring ice grains. These observations reflect the importance of crystal orientation in metamorphism processes and the possible selection of preferential orientations by metamorphism, which has many implications for the mechanics of snow and firn.

Reference:

Granger, R., Flin, F., Ludwig, W., Hammad, I., and Geindreau, C.: Orientation selective grain sublimation–deposition in snow under temperature gradient metamorphism observed with diffraction contrast tomography, *The Cryosphere*, 15, 4381–4398, 2021. https://doi.org/10.5194/tc-15-4381-2021

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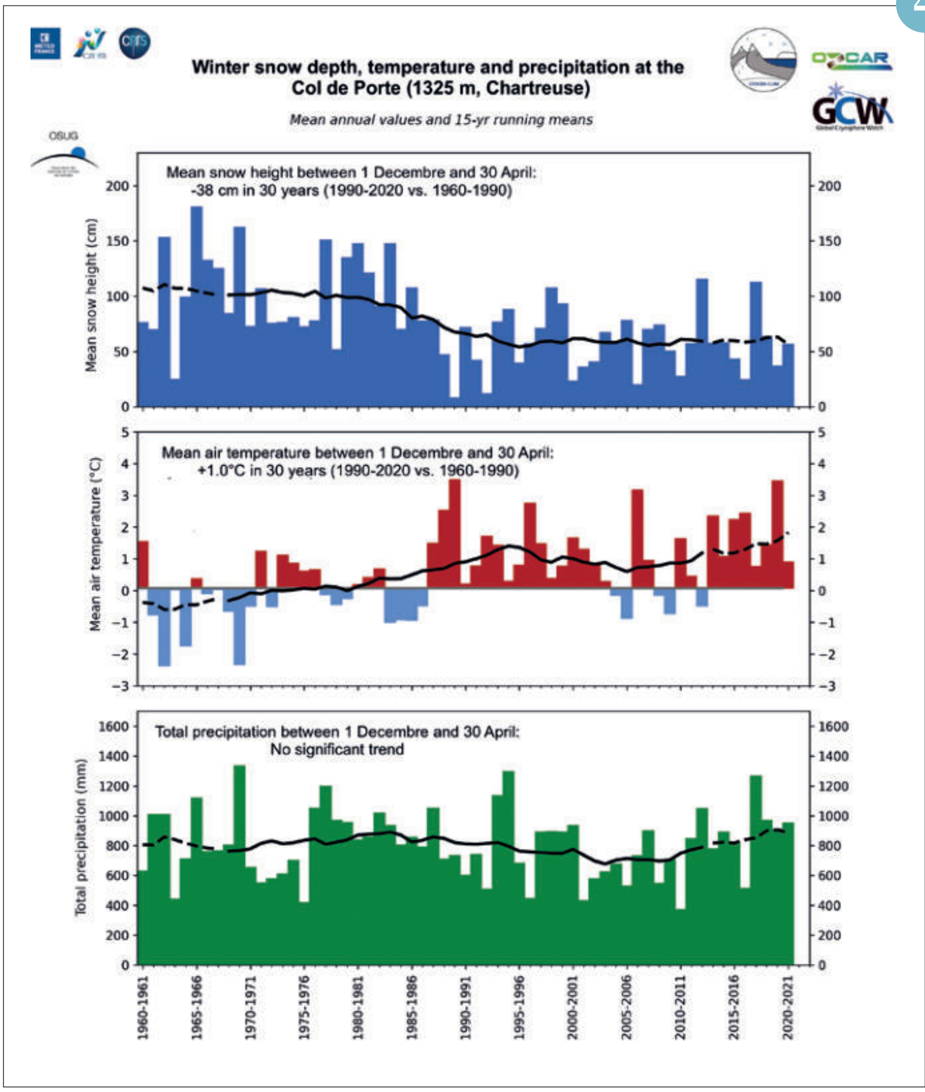
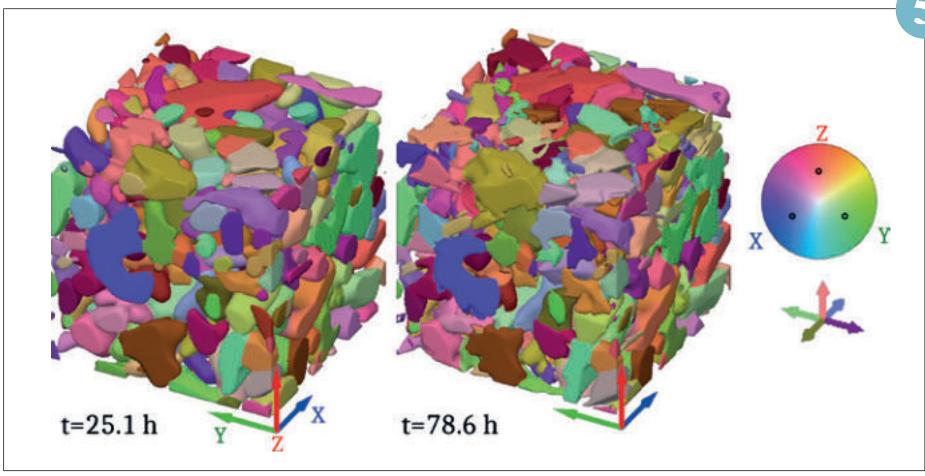


The ONERC indicator based on the winters at Col de Porte, as one of the 5 selected « Mountain and Glaciers » indicators of climate change effects in France.



