



Sentinels4Carbon (Sense4Fire)

Sentinel-based fuel, fire and emissions products to constrain the changing role of vegetation fires in the global carbon cycle

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Scientific roadmap

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1 Introduction

This document provides recommendations for further scientific support activities within the context of the ESA Earth Observation (EO) program and in particular the ESA Carbon Science Cluster (CSC). The ESA CSC aims at contributing to the establishment of a strong European carbon cycle research area while also encouraging networking, collaborative research, and international collaboration. This roadmap is based on the experience obtained during the ESA funded Sense4Fire project complemented with wider scientific knowledge including conferences and workshop participation of Sense4Fire members. This roadmap in particular defines a scientific agenda addressing the main scientific and observational gaps in this specific domain of science. The roadmap to a certain extent expands on the findings and recommendations from the ESA FLARE white paper (Hamilton et al., 2024). It also links to – an implicitly takes elements from – the EUMETSAT Future Focus workshop on fires from November 2024 where Sense4Fire was also presented (EUMETSAT has a workshop white paper in preparation).

This roadmap focuses on potential improvement of fire emission estimates, reconciliation of model approaches, the generation of EO products needed, and the instruments/missions required. It identifies the potential for exploitation and evolution of the fire characterization database. It provides considerations for new data products to include in the future (with an associated justification) and the potential for linkage to tools already developed by ESA (and wider where relevant) and interfaces required. It also includes a discussion of existing and future satellite instruments/missions that could add value to suite of tools used and developed in the Sense4Fire project. For example, the Sentinel Next Generation satellites will extend the Sentinel First Generation observational records while providing performances equal to or better than the Sentinel FG satellites that have been the backbone of the Sense4Fire activities. Additionally, Earth Explorer missions such as the BIOMASS missions (launch date 29 April 2025) will provide crucial information about the state of our forests and how they are changing.

This roadmap further provides recommendations to ESA to advance the use of EO technology to address the main knowledge gaps and scientific challenges associated with fires and their societal impacts. Its suggestions and recommendations could be incorporated in activities like ESA Climate Change Initiative (CCI) which aims to develop a suite of satellite data records of key components of the climate system. (Wild)Fire is one of the Essential Climate Variables identified by the Global Climate Observing System (GCOS) program of the World Meteorological Organization (WMO) that requires detailed monitoring. The developments in Sense4Fire have the potential to broaden the definition of fire as an Essential Climate Variable which has been so far focused only on fire detection (e.g. burnt area, active fires and fire radiative power) but not on fuel load, fuel moisture, combustion or fire emissions.

2 Review of resolved science questions and remaining knowledge gaps

The Sense4Fire provided set out to provide answers to the following scientific questions:

How do ecosystem changes influence fuel dynamics and fire behaviour?

Changes in land cover and ecosystem structure generally increase the availability of surface fuels such as litter and woody debris, unless those fuels are removed through human management

activities. Those surface fuels decrease combustion efficiency as the surface as well the piling of burning material on the surface hampers resupply of oxygen. Hence why burning litter and woody debris increase the smouldering combustion and production of CO emissions. This has been shown by using the TUD-S4F data model fusion approach which allowed to quantify the effect of surface fuels on fire emission factors (Forkel et al., 2025). Burning of woody debris and litter are a dominant source of fire emissions of forest fires and deforestation fires in the Amazon and Cerrado regions.

As a consequence, there is a strong need for more field observations on woody debris loads, its decay, density and chemistry to refine estimates of fuels, fuel combustion, emission factors and emissions and their large-scale effects on the atmosphere. For a long time, estimating wildfire emissions from satellite observations relied on a limited set of parameters that converted satellite observations into emission amounts. It is clear from the Sense4Fire results that emission factors are much more variable and depend on a range of environmental conditions that vary in space and time. Real world evaluation of spatio-temporally varying parameters that define emissions therefore is now very much needed.

In addition, Sense4Fire also highlighted large uncertainties in fire emission estimates simulated by dynamic global vegetation models, in turn driven by variations in fuel loads and combustion, particularly in deforestation fires. Global fire models have inaccurate estimates of fire emissions that are partly related to deforestation fires (Li et al., 2019). The Sense4Fire data helped in evaluating and reformulating global models for deforestation and the associated dynamics of fuel accumulation and decay (de Laat et al., 2025; Forkel et al., 2025). More effort based on the same approach expanding to other regions is warranted.

