Smoke forecasting using AQFx for the 2019-2020 summer bushfires.

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Introduction

The 2019-2020 Australian bushfire season was prolonged and widespread with numerous fires down the eastern seaboard of Australia. Many were large and sustained fires with plumes sometimes reaching the stratosphere. Satellite imagery showed smoke travelled from Australia, over New Zealand and around the globe. During Black Summer, smoke covered much of the Australian eastern seaboard for days on end with hazardous levels of $PM_{2.5}$ recorded in many population centres including the capital cities. The population health impacts (and health costs), have since been assessed to be significant.

Throughout Black Summer, the smoke forecasts provided by the Bureau of Meteorology (BOM) operational air quality forecasting system (AQFx) were used in the eastern states and territories to help manage hazards to health, aviation, and Australian Defence Force operations. However, the application of AQFx in this mode did present some challenges, as the system was originally developed with a focus on simulating smoke from prescribed burns to help make decisions about when and where to burn while minimising a community's exposure to smoke. Forecasting smoke transport from large and long-lived fires placed more emphasis on the need to better integrate bushfire burn behaviour, to forecast the likelihood of bushfire smoke rising above the boundary layer, and the need to accurately track smoke plumes over multiple days.

Recommendation 14.2 National Air Quality Forecasting Capability of The Royal Commission into Natural Disasters (undertaken following the Black Summer fires) stated-

- *Australian, state and territory governments should develop national air quality forecasting capabilities, which include broad coverage of population centres and apply to smoke and other airborne pollutants, such as dust and pollen, to predict plume behaviour.*

This task is currently being actioned by CSIRO, BOM and a consortium of universities with the support of AFAC fire agencies and many of the state and territory environment and health departments. Details of the six major work packages are given on our project website, and include an assessment of AQFx capability for forecasting smoke during the Black Summer period. The purpose of this assessment is to identify, test, and refine existing and new science capabilities with the goal of improving the robustness of AQFx for forecasting the onset timing, and duration of impact of significant smoke events in populated areas.

The next section provides a brief overview of the AQFx system. This is followed by a demonstration of the assessment methodology using a case study of a smoke impact on Melbourne in the second week of January 2020. We then wrap up with a summary of the other work in progress.

AQFx

The operational version of AQFx is a three-tiered system that has been run by the Bureau of Meteorology in Victoria for the Department of Environment, Land, Water and Planning since 2018, and in NSW for the Rural Fire Service commencing 2021.

- Tier 1 generates ensemble forecasts of fire weather for a five-day outlook.
- Tier 2 generates 24-72 hour forecasts of fine particles and photochemical smog (from all sources including smoke) for the Australian region at 9 km spatial, and for the Vic/Tas region and part of NSW at 3 km spatial.
- Tier 3 provides next day forecasts of prescribed burns for Victoria at 1.6 km spatial.

In the discussion to follow, we focus on the Tier 2 capability, and as the requirement is for a national system for forecasting large-scale smoke events, we currently limit our consideration to the continental 9-km domain. Note that AQFx_p represents the new AQFx capability, which will be operationalised by BOM once the current project is completed.

Figure 1 shows a workflow schematic and an example of the spatial data sets used in a Tier 2 national forecast (here for the Jan 2020 case study discussed in the next section). In the workflow schematic we have focussed mainly on the pipeline used to generate and link smoke emissions into the forecasting system. The pipeline components are as follows.

1. Fuel layer maps for fine fuels and coarse woody debris (CWD) and their consumption rate. In AQFx_p we source the fine fuel load from the AFDRS project, and use coarse woody debris generated by BIOS2 modelling to forecast smouldering emissions.
2. Temporal and spatial estimates of area burnt. We have developed a three-layer system (rated lowest to highest capability) for use with AQFx_p.
    i. cluster analysis of satellite hotspot data and forecasting of area burnt using statistical relationships between hotspot density and burnt area;
    ii. fire front data provided by agencies, with fire spread (area burnt) forecast using Spark;
    iii. fire spread data/shapefiles provided directly by agencies.
3. Speciated smoke emissions and smoke plume rise (the latter derived from fuel burnt and energy released).

