The WMO Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS): Concept, Current Capabilities, Research and Development Challenges and the Way Ahead

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ABSTRACT – Vegetation fires – including the application of fire in land use, land-use change and uncontrolled wildfire – affect the functioning of the Earth System and impose significant threats to public health and security. This paper presents the concept of a Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS). It describes the scientific rationale for the system and provides guidance for addressing the issues of vegetation fire and smoke pollution, including key research challenges. The paper proposes the establishment of VFSP-WAS regional centers and describes potential examples of this VFSP-WAS concept from two regions in (Southeast Asia and North America) where regional centers will partner with Regional Fire Monitoring/Fire Management Resource Centers.

Keywords: Fire and smoke pollution modeling; numerical weather prediction; atmospheric pollution observation; early warning systems.

Sistema de Consulta e Alerta de Poluição Causada pela Fumaça Decorrente do Fogo na Vegetação (VFSP-WAS) da Organização Meteorológica Mundial (WMO): Conceito, Capacidades Atuais, Desafios de Pesquisa e Desenvolvimento, e o Caminho a Seguir

RESUMO – O fogo na vegetação, incluindo a aplicação do fogo no uso da terra e na mudança de uso da terra, assim como os incêndios florestais, afetam o funcionamento do sistema terrestre e impõem ameaças significativas à saúde e segurança públicas. Este documento apresenta o conceito de um Sistema de Avaliação e Alerta de Poluição causada por Fumaça decorrente do Fogo na Vegetação (VFSP-WAS, na sigla em inglês). Apresenta-se o fundamento científico do sistema e diretrizes para abordar as questões de fogo na vegetação e poluição por fumaça, indicando-se os principais desafios para a pesquisa. O artigo propõe o estabelecimento de centros regionais VFSP-WAS e mostra exemplos potenciais do conceito VFSP-WAS em duas regiões (sudeste da Ásia e América do Norte), onde centros regionais VFSP-WAS trabalham em parceria com Centros Regionais de Monitoramento de Fogo/Manejo de fogo.

Palavras-chave: Modelagem da poluição por fumaça e fogo; previsão meteorológica numérica; observação da poluição atmosférica; sistemas de alerta precoce.

Sistema de Consulta y Alerta de Contaminación Causada por el Humo Resultante del fuego en la Vegetación (VFSP-WAS) de la a Organización Meteorológica Mundial (WMO): Concepto, Capacidades Actuales, Desafíos de Investigación y Desarrollo, y el Camino Adelante

RESUMEN – El fuego en la vegetación, incluida la aplicación del fuego en el uso de la tierra, en el cambio de uso de la tierra y los incendios forestales, afectan el funcionamiento del sistema terrestre e imponen amenazas importantes para la salud y la seguridad públicas. Este documento presenta el concepto de un sistema de alerta y evaluación de la contaminación causada por el humo del fuego en la vegetación (VFSP-WAS, por su sigla en inglés). Se presentan el fundamento científico del sistema y directrices para abordar los problemas del fuego en la vegetación y la contaminación por humo, indicándose los principales desafíos de la investigación. El artículo propone el establecimiento de centros regionales VFSP-WAS y describe ejemplos potenciales de este concepto VFSP-WAS de dos regiones (Sudeste de Asia y América del Norte) en donde los centros VFSP-WAS se asocian con Centros Regionales de Monitoreo de Fuego/Manejo de Fuego.

Palabras clave: Modelamiento de la contaminación por humo y fuego; pronóstico meteorológico numérico; observación de la contaminación del aire; sistemas de alerta temprana.

Introduction

Vegetation fires – including the application of fire in land use, land-use change and uncontrolled wildfire – affect the functioning of the Earth System (Goldammer, 2013). Vegetation fires release large amounts of particulate matter (PM) and toxic gases including carbon monoxide, nitrogen oxides, and non-methane organic compounds into the atmosphere. Large and frequent wildfires impact local and regional air quality and are a threat to human health. Recent studies estimate that around 180,000 to 340,000 premature deaths could be attributed to exposure from wildfire smoke (Bowman & Johnston, 2005; Lelieveld *et al.*, 2015; Johnston *et al.*, 2012). Studies have clearly and consistently demonstrated that wildfire smoke PM is associated with respiratory (Henderson *et al.*, 2011) and cardiovascular effects (Dennekamp *et al.*, 2015) and that exposure to fire emissions represents the highest risk to vulnerable subsets of the population i.e. people with existing respiratory or cardiovascular illnesses, infants and the elderly (e.g. Statheropoulos *et al.*, 2013). Health studies have primarily focused on PM so that the effects of other smoke components remain unclear, particularly effects with longer latencies (Reisen *et al.*, 2015).

The Southeast Asian region is regularly impacted by vegetation fires. In some years (most recently in 1997-1998 and in 2015), the extent of the fires can be severe. For example during 2015, visibility in southern Sumatra and southern Kalimantan was reported as 5-10% of normal (Field *et al.*, 2016). However, as argued regarding the use of fires in land-use change in Indonesia, "if the 2015 Indonesian fires were not the worst air pollution event of the past few decades, it is only because they were surpassed by the 1997 fires" (Burki, 2017). Model-based estimates of premature mortality due to smoke exposure during the episode vary widely, and range from 11,880 (Crippa *et al.*, 2016) to 100,300 excess deaths (Koplitz *et al.*, 2016) depending on different model assumptions and whether the effects on neighboring countries are included. In the aftermath of the 1997-98 Indonesian fires. the World Health Organization (WHO) produced Health Guidelines for Vegetation Fire Events (Schwela *et al.*, 1999). This guide recommended that a comprehensive approach to reduce the risk posed by emissions from vegetation fires on human health should include (Schwela *et al.*, 1999):

- Characterization of the magnitude and composition of the emissions and their transformations during transport;
- Quantification of resulting concentrations of ambient air pollutants in populated areas;
- Evaluation of likely exposure scenarios for affected populations (both indoors and outdoors);
- Assessment of consequent health risks posed by such human exposures.

These guidelines point to the need for integrated fire and smoke management, which include physical, social, economic, cultural and ecological evaluations for planning and operational systems, critical to reduce the vulnerability of people and landscapes to wildfires. Integrated fire management is built on technological and communication tools that incorporate observations and prediction. For example, satellite derived products offer real-time fire observations, which provide information and data on active fires, burned areas, and smoke emissions (noting that active fire observations more readily detect flaming fires rather than low-temperature smoldering fires). Identifying and mapping areas at risk of fires is crucial to integrated fire management and should be transparent and involve all agencies and stakeholders. This includes areas presenting significant fire risks and potential for generating transboundary haze pollution events.

Fire early warning systems are a key component of integrated fire and smoke management and build resilience against the increasing severity of future fire regimes under climate change (de Groot & Flannigan, 2014). The Third UNISDR International Conference on Early Warning (EWC III) and related consultations, recommended that the fire early warning system used in the Southeast Asia region and elsewhere should be based on early warning systems such as the Global Fire Early Warning System (Global Fire EWS) (de Groot & Goldammer, 2013) and/or the European Commission (EC) Joint Research Center Global Wildfire Information System which could be complementary to the fire danger rating systems used by Indonesia, Malaysia, and the Association of Southeast Asian Nations (ASEAN) (de Groot *et al*., 2007).

The Global Wildfire Information System (GWIS) is a joint initiative of the Group on Earth Observations (GEO) and the Copernicus Work Programs (see: http://gwis.jrc.ec.europa.eu/static/gwis_current_situation/public/index.html). GWIS builds on the ongoing activities of the European Forest Fire Information System (EFFIS), the Global Terrestrial Observing System (GTOS) Global Observation of Forest Cover – Global Observation of Land Dynamics (GOFC-GOLD) Fire Implementation Team, and the associated Regional Networks. The development of GWIS is supported by the partner organizations and space agencies such as the National Aeronautics and Space Administration (NASA).

The foundation of fire early warning systems such as the Global Fire EWS and the GWIS platform is the Canadian Forest Fire Weather Index (FWI) System, which provides globally information (Di Giuseppe *et al*., 2016) and is the most widely used fire danger rating system around the world (de Groot *et al*., 2015). The FWI danger rating system uses weather variables to assess fire danger. Currently FWI calculations in Southeast Asia are performed utilizing observations made at synoptic stations sparsely distributed in the most fire prone regions of equatorial Southeast Asia. Under GWIS, FWI information for the region is being improved using weather data inputs from satellites under NASA's Group on Earth Observations Work Programme.

