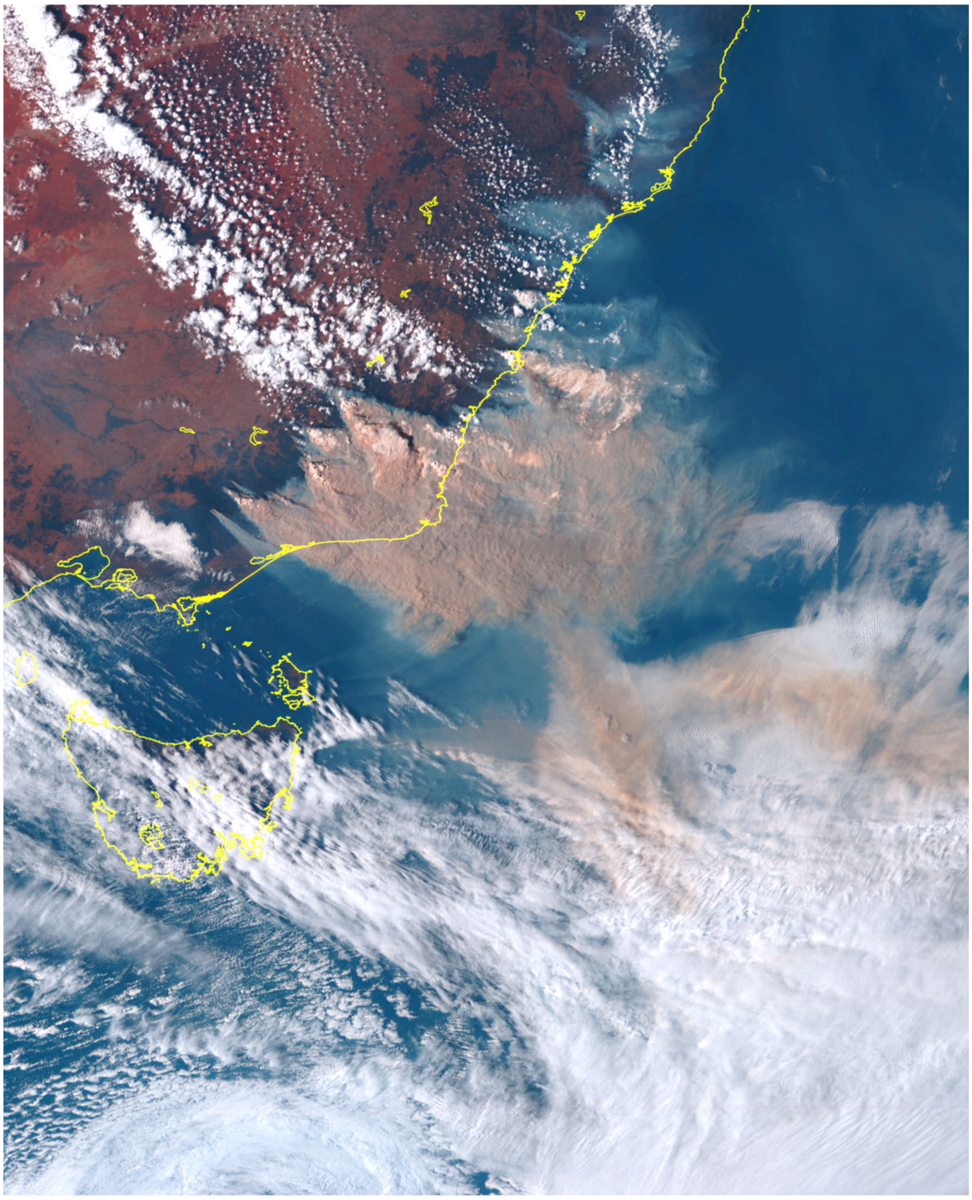
BLACK SUMMER: WHAT HAPPENED



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BLACK SUMMER: WHAT HAPPENED

This report details analyses of observational data from the eastern Australian 20919-2020 Fire Season, known as Black Summer. This is not aimed at the fire level – rather it explores the overview, ranging from sub-hemispherical to regional scales. This context information explains why the fires themselves were so unusually violent and impossible to control. It does not consider state / territory boundaries.

The work has been conducted by Adjunct Professor Rick McRae of the University of New South Wales, Canberra School of Science, located at the Australian Defence Force Academy. He has over 30 years of high level operational experience, including arson investigation, Level 3 Planning Officer, Fire Behaviour Analyst (including interstate and international deployments) and risk analyst. He has been conducting scientific studies into wildfires for 35 years. He has been involved in organising national workshops and conferences and international conferences.

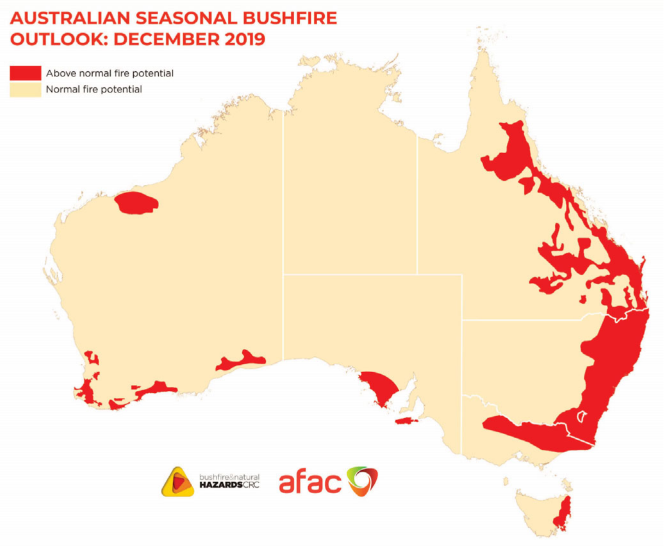
Contents

OVERVIEW

For over two years ahead of the fires, there was a major drought in place. This reflected sea surface temperature anomalies due to the Indian Ocean Dipole and the Southern Annular Mode. The Southern Oscillation was not relevant.

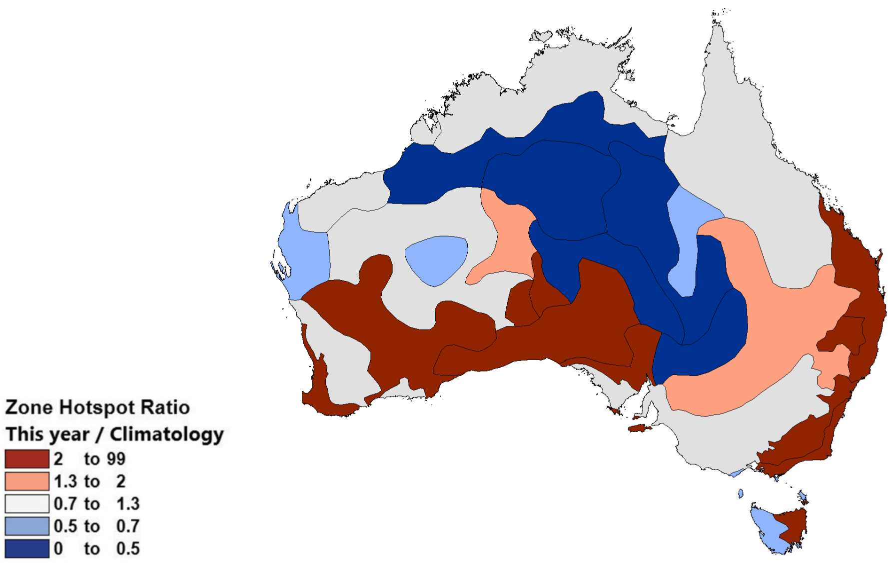
Based on this, the national bushfire seasonal update ahead of the fires was quite salient.

BELOW: The official bushfire seasonal outlook from December 2019.



- Many areas of eastern Australia, including Canberra, are in extreme drought stress, which may deteriorate as summer settles.
- BoM outlooks show little prospect of relief in the coming months.
- Lowland forests will be the main threat, with an early onset of flammability.
- Grasslands will have very low fuel loadings.
- Highland forests could turn rapidly, given their currently stressed condition.

ABOVE: Official outlook briefing for ACT – catch-line "As bad as it gets".



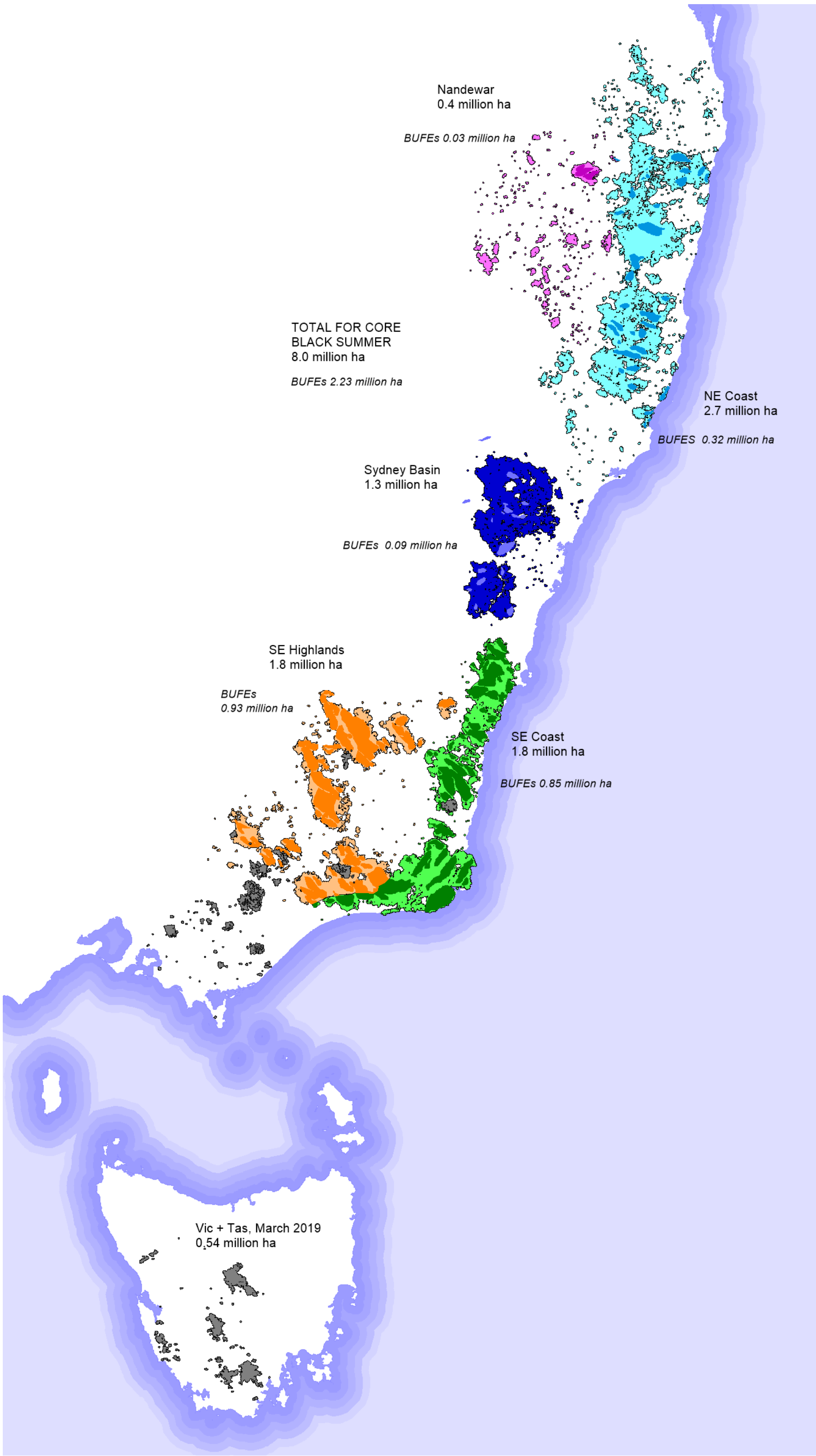
HOW MUCH BURNT IN BLACK SUMMER?

Too many burnt area values have been published, ranging from under 8 million hectares to over 20 million.

8.0 million hectares of forest burnt in the Black Summer core zones.

This analysis uses the MODIS fire hotspots seasonality zones. In the table, MODIS hotspots have had a 1km buffer area drawn around them. In the map, the core Black Summer forest fire Zones (red text) have been analysed to greater precision.

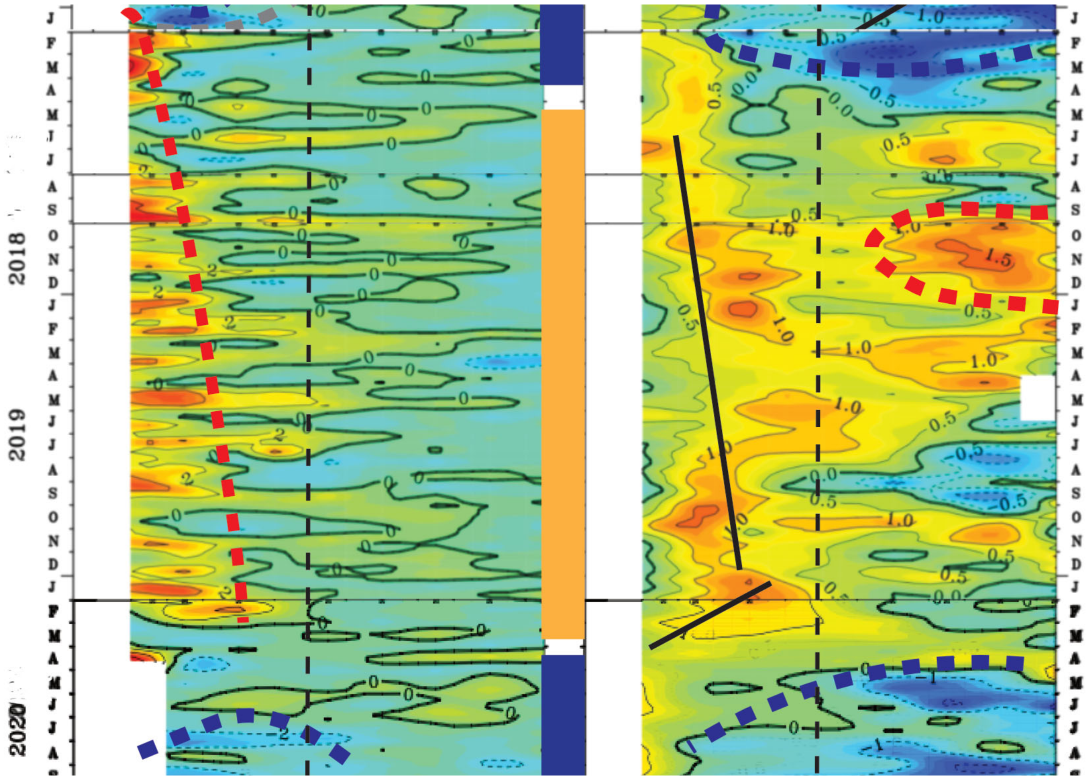
Zone	Seasonality	Ratio (Yr/Clim)	Area burnt (ha)	
01) Broome	Jul-Aug-Sep	1.1	480,000	
02) New England Escarpment	Aug-Sep-Oct	6.4	3,520,000	
03) Simpson Desert	Sep-Oct	0.01	24,000	
04) Queensland	Sep-Oct-Nov-Dec	1.1	6,380,000	
05a) Great Sandy Desert	Oct-Nov	1.1	850,000	
05b) Barklay - Channel Country	Oct-Nov	0.2	110,000	
05c) Savannah	Oct-Nov	0.2	660,000	
06) Woomera - Nullabor	Oct to Feb	4.8	230,000	
07a) SW Western Australia	Oct-Nov + Apr-May	2.3	510,000	
07b) Arnhem Land	Oct-Nov + Apr-May	1.2	13,800,000	
08) Nandewar	Nov-Dec	9.2	460,000	
09a) Gibson Desert	Nov-Dec-Jan	0.3	44,000	
09b) W Great Victoria Desert	Nov-Dec-Jan	11.7	420,000	
10) Murchison	Dec-Jan-Feb	5.7	1,730,000	
11a) Carnarvon	Jan-Feb	0.3	37,000	
11b) Great Victoria Desert	Jan-Feb	3.5	130,000	
11c) Mitchell Grass Downs	Jan-Feb	0.6	60,000	
11d) Broken Hill	Jan-Feb	0	0	
11e) SE Highlands	Jan-Feb	10.1	3,100,000	
12a) W Wheatbelt	Apr-May	0.9	550,000	
12b) E Wheatbelt	Apr-May	0.8	910,000	
12c) W Tasmania	Apr-May	0.5	65,000	
13) Tanami Desert	Aseasonal (Aug-Oct)	0.1	170,000	
14a) Pilbara	Aseasonal	1	540,000	
14b) Central Ranges	Aseasonal	1.4	340,000	
14c) Darling Plains	Aseasonal	1.8	1,010,000	
14d) SE Coast	Aseasonal	19.7	1,800,000	
14e) E Tasmania	Aseasonal	2.4	120,000	
14f) Gawler Ranges	Aseasonal	4.2	50,000	
			38,100,000	Total
		3.2		Average



ABOVE: Burnt areas in "geographical regions" rather than climatology zones. Note that about 27% of the burnt area was due to BUFEs. Also shown are the half million hectares in Tasmania and the Victorian high country that burnt in late summer 2019 – the "first act" of Black Summer.

Between July 2019 and June 2020 38.1 million hectares burnt. In the core area, 8 million hectares of forest burnt. Of the 38.1 million Ha, only 10 million Ha was from zones that normally burn in summer.

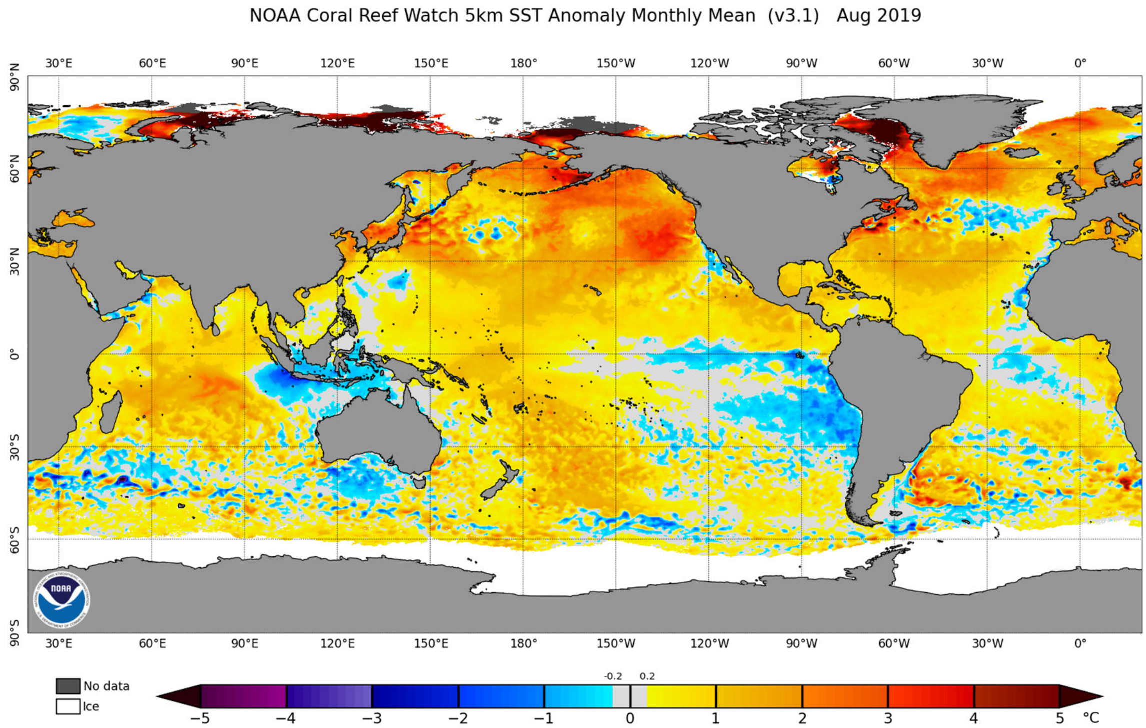
ANTECEDENT SSTAS



ABOVE: NOAA buoy data for the lead up to Black Summer through to the end., The left-hand panel is the zonal (west—east) wind anomalies. Orange is pushing moisture laden air systems away from Indonesia, blue pushing towards it. The zonal winds were keeping moisture away for two years prior to the fires. The right-hand panel shows the El Nino event. Anomalously warm SSTAs are orange, cool ones blue. The core El Nino event was in late 2018, with two or three El Nino *Modoki* events following. Thus the El Nino core was not linked to the major fires, except perhaps those in March 2019. Superimposed coloured lines demark trends only.