Evolution of the grain crystal orientation in a snow sample subjected to a gradient of 52°C/m. Each color represents a single crystal orientation. The meaning of the colors is given by the color wheel, representing the orientations in a polar figure centered on the X+Y+Z vector. The five axes below the color wheel show the color corresponding to the primary directions associated with X, Y, and Z.

Engineering, campaigns and observation products

In the field of experimental meteorology, the year 2021 was marked by the implementation of the international LIAISE campaign in Spain. Bringing together numerous ground, remote sensing and airborne sensors, it is part of a research effort on the impact of human activity - in this case agricultural practices - on the water cycle. The exploitation of the fog data collected during the winter of 2019-2020 as part of the SOFOG3D programme led by the CNRM is in full swing. Thanks to an instrumental setup involving original and complementary instruments, initial results have been obtained on the physics of the phenomenon and the differences that lead to contrasting developments. The programme also made it possible to exploit for the first time the synergy between the W-band radar detecting water drops and the microwave radiometer measuring temperature profiles and water content. This will improve the initial description of low-level conditions, and hence the forecasting of the phenomenon. The work on collaborative flight of fleets of small drones reached an important milestone in early 2020 during the EUREC4A campaign with the internal observation of trade wind cumulus over the ocean. This was the first operational deployment of the system. It has lived up to its promise. The observations made over a long period of time from sensor networks make it possible to validate the numerical models. The use of UV flux measurements is a new case this year, with the MOUV.RE research programme in Reunion Island, which aims to forecast these fluxes on a fine spatial scale.

A. Dabas

MOdeling Ultraviolet Radiation at REunion island

T. Portafaix

The MOUV.RE (MOdeling Ultraviolet Radiation at REunion island) project started in September 2021 (recruitment of a research engineer over 24 months).
The general aimof MOUV.RE is to carry out high spatial resolution UV radiation modelling at different time scales in Reunion and the Indian Ocean. These models will be compared with the measurement network operated by LACy.

This objective is detailed as follows:
1 - High spatial resolution modelling of ultraviolet radiation for all types of cloud cover and aerosol conditions in Reunion, and short-term forecasts.
2 - High spatial resolution climate projection UV radiation, in the tropics andfor all cloudy conditions.
The first phase of the project has started and includes the following elements:

- High Resolution Modelling in Reunion (Objective 1):
-Integration of the weather forecasting model Arome-Indian OceanoperationalatMétéo France, to study the impact of cloudiness on UV radiation. Coupling to the input of the Libradtran radiative transfer model.
-Case study on the impact of aerosols from biomass fires on radiation.
- Inventory, collection and processing of climate projection data from the CMIP6 scenarios (6th coupled climate model intercomparison exercise) used by the IPCC for climate change assessment(Objective 2).