Furthermore, the use of advanced numerical weather prediction models, makes possible longer-range predictions of FWI (for example one to two weeks in advance), enabling better planning and resource sharing within and between countries. The Global Fire EWS uses the deterministic Canadian Meteorological Centre forecast, while GWIS uses both a deterministic weather forecast and the European Center for Medium Range Weather Forecasts (ECMWF) ensemble prediction system and provides probabilistic fire weather index calculations up to 15 days ahead. The weather forecasts rather than observations mean that FWI values might be affected by model biases, which may be amplified or damped by nonlinear transformations in the fire model. For example, a dry bias in the model in a certain region will lead to the persistent prediction of relatively high fire danger values.

Good post processing tools minimize these errors by, for example, defining "model based" warning levels. To support the use of fire forecast data, ECMWF has developed a freely available post-processing tool called CaliVer (Calibration and Verification, an R package https://github.com/ecmwf/caliver) to define warning levels from model outputs at regional level (Vitolo *et al*., 2018). Others such as the "ranking" of FWI indices compared to historical time series of FWI values also provide information on the local variability of fire danger.

Regional calibration of the FWI System has been recently updated for Southeast Asia and is in the process of being implemented in the Global Fire EWS. Investigations to further strengthen the calibration with new datasets are ongoing and is seen as an important aspect to improve the usability of the systems in the region (for more information visit http://data.giss.nasa.gov/impacts/gfwed). Furthermore, in the context of GEO, NASA has funded a project for “Enhancements to the Global Wildland Fire Information System: Fire Danger Rating and Applications in Indonesia”, to enhance the potential support of GWIS at regional level. GWIS already provides daily information on fire emissions derived by Copernicus Atmospheric Monitoring Services (CAMS, see https://atmosphere.copernicus.eu).

Sub-seasonal to seasonal weather forecasts have been shown to be skillful in predicting fire activity in Southeast Asia (Spessa *et al.*, 2015). As proposed fire early warning systems are based on weather forecasts it is straightforward to also extend the prediction to seasonal lead times. There is a growing interest across the scientific community to explore the benefit of merging weather and climate forecasts as showcased by the ongoing joint WMO World Weather Research Programme (WWRP) – World Climate Research Programme (WCRP) Sub-seasonal to Seasonal Prediction Project (S2S) (Vitart *et al.*, 2017). Forecasts in the S2S range are not only informative with regard to anomalous conditions but also provide “actionable” information produced as short-range forecasts (White *et al.*, 2017). ECMWF has been particularly active in promoting the S2S timescale with the recent extension up to 46 days of its extended range ensemble prediction system and it is planning to provide fire forecast up to two months ahead. At longer lead times, the role played by model uncertainties becomes relevant and should be quantified. This can be achieved thanks to the availability of the information provided by the 51 runs of the ensemble prediction system, which can be translated in probability of occurrence.

Global fire early warning systems can provide a useful overview of cross-boundary fire danger conditions, and initial and boundary conditions for further downscaling. However, at the local level the utility of these global systems can be limited due to coarse calibrations. Therefore, the development of specific regional and national fire early warning systems, tailored to national and local needs, that “bridge the last mile” to the end-user, are required.

Collective international efforts are needed to address impacts of vegetation fires that are of transboundary nature and affect common global assets of the atmosphere and climate, natural and cultural heritage, and human health and security. Systematic application of principles of integrated fire management, based on the wealth of traditional expertise and advanced fire science, contributes to sustainable land management, ecosystem stability and productivity, maintenance and increase of terrestrial carbon stocks, and reduction of unnecessary emissions of pollutants that affect human health and contribute to climate change. In 2015, the participants of the 6th International Wildland fire Conference encouraged the COP 21 to acknowledge the role and endorse the support of IFM as an accountable contribution to reduce greenhouse gas emissions, maintain or increase terrestrial carbon pools in all vegetation types and ensure ecosystem functioning (IWFC, 2015a, 2015b).

Concept and methodology of the VFSP-WAS

The 18th World Meteorological Congress in June 2019 endorsed an ambitious plan to advance the integration of weather, climate, water and environmental applications and services for health, and work closely with the World Health Organization (WHO) to reduce risk to human health. Populations both near and downwind of wildfires are keenly interested in receiving better warnings about the fires themselves and related air quality risk levels, both of which pose serious threats.

WMO has responded to urgent requests for assistance in several impacted regions by initiating a Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS). The VFSP-WAS provides guidance for addressing both smoke and fire danger and proposes to support the potential foundation of regional centers.

Global and regional monitoring, prediction and warning systems are complex. As with any complex system, all the components of a VFSP-WAS need to be functional before the system can be fully operational and able to achieve the goals set for it by the international community.

The first research and development phase of the VFSP-WAS was launched in 2018. The most advanced research and development stage is currently in Singapore, where regional models are being run and forecasts from various centers are being collated to produce multi-model ensemble smoke forecasts (http://www.weather.gov.sg/vfsp-was/home/). Canada is also scheduled to set up a demonstration VFSP-WAS center for Northern America.

The principles, relationships and components of the VFSP-WAS center are described in the following sections of the paper. Before approval as an operational Regional Specialized Meteorological Centre (RSMC) for VFSP-WAS, the centers must be evaluated by WMO Technical Commissions and further included into the Global Data-processing and Forecasting System (GDPFS) (WMO, 2017).

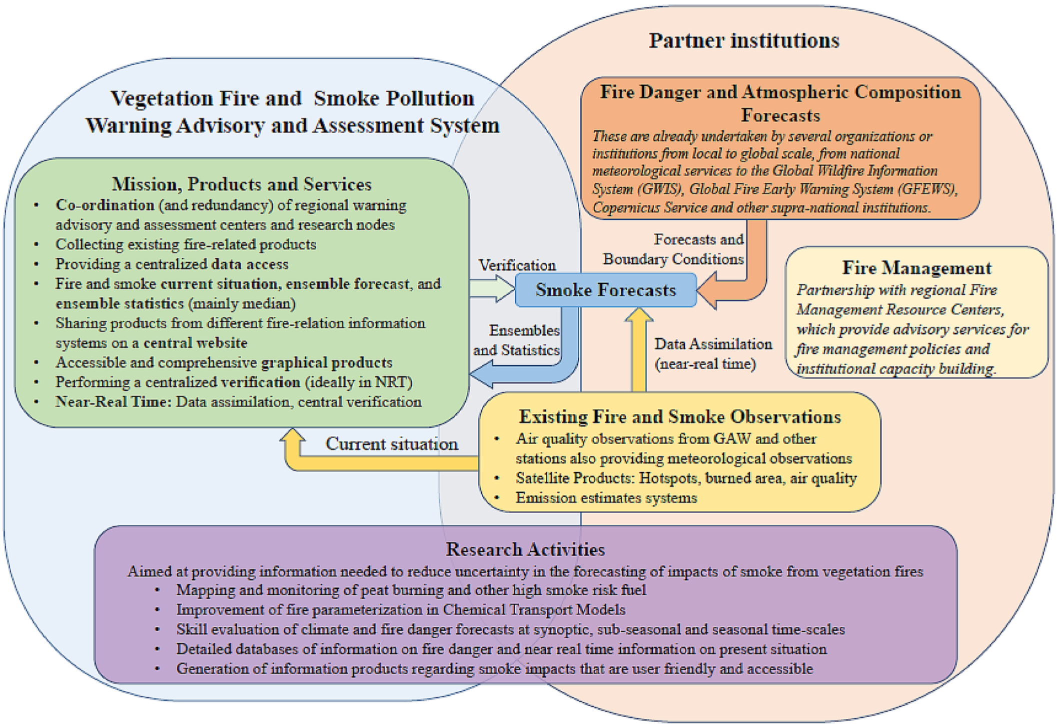

Figure 1 – Overview of a potential Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System.

Figure 1 demonstrates the overall concepts and activities of a potential VFSP-WAS, including the nature of the interactions between the system's components. The proposed warning and advisory system should build upon the experience acquired through comparable initiatives such as CAMS, WMO RSMCs, the ASEAN Specialised Meteorological Centre – ASMC, in Singapore, the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS; e.g. its regional centers in Barcelona and in Beijing), the Global Air Quality Forecasting and Information System (GAFIS, https://community.wmo.int/activity-areas/gaw/science-for-services/gafis) and the International Cooperation for Aerosol Prediction (ICAP). These initiatives demonstrated that relatively small efforts can add significant value to the end-user by making use of existing products.