The spatial data sets shown in Figure 1 demonstrate that the ACCESS weather forecasts are an integral component of AQFx, providing forecasts of the transport winds, boundary layer heights, atmospheric temperature and dryness, and precipitation. The chemical transport model couples this information with national emissions of smoke, dust, sea salt and anthropogenic sources (and precursors) of fine particles to generate air quality forecasts (split into total and smoke related $PM_{2.5}$ in the example given). Figure 1 shows an accumulation of fine particles and smoke over the eastern seaboard to Australia. The Victorian segment of this forecast is examined in more detail in the next section.

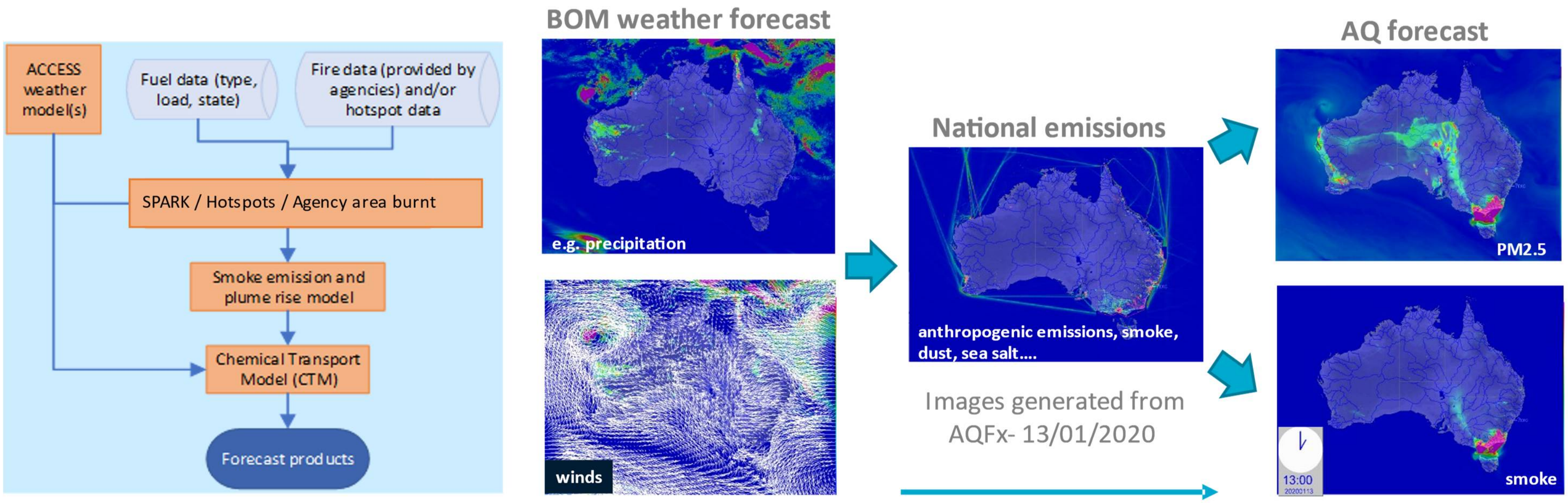

Figure 1 Left- workflow schematic of the AQFx_p system (with a focus on smoke emissions). Right- example of the spatial data associated with a national air quality forecast- here for 13th January 2020.

A deep dive into an AQFx_p forecast for 12-16 January 2020

Analysis based on surface observations

In this section we highlight some of the surface-based analysis undertaken in a deep dive of AQFx forecasting performance for Victoria in the second week of January 2020.

