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Space Weather

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Summary

- *Space weather combines observations of solar activity with the study of its effects on Earth's upper atmosphere and magnetic field.*
- *The all-pervasive use of electricity, transmission of information by electromagnetic waves, proliferation of satellites, boom in air transport and normalisation of manned space flights have increased the number of channels through which solar activity, especially if it is particularly intense, can affect human activity.*
- *Recent progress has raised hopes for the operational deployment of solar activity forecasting capabilities giving operators the possibility of better control over this hazard, as our knowledge extends beyond the recurring eleven-year cycles, and with the current cycle expected to reach its peak in 2025.*
- *Cooperation has begun between research and operators at the global level and in France. This must be stepped up.*

Christine Arrighi, Member of the National Assembly

First observations in the 19th century

The solar storm of 1859, known as the Carrington Event, is to date the best documented extreme event on the effects of solar activity on Earth. In late summer 1859, this large-scale solar flare produced numerous polar auroras visible even in some tropical regions, such as the Caribbean, and severely disrupted electric telegraph telecommunication systems, in some cases causing damage to the stations. This was the first time that a link was established between the discovery of a solar flare – i.e. a brightening observable near a sunspot – and the subsequent disruption, seventeen hours later, in the Earth's magnetic field, causing auroras to be visible at unusual latitudes.

We must therefore trace the beginnings of space weather back to this time, not as a set of variable phenomena affecting the Earth – they are of course as old as the Earth itself –, but as a scientific discipline that aims to account for them. Space weather can therefore be defined as the discipline aimed at understanding the influence of the Sun on the Earth's magnetic environment. This discipline is based on fundamental research in solar physics and looks into different environments, ranging from the solar core to the Earth's crust, focusing on their interactions.

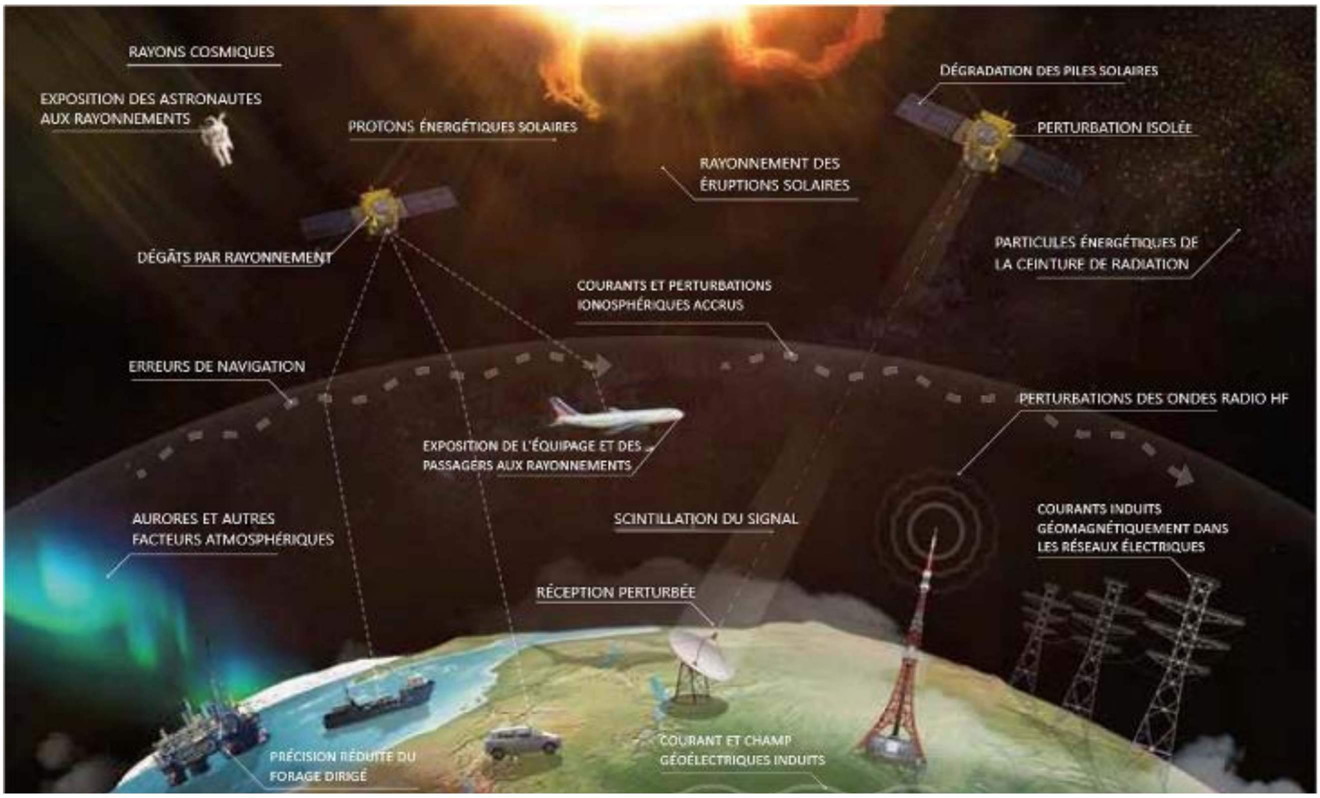
Space weather phenomena: some important consequences