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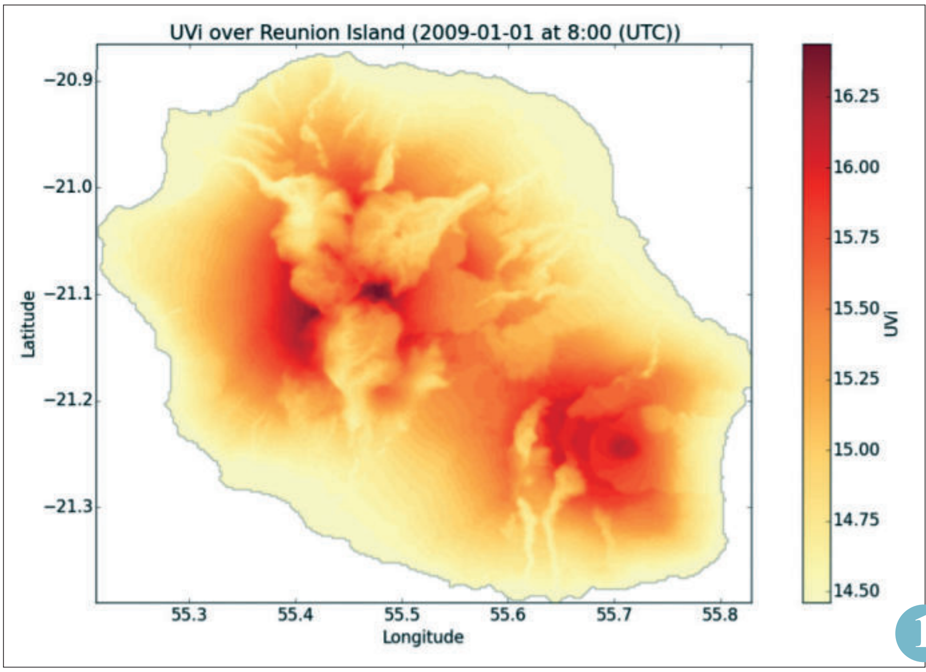
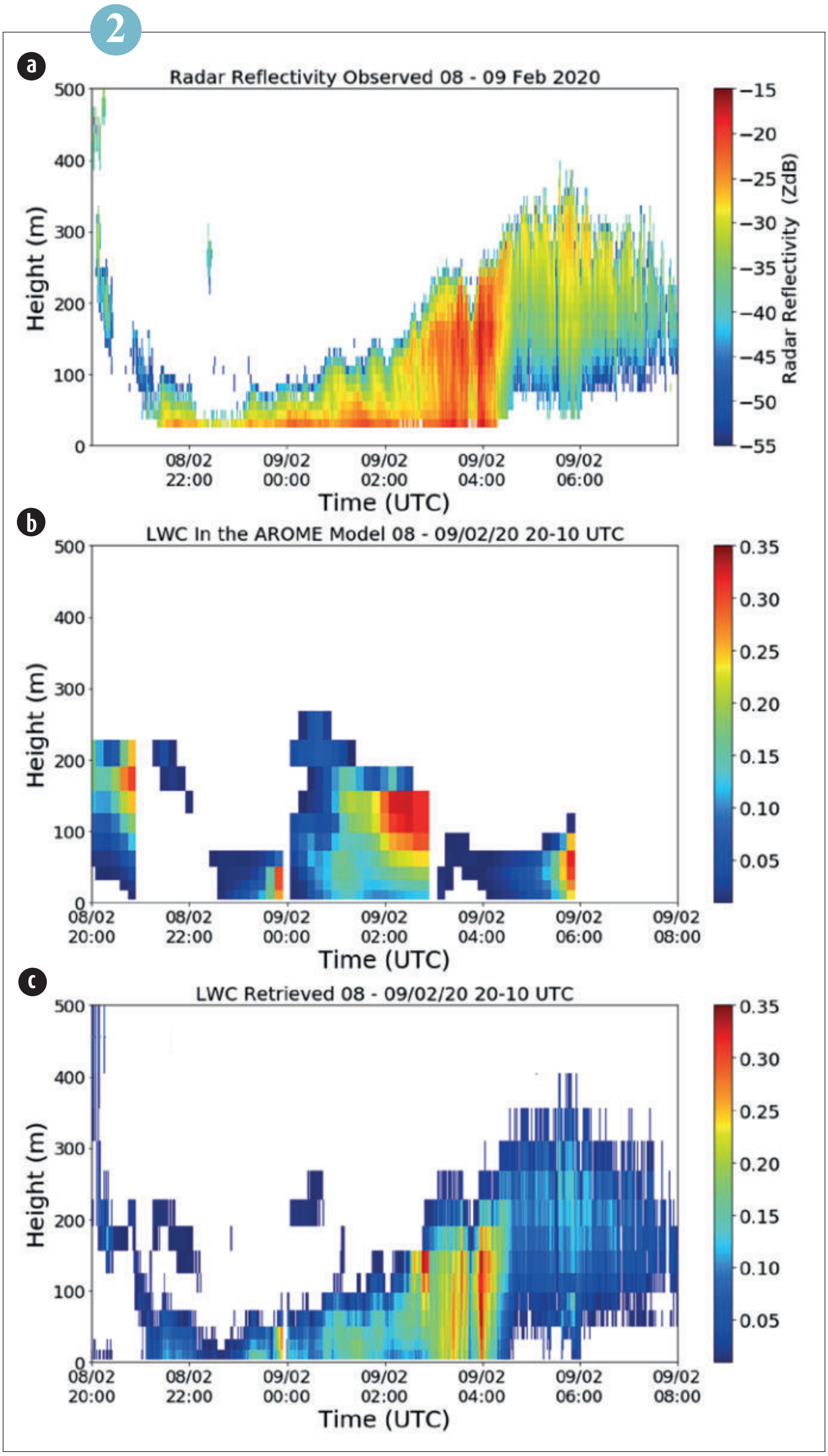


1

Example of a high-resolution UV index forecast map over Reunion (in clear sky).

Optimal estimation of thermodynamic and microphysical profiles within fog events from ground-based microwave radiometer and cloud radar synergy

P. Martinet, A. Bell, O. Caumont



Despite their strong impact on transport safety, fog events are still not correctly predicted by current numerical weather prediction models. One possible way to improve fog forecasts relies on the exploitation of new boundary layer measurements to better understand the sources of fog forecast errors and to improve the model initial state. To that end, a ground-based microwave radiometer and a 95 GHz cloud radar have been deployed during the fog dedicated field experiment SOFOG3D in order to take advantage of the instrumental synergy to retrieve vertical profiles of temperature, humidity and liquid water content within fog and low liquid clouds.

A simplified 1D assimilation scheme has been developed to combine short-term-forecasts from the AROME model with microwave radiometer (MWR) and cloud radar observations. For the first time, liquid water content retrievals have been carried out within fog layers and validated with in-situ measurements from a tethered balloon. The capability of the algorithm to retrieve liquid water contents with an approximate error of 0.05 g.m^{-3} but also temperature and humidity profiles with an accuracy better than 1 K and 1 g.kg^{-1} respectively has been demonstrated. Moreover, the 1D assimilation of cloud radar and MWR observations was proved to significantly improve large errors observed in the AROME initial profiles. Future studies will explore the capability of the retrieved profiles to improve fog forecasts by assimilating them within the new AROME ensemble data assimilation scheme.

Finally, this work will allow a fine description of both thermodynamic and microphysical properties of the SOFOG3D fog events in order to better understand the physical processes taking part in the fog lifecycle

2

Time series of (a) radar reflectivity (dBZ),
(b) liquid water content profiles (g.m^{-3}) predicted by the AROME short-term-forecasts,
(c) liquid water content profiles (g.m^{-3}) obtained after the 1D assimilation of microwave radiometer and cloud radar observations.

Vertical profiles of fog microphysical properties from in-situ measurements

F. Burnet, T. Costabloz

The main objective of the SOFOG3D project (SOuthwest FOGs 3D experiment for processes study), funded by Meteo-France and ANR, is to advance our understanding of fog processes in order to improve fog forecasts. During the campaign, which took place in the south-west of France during winter 2019/2020, 15 Intensive Observation Periods (IOP) were conducted to document the evolution of microphysical properties within the whole fog layer.