A VFSP-WAS should have a federation structure with regional nodes and involve a program of research activities that provide information needed to reduce uncertainty in the forecasting of impacts of smoke from vegetation fires. Research activities are shown in Figure 1.

The VFSP-WAS should be an international network of research, national operational centers and users organized through regional nodes (similar as it is realized for SDS-WAS, see WMO, 2015) assisted by VFSP-WAS regional centers (Figure 2). It should be coordinated by the VFSP-WAS Steering Committee.

At the level of regional nodes, VFSP-WAS should be structured as a federation of regional partners. A federated approach allows flexibility, growth and evolution, while preserving the autonomy of individual institutions. It involves a variety of participants (universities, research organizations, meteorological services, emergency management bodies, health organizations, etc.) gathered to cooperate and benefit without requiring changes to their own internal structures and existing arrangements.

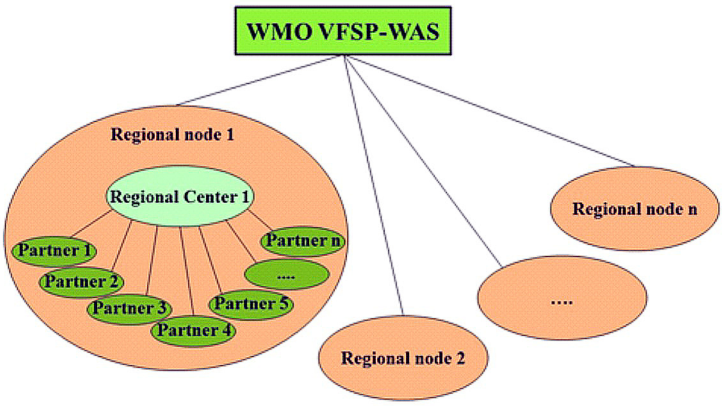

Figure 2 – Suggested regional structure of the Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System.

Research topic-related challenges and recommendations for VFSP-WAS

The research challenges facing fire and smoke prediction were evaluated by the Interdisciplinary Biomass Burning Initiative/IBBI and GAW Applications Science Advisory Group/APP-SAG (Kaiser & Keywood, 2015; Benedetti *et al*., 2018; WMO, 2018). The implication of some of these challenges on the realization of the VFSP-WAS are presented in the following section.

Fire danger and seasonal forecast

Currently a variety of fire danger indices are provided at the global and regional levels. For example, in Southeast Asia, the operational products provide up-to seven days forecast of fire danger (WMO, 2018). These products include the Indonesian Fire Danger Rating System, the ASEAN Fire Danger Rating System (developed and produced by Met Malaysia), the Global Fire EWS and the GWIS. All systems are based on the Canadian Forest FWI System, a subsystem of the Canadian Forest Fire Danger Rating System/CFFDRS, which has been calibrated for equatorial Southeast Asia only in a broad sense (de Groot *et al*., 2007). The systems provide index information on fire danger, but do not reflect potential/current level of atmospheric pollution associated with smoke. In addition, ENSO (Barnston *et al*., 2017) and regional precipitation (Spessa *et al*., 2015; Setiawan *et al*., 2017) can be reasonably predicted several months ahead, with other relevant modes such as the Indian Ocean Dipole (Shi *et al*., 2012; Zhu *et al*., 2015) and the Madden Julian Oscillation predictable at varying lead times (Li & Robertson, 2015).

Research and development needs

The initial FWI calibration of de Groot *et al*. (2007) was focused on equatorial Southeast Asia and was known to over-estimate fire danger in the "Upper ASEAN" region. The FWI system therefore required a separate calibration for Thailand, Vietnam, Laos, Cambodia and Myanmar. Further calibration of the FWI system within Indonesia is also needed to account for differences in fuel types and land use intensity. The 2013 episode in Riau province in Central Sumatra, for example, indicated that acute fire emissions events affecting Singapore occur under less severe drought conditions than in other fire prone regions (Gaveau *et al*., 2014), likely related to the intensity of land use (Hansen *et al*., 2013), suggesting that the drought conditions may not be the best overall emissions potential indicator in that region, or that the drought conditions require a different calibration. A more detailed calibration will also benefit from longer records of space-based fire and pollution data than were available when the initial calibration of de Groot *et al*. (2007) was conducted.

Research and development are also required to support long-term fire management planning through seasonal predictions, emphasizing the risks and usefulness to local agencies. Shawki *et al*. (2017) demonstrated the potential for combining seasonal climate forecasts with Indonesia's calibrated FWI system in operationalizing long-lead fire danger forecasts, but emphasized that further research is needed to determine how skill at different lead times, in different fire-prone regions, and for different models translates into predictions of fire danger. A VFSP-WAS should work together with the WWRP S2S project for regional downscaling and facilitate the development of sub-seasonal to seasonal predictions of fire severity in the area. To this end, there could be a clear benefit in accessing fire danger forecast produced by ECMWF at the S2S time scale.

In addition to the seasonal prediction of anomalous dry conditions, the sub-seasonal to seasonal time range can also provide actionable information with great potential for advance planning. ECMWF has already implemented a "seamless" forecasting system for floods and drought, which provides frequent forecast updates with up to six months horizon and performs well at the S2S time scale. The same approach can be implemented for fire forecasting in the region.

Fire emissions and haze forecast

Reasonably fast and comprehensive estimates of smoke constituent emissions are derived from satellite observations of fires using the approaches described below.

Fire radiative power

The thermal radiation of a fire can be observed from satellites in real time in the middle infra-red (MIR) spectral range. Such observations are called "active fire" observations. A quantitative signal can be interpreted as "fire radiative power" (FRP) product. FRP has been shown to be proportional to the biomass combustion rate under certain conditions. Subsequently, instantaneous emission rates of various smoke constituents can be calculated with published emission factors (Wooster *et al*., 2005). The advantages of this approach are the immediate availability of the observations and emission estimates (even while the fires are still burning) and the relatively weak dependence on the fire type for above-ground burning. Also, a quantitative characterization of the fires with a spatial resolution to 375m (e.g. with the National Polar-orbiting Partnership – Visible Infrared Imaging Radiometer Suite/NPP-VIIRS) and a temporal resolution of 10 minutes (e.g. from Himawari-8) is possible when all available satellite data are used. This approach is used, for instance, by the CAMS Global Fire Assimilation System/GFAS (Kaiser *et al*., 2012), and the Integrated System for wild-land fires IS4FIRES (Sofiev *et al*., 2009; Soares *et al*., 2015). It is also one of the methodologies available at the PREC-CHEM-SRC (Freitas *et al*., 2011; Frassoni *et al*., 2018), a flexible software suitable to regional and global domains developed to prepare emissions estimates of trace gases and aerosols. It has been used with the following regional models: Brazilian developments on the Regional Atmospheric Modelling System/BRAMS (Freitas *et al*., 2009; Longo *et al*., 2011) and the Weather Research and Forecasting/WRF model coupled with Chemistry (WRF-CHEM) (Grell *et al*., 2005), and the Flow-following finite-volume Icosahedral Model/FIM (Bleck *et al*., 2010).

Smoke detection

Smoke plumes can be readily detected in the atmosphere using remote sensing tools. Aerosol optical depth and carbon monoxide are relatively well observed by satellites and are used to infer fire emissions with "inversion" methods. While the atmospheric effect is relatively directly constrained for the observed species and the effect of any unobserved fire is also included, this methodology cannot distinguish the sources of observed constituents, e.g. from fire or from other sources (e.g. urban emissions) and has limited temporal and spatial resolution.

Burned area

The detection and quantification of burned area using satellite products is well established. Scaling burned area with fuel load and combustion completeness yields burned biomass, from which smoke emission can be calculated as in the FRP-based method described above. In addition, the similarity to *in-situ* methods employed locally by foresters on the ground means that significant validation and calibration has been carried out. Since area burned is persistent, it can be detected even after an observation gap, due to cloud cover for example. The spatial resolution is also relatively high (down to 250m for global coverage). However, since the area burned can only be observed after a burn has occurred, it is not suitable for true real-time applications. Active fire satellite observation that can only distinguish between “fire” and “no fire”, e.g. due to its MIR channel saturation the satellite can only produce binary “high-temperature event”/HTE products. Sometimes, relatively simple assumptions are used to estimate burned area from such products and emissions can subsequently be calculated as described above. This approach is being used to correct for missing small fires in the Global Fire Emissions Database/GFED (Randerson *et al*. 2012) or to calculate emissions in real time, e.g. with FINN (Fire Inventory from NCAR; Wiedinmyer *et al*. 2011) and to estimate emissions in the European Forest Fire Information System/EFFIS) and in the Air Quality Forecast System in operation at the Brazilian National Institute for Space Research, Center for Weather Forecasting and Climate Research/INPE/CPTEC (Freitas *et al*., 2017).