How do fires contribute to short- and long-term carbon emissions?

The Sense4Fire products have not been specifically analysed to investigate long-term fire emissions and hence the project does not provide a direct answer this question. However, the results from two main Sense4Fire approaches to estimate emissions (from the Global Fire Atlas - GFA-S4F and the Technical University Dresden - TUD-S4F) were used to quantify direct short-term fire emissions (Forkel et al., 2025; de Laat et al., 2025). In addition, the estimates of temporal dynamics in vegetation biomass and surface fuel loads from TUD-S4F provide information to derive the development of ecosystem carbon stocks and to analyse as a temporal derivative the long-term development of respiration from previously fire-affected fuels. Hence, the methodological developments and products from Sense4Fire indirectly provide crucial information to investigate post-fire carbon emissions in future studies.

What role do uncertainties play in estimating total fire-related carbon emissions?

A detailed uncertainty analysis was conducted for the 2020 fire season in the Amazon and Cerrado (Forkel et al., 2025) from which the following text is taken: Across several EO-based approaches, median total dry matter burnt (DMB) is 372 Tg ranging from 288 to 605 Tg DMB (6 estimates). The TUD.S4F approach estimates total DMB of 407_{277}^{537} Tg with a parameter uncertainty 32%. CO emissions are $39.1_{27.0}^{49.7}$ Tg across all EO approaches and $43.7_{28.8}^{58.6}$ Tg in TUD.S4F, aligning with the S5p.KNMI top-down validation estimate of $43.6_{32.7}^{54.5}$ Tg, which includes an uncertainty of 25%. The estimated DMB vary significantly at local to regional scales, with uncertainties up to 60%.

The results for the exceptional 2024 (sub)tropical South American fire season (de Laat et al., 2025) indicate that fire carbon emissions (both CO and CO₂) are largely underestimated even in state-of-the-art fire emission databases by up to a factor of three and with significant inter-dataset differences. This case could be considered as “out of sample test” for the state-of-the-art fire emission algorithms which have been developed and have been tuned on more typical fire seasons. The unexplained and thus unaccounted for emissions are hypothesised to be related to undetected small and mostly smouldering fires, consistent with recent progress in fire detection science. The currently commonly used satellites for fire monitoring like MODIS, VIIRS and Sentinel-3 can only detect fires above a certain size and magnitude due to the sensitivity and spatial resolution of the satellite sensors.

The Sense4Fire project and recommendations of the 4th Carbon from Space Workshop

The Sense4Fire project thereby contributed to several recommendations that resulted from the 4th Carbon from Space Workshop in 2022 (ESA, 2023). Note that that workshop was organized while the Sense4Fire was already ongoing. The Sense4Fire proposal and activities thus never were tailored to those recommendations.

In essence, Sense4Fire contributed by bringing together different expertise and state-of-the-art data and approaches from different crucial domains: terrestrial remote sensing of vegetation conditions, estimating biomass burning emissions based on earth observation data, atmospheric composition measurements from earth observation data and atmospheric composition modelling. The activities initially focused on developing integrated approaches to assess biomass burning emission estimates, but expanded towards exploring the potential for operationalization of these approaches which included the use of AI/ML to speed up certain aspects of the data processing and production.

The most important recommendations from the 4th Carbon from Space Workshop (ESA, 2023) that the Sense4fire project contributed to are:

- **[R1]** Identify and improve quantification of the major unknown or uncertain components the carbon budget (incl. CO₂) with an emphasis on the terrestrial component.
- **[R3]** Rapid updating (annual) of regional emission budgets and higher spatial resolution products to support smaller national-scale studies.
- **[R9]** Exploration of how expanding earth observation capacity and increasing data richness can be used to maximize understanding of the carbon cycle. Take advantage of current and upcoming data across variables and for variables from different data types. Identify gaps in terms of spatial and temporal provision.
- **[R13]** Improve understanding of the interaction between the carbon cycle and other cycles (e.g. water-energy-nitrogen). Develop a consistent and long-term observation approach over space and time. Establish historical estimates that are consistent over space and time and for different satellites (all space agencies). Provide clear intercomparison and validation outcomes that are globally representative.
- **[R19]** Develop approaches towards bridging disagreement of carbon budgets from top-down (atmospheric observations of carbon gases) and bottom up (observation of the surface characteristics and the resulting emissions). Estimates can differ because of issues with models and data provision/comprehensiveness (in space and time and height and including

uncertainty) with resulting disagreement in the budget calculations. Experiments over key regions with top-down and bottom-up data available needed – possibly RECCAP size areas.