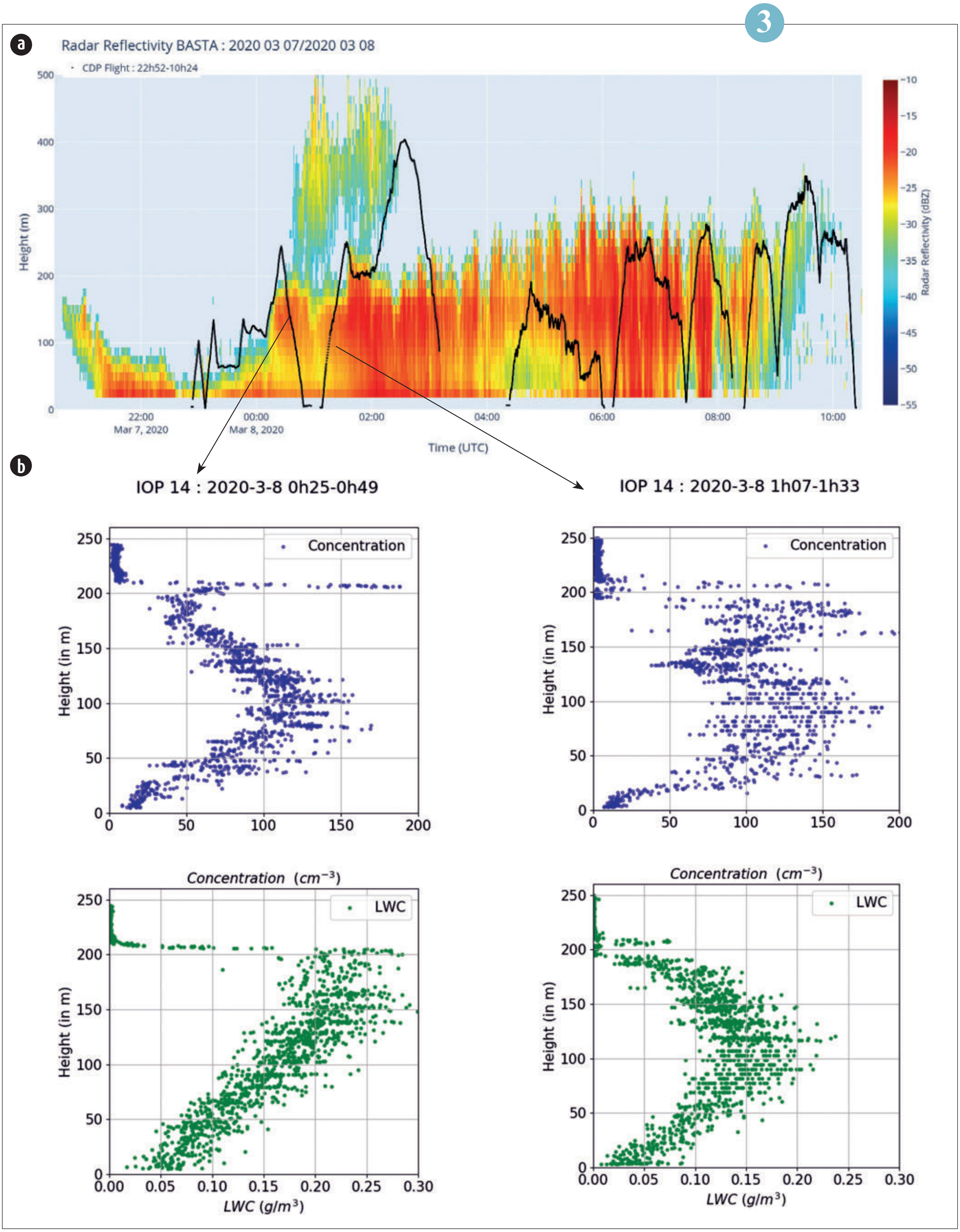
For this purpose, the observation strategy consisted in combining vertical profiles obtained with in-situ measurements from a tethered balloon platform which was equipped with a turbulence probe and an optical particle counter measuring water droplets, with remote sensing instruments such as a 95 GHz cloud radar and a microwave radiometer.

The first results on two cases where the fog layer reaches 200m high, show a strong variability regarding the vertical profiles in terms of microphysical properties (liquid water content, concentration and droplet diameter) during the different phases of the life cycle. Indeed, as the fog develops and becomes optically thick, and lifts finally into a stratus cloud, we observe dramatic changes of the vertical structure. Furthermore, within the mature phase only, strong differences can also be noticed.

Figure b) highlights this variability thanks to the concentration and liquid water content vertical profiles obtained during two consecutive ascents and descents between 0025UTC and 0133UTC. The tethered balloon flight is superposed in Figure a) on the RADAR reflectivity which allows the characterisation of the fog development.

These unique observations will now be further investigated to better understand the different processes that occur during the fog life cycle. In particular, we will focus on differences between thin and thick episodes, in order to document the transition between the formation phase, which happens in stable conditions, and the developed phase, which is more adiabatic.