These emission estimates are a key input to atmospheric composition and transport models that represent a main tool for haze and air pollution forecasts. A Regional Vegetation Fire and Smoke Pollution Warning Advisory and Assessment Center/VFSP-WAC could coordinate multi-model ensemble forecasts of air pollutants dispersion in the region through atmospheric transport using regional expertise and capacities. To support this, WMO Members outside of the focus region informally proposed to contribute to such a multi-model ensemble forecast and analysis (e.g. sharing outputs of the lower resolution global aerosol models).

Within the international atmospheric chemistry community, including ICAP, GAFIS and the International Global Atmospheric Chemistry/IGAC project, there exist a number of global aerosol models that include emissions from vegetation fires and could be included in a multi-model ensemble forecast. Only half of these models are operational, the others remaining in a research and development stage (for some, only the vegetation fire component is not operational).

Several real-time smoke forecasting products exist. The most established global aerosol forecasts are represented in the ICAP and GAFIS communities. Four models include dedicated smoke treatment: (i) CAMS ECMWF and partners; (ii) Model of Aerosol Species IN the Global AtmospheRe (MASINGAR) Meteorological Research Institute, Japan Meteorological Agency, MRI-JMA (see Tanaka *et al*., 2003); (iii) Goddard Earth Observing System model, version 5 (GEOS-5) NASA, (see: Rienecker *et al*., 2008); (iv) NAAPS: Navy Aerosol Analysis and Prediction System (US Navy, see https://www.nrlmry.navy.mil/aerosol_web/Docs/globaer_model.html), and System for Integrated modeLling of Atmospheric coMposition SILAM (see http://silam.fmi.fi); where the first two use emissions from GFAS (see http://apps.ecmwf.int/datasets/data/cams-gfas/), the third – from a similar FRP-based inventory of the Quick Fire Emissions Dataset/QFED, see https://geos5.org/wiki/index.php?title=Quick_Fire_Emission_Dataset, the fourth – from the active fires detected by the Fire Locating and Modeling of Burning Emissions/FLAMBE, see http://www.nrlmry.navy.mil/flambe/index.html, system and the fifth one – from IS4FIRES (http://is4fires.fmi.fi). In Australia, the Smoke Forecasting System/AQFx is currently being developed by CSIRO and the Australian Bureau of Meteorology https://www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/Smoke-forecasting.

The ICAP is an international forum for aerosol forecast centers, remote sensing data providers and lead system developers to share best practices and discuss pressing issues facing the operational aerosol community (Xian *et al*., 2019). The ICAP initiative itself has demonstrated that simply collecting different forecasts in a single database and generating web pages with common plotting conventions is an effective tool for the developers to assess and improve their forecasting systems.

EU’s CAMS is using its global atmospheric composition forecasts and GFAS fire emissions as common boundary conditions for an ensemble of seven operational regional air quality forecasting systems for Europe, including smoke (Marécal *et al*., 2015). A common real-time verification with station data greatly helps the interpretation and further developments of the individual models. The median of all models has been shown to benefit from the individual strengths of the seven models, as this statistical “analysis” is more accurate than any single forecast.

The ASMC provides operational and regularly updated information and products on the weather and smoke haze situation in the ASEAN region (http://asmc.asean.org). Using the fire distribution from CAMS-GFAS, means that it is similar to a member in the CAMS ensemble of European air quality models. The Bluesky Modelling Framework is a possible approach that has been successfully applied in North America, and in which the testing of different emissions scenarios as input to transport models is relatively straightforward.

Truly prognostic smoke forecasts require emissions forecasts. One approach for generating emission forecasts is to better understand the relationship between historical emissions and simple meteorological or fire weather parameters. Despite the role of non-weather factors in controlling fire activity, this approach is likely to be useful in Indonesia because of the strong climatic controls on fire activity and emissions relative to other fire-prone regions in the world (Bedia *et al*., 2015). ECMWF applies the FWI to modulate the global emissions of fires estimated from FRP data (Di Giuseppe *et al*., 2016). The daily emissions are modulated by a linear relationship between FWI and FRP during CAMS integration process. Novel techniques have been applied to attempt to forecast prescribed fires in order to improve air quality regional models (e.g. Agastra, 2020). The CAMS-GFAS (Kaiser *et al*., 2012) inventory is a widely used example of such a combined inventory (e.g. by ECMWF, NASA, JMA, ASMC and GWIS).

Research and development needs

Despite its application in other regions, the implementation of ensemble forecasts for transboundary haze events in Southeast Asia still requires substantial development. Since all CAMS services are freely available, the CAMS concept of implementing an ensemble of forecasts with common boundary conditions, presentation and verification could be applied to the smoke in Southeast Asia with ASMC already providing the first operational, high-accuracy ensemble member. Other VFSP-WAC could follow a similar roadmap for application to their own region.

Observation gaps that may result from cloud cover or lack of satellite coverage create gaps in the emission estimates. At the same time, consistent merging of FRP from different satellites still represents an open research topic. Furthermore, the FRP signal from peat fires is relatively small and its relationship to fuels consumed is less certain for these fires than for above-ground fires. Finally, the emission factors vary for individual fires so that estimates on a small scale have a limited accuracy.

The uncertainties in emission estimates from smoke observations remain large due to variable and relatively poorly known optical properties of aerosols, the poorly characterized errors in atmospheric chemistry and transport models, and noise in the satellite observations.

There is a need to better quantify the errors that lead to the use of the scaling factors and to improve the emission datasets and/or the models to reduce their use (Benedetti *et al*., 2018). A recent example of an inversion of Southeast Asian fire emissions is given in Huijnen *et al*. (2016).

Observations and data production for verification and assimilation

To support the assessment of fire impacts, measurements of the combustion species (aerosols, reactive and greenhouse gases) are needed. Monitoring stations across the globe operate under the WMO Global Atmosphere Watch Programme/GAW and other networks such as the Aerosol Robotic Network/AERONET (Holben *et al*., 1998) and the GAW Aerosol Lidar Observation Network (GALION). While these networks can support verifications of haze forecasts, the density of stations in these networks is low and the timeliness of data delivery is limited. To improve this coverage, ground-based reference instruments could be complemented by satellite observations and low-cost sensor (LCS) networks.

Recent developments in the production of low-cost, compact air pollution sensors have sparked the interest of air quality professionals, scientists, and communities concerned about air pollution (Morawska *et al*., 2018). The WMO produced a relevant report on LCS on behalf of international organizations working on atmospheric composition. We refer the reader to this report for more information (Lewis *et al*., 2018). This report highlights that: "As a class of device, LCS encompass a very wide range of technologies and as a consequence they produce a wide range of quality of measurements". LCS are currently not able to replace reference instruments, particularly for mandatory monitoring, and tend to be limited to measuring a handful of pollutants, (e.g. CO, NOx, O3, and PM). Recent evaluations have found that some dust sensors are proving effective for the measurement of particulate matter in smoke and networks of these sensors are being used to feed real time data on PM2.5 concentration into smoke forecasting systems. For example, the Smoke Observation Gadget/SMOG is used in Southeast Australia to provide data for the AQfx (https://ecos.csiro.au/smog/). Lastly, while there are transparent and open-source sensors available, many LCS rely on opaque (black box) or proprietary algorithms to estimate pollutant concentration. See Karagulian *et al*. (2019) and Lewis *et al*. (2018) for details on individual sensors.

Regional VFSP-WAC could also provide centralized data access to a variety of observations, from satellite observations to ground observations of fire and smoke. While not making observations directly, a regional VFSP-WAC should encourage the regional use and dissemination of observations.

Research and development needs

While some studies have investigated LCS for smoke monitoring (e.g. Gupta *et al*., 2018), the vast majority of studies have focused on urban air quality. Studying the performance of LCS specifically for smoke pollution will also enable the calibration of these sensors to detect pollutant concentrations most relevant for fire smoke monitoring. Furthermore, this would enable the application of Machine Learning algorithms (e.g. Zimmerman *et al*., 2018).