- **[R39]** Strategic coordination and cooperation of relevant programs on addressing the land carbon cycles and challenges that exist by Space Agencies and other key funders/actors to maximize the opportunities that exist.
- **[R44]** The proliferation of data means new approaches to data handling are also required constrained by scientific understanding. In addition new approaches to handling the increasing resolution and complexity of land surface/carbon models are needed to allow faster scenario assessment. Space Agencies need to undertake exercise in data exploration with AI. There is a need for model emulators to allow rapid testing of scenarios and to examine model behavior against data-driven equivalents. This requires coordination between model teams, AI expertise and data experts (in situ and EO)
- **[R46]** Space Agencies should develop a Data-based characterization of the carbon cycle for RECCAP regions in the form of RECCAP-Ready Data (RRD) to allow annual updates of RECCAP in parallel to the expert assessment.

The RECCAP (REgional Carbon Assessment and Processes) exercise involves significant effort in gathering together models, in situ, air and satellite observations to compile a large area assessment of the carbon cycle and by synthesis arrive at a global budget. A major strength is the compilation of assessment by experts in each region. However, this exercise takes significant time and is not considered practicable annually especially if 3 GHGs are planned (N₂O, CO₂, CH₄). Space agencies can improve the turnaround if they produce RECCAP-Ready Data for regions, with appropriate latency, which can supplement the assessment and be used to provide updates.

3 Future developments of the fire characterisation database

The Sense4Fire project has shown that fire characterisation databases can be improved by applying more elaborate data processing techniques and/or making use of new/more earth observation data than has been done over the past two decades. In addition, the new generation of atmospheric composition satellite instruments allow new and much more extensive evaluation of fire characterisation databases.

The Sense4Fire project specifically focused on bringing together different expertise and state-of-the-art data and approaches for developing integrated approaches to assess fire emission estimates. However, not all possible applications and approaches for fire emissions using European Earth observation dataset could be explored. There are many future developments which would benefit the fire characterisation database. This roadmap in detail addresses the following “talking points” and per bullet provides in the following a list of specific recommendations:

- *in situ* observations for development and validation of the fire characterisation database
- Operationalisation of the fire characterisation database for near-real time monitoring
- Development and integration of the Sentinel expansion, evolution and future earth explorers for characterisation of fire dynamics
- Use of the fire database for the development of global vegetation/fire models and earth system models

3.1 Assessment of required *in situ* observations for development and validation of the fire characterisation database

Currently there exist limited possibilities for validation and characterisation of wildfires and biomass burning based through *in situ* observations. Field campaigns and monitoring stations are expensive (and thus rare) and relevant and interesting locations are often remote, hampering logistics and maintenance. Environment conditions can be hazardous during intensive fire episodes with the possibility that field campaigns have to be cancelled. Currently available *in situ* data for characterizing wildfires will not be representative for the widely varying wildfire types and environmental conditions. Hence there is a need for more local measurements and information important for evaluation, validation and benchmarking.

In particular there is a need for detailed local information:

- Properties of fuels such as fuel type, physical properties (size, volume, density), chemical properties (fuel moisture, cellulose, lignin, extractives, decomposition state) and analyses and method development to quantify those properties from satellite observations.
- Quantification of surface fuel properties given the high importance of woody debris and litter for fire emissions
- Fire emissions (emission factors, completion of combustion, chemical fuel properties).
- Injection heights of emissions (incl. effect of added heat and buoyancy).
- Emission plume characterisation (dynamics, effect of added buoyancy, chemistry)
- Sites and field campaigns covering different fire regimes to monitor temporal dynamics in pre- and post-fire fuel and quantify impacts on fires.
- Atmospheric composition measurements (trace gases)

Recommendations

Support to improve and expand *in situ* observations and campaigns and the coordinated collection and/or harmonisation of existing *in situ* data in global databases of fuel properties and fire smoke plumes. This could be achieved through ESA funding initiatives (e.g. similar to activities like <https://data.geo-trees.org>) or by advocating for funding from other organizations, both at national levels, and through pan-European institutions and organizations.