3



(a) Radar Reflectivity from the 95 GHz BASTA cloud radar, regarding the fog episode sampled during the night of 7/8th March 2020 (IOP 14).
The flight of the tethered balloon which was equipped with an optical particle counter measuring water droplets is represented with the black line.
(b) Vertical profiles of the water droplets concentration (blue) and Liquid Water Content (LWC in green) during the descent from 0025UTC to 0049UTC (left) and the ascent from 0107UTC to 0133UTC (right).

THE HILIAISE PROJECT: Better understanding and modeling the human footprint on the water cycle in a semi-arid region

G. Canut, A. Boone

One of the greatest challenges facing environmental science and society is to understand and predict future changes in the terrestrial water cycle and their impacts on water resources. International organizations such as the World Climate Research Programme (WCRP) have also recognized that human activities play a key role in modifying the continental water cycle and therefore need to be considered in climate projections. This issue is particularly critical in regions of intensive agricultural production where water resources are already limited, such as the Mediterranean basin. Climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) predict that the Mediterranean region will be a so-called climate change "hot spot" in the 21st century. Understanding the processes that govern the hydrological cycle in this region has been a key objective of the international HYdrological cycle in the Mediterranean Experiment (HyMeX) project. To address these questions, the international project Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE) was recently launched. The French component is part of HyMeX and is called HILIAISE - Human Imprint on LIAISE. HILIAISE funded by ANR aims to better understand and model the human footprint on energy and the water cycle in a semi-arid region with limited water resources and high agricultural production. This project is based on a multidisciplinary approach with hydrological, terrestrial and meteorological models as well as numerous simultaneous observations of the surface, vegetation and atmosphere. The combination of in-situ observations by aircraft, measuring masts or balloons and remote sensing by wind profiler radar and water vapour lidar on highly contrasting irrigated and non-irrigated surfaces should address the following questions:

1. What are the major natural and anthropogenic processes on semi-arid surfaces that drive infiltration and runoff and govern turbulent flows and their spatial heterogeneities?

2. How does the high-contrast surface influence boundary layer development, mesoscale circulations, and potentially precipitation recycling in this region via feedbacks with the atmosphere?

To achieve the project objectives a special 15-day observation period took place in July 2021 to complement a long observation period covering the vegetation cycle from April to October 2021 over the Ebro basin. During this campaign many measurement means were deployed in order to observe the processes controlling surface-atmosphere interactions when the contrast between anthropized (irrigated) and natural (non-irrigated) areas is very strong and the need for water is maximum. To illustrate the strong contrast between the two surfaces studied, figure (1a) shows the discontinuity observed in this area on either side of the channel used for gravity irrigation. Figure (1b) shows the surface energy balance on 1 day representative of the special measurement period on an irrigated area and a non-irrigated natural area. This day was characterized by a partitioning of the heat transport and evapotranspiration fluxes that is very different between the two sites. The irrigated area is characterized by evaporation fluxes that are much higher than the sensible heat transport fluxes. This difference is expected to play a crucial role in the redistribution of water in the atmosphere. A complete database, including observations, models and satellite data will be integrated into the MISTRALS/Hymex database. This international project is based on strong collaborations and the involvement of many laboratories, in particular CNRM, LMD, CESBIO, LAERO, IRTA, METOFFICE, University of the Balearic Islands, University of Barcelona, University of Wageningen, University of Delft, University of Jülich, NASA and the Ebro Observatory.

4

Fleet of drones for observating trade wind cumuli during EUREC4A

G. Roberts

Since 2018, CNRM has led the NEPHELAE project in collaboration with the LAAS and ENAC laboratories to develop a fleet of lightweight drones that adaptively track trade wind cumulus clouds. The observations are then enhanced using advanced mapping techniques. After virtual flights in numerical simulations of cumulus clouds (Maury et al., 2022), the drones were deployed in Barbados during the EUREC4A campaign in February 2020 (https://eurec4a.eu/). More than 40 drone flights were carried out, which included following about twenty trade wind cumuli using autonomous adaptive sampling techniques. During the field campaign, two drones measured the properties inside cumulus clouds at two vertical levels for about ten minutes, providing information on the evolution of the cloud in four dimensions. These unprecedented observations were compared with the results of the numerical simulations quantifying the uncertainties related to turbulent mixing that still exist in cloud models.

This research highlights novel techniques for observing dynamic systems such as clouds.

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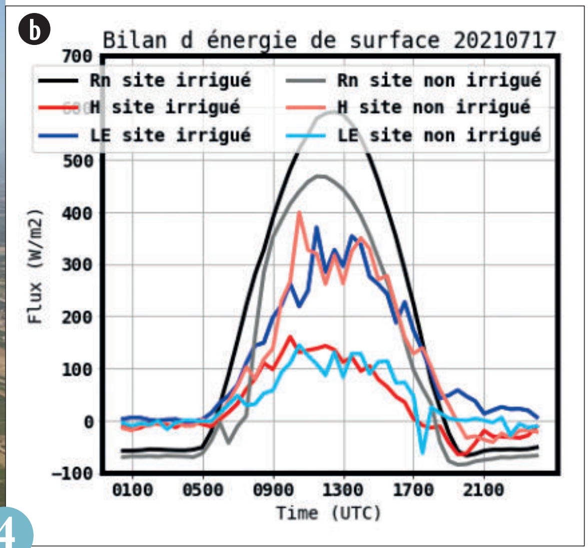
Hattenberger, G., T. Verdu, N. Maury, P. Narvor, F. Couvreux, M. Bronz, S. Lacroix, G. Cayez, G.C. Roberts, Field report: deployment of a fleet of drones for cloud exploration, 12th International Micro Air Vehicle Conference and Competition, Nov 2021, Puebla, Mexico.