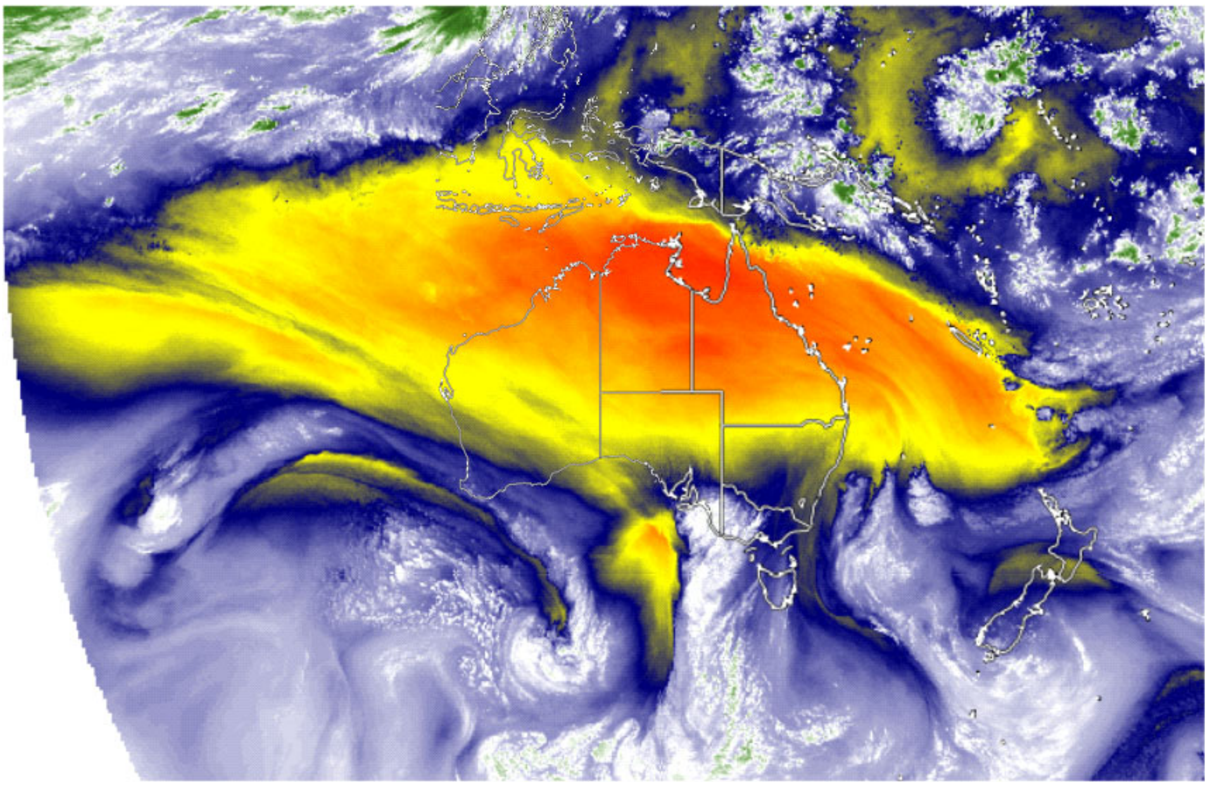
Sea Surface Temperature Anomalies affect synoptic weather systems.

The ENSO data only explores one aspect of the larger-scale drivers of Black Summer. Most climate discussions now include: the Indian Ocean Dipole, Southern Annular Mode, and Madden-Julian Oscillations.

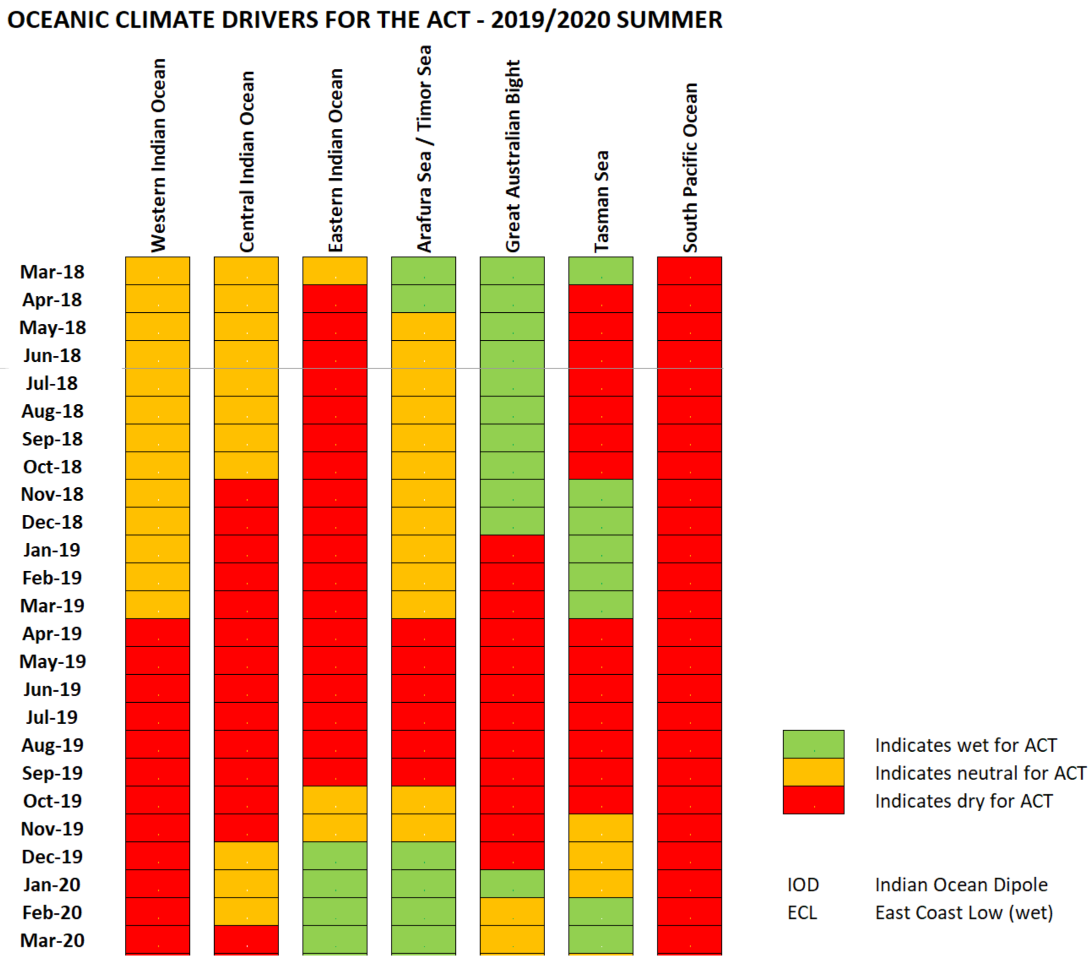


ABOVE: A monthly averaged sea surface temperature anomaly map, showing cool waters to the north and south of Australia, and warm waters to the east and west.

BELOW: A concurrent satellite image, showing the water vapor content of the atmosphere over 5km above the surface. Red is very dry, white and green are rain-bearing cloud-tops. This aligns well with the cold SSTAs seen in the previous graphic. It demonstrates the linkage between SSTAs and overall fire weather. [Himawari-8, RealEarth]

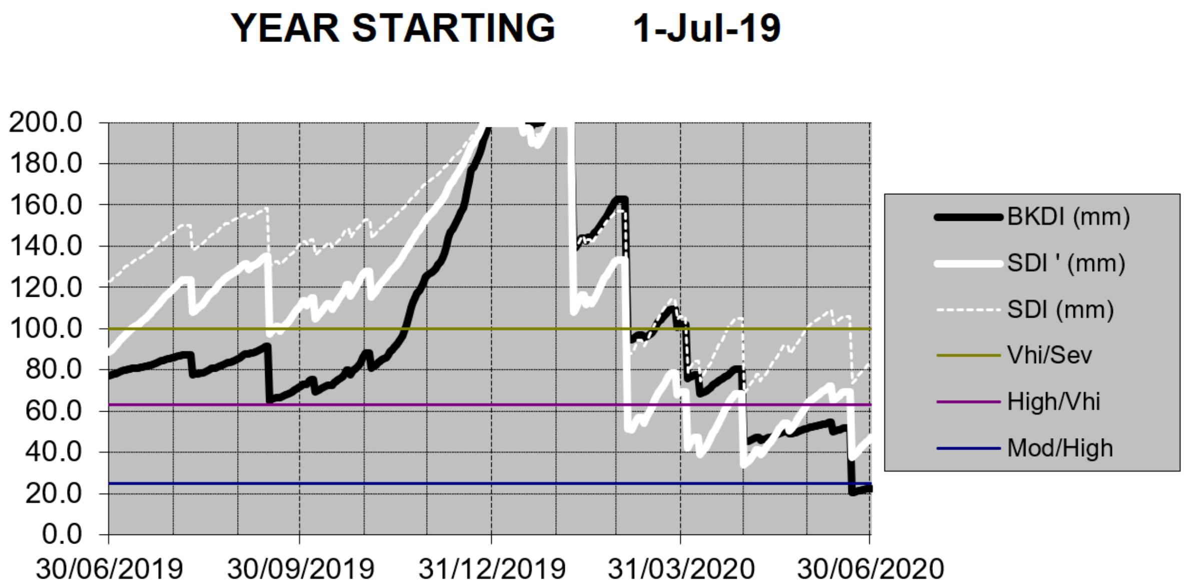


BELOW: A summary of the influences of SSTAs around Australia on fire conditions in the ACT. Green indicates an ocean area likely to push moist air into the continent, orange dry air. It is noteworthy how Conditions dried out in the lead up to the March 2019 fires, and then persisted through into BS itself, even as some drivers switched to different states.



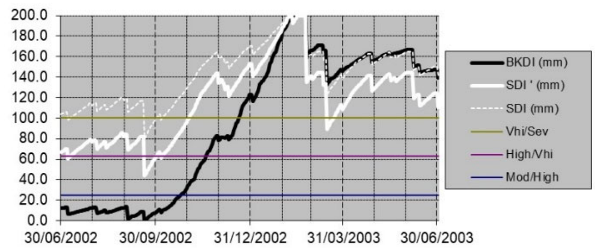
ANTECEDENT DROUGHT

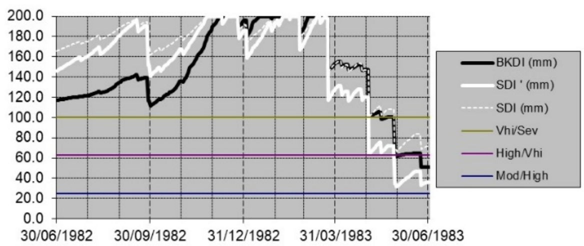
For steady-state forest fires, the Drought Index is a key component. Australia uses the Keetch-Byram Drought Index (developed for Daniel Boone State Forest in Kentucky) and Mount's Soil Dryness Index (developed in Tasmania and NSW). SDI's is a rescaling of SDI to make it fully comparable with KBDI.



ABOVE: Drought Index development during the 2019-2020 fire year for Canberra Airport. Drought Indices are on 0 mm (saturated) to 200 mm scale (completely dry) scale.

BELOW: Comparative graphs for two previous bad fires years: 2002-2003 and 1982-1983.



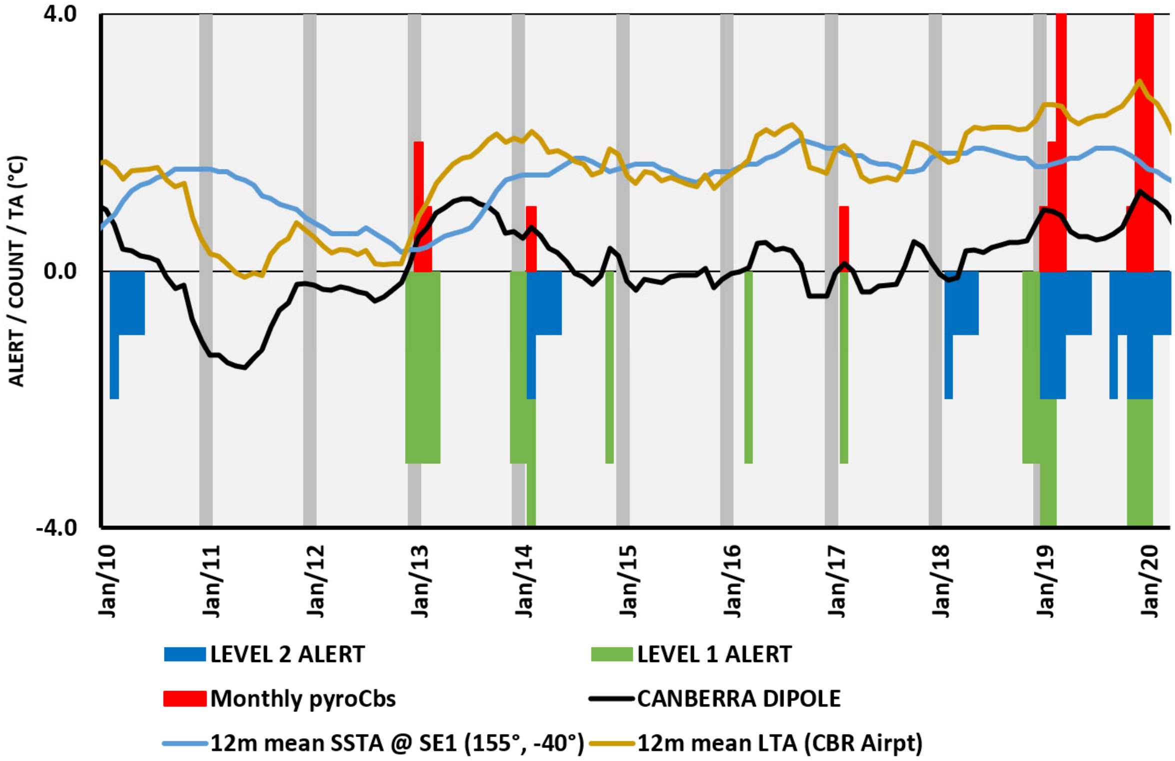


While droughts precede major fire events, *surface* dryness is not a useful metric.

For dynamic fires, there is no explicit role for DI. The severity of the 1982-1983 trace supports the notion of long-term fuel dryness. It supports the idea that large dead-and-down fuels, such as large logs lying on the ground, have a major role in dynamic fire behaviour. These become fully flammable after dryness events on a month-scale. Thus long-time-frame landscape hydrology needs to be explored further.

ANTECEDENT HYDROLOGY

BELOW: The Canberra Dipole is an index based on the means of the land and sea temperature anomalies for the previous 12 months, for the SE of Australia – Canberra Airport for the land and well offshore from Narooma for the ocean. These are the brown and blue lines respectively. The Dipole is the difference between them. When the black line is positive and rising in summer then there is potential for BUFEs, and a Level 1 alert is issued – the green bars. If there is one in place, then river drying events are looked for, producing a Level 2 alert (blue bars). Red bars show the pyroCb count (truncated at 4 per month).



The logic is that (given a precedent drought), the temperature anomalies involved in a Level 1 Alert reinforce the formation of branched troughs and other factors that support BUFE formation. If the rivers are drying up, then the sub-soil is totally dried out, and no moisture has been absorbed by any fire fuels - from leaf-litter up to logs. These allow the rapid escalation behind a BUFE. The red line is the count of pyroCb events, a subset of the BUFEs, but a good indicator of what is happening.

It is possible to predict extreme fire activity using new tools.

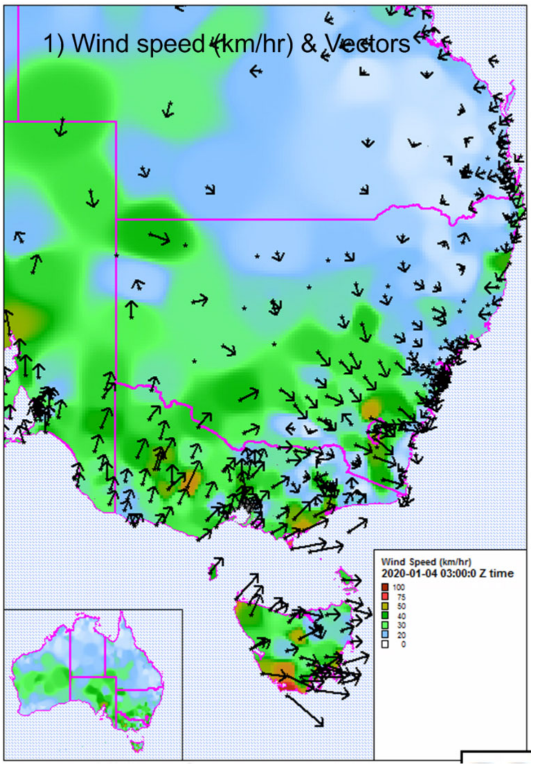
River dryings are based on a reference set of hydrology measuring stations, that look at un-dammed catchments.

The graph makes it clear that the late summer – early autumn BUFEs in the Victorian high country and the Central Plateau of Tasmania were an "opening act" of Black Summer.

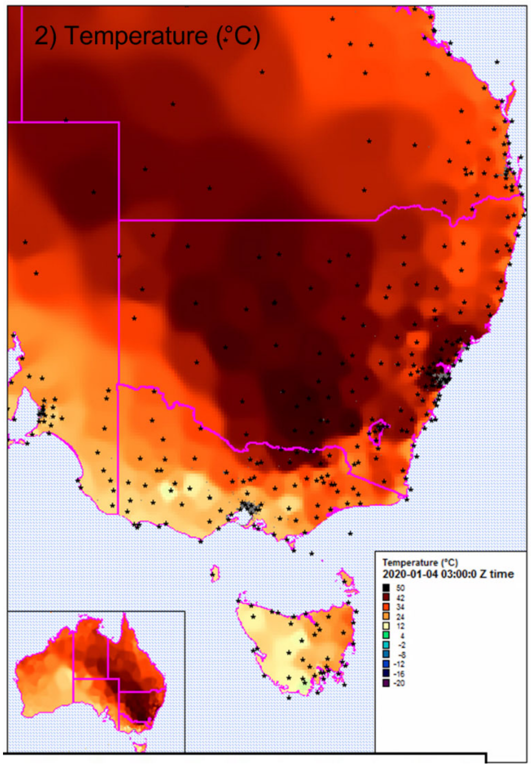
FIRE WEATHER

The set-ups for fire weather were, at times, extraordinary.

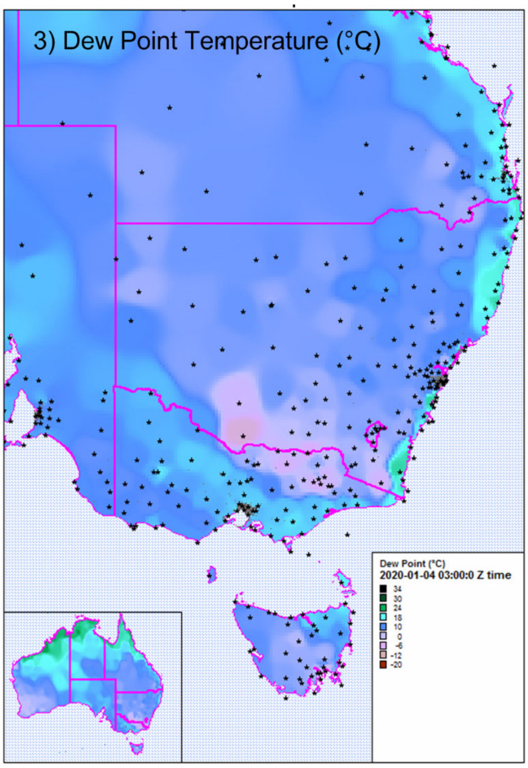
Excerpts from a real-time operational intelligence graphic showing weather conditions during some of the worst fire weather during Black Summer.



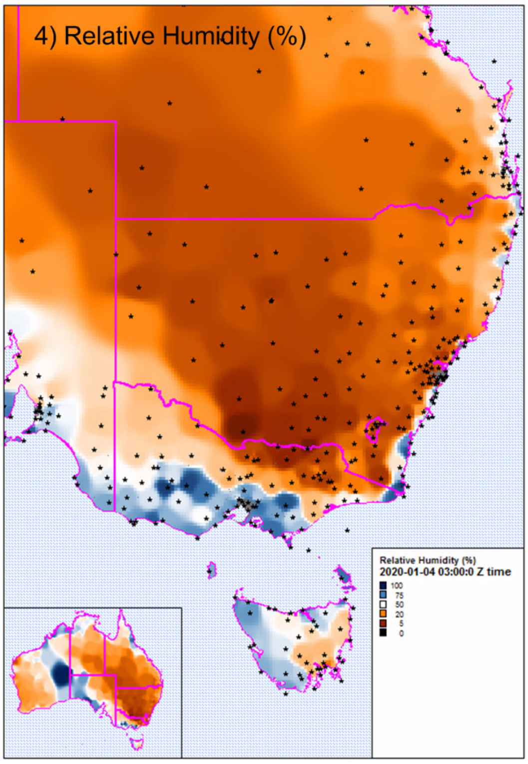
Observed wind vectors (km/hr). Dark blue and above is able to initiate lee-slope eddies, dark green and above allows headfire deep flaming.