Figure 2 shows a contour plot of 1-hour average $PM_{2.5}$ from AQFx_p over south-eastern Australia at 1300 UTC 13/01/2020. Many fires, indicated by the red hotspots, can be seen in eastern Victoria and south-eastern NSW. The coloured circles show observed 1-hour average $PM_{2.5}$ at 31 sites and the blue arrows show the observed wind. The forecast $PM_{2.5}$ concentrations compare well with the observed at most sites. Much of the smoke in the Central region (see [Victorian EPA fire regions,](#) includes the Greater Melbourne area) was forecast to arrive from the south after travelling from the south-eastern coastal area. This smoke plume behaviour highlights the complexities involved in forecasting $PM_{2.5}$ - if a complicated wind pattern is not forecast correctly then the onset and duration of smoke events cannot be robustly forecast.

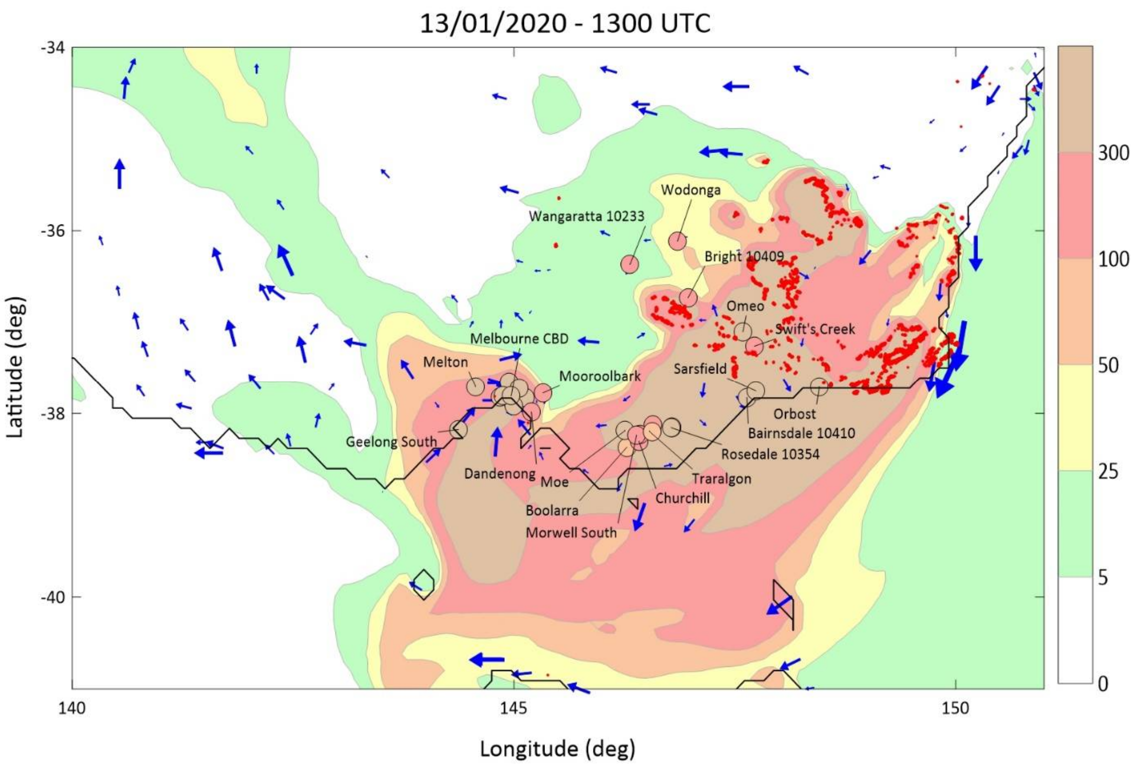

Figure 2 AQFx_p forecast 1-hour average $PM_{2.5}$ (μgm^{-3}) for 13/01/2020 at 1300 UTC. Observed $PM_{2.5}$ is indicated by the circles with some monitoring sites named. The observed winds are overlain. The red dots are VIIRS and MODIS hotspots for the day. (The colour scale follows the EPA Victoria's air quality categories scheme.)