The only space weather phenomena observable with the naked eye are the **auroras** that light up the polar night sky at high latitudes, either in the south (aurora australis) or the north (aurora borealis, from Boreas, the mythological North wind); [1] they are observed less frequently in the middle latitudes due to the geometry of the Earth's magnetic field. Their colour varies depending on the energy of the ionising particles (i.e. electrically charged) and the type of gas they are ionising (oxygen, hydrogen, nitrogen, etc.); at high latitudes, auroras are generally green, at the mid-latitudes, they have more of a pinkish red tint, like that observed in Brittany on 27 February 2023.

However, changing lifestyles expose us to some real risks in our daily lives. Transport and electricity distribution networks, also submarine cables and hydrocarbon transport systems are sensitive to currents caused by **magnetic storms**, which expose them to risks of overvoltage in the event of intense variations. In 2008, the American National Academy of Sciences extrapolated [2] the repercussions that an event of the same magnitude as the magnetic storm that the United States experienced in May 1921 could have in the 21st century:[3] it could cause ground currents of an intensity capable of knocking out 300 key electrical transformers, thus depriving 130 million Americans of electricity and causing damage not only to infrastructure, but also to individual equipment.

The use of Earth's ionosphere for radio communication and the deployment of fleets of satellites have also resulted in space weather phenomena becoming a hazard to be taken into account on a more regular basis. The ionosphere is modified by variable X-rays and UV radiation from the Sun, which affects the propagation of radio communications, damages the quality of Global Navigation Satellite Systems (GNSS) and may disrupt the navigation of satellites in low orbit due to the atmospheric drag effect.[4] The flow of high-energy particles linked to the activity of the Sun and the magnetosphere can accelerate the aging of the electronics on board the satellites, and cause computer errors or reduce the power of the solar panels that supply them with energy. "Puffs" of radio waves emitted by the Sun may even disrupt air surveillance radars.[5] Thus as a result of our technological age, there are new risks that have to be taken into account.

The risks to health are extremely low, however. In a 2014 guidance note,[6] the UK Health Security Agency recalled that 12% of the average radiation dose received by the UK population comes from cosmic rays. It pointed out that solar storms could occasionally produce increased doses – higher at altitude than at ground level –, but that this phenomenon is rarely measurable and that even a one-hundred-year event would not measurably affect an individual's lifetime risk from radiation.[7]