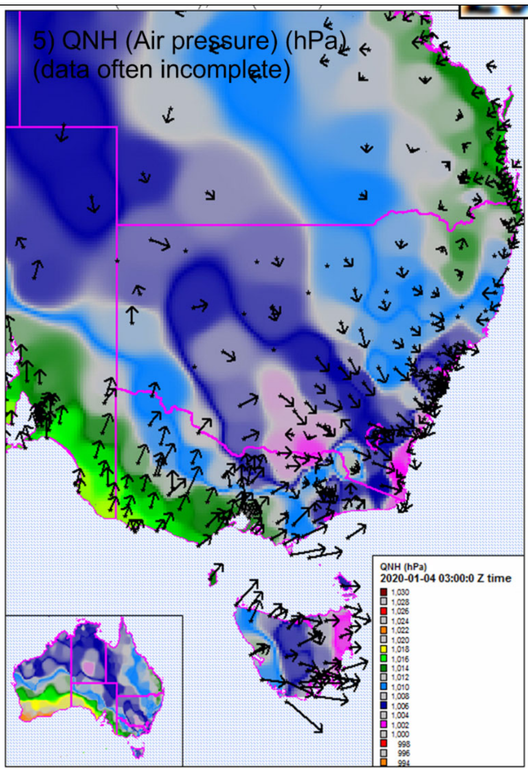
Observed temperature. Anything above red: is considered uncomfortably hot on the fire ground; and facilitates low fuel moisture content due to mixing down of dry air aloft.



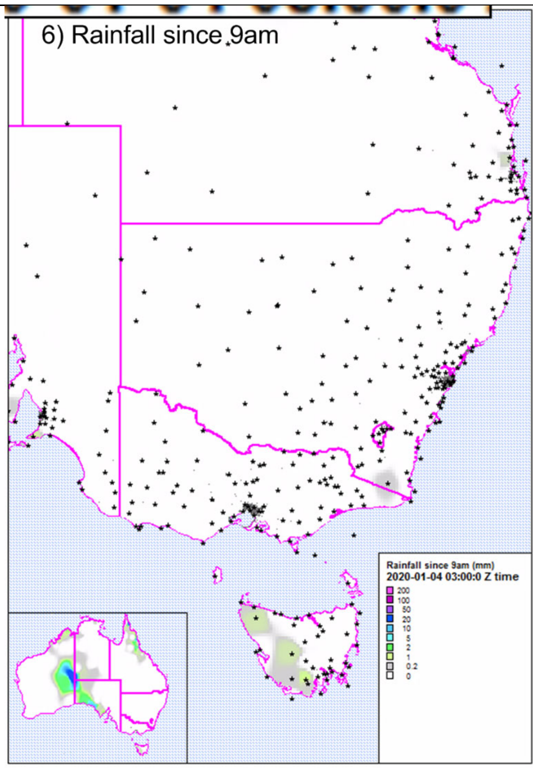
Observed dew point temperatures. Of critical importance is that the lowest DPs are behind the trough (see below). Note the moist air in the sea breezes on the coast.



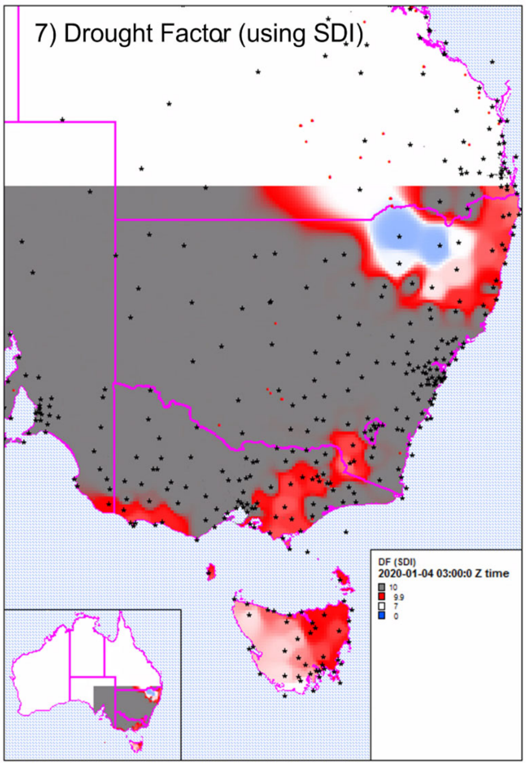
Calculated relative humidity.



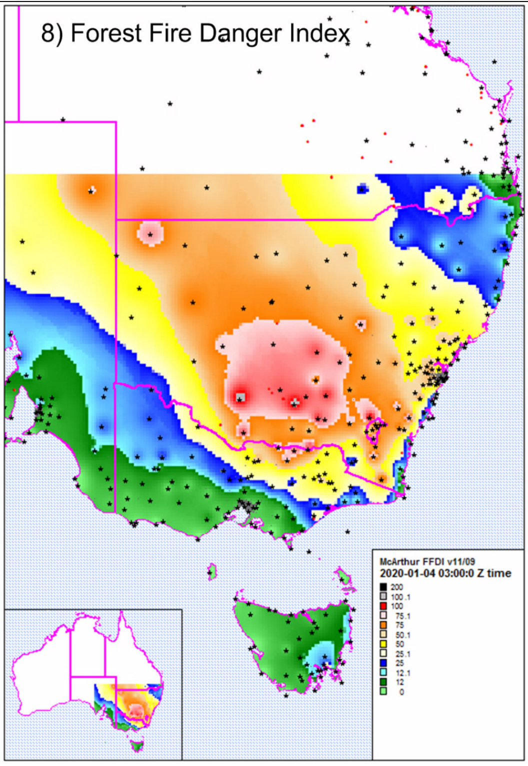
Observed air pressure (QNH). QNH shows the complex branched troughs and the lee trough over Sydney (i.e. dark blue to purple areas). These are not resolved in MSLP charts.



Observed recent rainfall. While there is significant rain in Western Australia, rainfalls in the east have are too low to have an effect on fire danger.



Calculated Drought Factor. This only addresses forest fuels as: (a) grass curing data were not reliable; the product is aimed at forest fires; and (b) FFDI is aligned with the simple FDI.

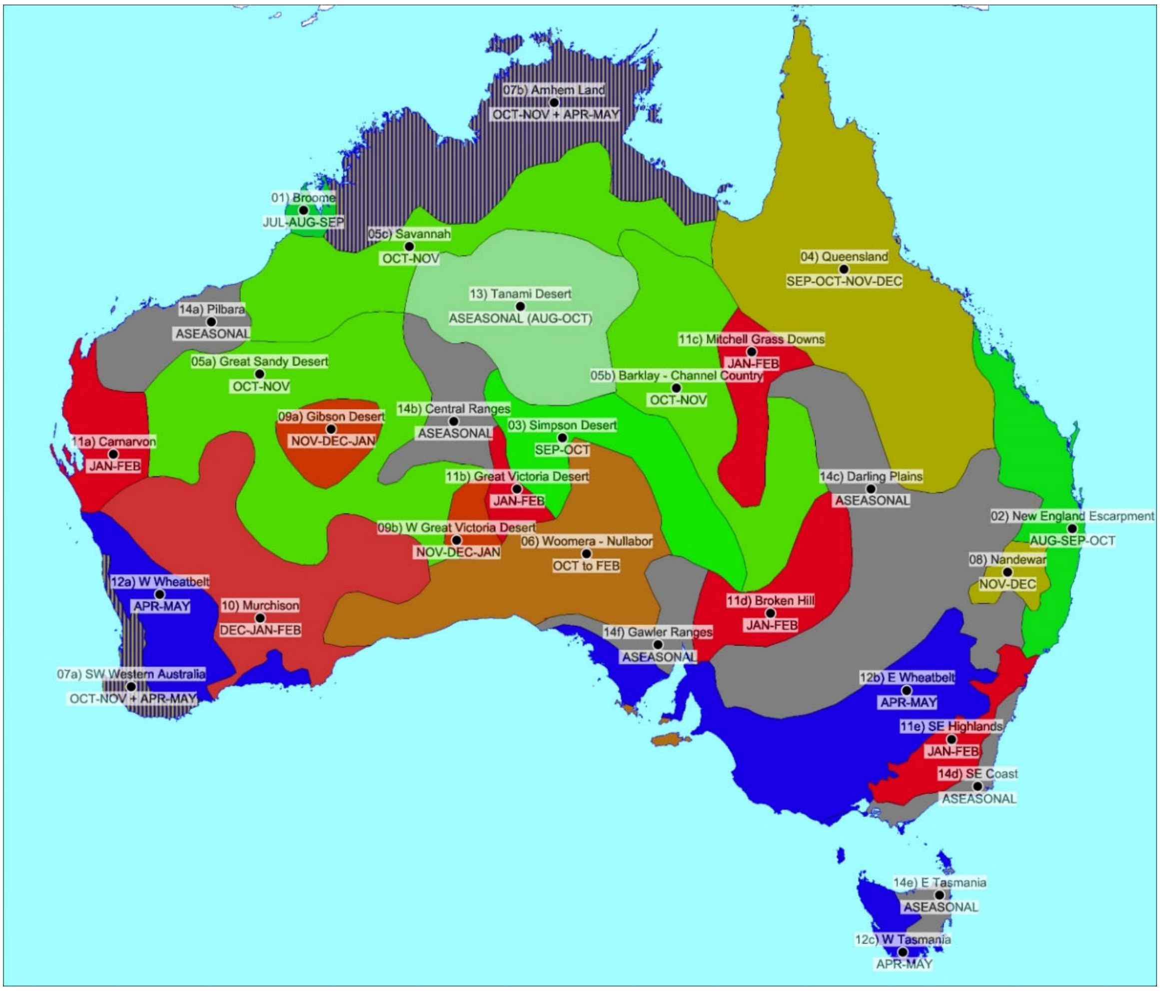


Calculated FFDI. Note the widespread elevated values aligned with, but often behind the trough system (panel 5).

UNPRECEDENTED ACTIVITY

It is has often been said, and is obvious to those who were there, that the fire activity was unprecedented. This can be quantified.

BELOW: McRae & Featherstone (2015) analysed seasonality pattern so fire activity across Australia. They developed a series of Zones with internally consistent seasonality – but not necessarily activity levels. These are shown below.

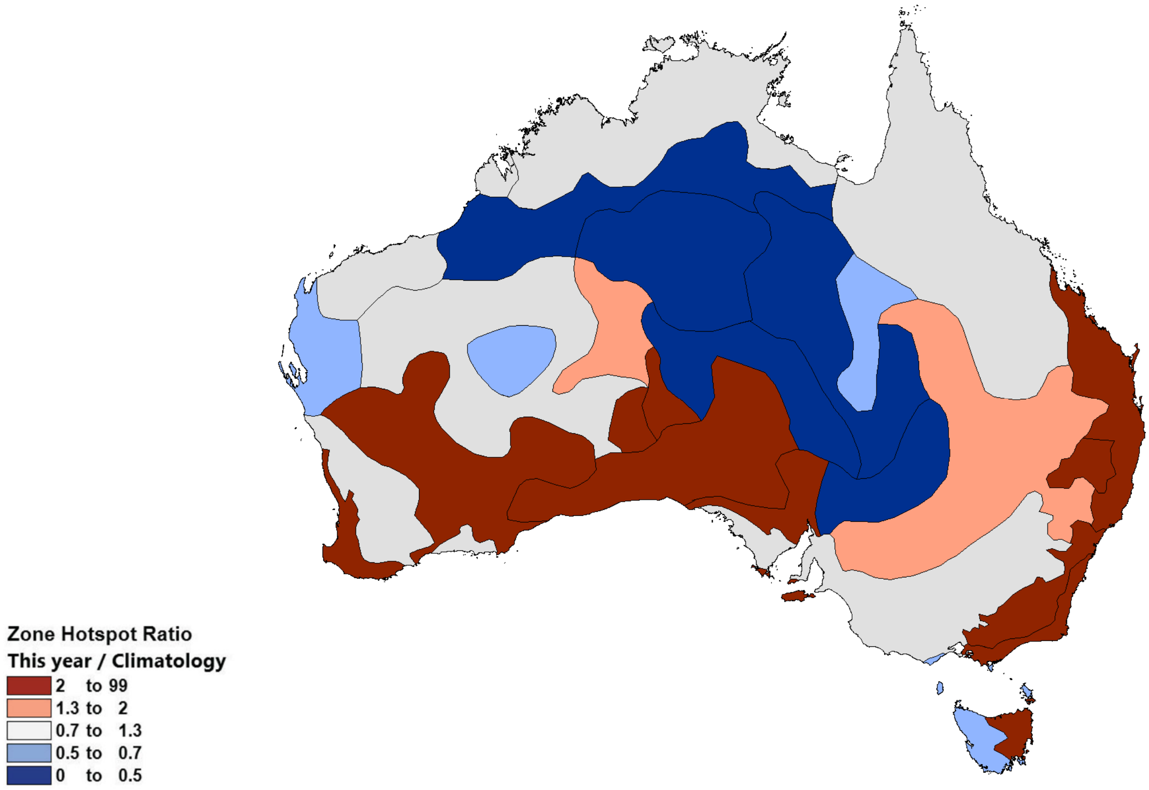


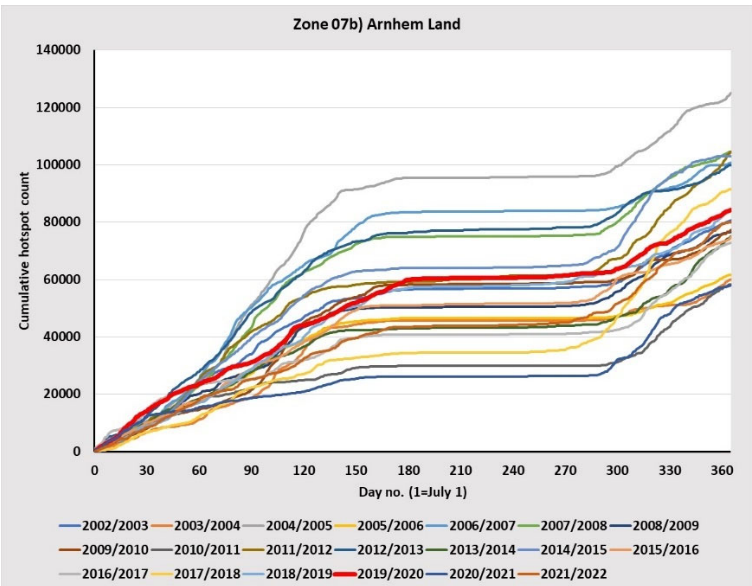
It is then possible to use the zones to aggregate each year's satellite hotspot data to show how they accumulated through the years. If Black Summer was indeed unprecedented then this should show up clearly.

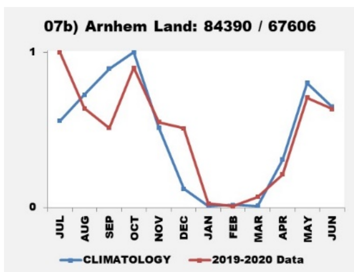
Affected fire seasonality zones carried fire well beyond that of any prior years in the MODIS era.

To begin, some zones showed no outlying activity at all in Black Summer. Below are the accumulation graphs for both Arnhem Land and Eastern Tasmania. The thick red lines show the 2019/2020 data. Years go from July to June. The second graphs show the scaled seasonality of BS hotspots. Both the climatology (July 2002 June 2012 data) and the BS lines are scaled from 0 to 1, allowing monthly anomalies to be seen, if present. In the Eastern Tasmania data below, the major spike in the new year overshadows the autumn climb, which still present but scaled down to low relative importance.

BELOW: A summary of the ratio of BS hotspot counts to the climatology.

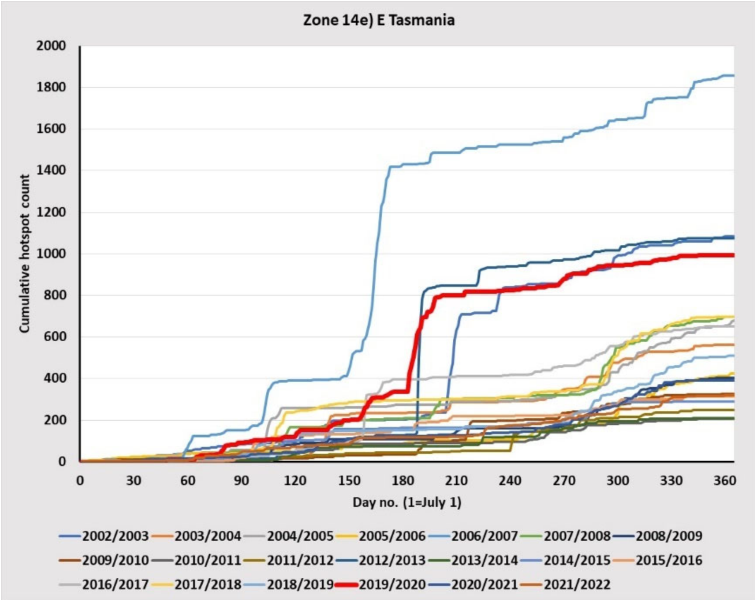


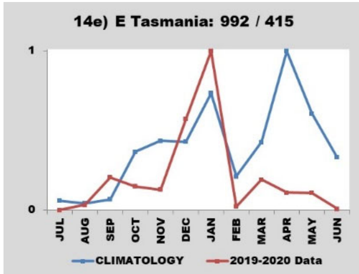




ABOVE: Arnhem Land. This tropical zone showed the normal seasonality and roughly average counts (1.2 times the average). Note that there were 84,390 MODIS hotspots recorded.

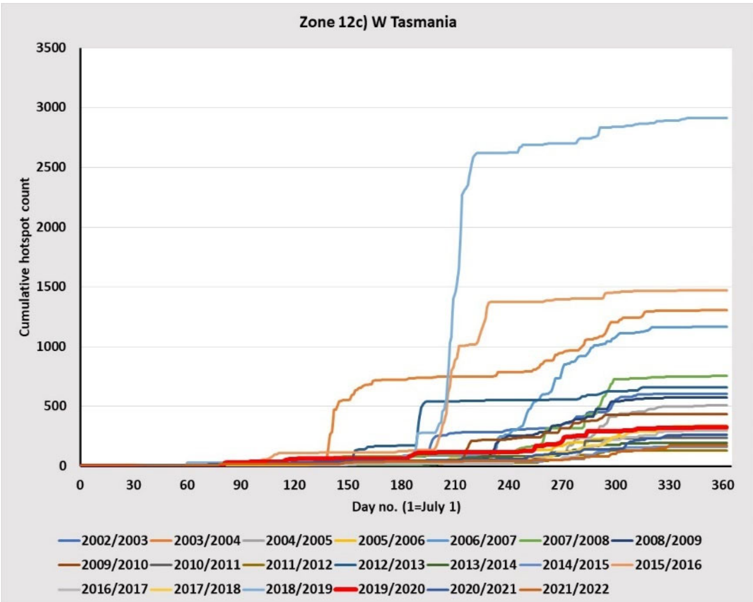
BELOW: Eastern Tasmania. This cool temperate zone showed roughly normal seasonality and 2.4 times the average count.