Both satellite and LCS observations should be compared and calibrated with accurate, but geographically sparse ground stations. Each VFSP-WAC can also seek to fill gaps in observations using regional atmospheric composition monitoring networks. While studies have shown the potential of near real time data assimilation for atmospheric composition (Bocquet *et al*., 2015; Innes *et al*., 2015), further research and development can assess the effectiveness of these assimilation methods for operational haze and smoke predictions.

VFSP-WAS regional centers and examples of their realization

Key principles and suggested structure of a Regional Center

At the regional level, VFSP-WAS can be organized as a federation of regional partners contributing to Nodes and realized through a Regional Center. The organization of regional nodes' research and development and forecasting activities can be defined and led by a VFSP-WAS Regional Steering Group (RSG) and practically realized by the Regional VFSP-WAC. The Nodes would be an open federation of different partners from interested countries of the region with equal votes of each partner involved (see Figure 1). The VFSP-WAS can be hosted by one or several countries/organizations (on the agreement of the Node members and its RSG) and focus on technical realization of the Regional VFSP-WAC and providing regional vegetation fire smoke pollution forecasts. A scheme of the governance structure of Regional VFSP-WAC is presented in Figure 3.

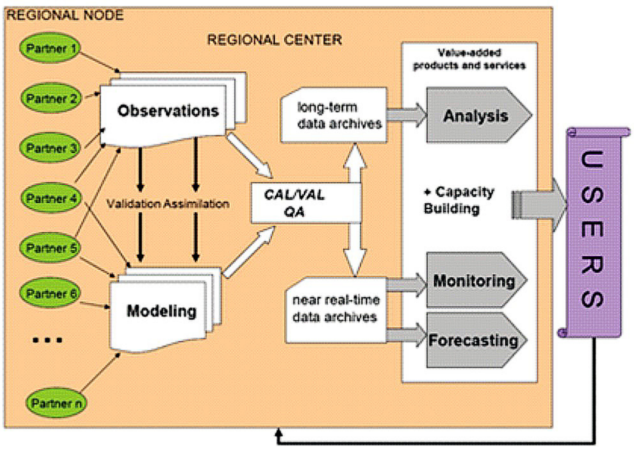

Figure 3 – Scheme of the governance structure of a Regional Node and Fire and Smoke Pollution Warning Advisory and Assessment Center (VFSP-WAC).

The establishment of a VFSP-WAS for a specific region would require existing providers of related services to collaborate with one central organization hosting the Regional VFSP-WAC, which would include capability to collect, analyze and publish products. A common verification system would provide quality checks and facilitate further research and continued improvements of operational systems. Such arrangements would ensure acknowledgement of product sources and allow linkages with existing regional activities in a flexible way.

The strength of such a Regional VFSP-WAC will be the production of ensemble forecasts based on the already available products, e.g. for Southeast Asia by ASMC and national hydro-meteorological services (NHMSs) in the region as well as partners outside of the region willing to contribute to the center. Lateral and surface boundary conditions for regional forecasts could be provided by external partners with advanced capabilities (for instance, CAMS).

A Regional VFSP-WAC could provide information in support of fire and emergency management. The often significant impact of fire and smoke pollution necessitates the provision of data and information that can inform decisions made by health and fire management sectors. While the provision of this information is central to the Regional VFSP-WAC mission and guides the developments of the user relevant products and services, the VFSP-WAC would not itself lead on policy advice but instead contribute to collaborating entities.

The process of establishing a Regional VFSP-WAC should begin with an understanding of potential partners. The ensuring dialogue with potential partner organizations could take place through stakeholder workshops. This step should ensure that relevant agencies from the global, to the regional, national and local level are involved in the dialogue. The stakeholder groups involved in this dialogue should include: meteorological departments, land (including peatland) and forestry management, fire management and firefighters, and health management and health practitioners. Understanding user needs is key to determining the type and quality of products and services required. This process would also be important for finalizing a statement of the goals of the VFSP-WAC.

Once a set of user-focused and impact-based products and services have been identified, as well as an indication of accuracy needed for their operational use, the implementation plan should follow a comprehensive series of steps, from initial research and validation efforts to impact-based services that are operationally generated (WMO, 2018).

A Regional VFSP-WAC (Figure 4) should aim to ensure that partners appropriately and systematically use the center's warning and advice to ensure harmful fire episodes are reacted upon appropriately. Because fire and smoke predictions still need considerable development, any center should also aim to bridge the gap between research and operational work.

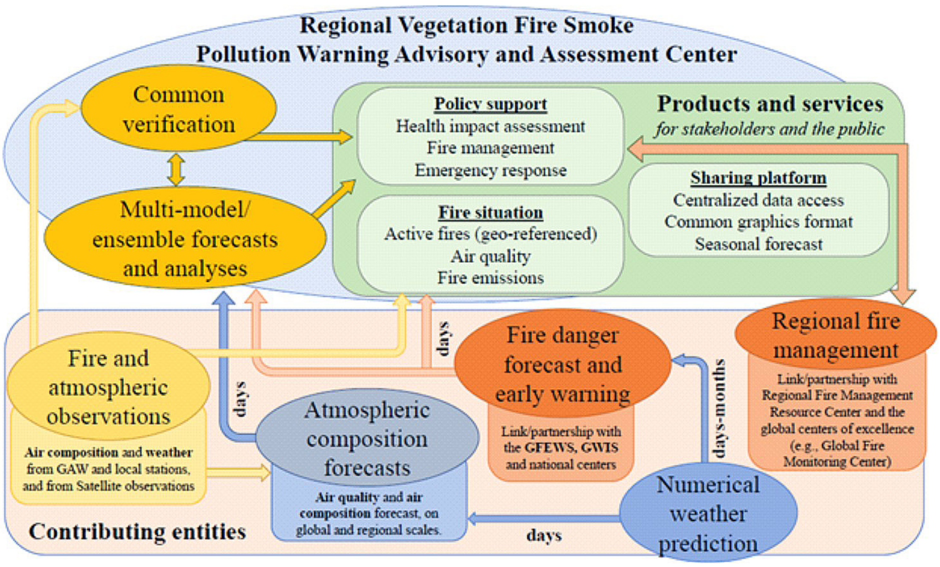

Figure 4 – Workflow of the proposed Regional Fire and Smoke Pollution Warning Advisory and Assessment Center.

As an example, the proposed VFSP-WAC (Figure 4), for the ASEAN region would maintain strong links with partner institutions that provide Fire Danger forecasts and Early Warnings (the ASMC for Southeast Asia), and national and regional institutions that support fire management, e.g. the Regional Fire Management Resource Center – South East Asia (RFMRC-SEA, see https://rfmrc-sea.org/). The VFSP-WAC would provide centralized access to products and services aimed at stakeholders and the public. Regional partners would contribute these products while the VFSP-WAC would facilitate their availability (website and data access). The VFSP-WAC would be responsible for providing multi-model ensemble of atmospheric composition forecasts and analyses and longer-term fire danger forecasts (e.g. sub-seasonal or seasonal). It would also perform a common verification of all of these.

Singapore VFSP-WAS regional center for Southeast Asia

The first regional VFSP-WAC was proposed in Southeast Asia and hosted by the ASEAN Specialised Meteorological Centre (ASMC), building on more than 20 years' experience at ASMC in monitoring fires and smoke haze for the region. ASMC, hosted by the Meteorological Service Singapore (MSS), was designated in 1997 as the official ASEAN center to monitor fires and transboundary haze in Southeast Asia (Regional Haze Action Plan, 1997). ASMC issues alerts when haze is expected to affect any ASEAN Member State and provides operational products and information on the regional weather and haze situation on its website. ASMC also serves as technical advisor for ASEAN committees on transboundary haze and conducts capability development programs for users including environment, forestry, meteorological and related agencies in the region.

To initiate the Southeast Asia VFSP-WAC, collaboration was sought with interested partners and existing providers of relevant products and services, particularly, for the development of a new multi-model ensemble from global and regional modelling centers. The Southeast Asia VFSP-WAC also leveraged the experience of the WMO SDS-WAS and its regional centers in Barcelona, Spain and in Beijing, China, as well as the ICAP.