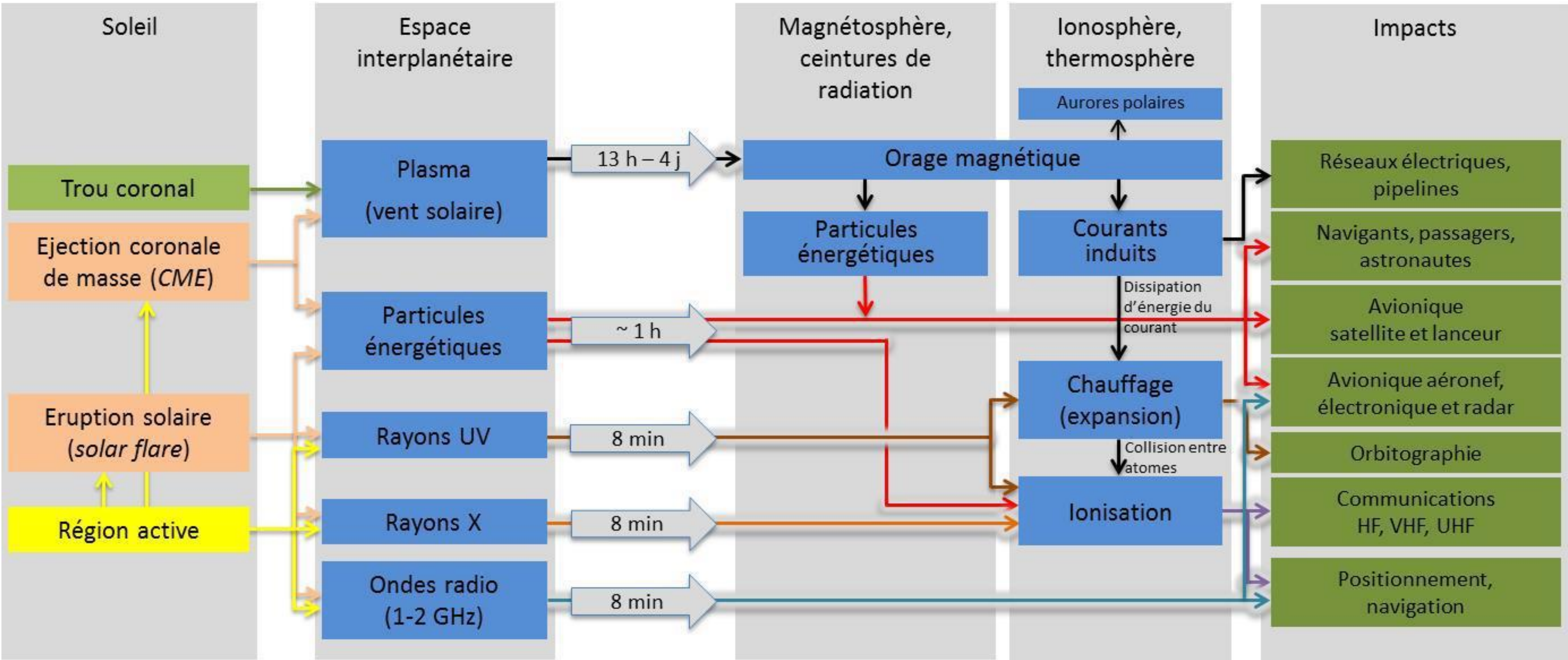
In Larisa Trichtchenko and Kenneth Holmlund, "Space Weather, Extending the Borders Beyond the Earth", World Meteorological Organisation (WMO) Bulletin 2021 (volume 70 (2)) @ESA/Science Office, CC BY-SA 3.0 IGO.

Routes to better forecasting

We must hope that it will one day be possible to draw a parallel between developments in space weather, which is currently flourishing, and those in terrestrial weather, which has evolved over just a few decades. A hundred years ago, it seemed that variations in rainfall and good weather had to be accepted inevitably, as if they were the result of pure chance, despite their age-old and seasonal regularity. The science of meteorology has grown through our understanding of the underlying physical phenomena, observations on the ground and from space, and developments in modelling. In just a few decades, the capability to forecast the weather on Earth has been extended by one day every ten years.[8]

To see space weather develop in the same way, we need **a better understanding of the physics of the Sun**. Contrary to popular belief, the Sun is not a star emitting invariable radiation: there is such a thing as solar weather. From the beginning of the second millennium BCE, Chinese astronomers observed black spots on the surface of the Sun. The abundance of sunspots follows a cycle of between ten and thirteen years.[9] The solar maximum in the current solar cycle is expected in 2025.