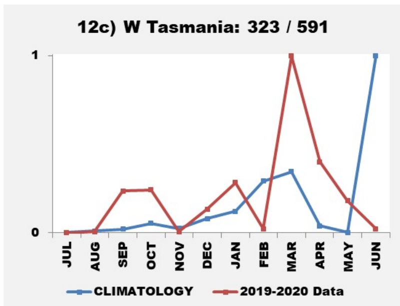


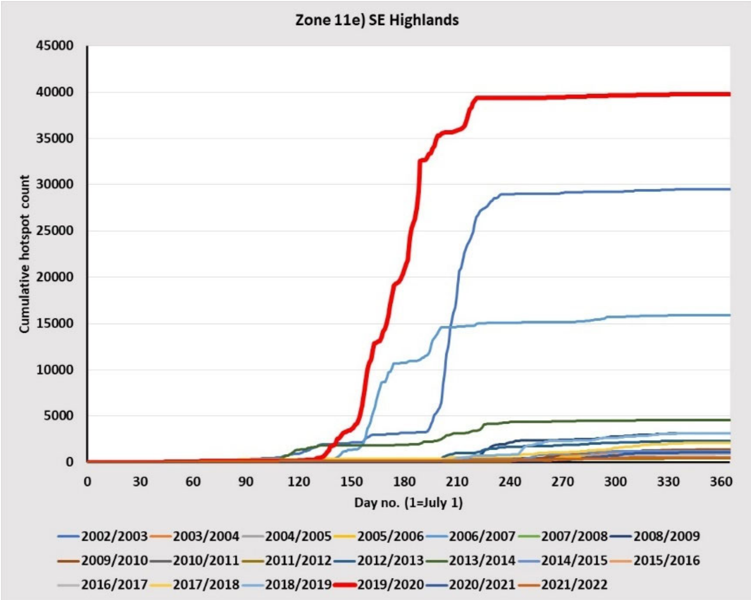


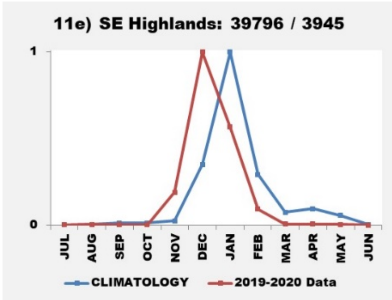
By contrast, a number of zones showed clearly unprecedented activity patterns.

BELOW: Western Tasmania. Large fires in the new year produced a massive spike of the hotspot count for 2018/2019.



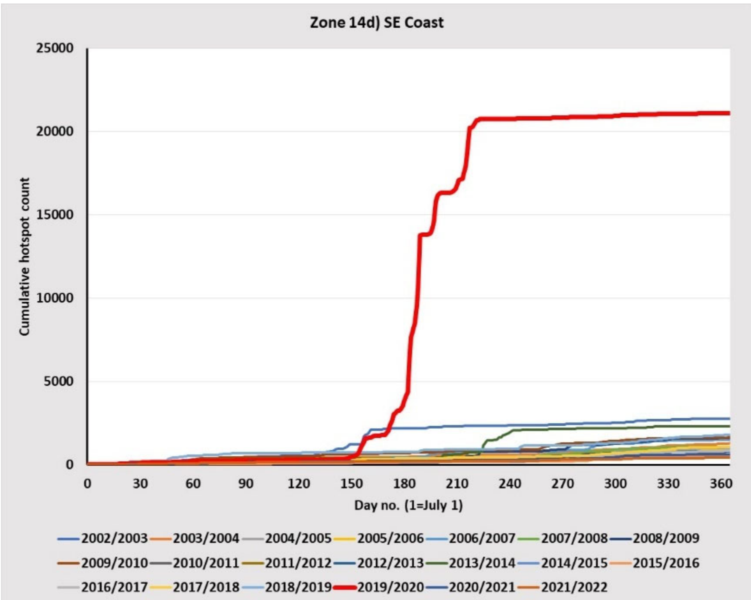


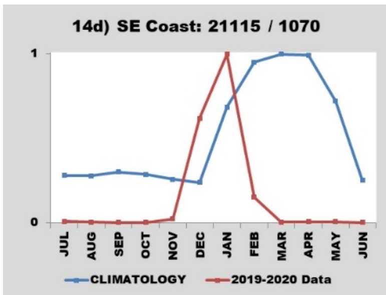


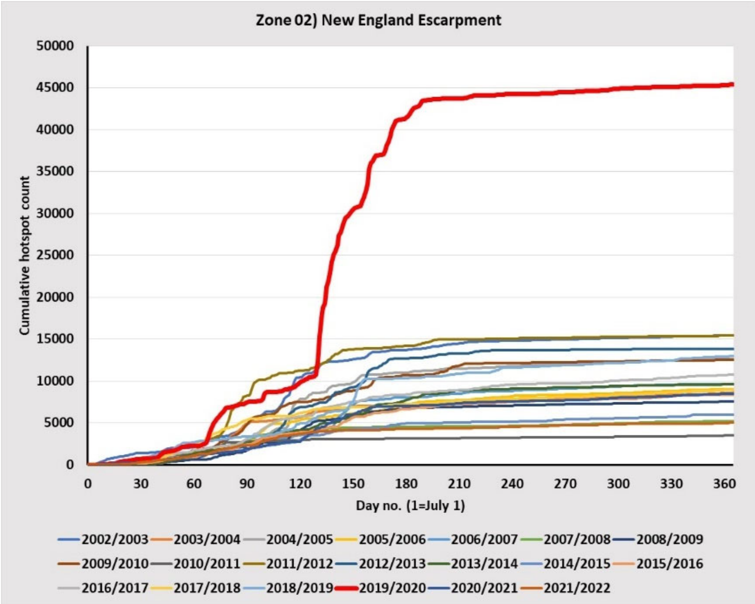


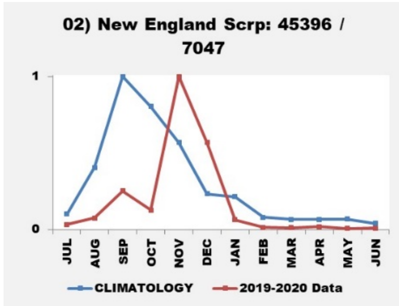
ABOVE: South-east Highlands. The pattern is remarkable. It resembles those of previous bad fire years – 2003, and 2006/2007, but is more extreme. It climbs for longer than either previous year did – nearly four months. This was 10.1 times the average.

BELOW: South-east Coast. This zone had no precedent for major fire activity. There is no comparison, and the count is eight times the previous record and 19.7 times the average.



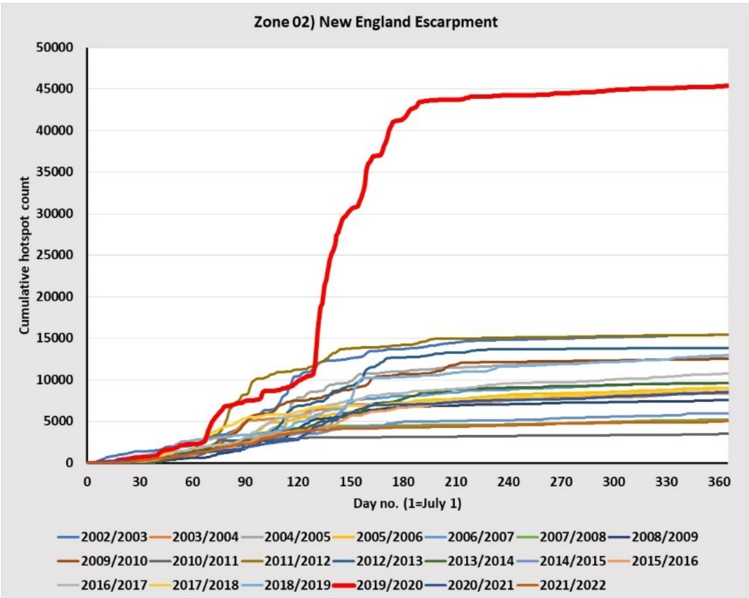


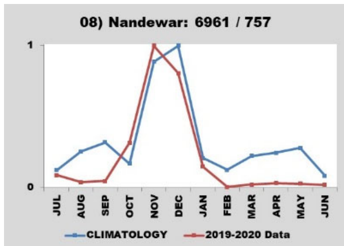




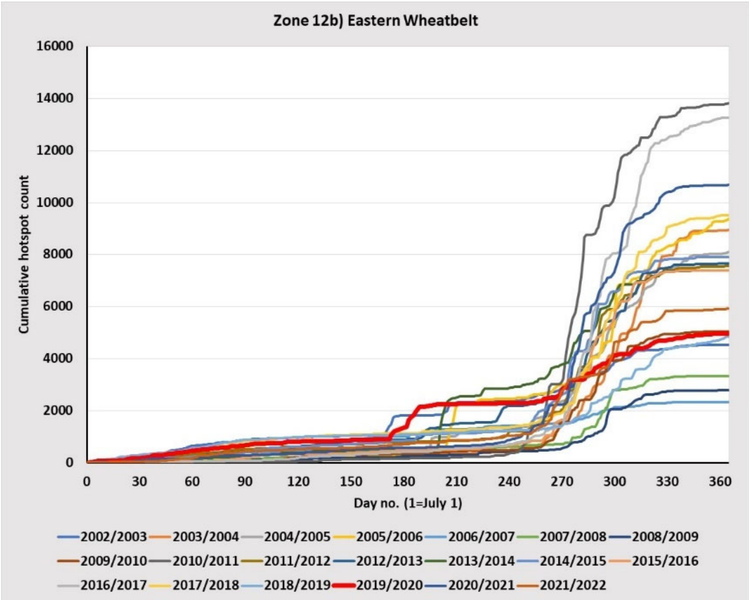
ABOVE: New England Escarpment. Similarly this zone produced an unprecedented count – to three times the previous record. Note that the pattern of increase is consistent with the normal one. This was 6.4 times the average.

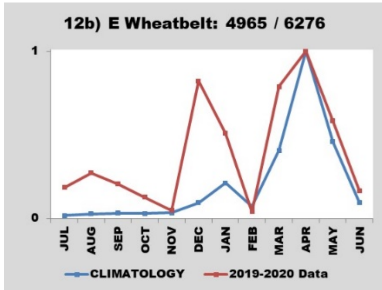
BELOW: Nandewar. Again similar, but the climb was quite early in comparison to other years. This was 9.4 times the average.





And yet…





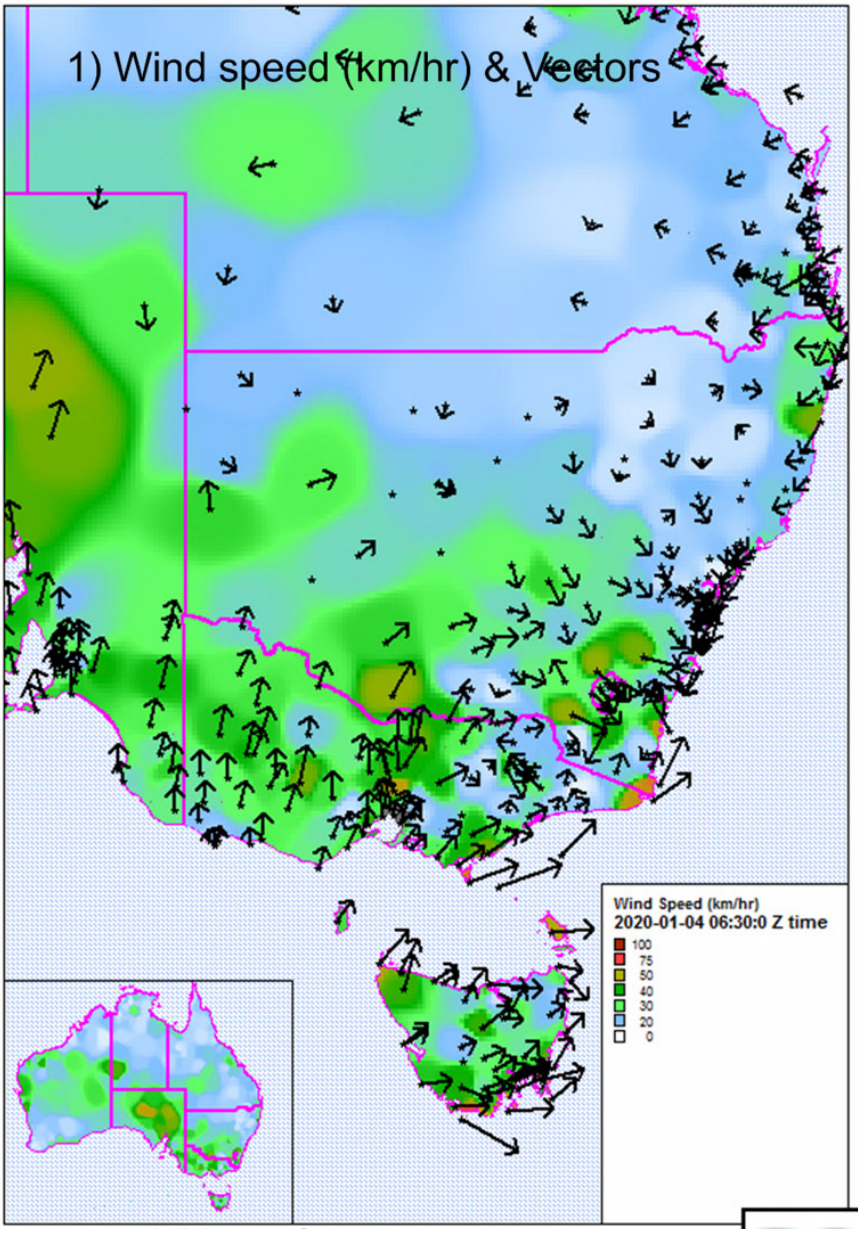
ABOVE: Eastern wheatbelt. Despite suffering the same antecedent conditions and being constantly threatened by large wildfires, the grasslands of this zone produced a below average result. This reflects a balance between elevated fire danger and severely reduced flammable biomass. Note however the spike around New Years, seen in some previous years.

DEEP FLAMING

There are seven known causes of deep flaming. Most were active during Black Summer.

Strong wind

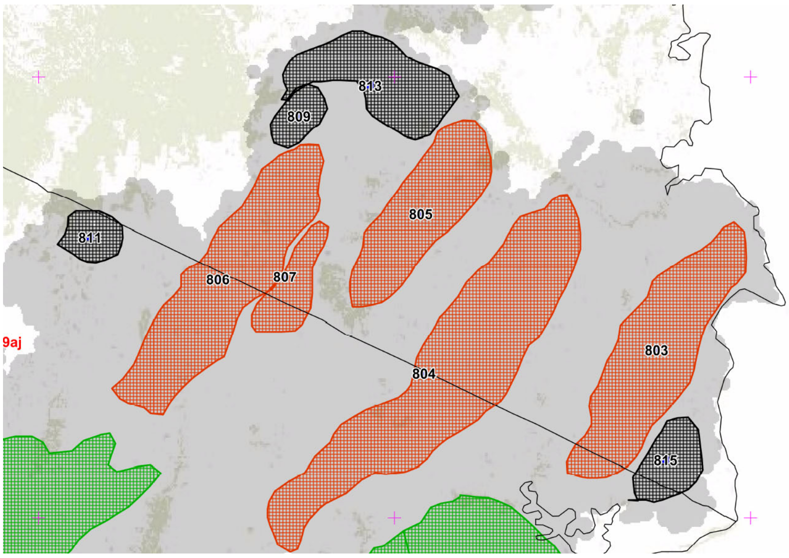
BELOW: Observed wind speed and vectors, late on the 4th January 2020. Note that orange areas showing winds over 40 km/hr.



Wind change

ABOVE: In the same image a cold front is passing over the region, with wind arrows swinging from NW to S or SW. The SW winds on the Vic/NSW border on the coast drove completely unprecedented multiple parallel BUFE runs to the NE.

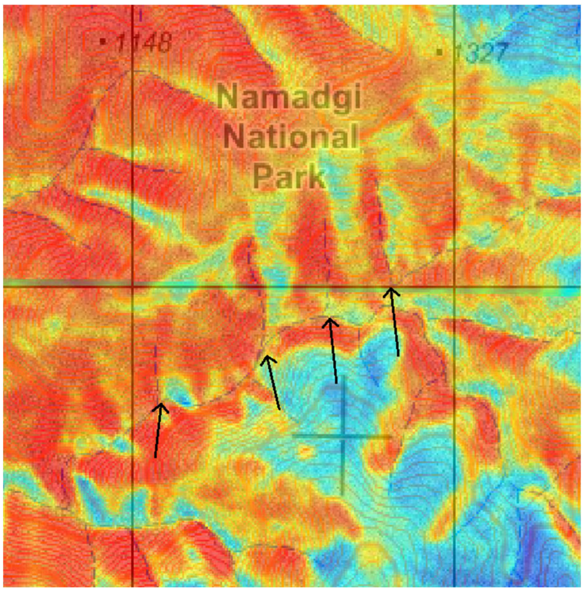
The data from Black Summer did not support the widespread notion that BUFEs always happen as the cold front passes. Instead, they may become *visible* as the cold front clears the smoke filled pre-frontal air.



Eruptive growth

There is evidence of instances of eruptive growth in play during Black Summer. Given the difficulty of gathering such evidence, there may have been many more cases.

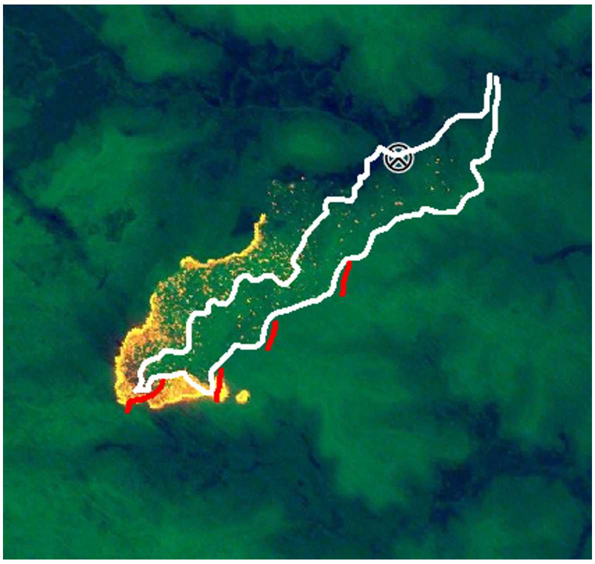
BELOW: (Left) A series of gullies with the correct geometry to support eruptive growth are shown in post-fire NDBI satellite imagery to have burnt hotter than the spurs around them. (Right) This is consistent with patterns seen in Canada. [Namadgi National Park, ACT]



Vorticity-driven Lateral Spread

VLS was widely seen in effect in linescans. It was the major driver of BUFEs in rugged landscapes.

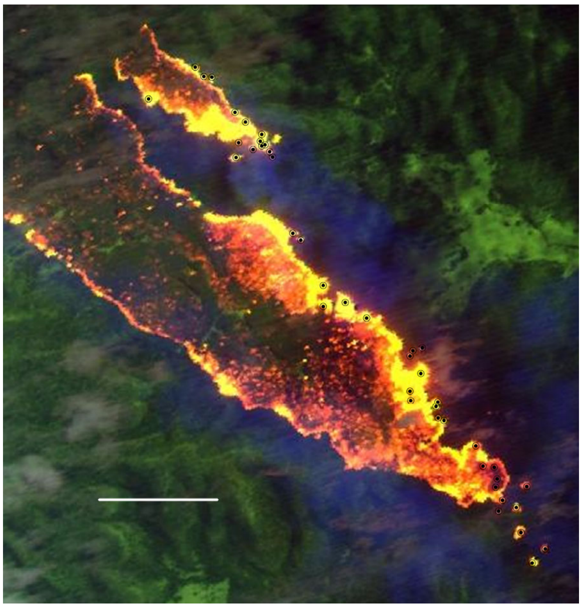
BELOW: Initiation of VLS as the leading edge of a burn-out effort (lower left) along a ridgeline enters VLS generator landforms (red lines).



Dense spotting

Linescans and Sentinel-2 imagery show many cases of dense spotting setting up a BUFE.

BELOW: Black dots indicate spotfires. The white line is 1 km long.



Use of accelerant

There were a number of occasions when radar data shows clear movement of plume bases at right angles to the wind on terrain unsuited to VLS. The only effective explanation of this that a back-burn or burn-out created deep flaming. In fact, the list includes some of the most intense fires ever recorded.

Interior ignition

Interior ignition is a concept from Canadian fires. The large flammability differentials between different fuel types is not evident in Australia. There are no cases where this process is implicated.

TERRAIN

Terrain plays a significant role in the chance of BUFEs occurring, especially through VLS and eruptive growth.

RIGHT: The maps shows terrain ruggedness: orange is flat (relief less than 150m within 1.5km radius); light green is undulating; and dark green is rugged (local relief over 300m within a 1.5 km radius).