Figure 3 shows a time-series of the observed (blue) and AQFx_p forecast (red) median values of 1-hour average $PM_{2.5}$ for the Central region (the median is calculated over 14 sites). The figure also highlights the range of $PM_{2.5}$ values across the sites (shaded regions). AQFx_p forecast a broad peak of the median value of $PM_{2.5}$ on the 13/01/2020 with onset and duration times in reasonable agreement with the observed. The maximum predicted median peak value of $PM_{2.5}$ was about half of the observed and while predicted values of $PM_{2.5}$ were large over much of the Central region AQFx_p underestimated the peak observed concentrations. The second predicted peak on 14/01/2020 compares well with the observed.

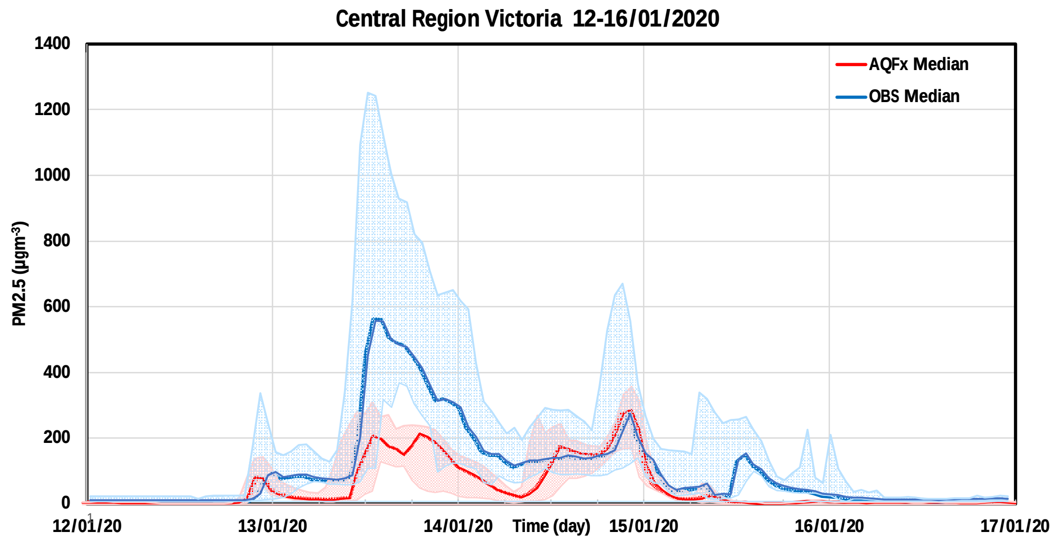

Figure 3 Time-series of $PM_{2.5}$ (μgm^{-3}) for the Central region of Victoria. The blue line is the observed median of all sites, and the red line is the AQFx_p forecast median value for the same sites. The shaded areas indicate the range of values over the sites (blue-observed, red-AQFx_p).