DIAGRAM OF SUN-EARTH RELATIONSHIPS



This diagram and paragraph are taken from the report by the Space Weather Working Group (2017). The diagram shows the processes involved and their repercussions for Earth. The first column gives an overview of solar phenomena, differentiating between those that are relatively stable (green), and likely to return after one solar rotation, those that vary slowly at the same pace as solar activity (yellow), and which are also modulated by solar rotation, then eruptive phenomena linked to instabilities in the magnetic field of the corona, for which the conditions are created on a scale of approximately one day (orange). Disturbances cross interplanetary space (second column) then, if they intercept Earth, they impact the magnetosphere (third column), the ionosphere and the thermosphere (fourth column). The effects are disruptions in the geomagnetic field, ionisation and the heating of the Earth's upper atmosphere. On Earth, potential impacts concern technical equipment, radio wave communications and living beings on board space vessels and aircraft.

A major effort was begun in 1995 with the launch of the **SoHo mission** *(Solar and Heliospheric Observatory)*, a collaboration between the European Space Agency (ESA) and NASA.[10] The satellite that was launched is studying the internal structure of the Sun, the corona and the solar wind.

With the **Solar Orbiter mission**, scientists now have a satellite that is synchronous with the Sun's rotation. NASA contributed to the development of this European Space Agency (ESA) orbiter, which was launched in 2020. Its mission is to study the processes behind the solar wind, the heliospheric magnetic field, solar energy particles, transient interplanetary disturbances and the Sun's magnetic field.

In December 2021, NASA's **Parker Solar Probe** mission collected particles from the Sun's upper atmosphere for the first time. Its broader aim is to trace energy flows and study the heating of the solar corona, and thus better understand the causes of the acceleration of the solar wind.

These missions are funded by international calls for contributions; in this way platforms can be developed that cost up to a billion euros.

Work is also ongoing to improve **knowledge of the near-Earth environment** and **modelling**. Researchers are already considering beacons that could be placed in space to measure the system at multiple points, thus providing data capable of constraining current models. In doing this, they are drawing inspiration from scientific models of Earth's weather to plan the deployment of satellite constellations that will provide data in real time from several points in space, so that the models can be refined.

■ Strong international cooperation where France must maintain its position

Two programmes are underway at the European Space Agency (ESA): the *Space Security Programme* (S2P)[11] and the *Space Situational Awareness Programme* (SSA, Period 3).[12] In this context, the aim of the RB-FAN project *(Radiation Belt Forecast and Nowcast)* is to provide data in virtually real time *(nowcast)* and 3 days ahead *(forecast)* on the state of Earth's radiation belts.[13]

In 2016, the World Meteorological Organisation (WMO) adopted a four-year plan for space weather; a second plan covers the period 2020-2023. In particular, its aim is to analyse, validate and assess the information collected on exploitation-oriented space weather models,[14] addressing the scientific challenges that currently hinder the development of space weather services, for example the impossibility of predicting the magnetic structure of ejections of coronal material or checking the effect threshold for services intended for air navigation.

France is heavily involved in all the major missions. French stakeholders are getting together to take part in the construction of a range of space weather services.[15] For example, the Sievert website already enables civil aviation, and the general public, to assess the radiation dose received during a flight.[16]

Launched in 1997, the National Sun-Earth Programme (PNST) is centred on the study of the Sun-Earth system from the generation and emergence of the magnetic field at the surface of our star and the associated flares and ejections of matter, to the impact on the Earth's magnetosphere, ionosphere and thermosphere, and including the dynamics of the solar wind.[17]

Since 2019, *Météo France, Collecte Localisation Satellites*[18] and *European Satellite Services Provider* have been operational on behalf of the International Civil Aviation Organisation (ICAO), providing significant research support. The ICAO also collaborates with the French Air Force around the FEDOME warning system.[19, 20] In the context of S2P, space weather service demonstrators have been set up.

On an operational level, the aim of the French Organisation for Applied Research in Space Weather (OFRAME)[21] is to meet the needs of the academic world, public bodies and industry in an efficient and structured manner. It is very much involved in organising important meetings, such as *European Space Weather Week*.[22]

Thus, it is essential that France maintains a significant commitment to research in order to retain its position in the field of space weather, an area that is still new but of great importance for all of our societies.