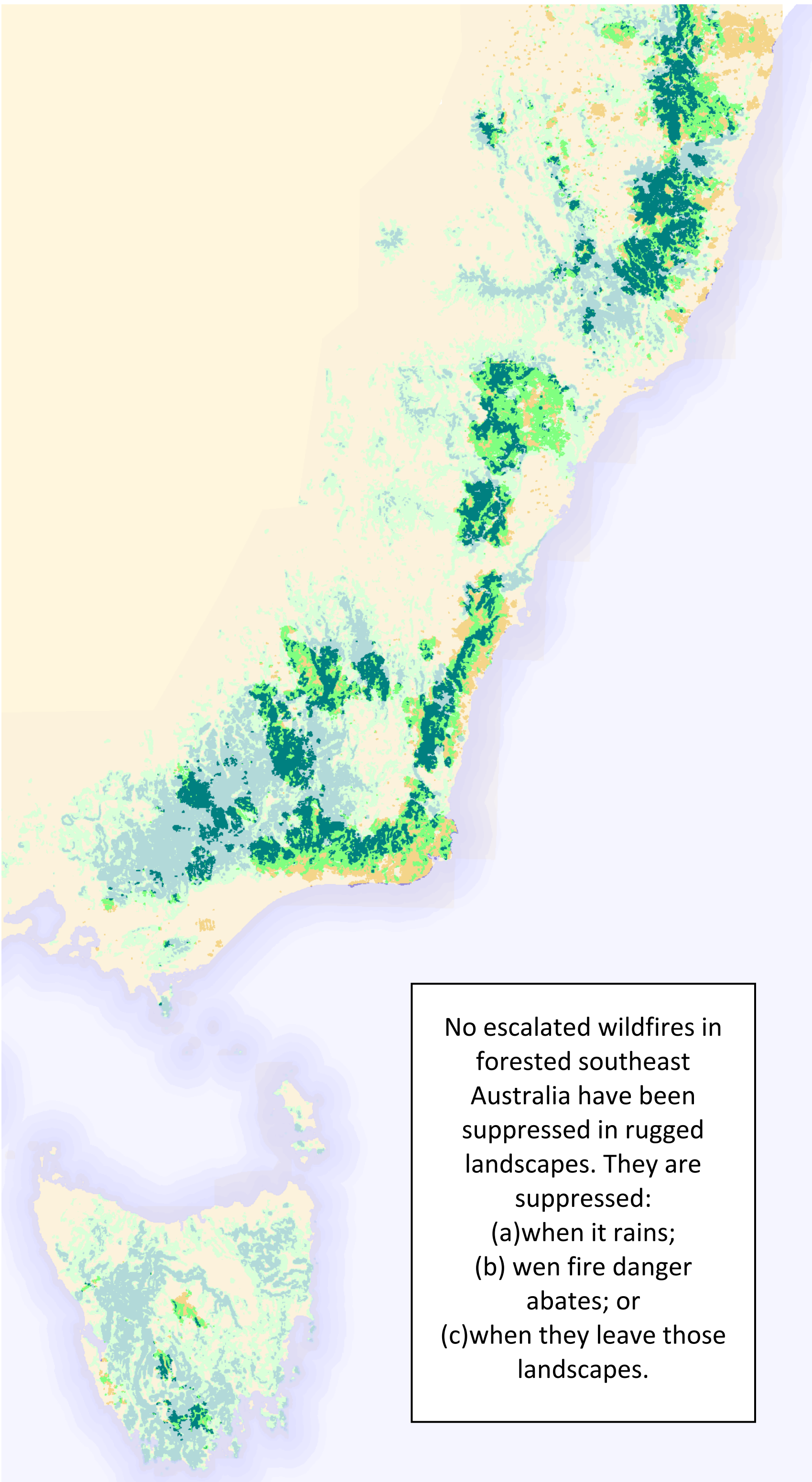
Areas that did not burn in Black Summer are ghosted back.

Rugged terrain – dark green – is seen to be prominent in the burnt areas.

Exceptions to this indicate the unusual nature of the clusters of BUFEs in coastal areas.

This is likely due to the emerging prevalence of the foehn effect along the coastal escarpment.

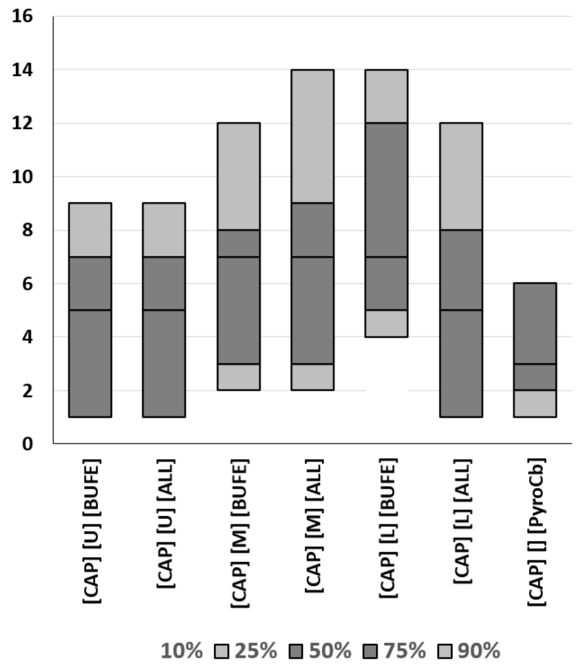
Satellite imagery showed that the hydraulic jump (which is where a major bushfire run would cease) is often off-shore. (Fire outbreaks such as in Victoria in 2006/2007 stopped at the edge of the rugged landscape, where wind/terrain interactions, fuel types and access all changed in unison.)



No escalated wildfires in forested southeast Australia have been suppressed in rugged landscapes. They are suppressed:
(a)when it rains;
(b) wen fire danger abates; or
(c)when they leave those landscapes.

STABILITY

There has been widespread discussion in fire services about the role of stability in BUFEs. Much of it has been ill-informed.



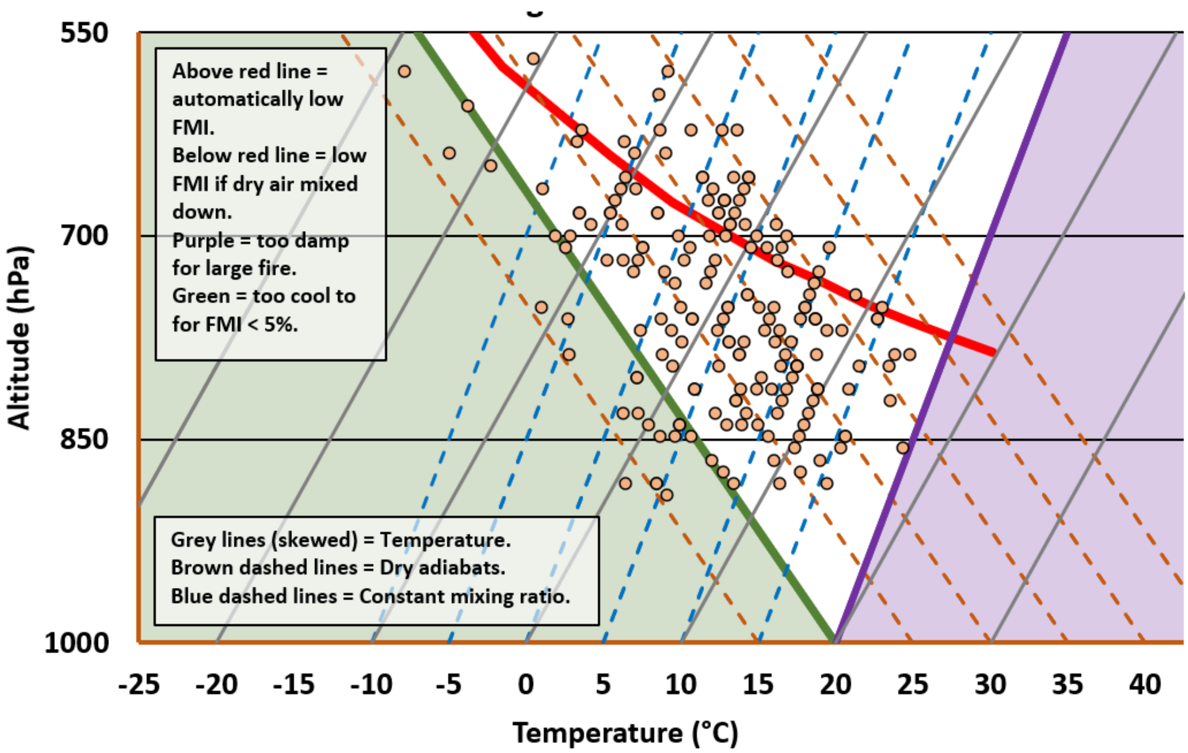
ABOVE: The distribution of convective cap size in radiosonde data across Black Summer. [U] refers to large inverted "V" profiles – classic elevated fire danger days – with convective caps at high altitudes only. [L] refers to days where either: (i) the cloud base is close to the ground, the air is relatively moist and fire danger is not high; or (ii) a subsidence inversion is close to the ground, with warm, dry air aloft that can be mixed down by a strongly convecting fire. [M] refers to all observations in between. [ALL] is all observations, [BUFE] is observations close to a BUFE, and [PyroCb] is observations close to a BUFE that produced a pyroCb.

Some conclusions from this are:

- PyroCbs require a small convective cap, typically below 4°C.
- For [M] and [U], there is little difference between BUFE observations and the entire set of observations – they have no preference.
- For [L], BUFEs are driven by the foehn effect, and these require a large convective cap, typically above 8°C.

Stability also implies a moisture dynamic. It has been found from Black Summer data, at times when BUFEs could occur, that C-Haines is not an index of stability. It then serves the same role as the Relative Humidity at the 850 hPa pressure level. This means that applying DALR dynamics to surface weather data allows an assessment of the potential for a BUFE to occur.

BELOW: A phase chart for BUFE stability settings. The dots show the implied saturated point for lifted dry air from the surface. A green background means that there no way for a fire to access air dry enough to produce dry fine fuel. A purple background means that there is a potential for ambient Cbs to occur, and maybe rain could prevent a BUFE from occurring. Alternatively the fire and Cb could interact, producing dangerous fireground conditions. In the white area the red line is important. A dot above that line shows that dry fine fuel is expected. A dot below the line requires mixing down of dry aloft, and that mixed down air takes the dot above the red line. This happened frequently.



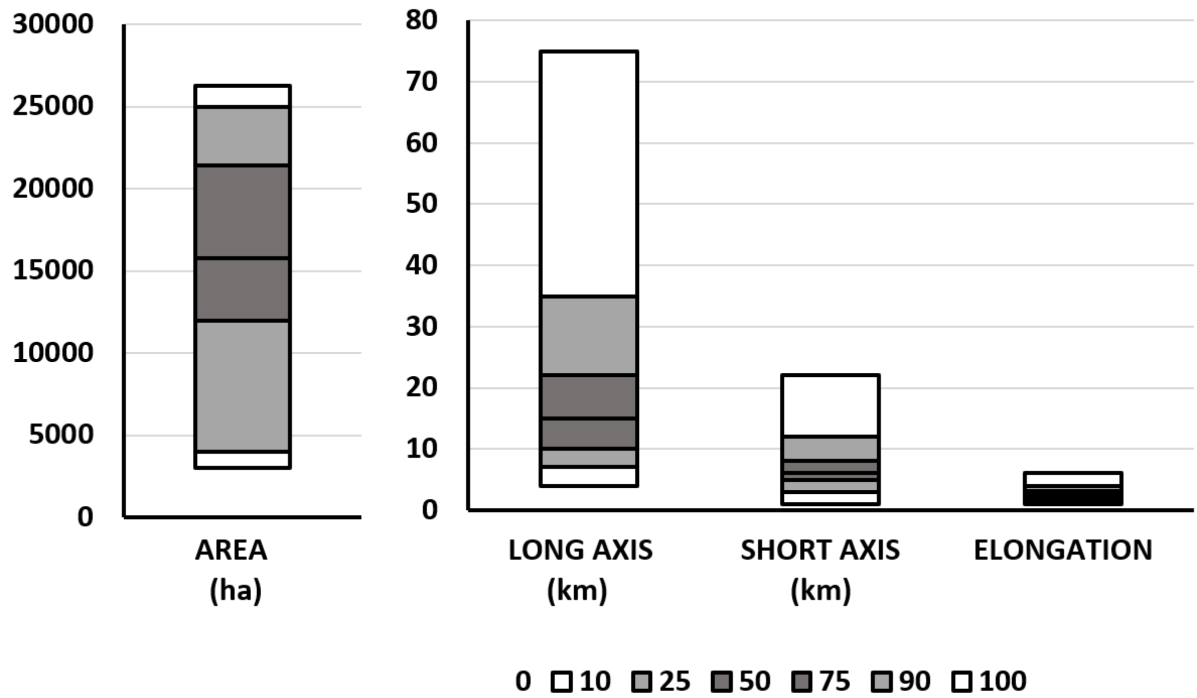
BUFES

Blow-Up Fire Events happen when a fire develops deep flaming and couples with the atmosphere above. This forms feedback loops that radically change the fire's behaviour locally.

Black Summer produced around 120 BUFEs. These were mapped and measured.

There were pulses of extreme fire activity separated in space and time.

BELOW: BUFEs are roughly elliptical, and have a long-axis, a short-axis and an area. The ratio of the two axes is the elongation. The charts below show the percentiles for these parameters. The typical Black Summer BUFE was 15km long and 6 km wide, spanning an area of 16,000 ha. These burn out over two to five hours – typically 3 hours. Thus they burn at a typical rate of about 5,000 ha per hour.

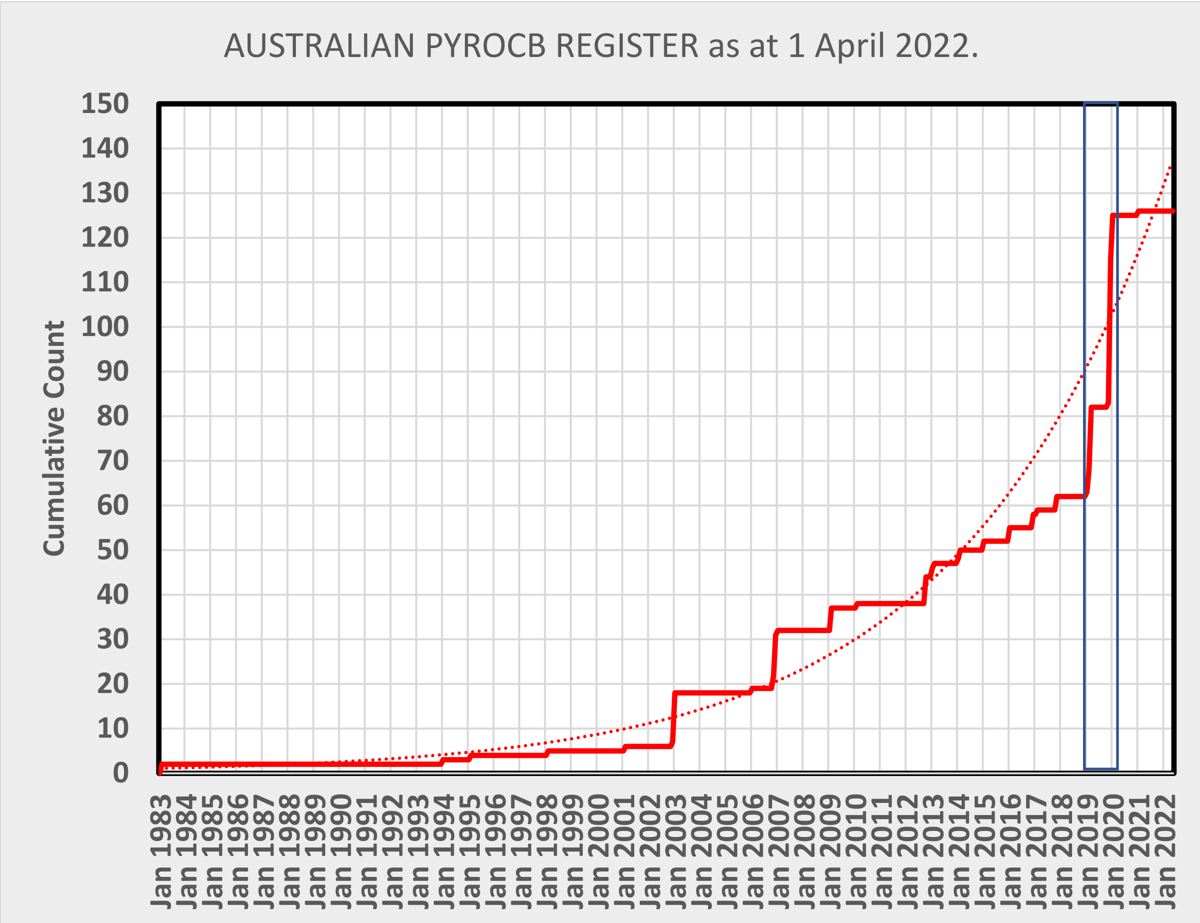


PYROCBS

In an unstable atmosphere, the smoke plume above a BUFE can keep rising to the top of the troposphere. It forms a fire thunderstorm, or pyroCb.

The Australian pyroCb count doubled during 2019 and 2020.

The earliest known Australian pyroCb was during Ash Wednesday in 1983. A small number occurred up to the 2003 alpine fires. Since then, a roughly exponential growth in the count has occurred. The count doubled during Black Summer *sensu lato*. This was then the largest group of pyroCbs recorded, globally. From December 28 to January 4 the only recorded super-outbreak occurred (the Australian New Years Super Outbreak, ANYSO). ANYSO was the most extreme fire activity ever recorded, peaking at a million MegaWatts from the burning of nearly 100,000 ha per hour.



FOEHN EVENTS

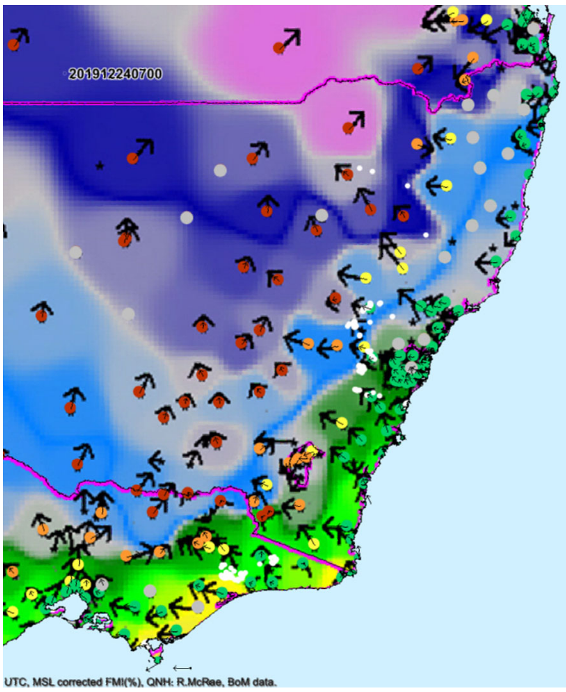
Foehn winds based on isentropic drawdown occur when the ranges block low level moist air upwind, allowing drier upper air to flow downslope instead. As it goes it gets warmer and drier and can accelerate due to gravity. This can easily cause a spike in fire danger. A key component of that is the drying out of fuel.

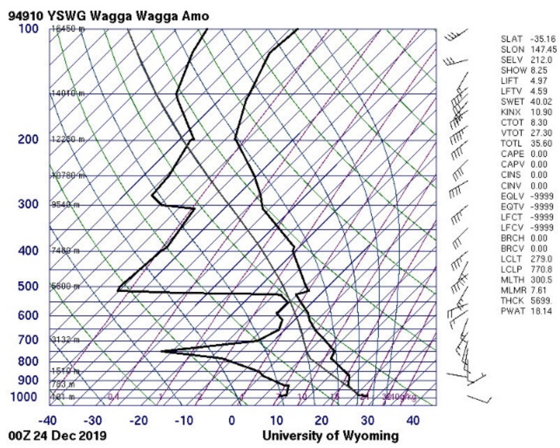
Similar effects can arise due to pressure systems, and the foehn effect is easily swamped by elevation effects over the high country. The separate them out, an analysis was done on each time-set of weather observations. The synoptic pressure systems were mapped. Wind arrows were plotted. A point was placed at each observation site showing estimated fuel moisture index (as it was Black Summer, assuming a maximum drought factor). However data were adjusted to account for the observation site's elevation assuming a dry adiabatic lapse rate. The points were coloured to show changes in potential FMI along a wind flowline which could only be due to terrain.

Foehn wind driven fires are now a major problem in Australia.