5

(a) Aerial photo aboard the French research aircraft ATR42 during the measurement campaign in July 2021.



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(b) Daily evolution of the surface energy balance on an irrigated and non-irrigated site. The parameters represented are net radiation (Rn), sensible heat flux (H) and evapotranspiration flux (LE) for the day of July 17, 2021.

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(a) Image from the camera on board the drone approaching the ocean, with the coast of Barbados and the trade wind cumuli.
(b) Trajectories of two drones flying simultaneously following a cloud using adaptive sampling
The zone E1 is the take-off zone; the Zone E2 is the climb phase; the Zone E3 corresponds to racetracks while waiting to intercept the trade wind cumuli; and the Zone E4 corresponds to following the cloud adaptively. Adapted from Hattenberger et al. [2021].

Appendix

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Glossary

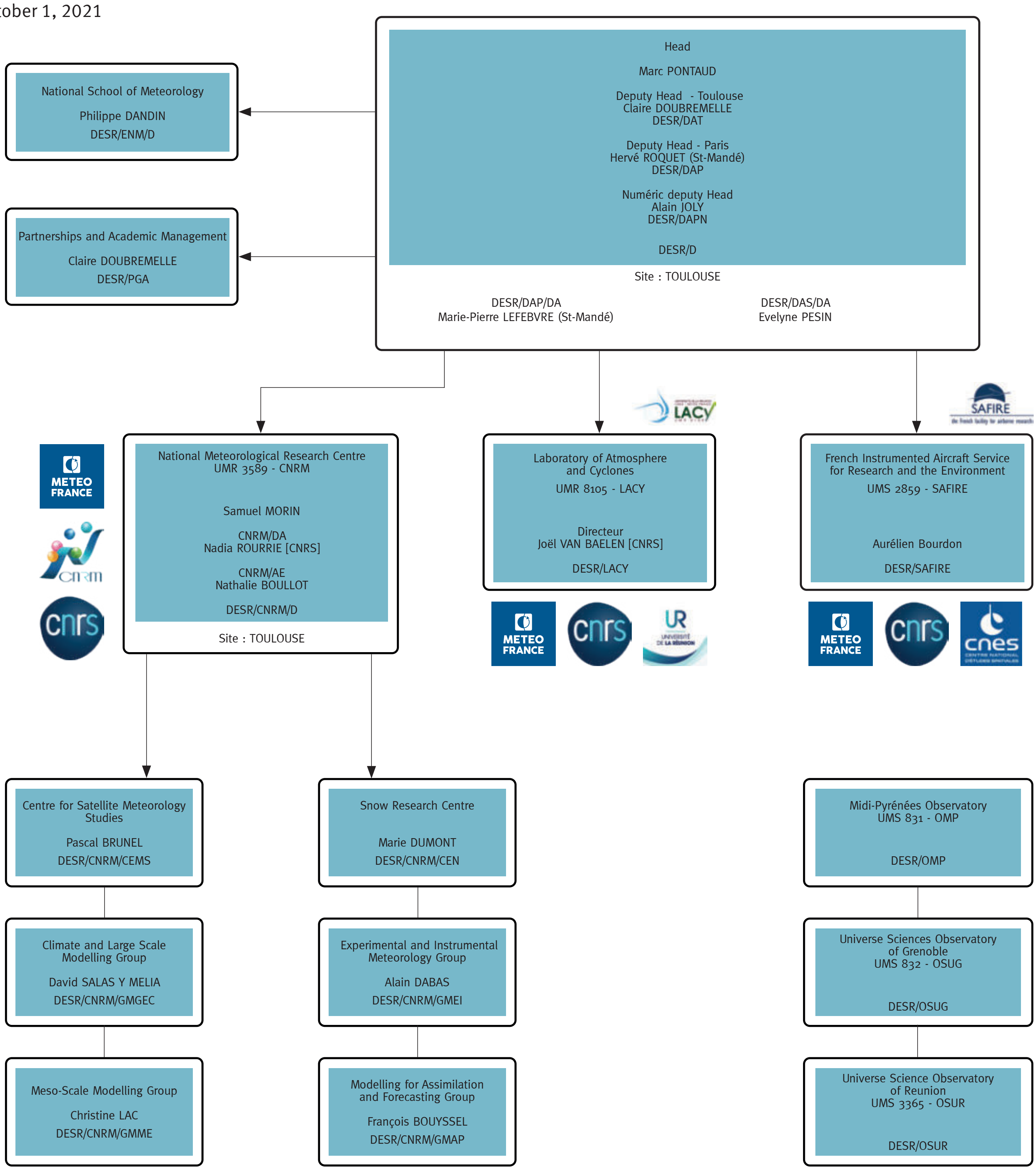
3DEnVar Schéma d'assimilation variationnel ensembliste tridimensionnel
3SR Sols, Solides, Structures, Risques
4DEnVar Schéma associant l'approche variationnelle utilisée traditionnellement à Météo-France aux approches ensemblistes utilisées
ADAMONT Impacts du changement climatique et adaptation en territoire de montagne
ADEME Agence de l'Environnement et de la Maîtrise de l'Energie
ADM Atmospheric Dynamics Mission
AEMET Agencia Estatal de Meteorología (Espagne)
AEOLUS Atmospheric Explorer Observations with a Lidar UV System
ALADIN Aire Limitée Adaptation Dynamique et développement InterNational
ALAMO Air-Launched Autonomous Micro Observer
ALPHA Algorithmes et modèLes pour la Production Homogène globAle
AMSR Advanced Microwave Scanning Radiometer
ANR Agence Nationale de la Recherche
AOS Aérosols secondaires organiques
AOS Atmosphere Observing Systems
AROME Applications de la Recherche à l'Opérationnel à MEsoéchelle
AROME-PI Configuration AROME Prévision Immédiate
ARPEGE Action de Recherche Petite Échelle Grande Échelle
ASCAT Advanced SCATterometer
AVHRR Advanced Very High Resolution Radiometer
BIDER
BIPER
BSC Barcelona Superconputing Center
BSRN Baseline Surface Radiation Network
CALIPSO Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMS projet Européen Copernicus
CART Classification And Regression Trees
CAT Clear Air Turbulence
CCM-I Chemistry-Climate Model Initiative
Cedre Centre de documentation, de recherche et d'expérimentations sur les pollutions accidentelles des eaux
CEMS Centre d'Etude en Météorologie Satellitaire
CEN Snow Research Center
CEPMMT Centre Européen pour les Prévisions Météorologiques à Moyen Terme
CEREA
CERES Satellite
CFOSAT Chinese-French SATellite
CGLS Copernicus Global Land Service
CIFRE Conventions Industrielles de Formation par la REcherche
CLA Couche Limite Atmosphérique
CLIMSNOW Adaptation au changement climatique et projections de l'évolution de enneigement
CLIO Lidar
CLMcom-CCLM4-8-17 Modèle climatique régional
CMCC Centre euro-Méditerranéen sur le Changement Climatique (Italie)
CMIP Coupled Model Intercomparaison Project
CMIP5 and CMIP6 Climate Models Intercomparison Project n°5 and 6
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
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
CROCO modèle d'océan
CROCUS Modèle de simulation numérique du manteau neigeux développé par Météo-France
Cry-ObsClim CRYosphere as a CLIMate OBServatory
C3S Copernicus Climate Change Service
CTRIP CNRM-Total Routing Integrated Pathway
DAK Doubling Adding KNMI
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
DSSF Downwelling surface short-wave radiation flux
DWD service météorologique allemand
ECCC Environnement et Changement Climatique Canada
ECMWF European Centre for Medium-Range Weather Forecasts
EcRad code de transfert radiatif
ECUME ECUME paramétrisation des vagues