The Office's websites:
http://www.assemblee-nationale.fr/commissions/opecst-index.asp
http://www.senat.fr/opecst

Persons consulted

- *Mr Sébastien Bourdarie, research director at the French National Office of Aerospace Studies and Research (ONERA), specialising in external geophysics, notably in the research field of radiation belts*
- *Mr Alexandre Bresson, research engineer at the French National Office of Aerospace Studies and Research (ONERA), researching into instrumental physics, notably quantum sensors*
- *Mr Allan Sacha Brun, research director at the French Atomic Energy Commission (CEA), team member of the European Whole Sun project (www.wholesun.eu)*
- *Mr Jean-Marie Carrière, director of meteorological services at MétéoFrance*
- *Mr Ludwig Klein, astronomer at the Meudon Observatory, member of the French National Air and Space Academy, specialising in solar physics*
- *Mr Jean Lilensten, researcher at CNRS, specialising in polar auroras and head of space weather*
- *Ms Aurélie Marchaudon and Mr Alexis Rouillard, researchers at the Research Institute in Astrophysics and Planetology (IRAP), in the joint research unit CNRS/Université Paul Sabatier – Toulouse III*
- *Mr Henry de Plinval, Deputy Director of the Department of Physics, Instrumentation, Environment and Space (DPHY) at ONERA.*

Références

[1] Because they are visible, these "occasional spectacular displays of the aurora borealis or australis" are presented as an 'exception' among space weather phenomena in Larisa Trichtchenko and Kenneth Holmlund, "Space weather, extending the borders beyond the Earth", Bulletin 2021 (volume 70 (2)) World Meteorological Organisation (WMO).

[2] National Research Council 2008. Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop Report. Washington, DC. The National Academies Press (https://doi.org/10.17226/12507).

[3] Hapgood, M. (2019). The great storm of May 1921: An exemplar of a dangerous space weather event. *Space Weather,* Vol. 7-17, July 2019 (https://doi.org/10.1029/2019SW002195).

[4] Noé Lugaz, Huixin Liu, Brett A. Carter, Jennifer Gannon, Shasha Zou, Steven K. Morley, "New Space Companies Meet a 'Normal' Solar Maximum", *Space Weather,* Vol. 21-9, September 2023 (https://doi.org/10.1029/2023SW003702).

[5] See LESIA - Laboratoire d'études spatiales et d'instrumentation en astrophysique (Observatoire de Paris): "6-10 septembre 2017 : une soudaine recrudescence de l'activité solaire", 11 September 2017 (https://lesia.obspm.fr/10-septembre-2017-une-soudaine.html); in a slightly different register, see also: "A Solar Storm Reportedly Made Airplanes Disappear From Radars" (https://www.iflscience.com/airplanes-disappear-swedish-radars-due-solar-storm-31788) and "The Sweden Case: Airplanes disappear from radars due to 'solar storm'" (https://watchers.news/2015/11/05/the-sweden-case-aircrafts-disappear-from-radars-due-to-solar-storm/).

[6] UK Health Security Agency guidance on space weather and radiation (https://www.gov.uk/guidance/space-weather-and-radiation).

7 For a detailed analysis of radiation exposure caused by a solar storm, see, for example, N. Larsen, A. L. Mishev, "Analysis of the Ground Level Enhancement GLE 60 on 15 April 2001, and Its Space Weather Effects: Comparison With Dosimetric Measurements", *Space Weather*, Vol. 21-8, October 2023. The article models the impact of one of the strongest events during solar cycle 23, on 15 April 2001, for different altitudes and latitudes. To test the relevance of this model, the authors compare two values for the dose received during a Prague-New York flight on the day of the event, on the one hand the dose estimated by their model with upper bound hypotheses and on the other hand that measured by a dosimeter on board the aircraft. The measured exposure was 55 µSv and the modelled exposure 75 µSv. After discussing the significance of this difference, the authors point out that, in normal flying conditions (i.e. not during a solar event), the exposure estimated by the model is 40 µSv. The impact of the solar event is therefore virtually to double the received dose. Finally, the authors state that the real flight contributed 2.5% of a pilot's annual dose, for a flying time of 7.5 hours.