3.2 Possibilities for operationalisation of the fire characterisation database for near-real time monitoring

There is a strong need and there are equally strong ambitions in atmospheric and climate research communities towards operational monitoring of the Earth system including timely updates of emissions. As fires – identified as an Essential Climate Variable - are an important and integral part of the Earth system and significantly contribute to air pollution and greenhouse gas emissions, an operational monitoring capacity of fires and associated emissions should be an integral part of that global operational monitoring system.

There are currently already operational near-real-time fire monitoring systems that provide fire emissions. Similar systems also exist for monitoring vegetation conditions, fire risk, for monitoring fire weather and early warning fire detection (e.g. European Forest Fire Information System, Copernicus Atmosphere Monitoring System/Global Fire Assimilation System). However, these

were not the focus of the Sense4Fire project. New analyses based on new satellite data – including those from the Sense4Fire project – have proven that there is significant room for improvement in fire emission estimates including those from the existing operational near-real-time fire monitoring systems. Furthermore, the Sense4Fire project has also shown that state-of-the-art and innovative new approaches aimed to derive more accurate fire emissions can indeed also be used for near-real time monitoring (here defined as the availability of emissions within approximately two weeks). There are, however, a number of conditions or requirements for such an operational system to be valuable and thus successful:

- ✓ that sufficient computational resources are available
- ✓ that the suite of tools like those in Sense4Fire provide fire data fast enough (timely)

The latter not only depends on the former - sufficient computation resources - but also on the computational efficiency of the algorithms themselves, the latency of inputs that are needed and the level of continuity of production that is required.

The innovative methods introduced and explored by Sense4Fire are more computationally intensive than existing fire emission monitoring systems. This is part related to ingestion of much more data and because more data and refinement require more calculations. The computational resources used/available within the Sense4Fire project did for example not allow for global near-real-time monitoring. Hence within the Sense4Fire project the focus was on a limited set of regions representing different fire types and vegetation conditions. In order to make the Sense4Fire results global and have results readily available, upscaling or a more targeted use of computational resources is necessary, possibly combined with re-engineering algorithms and/or development of learning algorithms (AI/ML) trained on the current computationally expensive algorithms.

That may still be insufficient to reach the requirement of timely data provision so future activities should also explore other directions that enable near-real-time monitoring. The Technical University Dresden for example developed a learning algorithm that estimated emissions trained on their full fuel characterisation and emissions algorithm (TUD-S4F). Their formal algorithm was too computationally intensive and the required input data (e.g. Copernicus leaf area index and land cover maps) were not timely available to provide fuel dynamics and fire emissions within two weeks. Further development and efforts for a more real-time production of basic Earth observation products such as leaf area index and land cover change as well as optimisation of methods or alternatively the development of machine learning emulators is therefore needed to adopt it for routine application.

Finally, the CAMS GFAS system provides daily updates of emission estimates, based on user requirements. The capacity of the innovative Sense4Fire algorithms to produce ancillary data on fire characteristics on a daily basis was not tested, user needs for such information should also be explored. One could envision a joint system of emissions of near-real-time, offline, and reanalysis that provide information on timescales of one day, one month, and one year. Note that defining user needs for the products on fire characteristics offered by Sense4Fire algorithms were not a formal part of the project.

Based on what is discussed above one could envision a following suite of data processing chains:

- **Near Real Time** (NRT) data would be aimed at quick looks and fast assessments and is the least accurate data, not meant for trend analysis. Likely this would include some form of AI/ML.
- **Offline** (OFFL) data would be more sophisticated and fully accountable without the mathematical shortcuts of AI/ML in the NRT data. OFFL data would typically become available within weeks to a month. For the OFFL processing underlying data may change over time, for example by an algorithm change or recalibration. The OFFL processing would be simply applied to the new underlying data without modifying the OFFL data prior to the switch in the underlying data. OFFL data thus could be not fully consistent.
- **Reprocessed** (RPRO) data on the other hand would be processed in one go with one fixed set of underlying data, making it stable and best suited for long term trend analysis and use in for example climate modelling like CMIP and FireMIP. RPRO data would only be produced every couple of years or so.