EDMF Eddy-Diffusivity-Mass-Flux
EDR Eddy Dissipation Rate
ELTER Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure
ENAC Ecole Nationale Aviation Civile
ENSO El Nino Southern Oscillation
EOF Fonction Orthogonale Empirique
EPS-SG Système polaire de 2e 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
ETP Évapotranspiration Potentielle
EUMETSAT European organization for the exploitation of Meteorological Satellites
EUREC4A Elucidating the role of clouds-circulation coupling in climate
EUROCORDEX Modèle régional de climat
EUSPA l'Agence du programme spatial de l'Union européenne
FCI Flexible Combined Imager
FORUM Sondeur Infrarouge
FTP File Transfert Protocol
GCM Modèle de circulation Générale
GELATO Global Experimental Leads and ice for ATmosphere and Ocean
GEO Group on Earth Observations
GES gaz à effet de serre
GET laboratoire de Géosciences Environnement Toulouse
GHER GeoHydrodynamic and Environmental Research
GHG Green House Gazes
GIEC Groupe Intergouvernemental d'experts sur l'Evolution du Climat
GIRAFE capteur Gravimétrique Interférométrique de Recherche à Atomes Froids Embarqué
GlacioClim National Observation Service: GLAciers as a CLIMate Observatory
GMAP Groupe de Modélisation et d'Assimilation pour la Prévision
GMEI Groupe de Météorologie Expérimentale et Instrumentale
GNSS systèmes mondiaux de navigation par satellite
GOES Satellites météorologiques géostationnaires américains
GOME-2 Global Ozone Monitoring Experiment
GPCP Global Precipitation Climatology Project
GSX partenaire de Météo-France exploitant l'outil PROSNOW
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
HKO Hong Kong Observatory
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
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
INERIS
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
IPSL Institut Pierre Simon Laplace
IR Infra Rouge
IRD Institut de Recherche pour le Dévelopement
IRIS InfraRed Interfometer Spectrometer
IRS InfraRed Sounder
ISBA Interaction Sol-Biosphère-Atmosphère
KNMI Koninklijk Nederlands Meteorologisch Instituut
LA Laboratoire d'Aérologie
LAAS Laboratoire Analyse Architecture Systèmes
LACY Laboratoire de l'Atmosphère et des Cyclones – UMR 8105
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
LIAISE Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment
LIDAR light detection and ranging
LIMA schémas microphysiques
LMD Laboratoire de Météorologie Dynamique
LMI Lifetime Maximum Intensity
LSA Land Suface Analysis
LSCE Laboratoire des Sciences du Climat et de l'Environnement
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
MERIT-DEM Modèle Numérique de terrain
MESO-NH Modèle à MESO-échelle Non Hydrostatique
Met Office Service national britannique de météorologie
METAR METeorological Aerodrome Report
METOP METeorological Operational Polar satellites
MFWAM Météo-France WAve Model
MIN2OS Projet de satellite de surveillance des sources de protoxyde d'azote
MJO Madden-Julian Oscillation
Mlake Modèle de bilan de masse des lacs
MOCAGE MOdélisation de la Chimie Atmosphérique de Grande Echelle (modélisation)
MODCOU MODèle hydrologique COUplé surface-souterrain.
MODIS MODerate-resolution Imaging Spectro-radiometer (instrument)
MOHC-HadGEM2-ES Modèle climatique global
MOTHY Modèle Océanique de Transport d'HYdrocarbure
MOUV.RE MOdeling Ultraviolet Radiation at REunion island
MPI Max Planck Institute
MPI-M Max-Planck-Institut für Meteorologie - Institut Max-Planck de météorologie
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
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
NEPHELAE Network for studying Entrainment and microPHysics of cLouds using Adaptive Exploration
NOAA National Ocean and Atmosphere Administration
NWP Numerical Weather Prediction
OA Océan-Atmosphère
OACI Organisation de l'Aviation Civile Internationale
OAD Outils d'Aide à la Décision