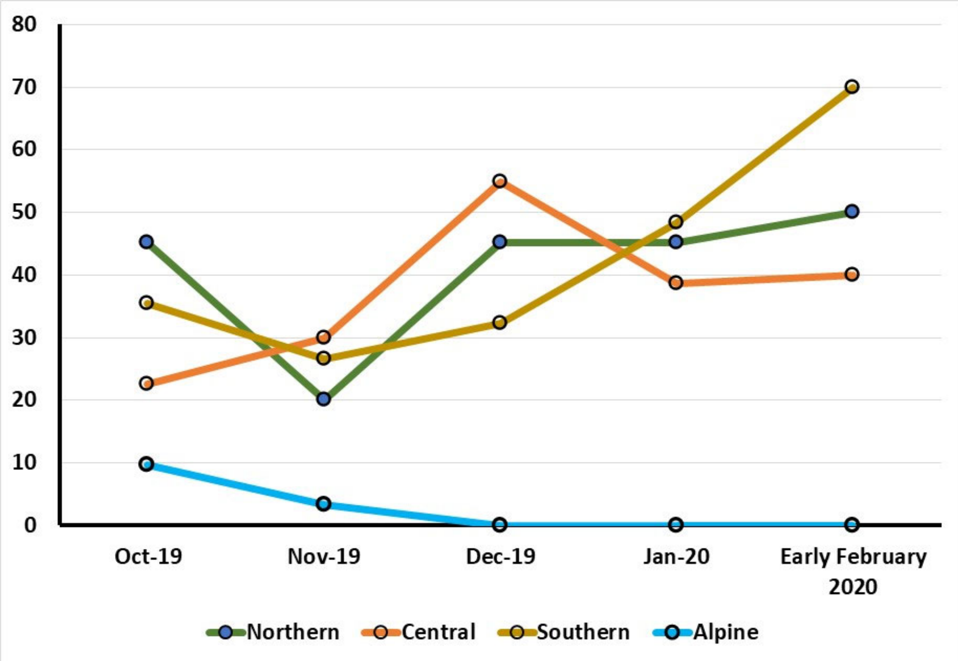
BELOW: (Left) A foehn analysis chart for the evening of December 24 2019, showing MSL-corrected FMI range: red = 0% to 5% - spotting very easy; orange = 5% to 10 % - spotting may occur; yellow = 10% to 15% - spotting unlikely; and green = over 15% - no spotting. While these may not show fire ground conditions, the spatial pattern clearly indicates a foehn effect – isentropic drawdown – causing low FMI to emerge as air flows east to west over the Great Divide.

[Right) A aerological diagram for that morning from Wagga, showing a weak, moist easterly flow under the nocturnal inversion, with a dry southerly above.





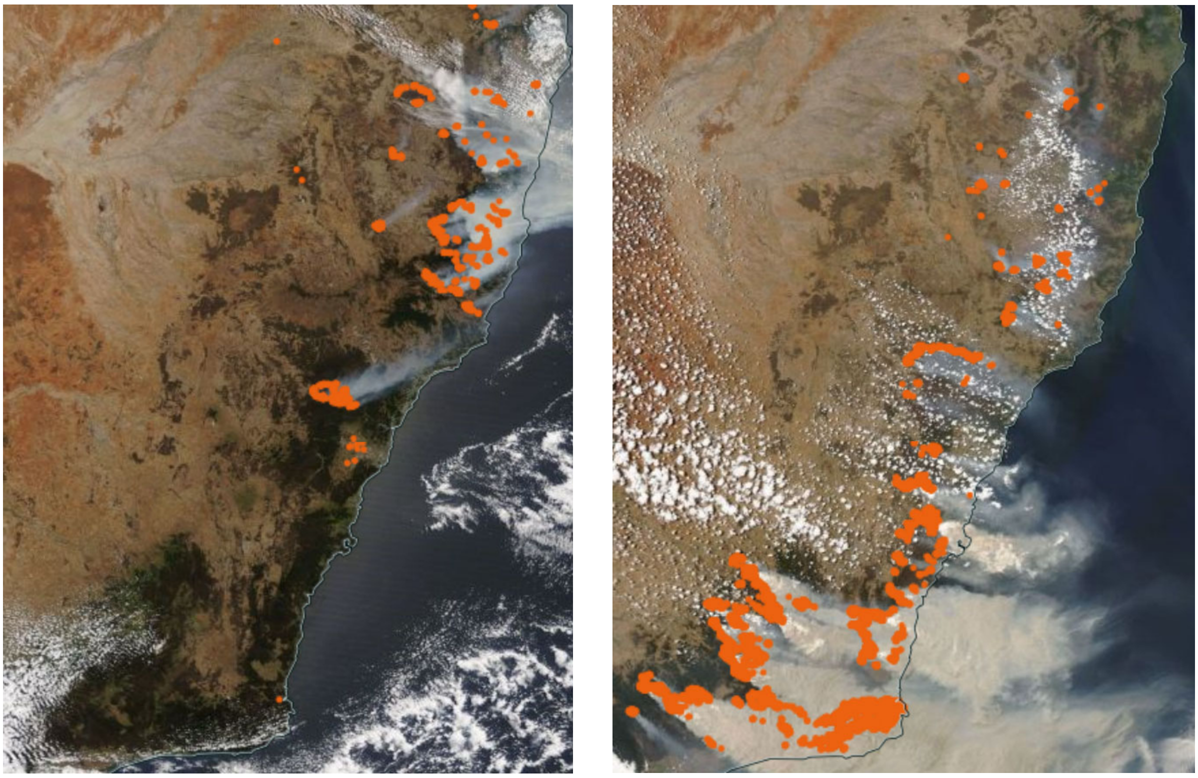
Using these charts, it was possible to estimate the prevalence of the foehn effect through BS.



ABOVE: The percentage of days with a measurable foehn effect in place for different regions.

BELOW: Foehn-driven fires in the Sydney Basin, 4 Dec 2019. [Worldview, VIIRS]

OPERATIONAL TEMPO



ABOVE: MODIS imagery from 20191113 (left, Terra) and 20200104 (right, Aqua) showing the overall movement of activity from north to south. (NASA WorldView)

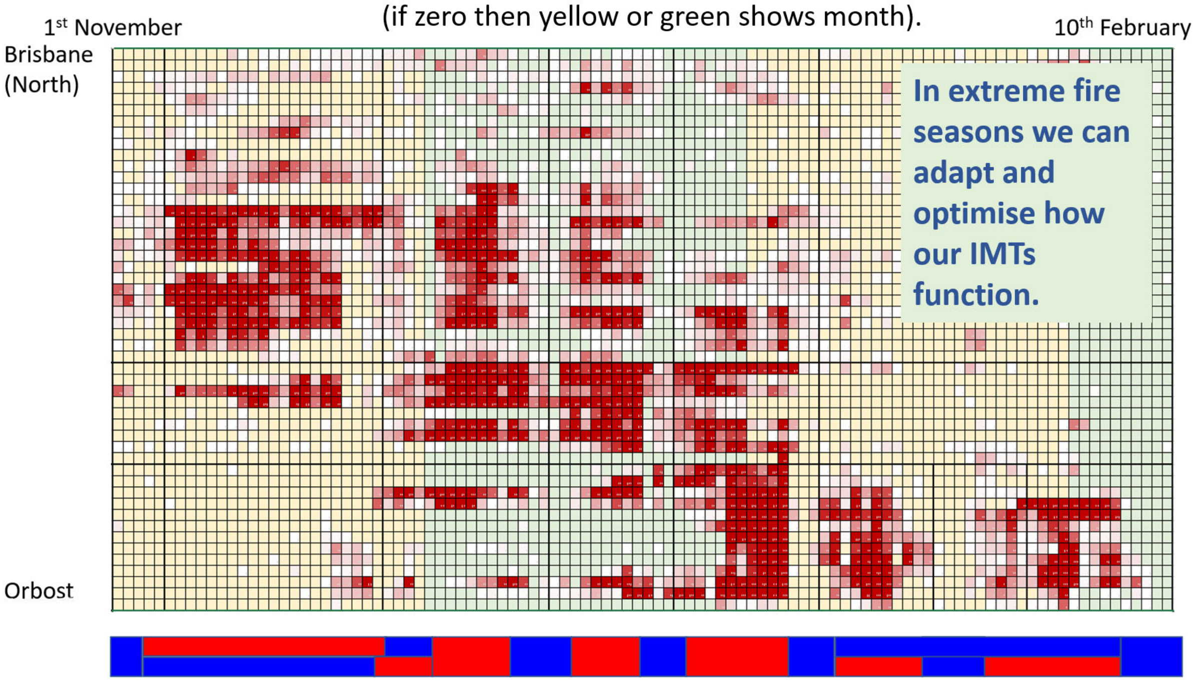
With such a protracted but regional event, it was possible to track changes in the density of hotspot data. In turn this is considered a useful indicator of fire activity, and of the demand son Incident Management Teams.

There were pulses of extreme fire activity separated in space and time.

To do this, the Black Summer event was divided into quarter-degree latitudinal bands (from Brisbane nearly to Melbourne) and single days. For each, the MODIS hotspots were aggregated – in the form below it is the count of hotspots. Similar patterns are found using mean or maximum FRP data.

BELOW: Cell colours show increasing counts. If it is zero, the background colours (yellow and green) change with the month. Note how the dense red cells concentrate into blocks. This makes clear that there were pulses of fire activity. In the red blocks, IMTs found that they had to focus on defensive strategies, such as saving towns. In-between there is a scope for offensive strategies, such as containing fire sectors or divisions. The swings between the two are summarised by the colour blocks under the charts, showing trends north and south of Sydney.

1 day by 0.25 degree-latitude grid-cells
with red-shading indicating count of MODIS hotspots
(if zero then yellow or green shows month).



Red = Defensive-mode IAPs & IMTs; Blue = Offensive-mode IAPs & IMTs

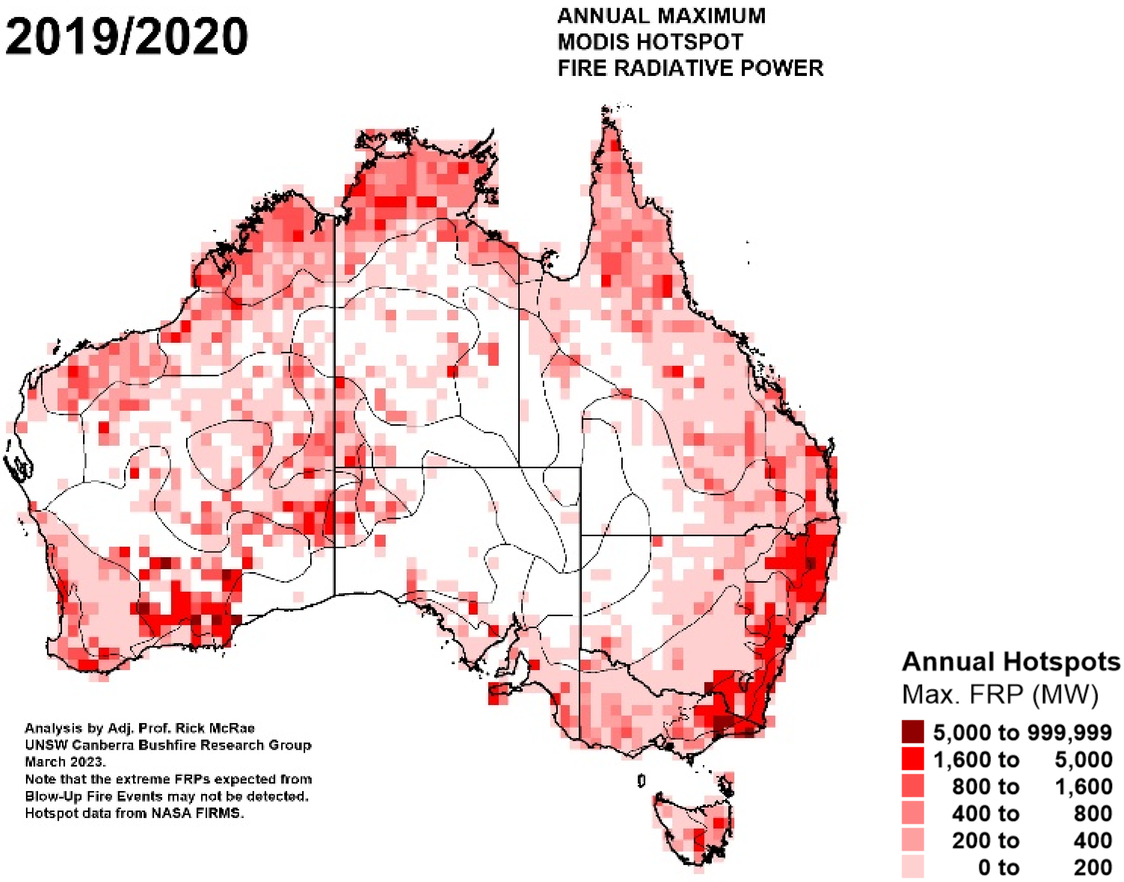
The traditional overview that fire activity starts in the north early in the season and then moves southwards to the start of Autumn is present in the chart, but the detail superimposed in potentially very useful for avoiding IMT specialist fatigue and for using key skills when needed.

(Edm)

HOTSPOT INTENSITY

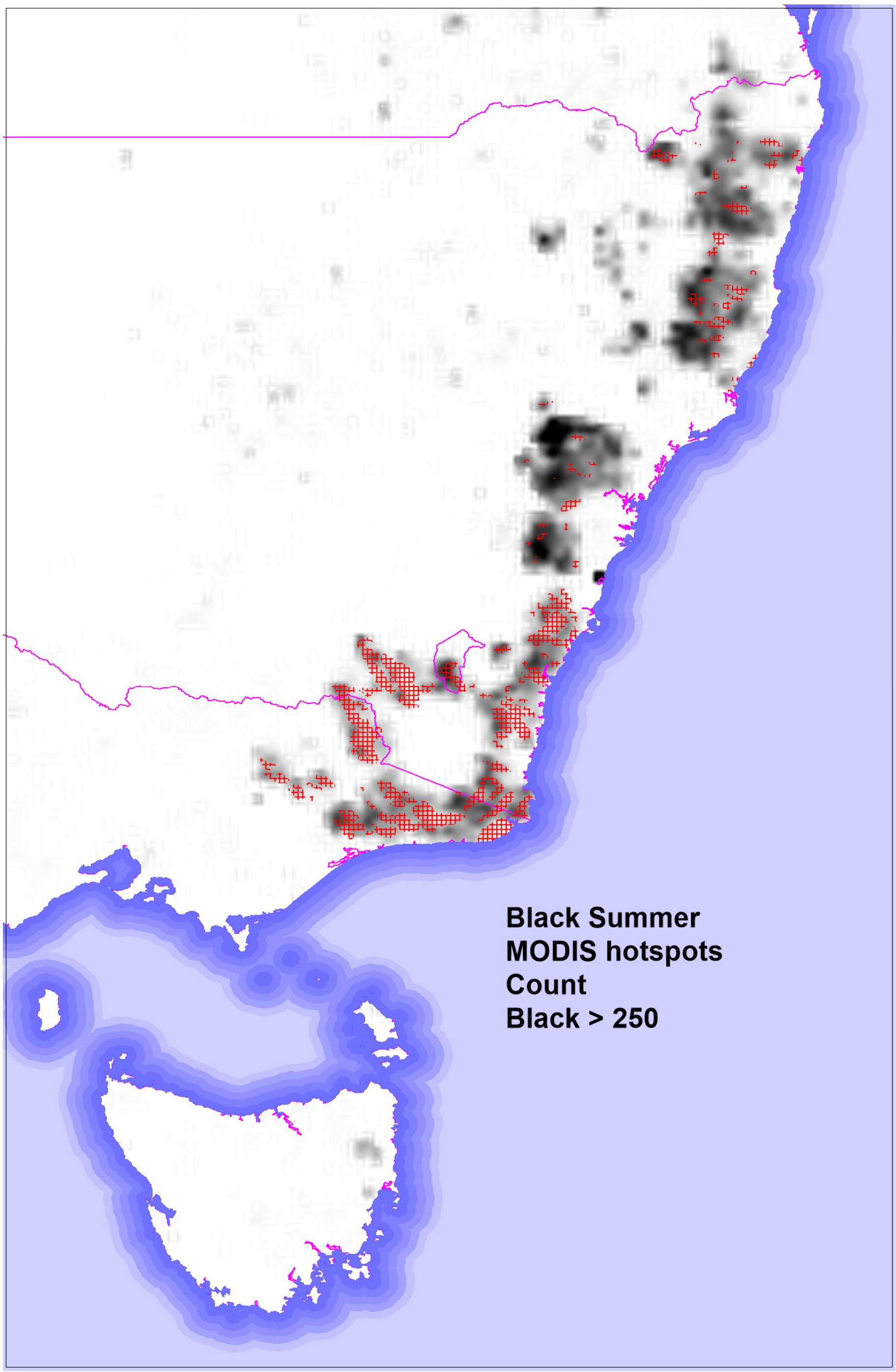
Hotspots derived from MODIS data include the Fire Radiative Power index (MegaWatts).

BELOW: Map of maximum FRP distribution during Black Summer (Jul 2019 to Jun 2020). Hotspots have been aggregated into half-degree grid-cells. Note that activity in south-west WA was at a similar intensity. Six pyroCbs were recorded there. (Another five were recorded there from late Feb 2019.)

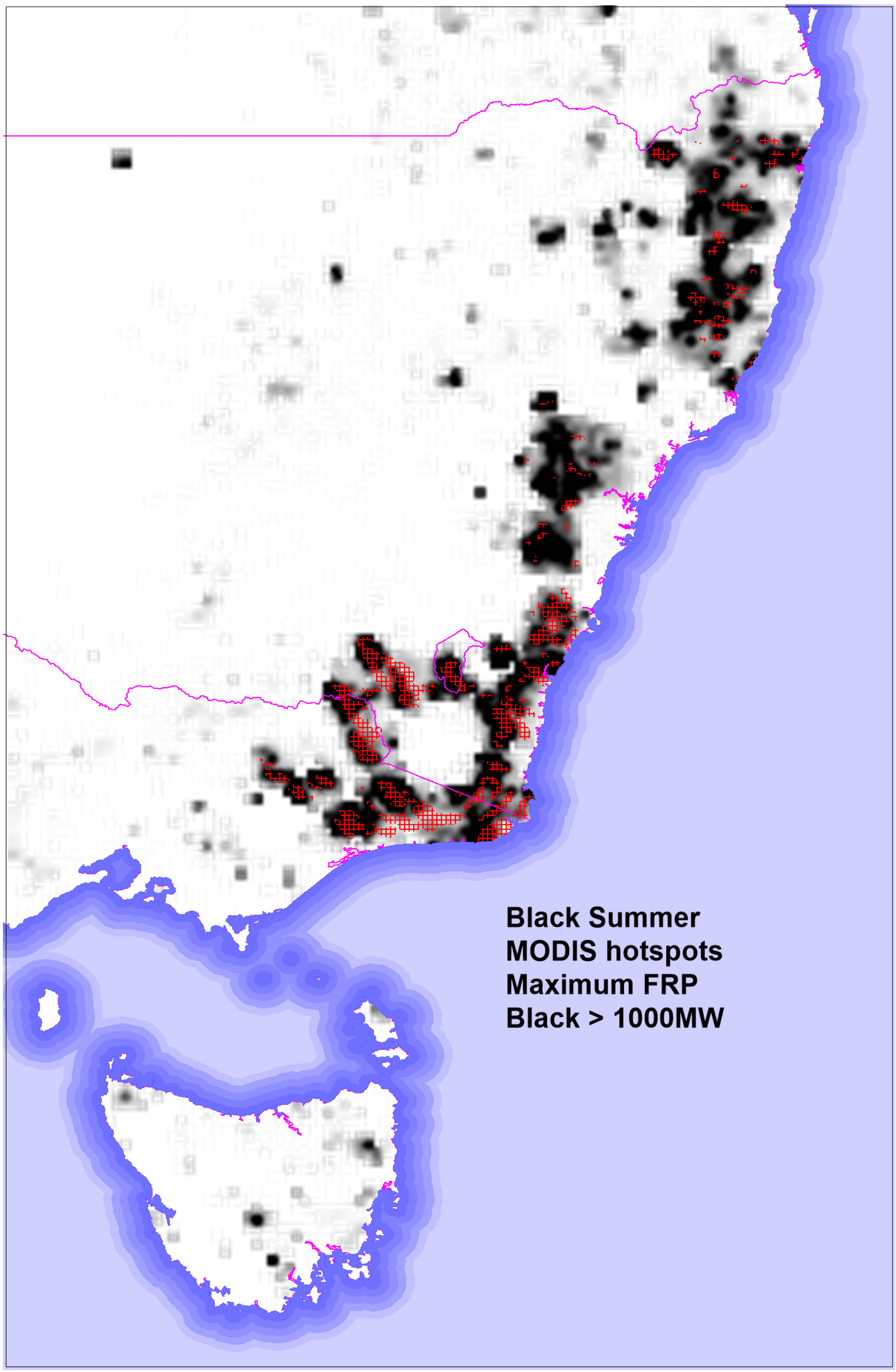


Some extraordinarily high FRP values were recorded.