OFFL data and RPRO data could contribute to efforts to provide annual assessments of the global state of fire (Jones et al., 2024) as part of a community effort to avoid discrepancies between methods, assumptions and data dependencies. However, that would require careful planning and testing, as users might focus one particular dataset and not acknowledging/updating their data use when better/more accurate data becomes available.

Finally, synergy with other (European) activities on emission monitoring and earth observation dataset and application development is important. These communities are either dataset providers, main users or provide linkages with other user communities. Activities within this context should focus on obtaining and providing feedback in various directions. Some communities are already in place, such as ESA's EarthCODE initiative, the ESA Stakeholder Engagement Facility (ESF) and the ESA Carbon Science Cluster.

Recommendations

- Exploration and assessment of computational resources needed for global operationalisation of the innovative tools used and developed within the Sense4Fire project with in particular a focus on the ESA Earth Code facilities.
- Exploration and assessment of the Sense4Fire tools (or their likes) identify innovations needed to provide timely global near-real-time fire emission data. This includes the development and use of learning algorithms (AI/ML) as emulators.
- Establish links with the emission monitoring community – for example the Copernicus CO₂ Monitoring and Validation Service (CO2MVS) – to jointly start adopting developments from Sense4Fire in the CO2MVS tools. For example, emissions and conversion factors used in GFAS could be updated based on findings in Sense4Fire.
- Assess user needs for which timeliness is needed or preferred for various data products on fuels and fire. This could be part of activities from the previous recommendation.

3.3 Recommendations for the development and integration of the Sentinel expansion, evolution and future earth explorers for characterisation of fire dynamics

3.3.1 Geostationary satellites

Integration of geostationary satellite data into earth observation-based fire emission algorithms could contribute to provide true near real time fire emissions estimates. New generations of satellites like the EUMETSAT METEOSAT Third Generation (MTG) series provide useful information for fire monitoring. The sub-satellite spatial resolution of the geostationary MTG Flexible Combined Imager (FCI) instrument - and the American geostationary GOES satellites likewise - has started to approach that of the MODIS satellite. FCI also provides continuous observations throughout the day compared to the twice-per-day overpass of polar orbiting satellites like MODIS.

Furthermore, FCI provides new wavelengths for surface monitoring and the so-called "IR 3.9 micron channel" has been optimised for temperature anomaly detection which can be used for estimating fire radiative power. The Geostationary MTG data thus allow for better monitoring an important aspect of the fire diurnal cycle compared to both the METEOSAT Second Generation (MSG) satellites but also Polar orbiting satellites such as MODIS, VIIRS and Sentinel-3. It would also be worth exploring FCI visible wavelength channels for deriving burned area.

The geostationary MTG/Sentinel InfraRed (IR) and UltraViolet/Visible (U/VIS) sounders (will) also provide information about trace gases and smoke (Sentinel-4) and possibly even diurnal variations in burned area.

There are also limitations to geostationary satellites. For global coverage multiple geostationary satellites are needed (geo-ring) which requires effort into inter-instrument calibration. In addition, pixel sizes of geostationary satellite observations increase away from the sub-satellite viewing point, for example viewing in a more westerly or easterly direction. Also, north of approximately 60°N the usefulness of geostationary satellites for fire monitoring rapidly decreases due to the scant viewing angle. Even further north – beyond approximately 75°N – geostationary satellite observations are not useful for monitoring latitude fires. Whereas interest in fires the Arctic and northern boreal regions has been increasing due to a warming climate.

Note that similar observational capacity exists for other geostationary satellites including the American GOES⁴ satellites and the Japanese HIMAWARI satellites. It is imaginable that over time a so-called "geo-ring" of fire monitoring applications could be feasible.

The European geostationary satellite instrument InfraRed Sounder (IRS) further provides information about atmospheric weather conditions that are also relevant for fire monitoring and fire characterisation, in particular in relation to "fire weather". In addition, the IRS instrument also allows measurements of a range of fire-relevant atmospheric trace gases including long-lived carbon monoxide but potentially also short-lived gases such as NO₂, NO, N₂O₅, HNO₃, PAN and C₂H₂. However, the sub-satellite spatial resolution of the IRS instrument of 4x4 km and the temporal coverage of once per hour over Europa (less so over Africa) is worse than for example the FCI instrument. In addition, IRS only covers the Euro-African Earth disc, and as no analogue instruments exists on other geostationary satellites can only provide information wildfires over that part of the globe. Also, note that the IRS measurement frequency differs spatially: 30 minutes

over Europe, 3 hours over the Sahara and the Sahel and 6 hours for equatorial the southern half of Africa.