OLCI capteur satellitaire
OMM Organisation Météorologique Mondiale
ONERA Office national d'études et de recherches aérospatiales
ONERC National Observatory of the Effects of Climate Warming
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 Grenoble Observatory for the Sciences of the Universe
OZCAR Critical Zone Observatories: Re-search and Application
PCMT Prognostic. Condensates Microphysics and Transport
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
PISSARO Projet de prévision à l'échelle intra-saisonnière pour des applications sur le bassin sud-ouest de l'océan Indien (SOOI)
PM10 PM10 (particules aérosols de moins de 10 microns) ca
PNRC Natural Regional Parc of 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
RGB Red Green Blue (satellite)
RHT Relative Humidity Threshold
RMSE Root Mean Square Error
RTTOV Radiative Transfer for TOVS
S2S Sub-seasonal to Seasonal
S8 Système 8 de prévision saisonnière de Météo-France
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
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
SMA Seychelles Meteorological Authority
Smart4RES Projet d'amélioration de la prévision de production à court terme d'énergie renouvelable solaire et éolienne
SNO Service National d'Observation
SOERE Cry-ObsClim Système d'Observation et d'Expérimentation sur le long terme pour la Recherche en Environnement
SOFOG3D SOuth westFOGs 3D (compréhension des processus de petites échelles pour améliorer les prévisions du brouillard)
SOOI Sud-Ouest Océan Indien
SRON Space Research Organisation Netherlands
SSH-Aerosols Module du modèle MOCAGE
SSM Special Sensor Microwave
SSP Shared Socio-economic Pathway
SST Sea Surface Temperature
Stratéole-2 Projet franco-américain dédié à l'étude des phénomènes atmosphériques au niveau de l'équateur terrestre
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)
THIR Temperature-Humidity Infrared Radiometer
TIROS Television InfraRed Operational Sounder
TROPOMI TROPOspheric Monitoring Instrument
TSEN Thermodynamic sensors - système d'observation de haute précision sur ballon
TSM Températures de Surface de la Mer
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 centre d'avertissement des cendres volcaniques Volcanic Ash Advisory Centre
VIIRS Visible Infrared Imager Radiometer Suite
WCB Warm Convection Belts
WIRE Winter Risks for Energy
WMO World Meteorological Organization
WW3 Modèle de prévisions de vagues côtières

DESR: Management structure

October 1, 2021



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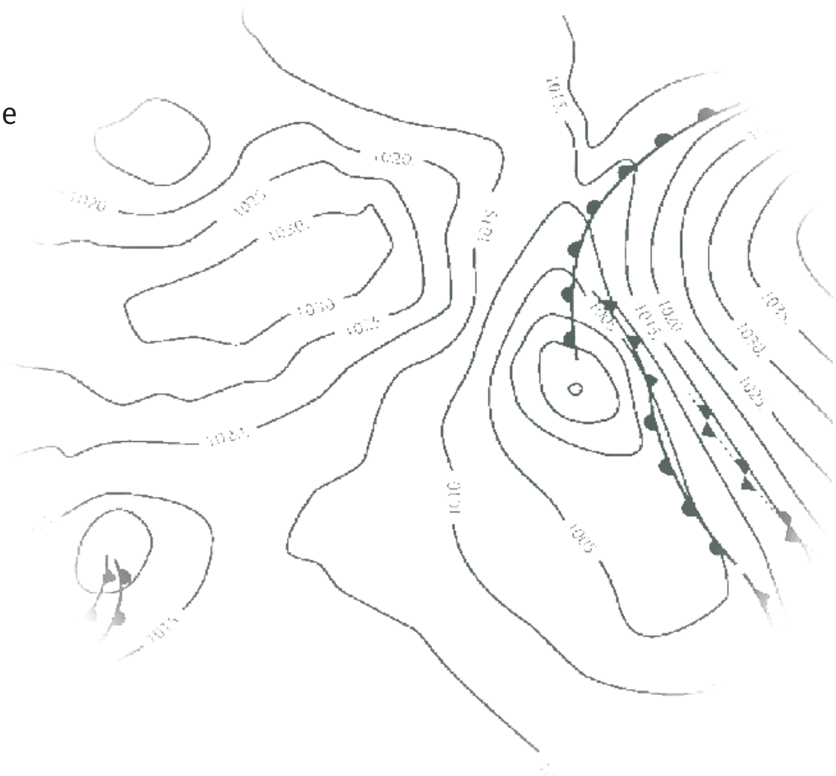

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