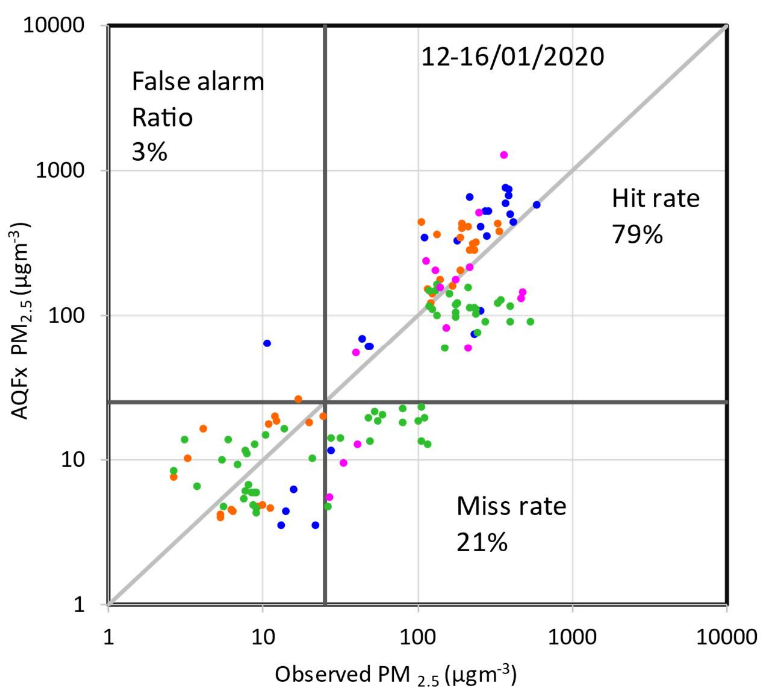

Figure 4 Scatter plot of 1-day average $PM_{2.5}$ (μgm^{-3}) (log axis). The colour of the dots represents different Victorian regions: blue – East Gippsland, orange – West & South Gippsland, green – Central, pink – North East. The diagonal line is the 1:1 line and the parallel lines mark 25 μgm^{-3} (NEPM 1-day average $PM_{2.5}$ standard).

Figure 4 shows a scatter plot of observed 24-hour average $PM_{2.5}$ versus forecast $PM_{2.5}$ for the period 12-16/01/2020 (daily points for each site), thus enabling a categorical evaluation of the $PM_{2.5}$ forecast. The parallel lines mark 25 μgm^{-3}, the National Environment Protection

Measure for Ambient Air (NEPM) 1-day average $PM_{2.5}$ standard. The colour of the dots represents different Victorian regions (see figure caption). Most of the dots appear in the upper right quadrant (thus correctly forecasting an exceedance of the NEPM standard) and the lower left quadrant (correct forecast of non-exceedance of NEPM standard). Categorical metrics are also shown, where the hit rate is the % of observed exceedances that were forecast, this is 79% for all sites while it is 63% for the Central region.

In general, $PM_{2.5}$ was underestimated in the Central region, while in the East Gippsland region, West and South Gippsland region and North East region $PM_{2.5}$ was often overestimated. Importantly, AQFx_p captured the timing of the extended period of high $PM_{2.5}$ during 12-16/01/2020 in all those regions and therefore did well in predicting the prolonged smoke exposure.

Scoping the use of remote sensing data

The smoke plumes of Black Summer cover a very large spatial area and can extend to considerable altitudes. The associated $PM_{2.5}$ concentrations are often complicated by the mixing of smoke and elevated dust in strong, fire-generated convective cells or by the presence of smoke and water droplets mixed within pyrocumulus clouds. It is not possible to test the accuracy of any forecasts of such complex events using a, generally-sparsely distributed, ground sensor network. Satellite remote sensing observations, however, do have the global coverage needed and some, like the lidar carried by the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite, produce information on the vertical distribution of various types of clouds and aerosols in the atmosphere. Satellite observations, however, cannot always cover the whole depth of the atmosphere at all locations, and this limitation has implications for their use in testing the forecast system.

The complexity of the events that need to be forecast is exemplified in Figure 5, which depicts the vertical cross-section of the atmosphere along the path (the green section in the inset) of CALIPSO over Australia beginning at 1533 UTC on 12 January 2020. Aerosols and clouds, as determined by CALIPSO's cloud-aerosol discrimination (CAD) algorithm, are shown in the upper panel, while the various types of aerosols, as determined by CALIPSO's aerosol sub-typing algorithm, are shown in the bottom panel using various colours shown in the key.

Various aerosol types were identified within a layer ~ 3 km deep extending from the Yarra Ranges in the south, northeast along the CALIPSO ground track. Around 25°S, aerosols can be seen above low cloud, but high cloud prevents the detection of aerosols farther north. Because performance of CALIPSO's CAD algorithm is limited by the signal-to-noise ratio, mistyping of aerosols can occur, and this dust layer may contain smoke.