A pilot website for the Southeast Asia VFSP-WAC was first released in 2018 and launched in research and development phase in 2019 (http://www.weather.gov.sg/vfsp-was/home/). The initial efforts focused on establishing the multi-model ensemble and near real-time forecast evaluation. The amount and quality of the content published is planned to progressively increase. An upgraded version of the website is under development and will include the addition of observation and fire risk products.

A review of the current weather and smoke haze situation, and outlook over the next few days issued by ASMC is available on the main page of Southeast Asia VFSP-WAC website. Products will be organized into three categories: Forecasts, Observations and Fire Risk, as detailed below. From the website, users can access links to various partner institutions including modelling centers, observation networks, fire risk and fire management centers relevant to the region.

1) *Forecasts* include individual and multi-model ensemble predictions of smoke aerosol optical depth (AOD) and surface particulate matter concentrations, as well as weather forecast information for the region. Near real-time forecast evaluation and evaluation metrics are available.

   a. Multi-Model Ensemble Smoke Forecasts

   There are six contributing model members as of mid-2020, five are from global models: ECMWF-CAMS (Europe), JMA MASINGAR (Japan), NASA GEOS-5 (USA), NCEP-NGAC (USA), FMI SILAM (Finland) and one from a regional model: MSS-UKMO NAME (Singapore). While most of the ensemble members have built-in aerosol optical models to compute AOD, MSS-UKMO NAME (Hertwig *et al*., 2015) derives $PM_{2.5}$ aerosol optical properties based on an empirical study of biomass burning smoke over Singapore by Lee *et al*., 2016. The center retrieves available 00 and 12 UTC forecasts from the various models and represents them using a common grid resolution of 0.5° x 0.5° and geographical domain covering major burning areas and smoke transport pathways in the Southeast Asia region. The forecast variables are smoke AOD at 550 nm and surface concentrations of PM_{10} and $PM_{2.5}$. Individual models' and multi-model ensemble forecasts are provided at 3-hourly intervals up to 48 hours ahead. The ensemble has two products describing centrality (multi-model median and mean) and another two describing the spread (standard deviation and range of variation). Figure 5 shows example products from the multi-model ensemble median forecast of smoke AOD and $PM_{2.5}$ surface concentration.

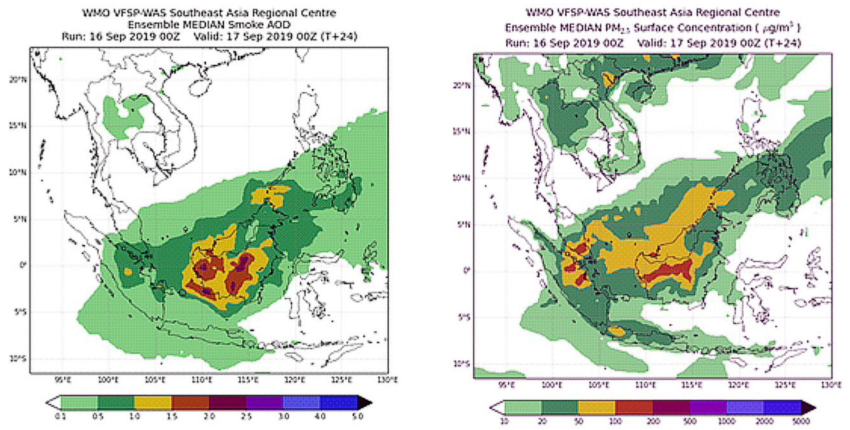

Figure 5 – Example Southeast Asia VFSP-WAC multi-model ensemble median 1-day forecast of smoke AOD (left) and $PM_{2.5}$ surface concentration (right) for the Southeast Asia region in September 2019.

b. ICAP Ensemble

The ICAP multi-model ensemble is constructed from the following global aerosol models: CAMS, GEOS-5, NAAPS, MASINGAR, NGAC, MOCAGE and SILAM (see Sessions *et al*., 2015). Smoke AOD forecasts from the ICAP ensemble are shown in this section alongside the Southeast Asia VFSP-WAC ensemble for comparison.

c. Weather Forecasts

Sub-seasonal outlooks of rainfall and temperature provided by ASMC for the Southeast Asia region are published. For the upcoming website upgrade, NWP forecasts of winds at various height levels over the region will be added.

2) *Observations* of the regional fire and smoke situation include satellite images, weather and air quality station measurements. This section will be added in the upcoming website upgrade.

a. Satellite observations

Product images from geostationary (Himawari-8) and polar-orbiting (NOAA20, SUOMI-NPP, AQUA, TERRA) satellites including true/false color, natural, fire temperature and night images will be published.

b. Weather and Air Quality Observations

The ground weather observation reports collected through the WMO Global Telecommunication System (GTS) will be displayed on a map showing wind, visibility and weather conditions e.g. smoke haze. Available station measurements of surface particulate matter concentrations will be provided.

3) *Fire risk* provides information to identify areas in the region at risk of fire occurrence based on prevailing weather conditions. This section will be added in the upcoming website upgrade.

a. ASEAN Fire Danger Rating System (FDRS)

The ASEAN FDRS is based on the Fire Weather Index (FWI) System developed by Canada and has been calibrated for the

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Southeast Asia region (de Groot *et al*., 2007). The ASEAN FDRS product is produced daily by the Malaysian Meteorological Department.

b. Global Fire Weather Database (GFWED)

GFWED integrates different weather factors influencing the likelihood of a vegetation fire starting and spreading and is similarly based on the FWI System. Details on the development and testing of GFWED can be found in Field *et al*. (2015), and evaluation of GFWED products in Field (2020).

Forecast Evaluation and Evaluation Metrics

To evaluate the VFSP-WAC forecasts, the 1-day ensemble forecasts of smoke AOD are compared to total AOD as observed at 22 NASA AERONET sites across Southeast Asia. Eleven of these AERONET sites are situated in Peninsular Southeast Asia (i.e., Cambodia, Laos, Myanmar, Thailand, Vietnam), while the other eleven are situated in the Maritime Continent (i.e., Brunei, Indonesia, Malaysia, Philippines, Singapore). Many of these sites have been set up in collaboration with local government and researchers and enhanced during the 7SEAS (7-Southeast Asian Studies; Reid *et al*., 2013) and CAMP2Ex (Cloud, Aerosol and Monsoonal Processes: Philippines Experiment) programs.

For near real-time forecast assessment, AERONET Level 1.5 products (Version 3) are used. Although the AERONET sun photometers do not measure AOD at 550 nm for direct comparison with model outputs, this metric can be calculated from AOD measured in other wavelengths, namely 440, 675 and 870 nm, using the Angstrom Law. Clouds, especially cirrus clouds, are endemic in Southeast Asia and are a source of potential bias in passive aerosol remote sensing datasets such as AERONET (e.g. Chew *et al*., 2011), thus in addition to the standard AERONET cloud screening (Smirnov *et al*., 2000), a threshold of Angstrom Exponent (440 – 870 nm) > 0.75 is applied to screen for cloud contamination in the region (e.g. Salinas *et al*., 2009; Chew *et al*., 2013). An example of the near real-time forecast evaluation product is shown in Figure 6.

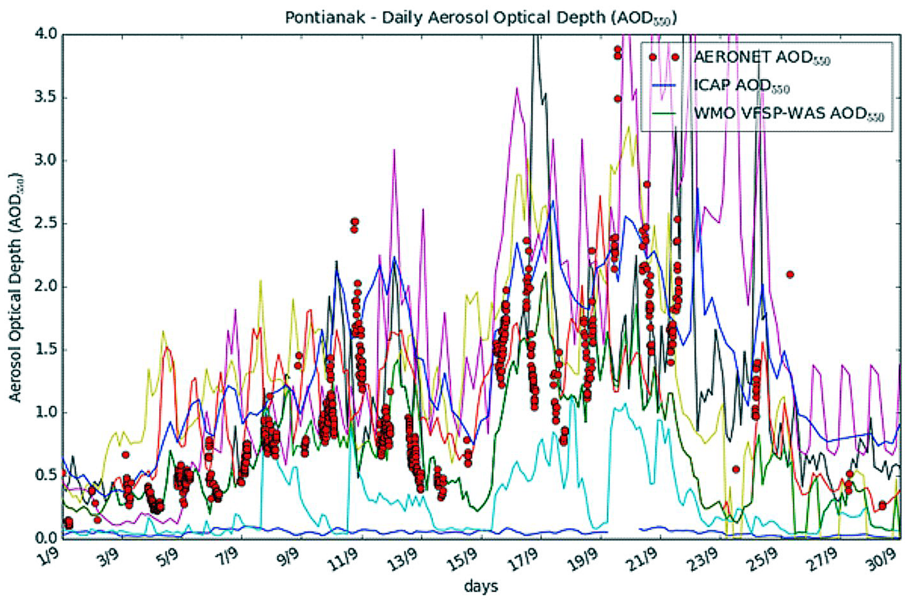

Figure 6 – Near real-time Southeast Asia VFSP-WAC forecast evaluation over Pontianak, West Kalimantan, during the peak of fire activity in September 2019. Unlabeled colored lines represent individual model members of the Southeast Asia VFSP-WAC ensemble.