[8] This estimate of the progress made over the last decades in terms of weather forecasting on Earth is taken from a presentation given in 2012 at ENS Ulm by .Jean-Marie Carrière (see list of persons consulted) on the state-of-the-art and the progress to be expected in meteorological and hydrological predictability (http://savoirs.ens.fr/conferencier.php?id=920).

[9] See Jean Lilensten et al., op. cit. note 1, p. 37-38. In particular, the authors make reference to the Chinese astronomical treatise by Song Shi (宋史), completed in 1345 and dealing with the period of the Song dynasty (960–1279).

[10] SoHo Mission on the CNES website: https://soho.cnes.fr/fr/soho/en-resume/accueil; also on the ESA website: https://www.esa.int/Science_Exploration/Space_Science/SOHO_overview2 and the NASA website: https://soho.nascom.nasa.gov/home.html.

[11] https://swe.ssa.esa.int/space-weather-and-space-safety-programme.

[12] https://www.esa.int/Space_Safety/The_story_so_far.

[13] Example of RB-FAN project: https://pnst.ias.u-psud.fr/sites/pnst/files/poster_PNST2022_AFERLIN_16.pdf.

[14] Four-year plan 2020-2023 for WMO space weather activities (https://wmoomm.sharepoint.com/sites/wmocpdb/_layouts/15/download.aspx?SourceUrl=%2Fsites%2Fwmocpdb%2Feve%5Factivityarea%2FWMO%20Space%20Programme%20%28WSP%29%2F7%2E%20Space%20Weather%2FWMO%20SWx%20FYP2020%2D23%2F2019%2DMISC%2DOBS%2DSPACE%2DWEATHER%2DFOUR%2DYEAR%2DPLAN%2D2020%2D2023%2D19258%5Ffr%2Epdf).

[15] ESA already offers a range of services through the ESA Space Weather Service Network (https://swe.ssa.esa.int/user-domains). This is organised to provide 39 services distributed over 8 domains targeting specific groups of end users. The service domains are: Spacecraft Design (SCD), Spacecraft Operation (SCO), Human Space Flight (SCH), Launch Operation (LAU), Trans-ionospheric Radio Link (TIO), Space Surveillance & Tracking (SST), Non-space System Operation (NSO), and General Data Services (GEN). The NSO domain groups together several sub-domains, including auroral tourism, aviation, power system and pipeline operation.

[16] https://www.sievert-system.org/.

[17] The website of the national Sun-Earth programme (PNST) is a mine of information on the latest French and international research in the field of space weather (https://pnst.ias.u-psud.fr/fr/presentation/objectifs).

[18] *Collecte Localisation Satellites* provides information on the ocean and regional forecasting ocean models adapted to assess, protect and manage coastal areas and maritime activities (https://www.cls.fr/).

[19] Forecasts are obviously useful for managers of civilian satellites, communications and terrestrial networks, but analysis of space weather disturbances is also of military significance. If satellites are exposed to ionising particles that may damage them, or if radio communication is disrupted, it must be possible to analyse from the data collected whether the disruption is due to a solar event or to an attack (jamming, dazzling, induced radiation, etc.).

[20] *Le Monde,* 13 May 2013, "Les militaires français scrutent les colères du Soleil", by Vahé Ter Minassian, (https://www.lemonde.fr/sciences/article/2013/05/13/les-militaires-francais-scrutent-les-coleres-du-soleil_3176446_1650684.html).
An instructive 5-minute presentation video is also available: https://www.youtube.com/watch?v=4iJPgjPHal4.

[21] OFRAME was created by INSU (National Institute of Sciences of the Universe at CNRS), CNES, CEA and ONERA (http://www.meteo-espace.fr/).

[22] French National Centre for Space Studies (CNES), Prospective scientific seminar, 8-10 October 2019, Le Havre, p. 116-125 (https://sciences-techniques.cnes.fr/sites/default/files/drupal/202009/default/st_actes-sps_rapport-complet.pdf (report from the last five-year meeting).