3.3.2 Polar orbiting satellites

The Sentinel-5p data shows that Earth observation of atmospheric composition has reached a quality and refinement allowing observations of daily fire emission plumes of sufficiently large fires on a daily basis. This allows to link fire specific characteristics to emissions. And there have already been several approaches developed (to identify emission plumes in Sentinel-5p data by making use of new learning algorithms for pattern recognition (Finch et al., 2022; Goudar et al., 2023; Kurchaba et al., 2023; Schuit et al., 2023). Some of the emission plume detection approaches also incorporate estimates of emissions. Those activities could be expanded towards applying various existing emission inversion approaches that have not been applied to fire emission plumes before (from Gaussian plume modelling to formal emission inversions).

Moreover, a fire-specific-emission database then could be combined with vegetation condition databases to identify and explore relationships. This does also require efforts towards inter-comparison of various land use / land cover (LULC) databases (see further below).

There are several other existing and upcoming ESA satellites and satellite instruments that have the potential to further contribute to improve the characterisation of fire dynamics.

The EarthCare instrument (launched 2024) provides detailed information about the height of aerosols (smoke) layers (Wehr et al., 2023). The instrument – focused on measuring atmospheric particles - is specifically designed to separate cloud particles from aerosols (van Zadelhoff et al., 2023).

Sentinel-1 (Torres et al., 2012) has been considered for use within Sense4Fire but has not been applied within the Sense4Fire approaches so far. Sentinel-1 radar backscatter is suited for near real time deforestation monitoring and to assess carbon loss and gain (see the ESA S14SCIENCE AMAZONAS project, <https://sen4ama.gisat.cz/>), which could enhance the capabilities of the TUD-S4F to estimate dynamics of vegetation surface fuels. In addition, Sentinel-1 can be used to retrieve live fuel moisture content.

Note that there will be a continued need for sun-synchronous polar orbiting satellites such as Sentinel-5p or Sentinel-3 for intercomparison and calibration, even if geostationary satellites are becoming increasingly advanced. The sun-synchronous polar orbiting satellite will always have – compared to geostationary satellites - the benefit of a consistent and near identical the surface illumination angle on the planet underneath. In addition, they also benefit from being much closer to earth which in principle leads to favourable spatial resolutions.

3.3.3 Upcoming ESA satellites

The very recently launched BIOMASS mission (Quegan et al., 2019) will allow to map the vertical distribution of vegetation layers in its TomoSAR mode, which can help to better estimate vegetation biomass in different layers (e.g. Liu et al., 2024) and hence their effect on surface fuel estimates. However, this requires the development of appropriate methods. Note that NASA is preparing the NISAR missions that similarly will map and characterize Earth's vegetation.

Satellite instruments like CO2M (Meijer et al., 2023) and TANGO (Landgraf et al., 2020) will provide more spatially refined information on emissions, including CO₂ that (also) allow for directly

monitoring CO₂ emissions from fire. Note that the primary focus of the TANGO missions is on anthropogenic emissions, not wildfire emissions.

Observations from ROSE-L (L-band Synthetic Aperture Radar) (Davidson and Furnell, 2021) could help to better estimate surface fuel moisture, biomass and fuel loads. In the long-term, the approach could also integrate observations from the future Copernicus High Priority Candidate missions.

3.3.4 Datasets based on satellite observations

Over the past decades multiple satellite-observation based land use / land cover (LULC) databases have been developed. Such LULC databases are used as input data for vegetation characterisation and emission calculations. Experience amongst the Sense4Fire consortium is that there are considerable differences between the various LULC databases. However, an integrated assessment of all these databases is lacking. How those LULC differences translate to differences in fuel load estimates and finally fire emissions are thus unknown. These provide incentives to support efforts towards a detailed integrated assessment of the currently existing and operational.

Finally, observations from LSTM (Copernicus Land Surface Temperature Monitoring) could help to better estimate evapotranspiration and hence fuel moisture content and could also help in the forecasting and detection of fires.