Besides near-real-time forecast evaluations, evaluation metrics for modelled and observed AOD comparisons are calculated monthly, seasonally and annually. The evaluation metrics for the forecasts currently comprise of mean bias error (BIAS), root mean square error (RMSE), correlation coefficient (CORR) and fractional gross error (FGE). The AERONET AODs closest in time to the model outputs within a 30-minute window are compared with the modelled outputs in computing the evaluation metrics. These statistics will be included in the upcoming website upgrade.

The monthly and annual statistics are computed retrospectively. The seasonal statistics are derived for February – April (FMA), May – July (MJJ), August – October (ASO) and November – January (NDJ) to best group the dominant regional monsoonal circulations with regional burning processes observed annually (Reid *et al.*, 2012). In Southeast Asia, there are two primary monsoon seasons, i.e., the Northeast Monsoon during the boreal winter (December – March) and the Southwest Monsoon (June – September) during the boreal summer, which are separated by relatively shorter inter-monsoon periods (April – May and October – November). During north hemisphere winter, the ITCZ (Intertropical Convergence Zone) and a secondary South Pacific convergence zone result in dual zonal rain bands embedded within the trade winds in the Central Pacific (Masunaga & L'Ecuyer, 2010). The associated monsoonal trough changes from being a zonal feature across the Maritime Continent in winter to a diagonal one extending over Peninsular Southeast Asia and into the Northern South China Sea in summer (Reid *et al.*, 2012). The biomass burning seasons are generally anti-correlated with the monsoonal trough as it oscillates through the year, thus the biomass burning season for Peninsular Southeast Asia occurs in the boreal winter, while the biomass burning season for the Maritime Continent occurs in the boreal summer (Reid *et al.*, 2013), although off-season burnings are occasionally observed outside these seasons (Chew *et al.*, 2013).

Table 1 illustrates the evaluation statistics consolidated for eleven sites in the Maritime Continent for ASO 2019 and eleven sites in the Peninsular Southeast Asia for FMA 2020 when biomass burning for the respective region occurred. The Southeast Asia VFSP-WAC ensemble has almost no bias as the ensemble members have both positive and negative bias in their forecasts, thus averaging out within the ensemble. The ensemble also has the lowest RMSE and one of the lowest FGE among members, as the ensemble consists of skillful and independent models for the region and is likely to perform better than any individual member (e.g., Sessions *et al.*, 2015). The ensemble AOD is well-correlated with AERONET observations as indicated by correlation coefficient of 0.72 for the Maritime Continent in ASO 2019 and 0.76 for the Peninsular Southeast Asia in FMA 2020, despite extensive cloud obscuration in the region frequently hindering satellite-based fire observations used to derive smoke emission inputs in the models.

Table 1 – Evaluation Statistics for 11 sites in the Maritime Continent for ASO 2019 and 11 sites in the Peninsular Southeast Asia for FMA 2020.

Region	Evaluation metrics	Southeast Asia VFSP-WAC ensemble
Maritime Continent (ASO, 2019)	BIAS	-0.04
	RMSE	0.34
	CORR	0.72
	FGE	0.69
Peninsular Southeast Asia (FMA, 2020)	BIAS	0.04
	RMSE	0.15
	CORR	0.76
	FGE	0.46

Environment and Climate Change Canada VFSP-WAS regional center for North America

The Government of Canada has recently completed several studies related to wildfire pollution and associated population exposure over North America (Matz *et al.*, 2020, Munoz-Alpizar *et al.*, 2017) using the operational Environment and Climate Change Canada (ECCC) air quality system, named FireWork (Chen *et al.*, 2019; Pavlovic *et al.*, 2016). The economic cost for Canada regarding the population health impacts from wilfire-$PM_{2.5}$ exposure was estimated at $410M-$1.8B per year for acute health impacts and $4.3B-$19B for chronic health impacts (Matz *et al.*, 2020). The importance of these impacts is one of the drivers for improving international collaboration in data sharing supporting wildfire preparedness and response. In 2019, ECCC, a department of the Government of Canada, responded to the WMO's initiative and volunteered to create a North American (NA) Regional VFSP-WAC. As such, ECCC has been working on product development planned for NA VFSP-WAC with the objective to start disseminating the products in 2020. This NA centre will be the world's second Regional VFSP-WAC. ECCC is planning to have products similar to the Southeast Asia's VFSP-WAC with near-real-time wildfire-related forecasts and data collected from various observation networks and modelling systems. The creation of this NA regional centre involves close and effective collaboration with different national and international organizations, such as NOAA, NASA, USFS, NRCan, ECMWF, JMA, FMI, etc. This partnership is essential for data collection and product tailoring with respect to the various national and international user needs.

The NA VFSP-WAC plans to disseminate products under two sub-groups: *Current* and *Forecasted* wildfire-related information.

Under the *Current* section, two products are planned:

1) Hotspots Maps over North America

   These maps will be available for the period covering the last 24 hours and previous 7-day period. This product will provide information about current and most recent wildfire activity as detected by satellites.

2) Fire Danger Map

   This collaborative map product is under development and is currently produced daily by combining the fire danger products produced for Canada and Mexico through the Canadian Wildfire Information System (CWFIS) and the fire danger products from the US Wildland Fire Assessment System (WFAS). This map displays fire danger as classified by Canadian provincial, territorial and US state fire management agencies. Data Sources: Canada/Mexico – NRCan-CWFIS; Contiguous USA – USFS-WFAS, and Alaska – MesoWest. Some of these maps are already disseminated by USFS-WFAS (US Forest Service – Wildland Fire Assessment System).

Under the *Forecasted* section, five products are planned:

1) Ensemble $PM_{2.5}$/PM_{10} Forecast:

   The multi-model ensemble PM forecast will be based on six members, two of which are regional [ECCC FireWork (Canada) and NOAA NCEP NAQFC (USA)] and four are global [ECMWF CAMS-IFS (Europe), FMI SILAM (Finland), JMA MASINGAR (Japan) and NASA GEOS-FP (USA)]. In addition to the ensemble, forecasts from each member will be presented separately. The common lead-time for these ensemble members is 48h, and it is planned to update the related forecast products once daily.

2) $PM_{2.5}$/PM_{10} Performance Evaluation Statistics: Ensemble and Model-Specific Forecast

   Performance evaluation for particulate matter concentration forecasts will be done using ground-level measurements from NA networks. The evaluation performance will be done using ECCC's Verification of Air QUality SModels (VAQUM) system. This system was developed in 2017 by ECCC in collaboration with ECMWF-Copernicus CAMS-IFS and NOAA, and is used for operational AQ multi-model performance analysis over North America (Pavlovic *et al.*, 2018). It is planned to have different ensemble windows over NA, as two regional (NOAA's and ECCC's) systems do not entirely cover the NA continent.

3) ICAP Smoke Aerosol Optical Depth (AOD)

The ICAP Multi-Model Ensemble smoke AOD products are constructed from the following aerosol forecast systems: ECMWF CAMS-IFS, NASA GEOS-FP, NRL NAAPS, and JMA MASINGAR. It is planned that products from ICAP will be displayed on the NA VFSP-WAC web page (Figure 7).

4) Fire Weather Index (FWI)

The Canadian FWI equations, provided by National Resources Canada (NRCan), are used to calculate FWI over NA using ECCC's Operational Regional Deterministic Weather Forecasts. The latter is at 10-km horizontal grid spacing and is launched twice daily producing 72h lead-time forecasts. It is planned to provide this FWI product in forecast mode, with maps valid at TT+ 24h, TT+48h and TT+72h (Figure 7). These maps are under development as different options for the provision of risk forecast products are being discussed between partners.