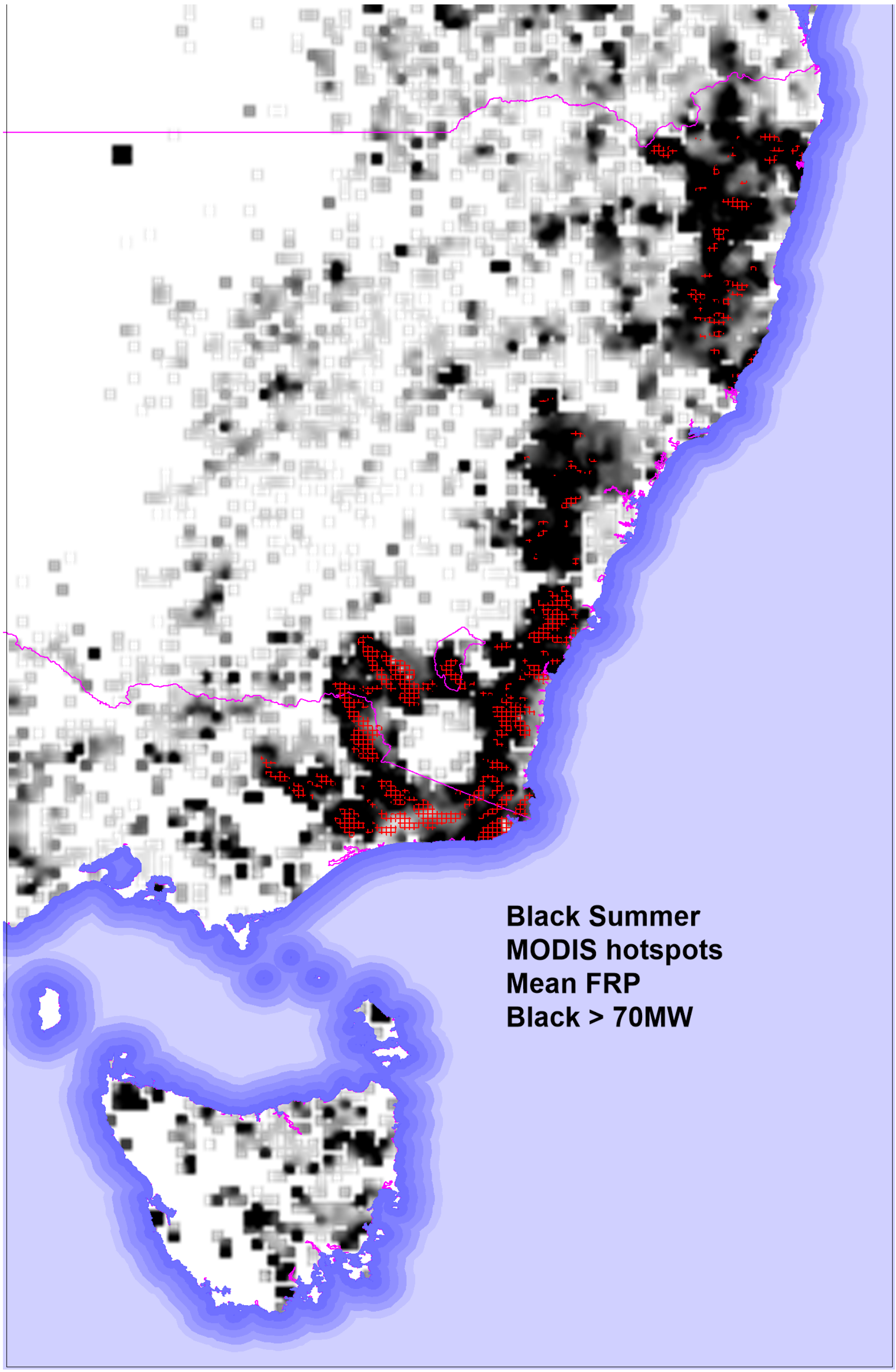
The maps below summarise the MODIS hotspot patterns across Black Summer. The red hatched areas are BUFEs, where hotspots data is often missing. For the mean should be considered high (200MW) and the maximum very high (over 1000MW). (Hotspot data are aggregated in 0.1° gridcells for this summary.)



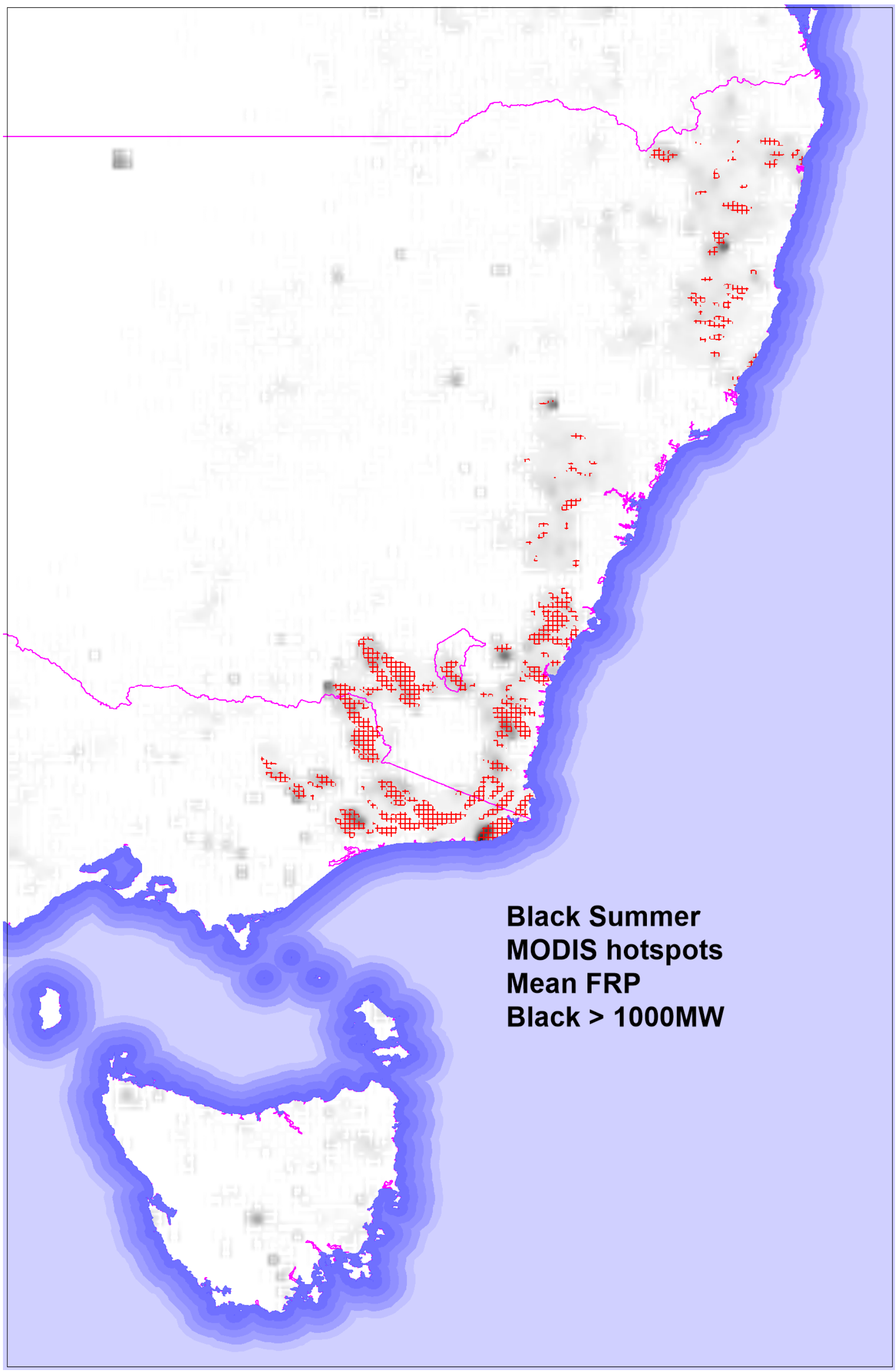
ABOVE: A gridcell used in this analysis covers roughly 100 km^2. Fitting 250 hotspots into one of these suggests long-duration burning, as seen in the Gospers Mountain Fire in the Blue Mountains. South of the Shoalhaven River, a large proportion of the region was burnt in BUFEs, which had short duration, and were picked up by few (if any) MODIS over passes. With BUFEs often (but not always) heading towards the coast, it is therefore consistent that higher counts are typically on the western edge of burnt areas.



ABOVE: There was an extremely high proportion of MODIS hotspots. Roughly one in eight grid-cells has a maximum FRP over 1000MW before correcting for the missing BUFE data.



ABOVE: The mean FRP was raised across a considerable tract of land, with a lot more outliers than was seen in the previous graphic for maximum FRP.



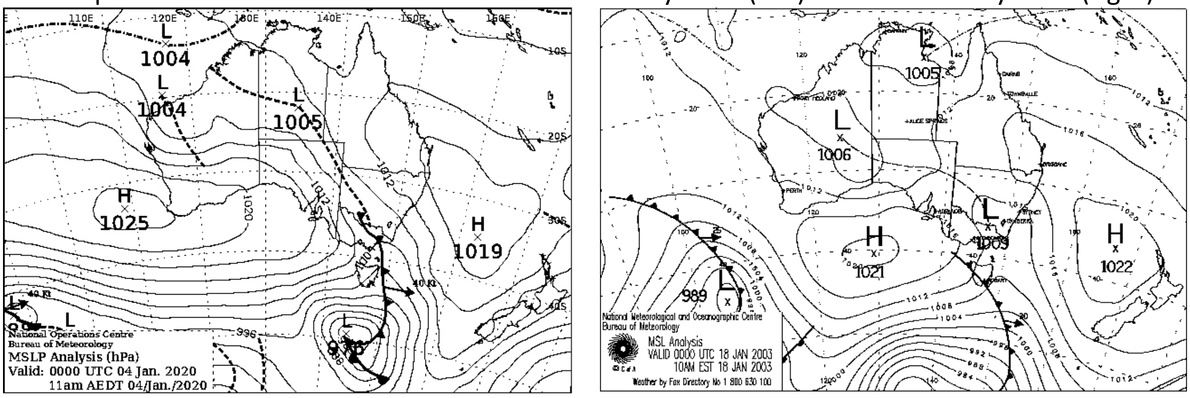
ABOVE: The mean FRP data presented using the same parameters as were used for the maximum FP graphic. About 10 fire areas stand out as have higher means than the others, all linked to BUFEs, and therefore likely to be artefacts of the missing BUFE hotspot problem.

TROUGHS & FRONTS

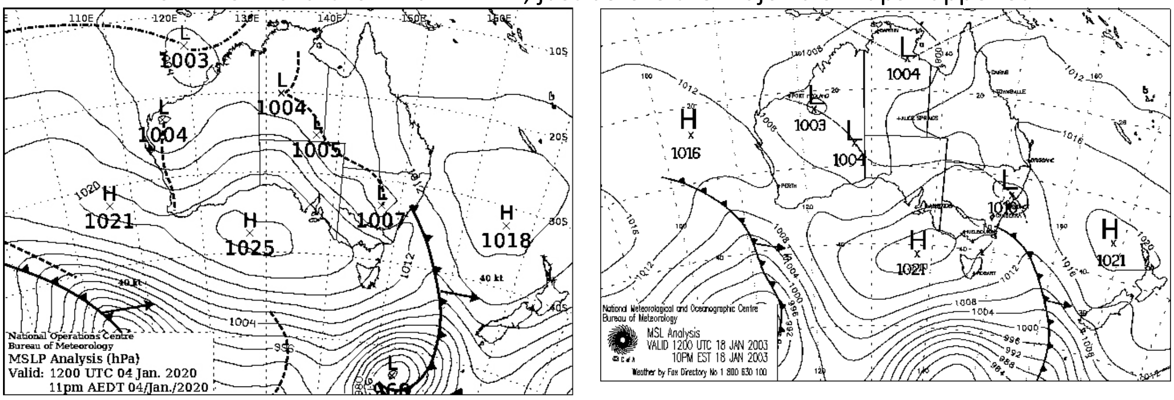
When the 2003 alpine fires were burning in Victoria, NSW and the ACT, it was evident that the configuration of trough-lines was causing dangerous fire behaviour. Branched troughs form a complex synoptic pattern over the high country, and then jump to the coast near Sydney. This happens well ahead of the cold front.

During BS, the same thing happened.

A comparison of weather conditions for the 4th January 2020 (left) and 18th January 2003 (right).



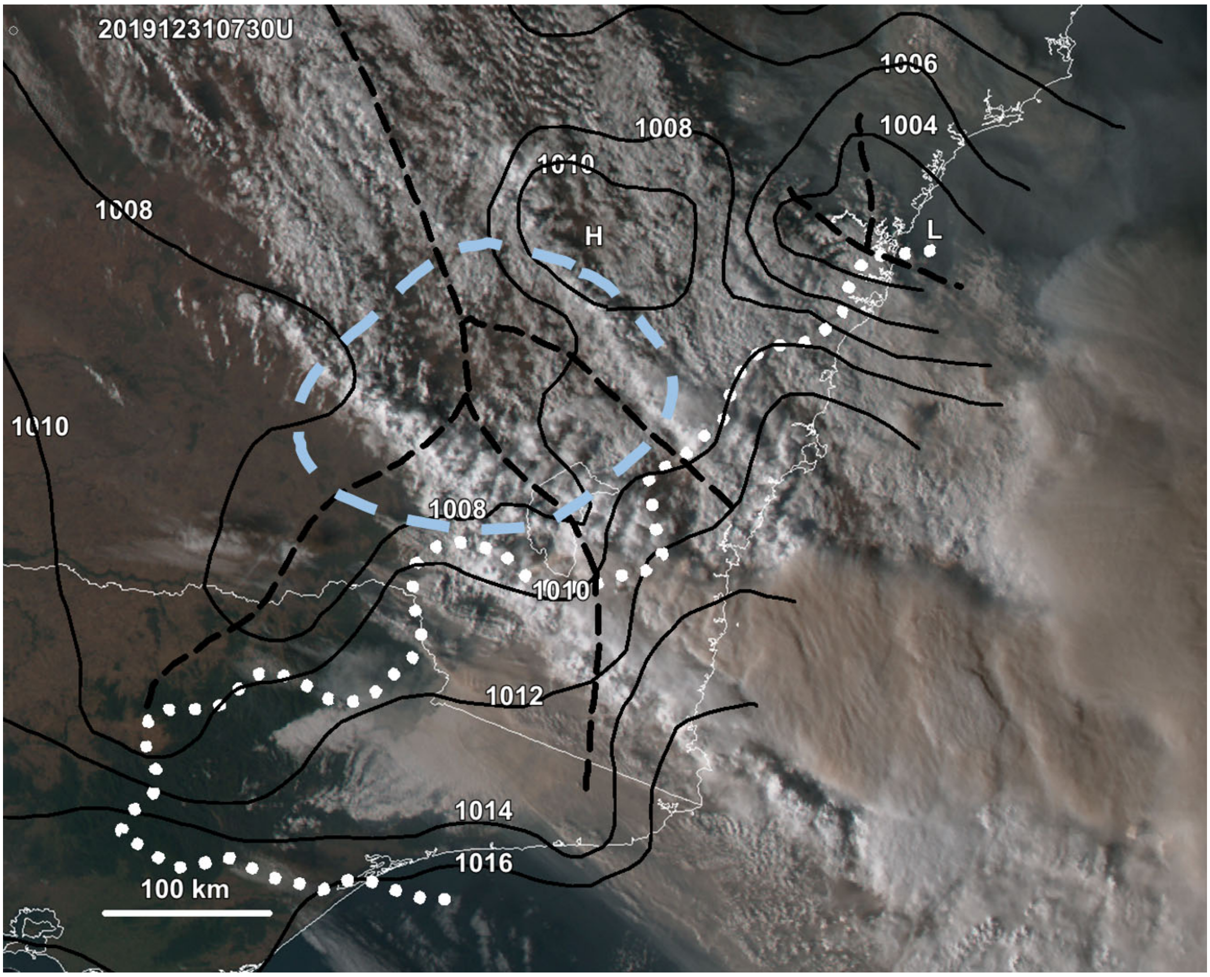
BoM MSLP chart for 11am AEDT, just before the major blow-ups happened.



BoM MSLP charts for 12 hours later.

Branched troughs are an emerging challenge for fire managers.

BELOW: A set of isobars derived from observed QNH (black lines, 2 hPa increments) overlaid on a Himawari-8 satellite image, both from 6:30pm AEDT, 31 December 2019. The blue dashed line indices a potential recirculation areas, functionally a meso-scale low pressure cell. The white dotted line shows the limit of inland progression of a maritime air mass, based on observed wind directions and dew point temperatures. A number of pyroCbs are associated with this line (brown cloud-tops).



It is feasible that these trough systems impede arrival of cold fronts. The meso-scale circulation may be related to heat domes, such as seen in Lytton, British Columbia in 2021.

SMOKE

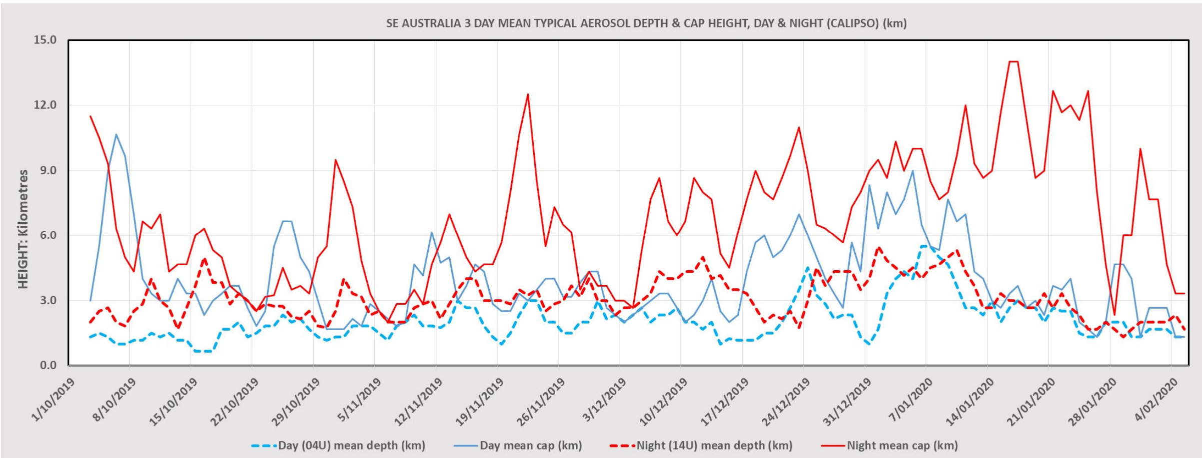
Prior to BS, the main natural hazards in no-tropical Australia, in terms of loss-of-life, were heatwave then bushfires (at about 50% of heatwave's toll). During BS, the impact of smoke greatly exceeded that of those hazards.

There were a number of factors in play to cause this:

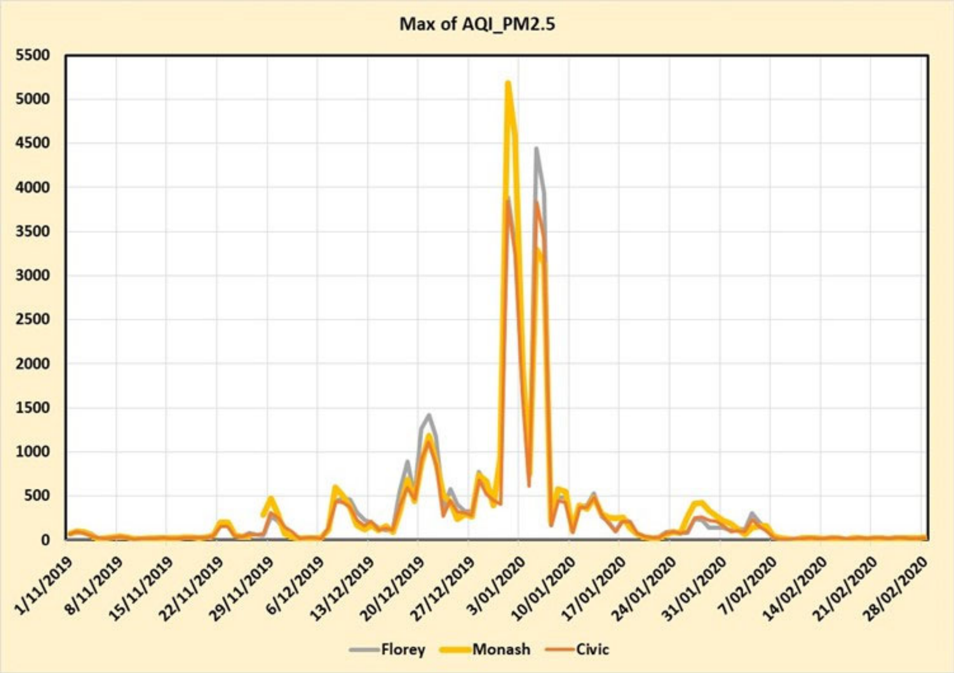
- The duration of the fires.
- The high proportion of intense fire activity, lofting smoke above the surface layer.
- The complex branched troughs that formed in the SE, which recirculated smoke.
- The unprecedented fire activity below the NSW South Coast escarpment, which lofted smoke onto the tablelands with every sea breeze.
- The mega-fire which consumed most of Blue Mountains and Wollemi National Parks.