These descriptions indicate the difficult tasks required of the forecasting system. Lofting of smoke above the mixed layer and mixing with clouds and dust need to be considered. For severe fire events, the ability to predict stratospheric intrusions and transport is also needed. The complex and varying vertical distribution of the various aerosol types also indicate that care is needed in comparing forecast aerosol optical depths with the column measurements made by ground-based sun-photometers.

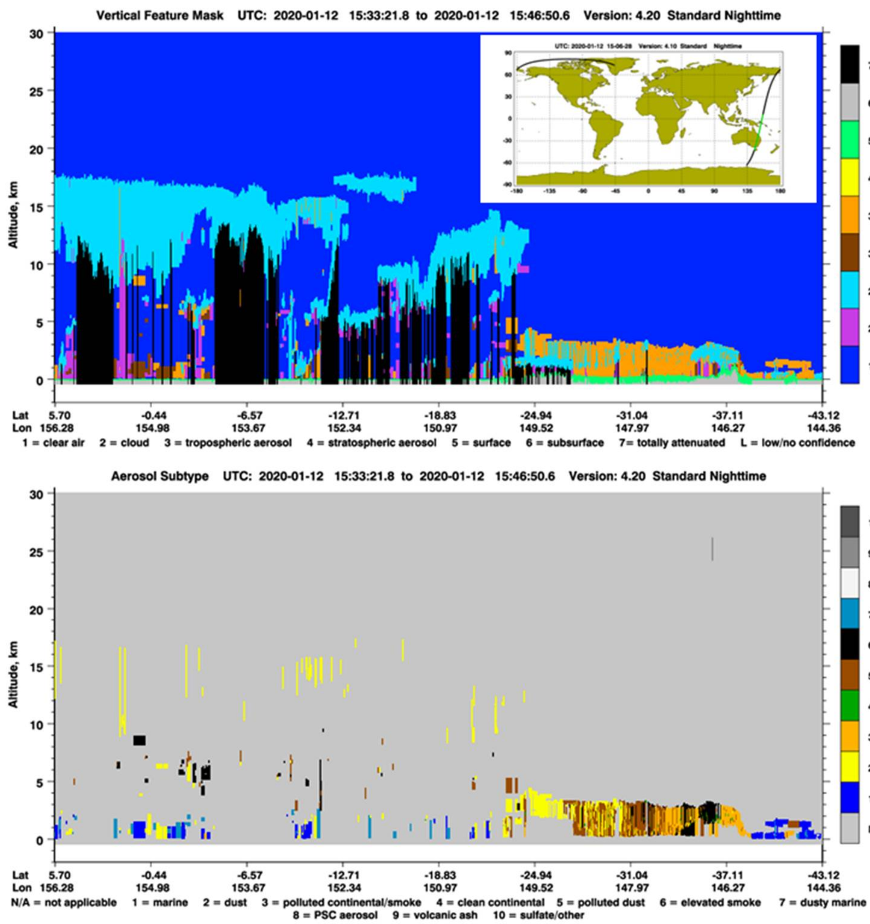

Figure 5. CALIPSO vertical feature mask (top) and aerosol subtype (bottom).

Summary and Conclusions

Work is well underway on upgrading AQFx to provide a robust, national air quality forecasting capability for smoke from large, long-lived bushfires. Guidance as to areas which require most improvement is being provided by a deep dive into forecasting performance for the Black Summer fires. We are using ground-based (in situ), remote sensing data, and detailed agency data on fire behaviour to identify the system components which may need further improvement. One of our primary goals is to quantify the skill with which AQFx can predict the onset of smoke impacts in populated areas, and the subsequent duration and magnitude of the exposure. This will enable forecasters to better inform the public and if/when to take measures to reduce smoke exposure, and thus minimise the risk of adverse health impacts.

Acknowledgements

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The meteorological data was sourced from the Bureau of Meteorology (ACCESS data and AWS data).

The State EPAs provide emission inventories and observational data.