5) Sub-Seasonal Outlook

ECCC is producing sub-seasonal precipitation and temperature anomaly maps using the Global Ensemble Prediction System (GEPS). A 20-year climatology study (1998-2017) of this prediction system obtained from a reforecast is used to calculate forecasted anomalies. The monthly forecast is updated every Thursday and covers the following 28 days, starting on Monday. Information about this system and more recent updates can be found in Lin *et al*. (2019).

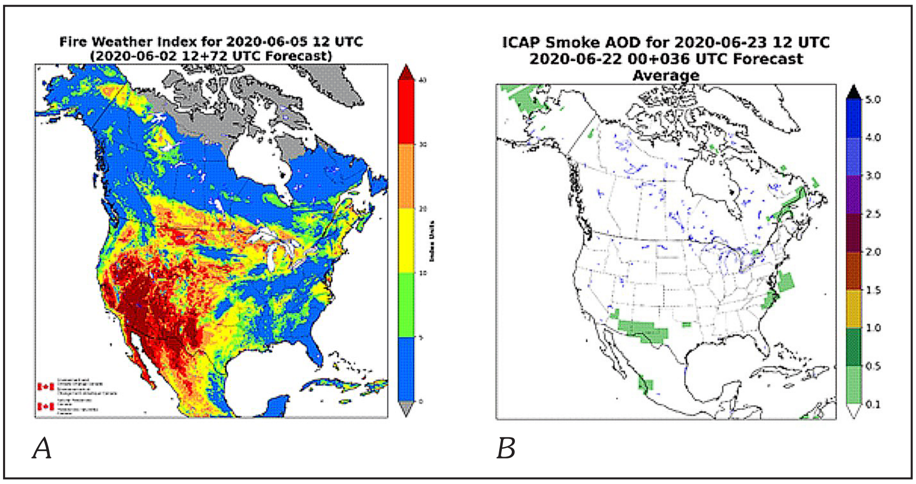

Figure 7 – (A): Forecasted FWI valid at 2020-06-05 12UTC, from 2020-06-02 12UTC initial run; (B): forecasted average ICAP Smoke AOD valid at 2020-06-23 12UTC, from 2020-06-22 00UTC initial run.

Products planned for North American Regional VFSP-WAC, briefly presented here, are under development and can be changed, modified or expanded in the near future. ECCC will continue to work in collaboration with its partners, and in consultation with the user community, to enhance the value of the proposed NA Regional Vegetation Fire and Smoke Pollution – Warning Advisory and Assessment Centre.

Opportunities for other Regional VFSP-WAC

Several other regions are interested or have demonstrated infrastructure necessary to host a Regional Center for the realization of VFSP-WAS and also have good experience and research. For example, in Latin America, INPE in Brazil maintains a well-established operational routine

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to monitor biomass burning in South and Central Americas, as well as Caribbean and Mexico, making use of remote-sensed data and weather forecasts. INPE's Wildfire Monitoring Program "Queimadas" (for more information visit http://queimadas.dgi.inpe.br) routinely produces a spatial-based product of vegetation fire risk (FR) available for the Latin American domain. FR takes into account environmental variables like the number of consecutive days with no rain, the maximum daily air temperature, minimum relative humidity, characteristics of vegetation type, topographic elevation and latitude, as well as active fires detected by remote sensing (Setzer *et al*., 2019). In addition, the "Queimadas" Monitoring Program also offers daily FR forecast up to five days, which is based on meteorological forecasts provided by global modeling. As one of the WMO Global Producing Centers for long-range forecasts, INPE/CPTEC produces operationally seasonal climate forecasts (Coelho *et al*., 2012), integrating the GDPFS. More recently, Guimarães *et al*. (2020) provided an optimal configuration for the INPE/CPTEC global sub-seasonal prediction system and assessed the ability of up to 4-week retrospective predictions of meteorological variables. Sub-seasonal to seasonal predictions are key ingredients to provide predictions of fire severity in the sub-seasonal to seasonal timescales for Latin America. The Brazilian Institute also provides operational air quality forecasts with temporal resolution of 3h up to the 72h lead-time in a 20km horizontal resolution. Air quality products like graphical displays of ozone and carbon monoxide concentrations, smoke, AOD among others, are freely available at INPE/CPTEC webpage (http://meioambiente.cptec.inpe.br). Forecasts are based on the fully coupled meteorology/chemistry regional model BRAMS (http://brams.cptec.inpe.br/), the main component of the Air Quality Forecasting System in operation since 2003 at INPE/CPTEC (Freitas *et al*., 2017). As a way forward for the implementation of a VFSP-WAS in Latin America, it is needed to deepen partnerships among different actors in Latin American countries, regional and local agencies. INPE is currently part of the "La Red Latinoamericana de Teledetección e Incendios Forestales" (RedLaTIF), a regional network with the aim to integrate efforts in the field of observation and management of forest fires in all Latin American countries (for more information, visit http://www.redlatif.org). In addition, INPE and the Operations and Management Center of the Amazonian Protection System (CENSIPAM) are joining efforts to integrate Amazon monitoring systems, whose data support actions to mitigate environmental crimes in the region (INPE, 2020).

Conclusions

In addition to the direct threat from burning, including the risk to many communities, wildfires also release harmful pollutants including particulate matter and toxic gases such as carbon monoxide, nitrogen oxides, and non-methane organic compounds into the atmosphere.

The 18th World Meteorological Congress in June 2019 endorsed the plan to advance the integration of weather, climate, water and environmental applications and services for health, and work closely with WHO to prevent health risks. Populations both near and downwind of raging wildfires are keenly interested in receiving better warnings about the fires themselves and related air quality risk levels as both are serious threats to life and health.

WMO has initiated a Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS). Arising from the keen interest of WMO Members in several impacted regions, the concept provides guidance for addressing the issues of vegetation fire and smoke pollution.

The following research topic-related challenges have been identified and recommendations have been made for further VFSP-WAS related research: (i) Fire danger and seasonal forecast; (ii) Fire emissions and haze forecast (including the fire radiative power, smoke and burnt area detection, global forecast and regional downscaling); (iii) Observations and data production for verification and assimilation; (iv) Links and coordination with GWIS, GFMC and Regional Fire Management Resource Centers.

The first research phase of the system was launched in 2018. This paper provides a description of two examples of the most established research and advanced development stage: in Singapore, where regional models are being run and forecasts from various centers are being collated to produce multi-model ensemble smoke forecasts for the Southeast Asia region, and ECCC in Canada, where a demonstration VFSP-WAS center for North America is being established. These examples are recommended as prototypes for Regional VFSP-WACs.

Successfully linking research to services and building close partnership between regional VFSP-WACs and end-users in order to deliver timely fit-for-purpose information requires collaboration and co-design. It is particularly important to link Regional VFSP-WAS with the communities of policy makers, practitioners and civil society.

In 2010, the Global Fire Monitoring Center (GFMC) initiated a process to build thematic centers of excellence in various regions of the world. The mandate and services of "Regional Fire Monitoring Centers" (RFMCs)/Regional Management Resource Centers" (RFMRCs) includes advisory support to nations and to the regional organizations in:

- development and implementation of cross-sectoral landscape fire management policies;
- support of participating countries of the region to develop informal or formal agreements/protocols for cross-boundary cooperation in fire management, including mutual emergency assistance;
- capacitation of state institutions in integrated landscape fire management at national level, based on principles of transdisciplinary innovation, integration, coherence, cohesiveness and interagency coordination;
- involvement of civil society (community-based fire management);
- integrated and nature-based fire management solutions.

The following Regional Fire Monitoring/Fire Management Resource Centers are available for coordination and collaboration with VFSP-WAS:

- Regional Fire Monitoring Center: Southeast Europe/Caucasus Region (RFMC) (Skopje, Republic of North Macedonia);
- Eastern Europe Regional Fire Monitoring Center (REEFMC) (Kyiv, Ukraine);
- Regional Fire Management Resource Center in Central Asia (RFMRC-CAR) (Ulaanbaatar, Mongolia);
- Regional Fire Management Resource Center in South East Asia (RFMRC-SEA) (Bogor, Indonesia);
- Regional Central Eurasia Fire Monitoring Center and Russia (Krasnoyarsk, Russia).

Regional Fire Management Resource Centers in South America (RFMRC-SAR), Eastern Subsahara Africa (Madagascar) and Eastern Asia (Harbin, P.R. China) are currently being planned. These centers will allow to bring the VFSP-WAS service to the target groups that need to receive the information generated by VFSP-WAS.

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