Recommendations

- Continue support for efforts to explore measurements from existing and upcoming satellites for their added value for, and use in, characterising fire dynamics.
- Continue support for integration of valuable data from new satellites into fire characterisation and fire emission databases.
- Provide support to harvest the potential of passive and active microwave satellite to quantify fuel loads and fuel moisture by developing appropriate methodologies.
- Support for refining atmospheric composition modelling. This involves both modelling the global atmospheric composition like the IFS-COMPO model at higher spatial resolution (5-10 km, possibly even better) as well as exploring and developing the use of large eddy model simulations of atmospheric composition that includes fire dynamics.
- Explore the integration of fire-relevant data from geostationary satellites and polar orbiting satellites with a particular focus on the synergy between both as they have differing pros and cons. This should also focus on synergetic use of passive and active satellite sensors.
- Setup activities for intercomparison and evaluation of land-use/land-cover databases which is currently non-existent and hampers decisions on which dataset is most suitable for what application.
- Develop and establish detailed fire emission databases based on assessment of individual fires for validation, evaluation and benchmarking purposes. This includes the use of such a database for learning algorithms (AI/ML) which require well established and benchmarked datasets to be trained on.

3.4 Recommendations for the use of fire databases for the development of global vegetation/fire models and earth system models

Sense4Fire project results have shown that fire emission estimates can be improved by using more and/or refined earth observation data to characterise fire dynamics and vegetation conditions.

Integrating these emissions into atmospheric composition models and subsequently intercomparing them with satellite measurements of atmospheric composition have proven to be a valuable method for evaluating bottom-up fire emission estimates. This approach has also been effective for assessing different global vegetation-fire models (OCN, JULES, and ORCHIDEE have been evaluated). Those models also participate in the Fire Model-Intercomparison Project (FireMIP) as part of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).

Based on those comparison we recommend that fire modelling teams should put higher emphasis on the evaluation and development of fuel properties and their effects on fire emissions. Currently, model validation of fuel loads and fuel moisture are limited as those models do not by default output surface fuel loads as woody debris or fuel moisture, for example. Also, most models do not account for live fuel moisture content, which is a variable that is nowadays readily available from several satellite products.

Recommendations

- Expand existing validation and benchmarking protocols for fire models to fuel properties, which includes to output fuel loads and fuel moisture from models by default.
- Strengthen connections between remote sensing and climate modelling communities in the field of fire science for evaluating the model representation of fires, for example within the Fire Model Intercomparison Project (FireMIP)
- Assist fire modelling teams to make satellite products more easily available by e.g. providing re-gridding tools, data cubes or by already providing re-gridded products. Effort is needed on providing and/or clarifying definitions, assumptions, data dependencies and strength and weakness.
- Evaluate historical CMIP model simulations over fire prone regions with satellite observations of atmospheric composition – like Sentinel-5p – as it was also done within Sense4Fire with IFS-COMPO
- Use observation-based fuel or fire emission estimates such as developed within Sense4Fire as input for historical DGVM or CMIP model simulations to assess the effect of an improved representation of fire dynamics and emissions on the estimated impacts on vegetation and the carbon cycle.
- Continue to work on - and expand - the framework for assessing and evaluating fire emissions based on earth observation data.
- Continue to support efforts on approaches that use and integrate the “richness” and detailed information about fire dynamics and fire conditions that can be derived from current and future satellite instruments (like Sense4Fire did)

Recommendations (continued)

- Explore the use of high(er) resolution models – from regional vegetation and climate models at the 1-10 km scale all the way to large eddy models at the 1–100-meter scale that solve turbulence related to fire-smoke-atmosphere interactions – so that all relevant scales are covered by these models and fire effects can be appropriately assessed.
- Explore the integration of the suite of numerical models and how to scale high resolution information about fire dynamics and vegetation conditions to the global vegetation/fire models and earth system models.
- Establish connections with emission monitoring activities, for example the Copernicus CO₂ monitoring and verification system (CO2VMS)
- Dedicated effort should be put into better characterizing and quantifying the effect of small fires on satellite-observations-based fire emission estimates. These hitherto have been underreported as the existing suite of satellite instruments was incapable of detecting them. Recent research results clearly indicate that this leads to an underestimation of fire emission estimates.

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