These together served to exposed significant populations to smoke from intense burning, which is usually convected well above the ground. This very different to the low-level smoke that people are normally exposed to, which is derived from low-intensity burning. The brown colour was a hallmark of the BS smoke palls.

BELOW: 3-day means of day and night smoke depths (km, blue lines and red lines respectively) from the main layer (dashed lines) and the uppermost cap (solid lines). These are regional averages derived from Calipso curtains (NASA data). It is seen that from October to February there was a significant depth of smoke, and that at times the cap reached up to the top of the troposphere.



ABOVE: Canberra International Airport control tower, 6pm New Year's Eve 2019.



ABOVE: Time series of Air Quality Index based on PM2.5 particulate data from ACT Health Directorate from three sites in Canberra. Extremely poor air, requiring action to avoid health impacts, occurs at 200 on this scale. At the spikes these were the worst air quality values globally.

For the first time, smoke became Australia's worst natural hazard.

BELOW: Photograph by an astronaut on the International Space Station of the smoke over SE Australia, 12th January 2020. The oblique view to the NE includes Melbourne (lower right), Echuca (lower left) and Sydney (obscured, upper left). The smoke is moving inland with sea breezes, and inland fires are adding to it. Some sea breeze stratoculumus cloud is embedded in it. Only the parts of the Kosciuszko Plateau above 2000m ASL are above the smoke (image centre).

Image iss061e123425, Gateway to Astronaut Photography of Earth, NASA.

UPPER ATMOSPHERE IMPACTS

A key paper on this topic was:

Peterson, D.A., Fromm, M.D., McRae, R.H.D. *et al.* Australia's Black Summer pyrocumulonimbus super outbreak reveals potential for increasingly extreme stratospheric smoke events. *npj Clim Atmos Sci* **4**, 38 (2021). https://doi.org/10.1038/s41612-021-00192-9

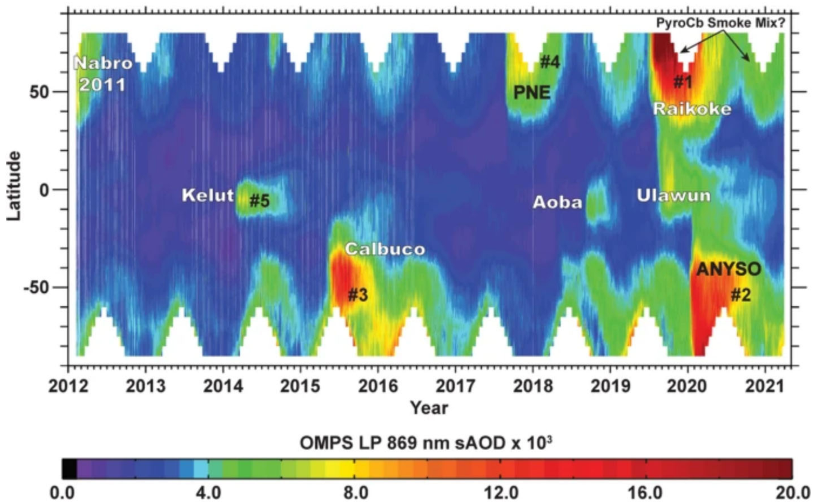
Atmospheric scientists use sophisticated satellite systems to monitor the movement of bushfire aerosols upwards through the atmosphere. BS smoke reached 35 km in height before the systems were not able to track it any more. More significantly it formed into rotating discs and moved from east to west in the stratosphere. It has now been found to generate chlorine compounds that have enlarged the Antarctic Ozone Hole.

The smoke impact on the upper atmosphere was of the same scale as that of a major volcanic eruption.

In past fire events, such as in 2003, it was surprising enough that a lot of aerosol had been able to leave the troposphere – passing, say, 15 km in height.

BELOW: A figure, from Peterson et al., 2021, comparing the aerosol injection from BS to that from recent major fire events and volcanic eruptions.

Fig. 10: Comparing ANYSO with all significant stratospheric plumes observed during 2012–2021.



Shading indicates daily OMPS LP stratospheric aerosol optical depth (sAOD) calculated in five degree latitude bands using extinction profiles at 869 nm. White labels indicate volcanic plumes and black labels indicate pyroCb smoke plumes. Numbers rank the five largest plumes in this record based on maximum sAOD.

OZONE LAYER

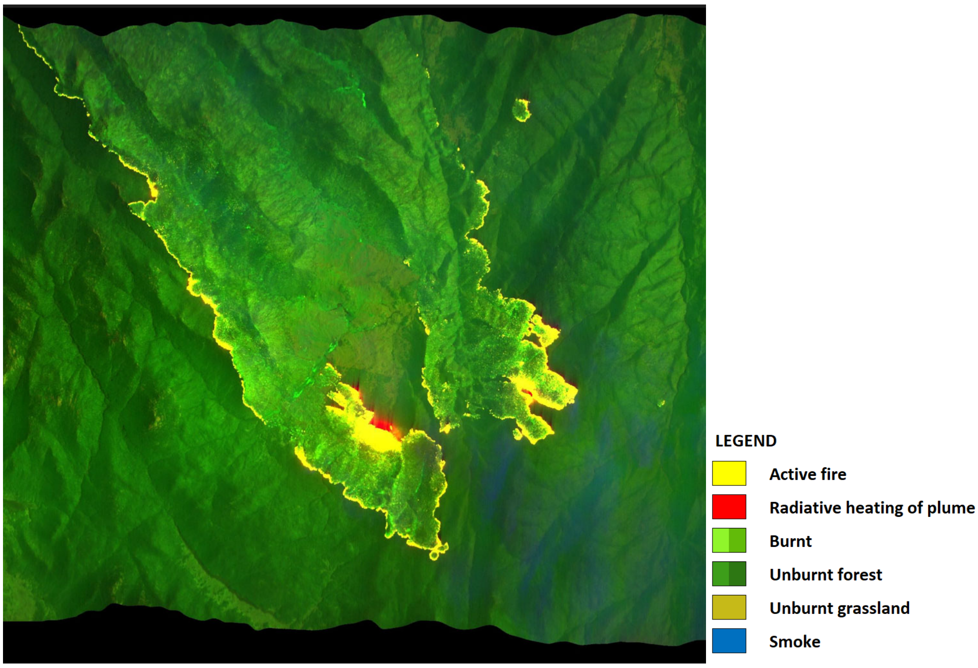
OBSERVATIONAL TOOLS

Material covered in this review is observational. Data came from a range of sources, discussed below. It is a result of the scale of these fires that direct observations played such a minor role in resolving what happened.

Linescan

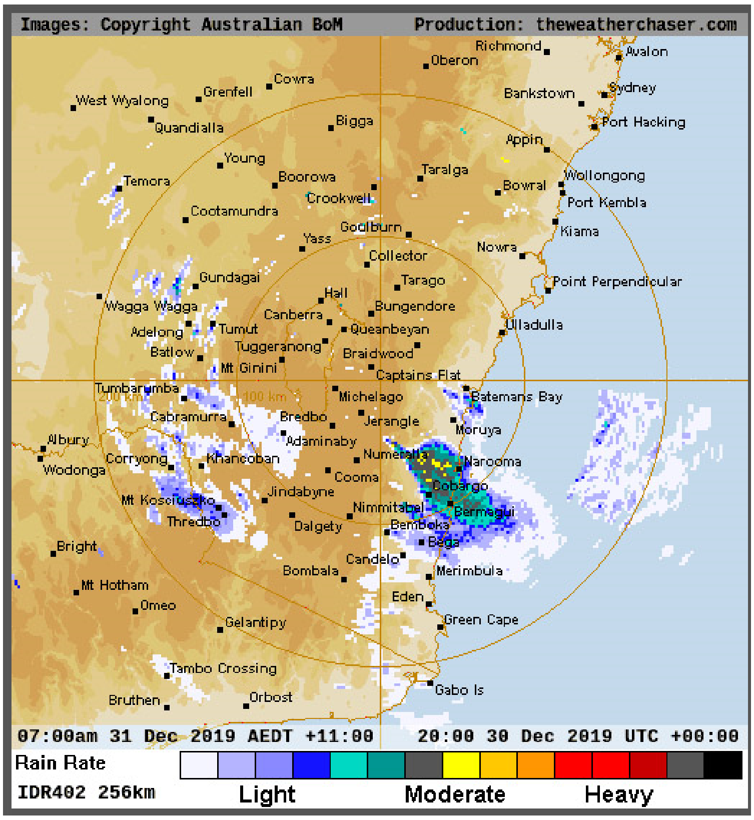
The NSWRFS flew airborne linescans over many of its fires. These are an invaluable source of detailed information of how fires were spreading across the landscape. Linescans are superior to satellite imagery at times, as they are taken underneath the smoke plume and pyroclouds.

BELOW: Linescan of Orroral Valley Fire, ACT, 1 Feb 2020. The image spans over 20 km on the ground. [Image: NSWRFS].



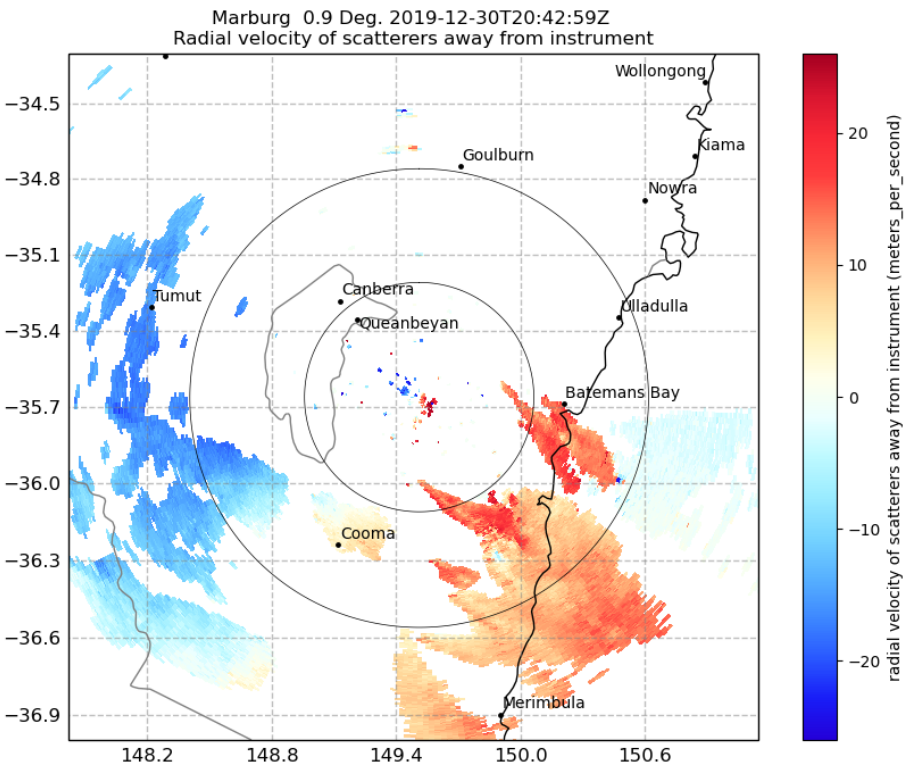
Radar

BoM weather radar is the best tool for assessing plume base dynamics. At time during BS entire regions were covered by dense smoke, and plume bases were needed to assess where the fire were burning.



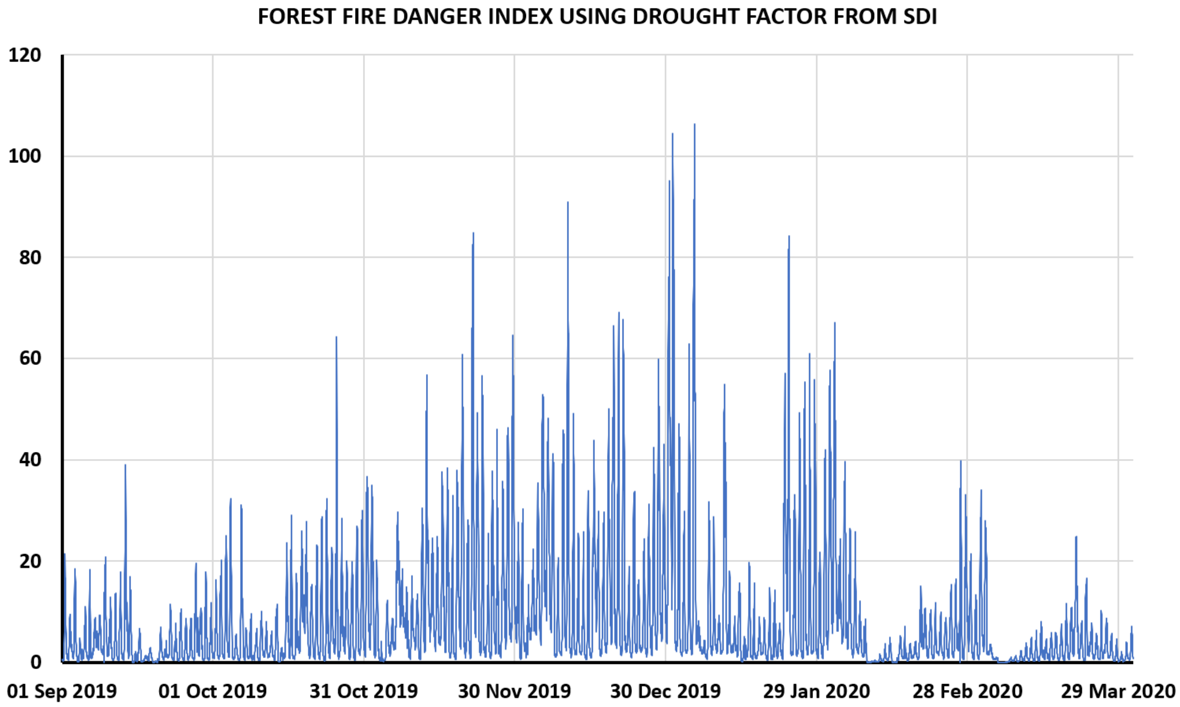
ABOVE: Rain rate radar image showing a series of large plumes, morning 30 Dec 2019. Minor clouds are visible between Tumbarumba and Temora. [Image: BoM]

BELOW: Matching Doppler radar image, showing motions towards (blue) or away from (red) the radar. [Image: BoM]

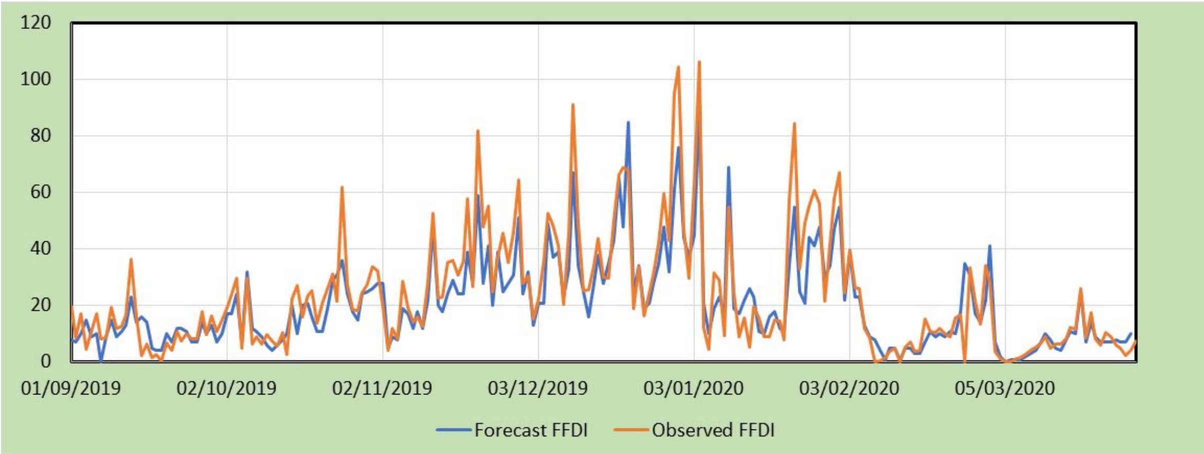


Automatic Weather Station

Automatic Weather Stations are run by BoM to provide routine surface weather updates. These were archived roughly every half hour (more often when key changes were underway).

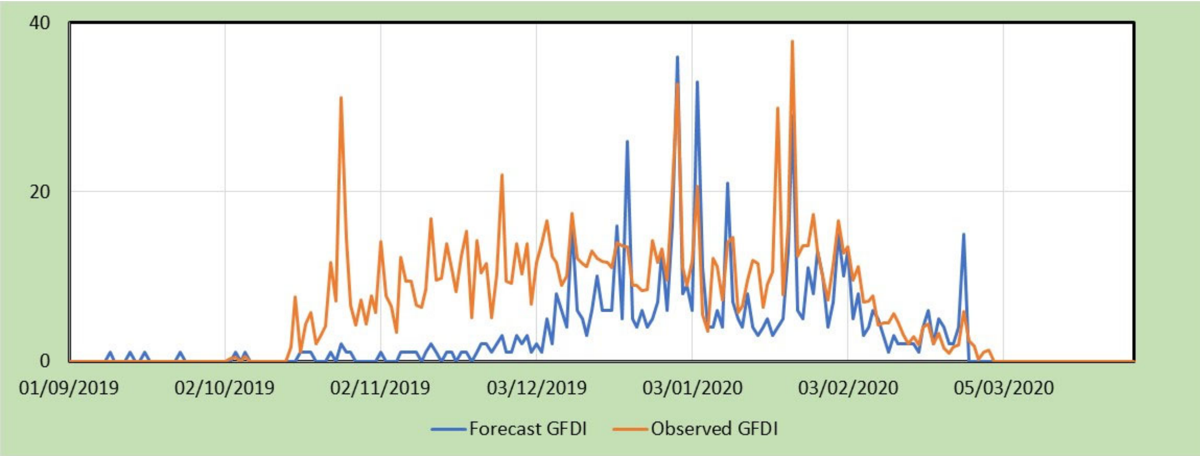


Above: Hourly fire danger observations.



ABOVE: Daily maximum Forest Fire Danger Index for Canberra Airport across Black summer. This compares forecasts (blue) with observations (orange), showing the value of observations [Data: BoM, analysis: McRae].

BELOW: The same for Grassland Fire Danger Index.



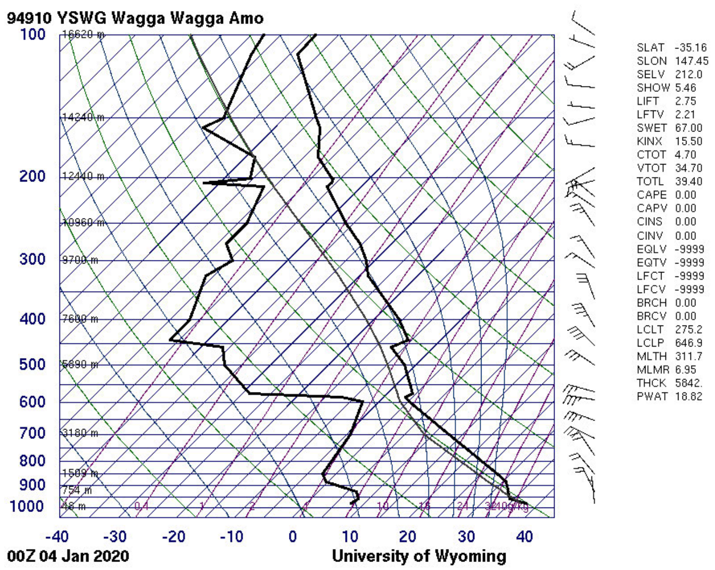
Radiosonde

Weather balloons, radiosondes, loft an instrument package up through the atmosphere, with data downloaded to the base station. These are entered into a global database, which helps make weather forecast models more accurate and precise.

The key data are the temperature and moisture content of the air through which the balloon passes. It is tracked as it rises, allowing wind vectors to be calculated.

A direct plot of temperature with height is somewhat useless, as the air cools so quickly all that you get a line that slopes steeply to the upper left. Instead (among other things) the line is skewed by subtracting a height function. This is called a “Skew-T Log-P” aerological diagram.

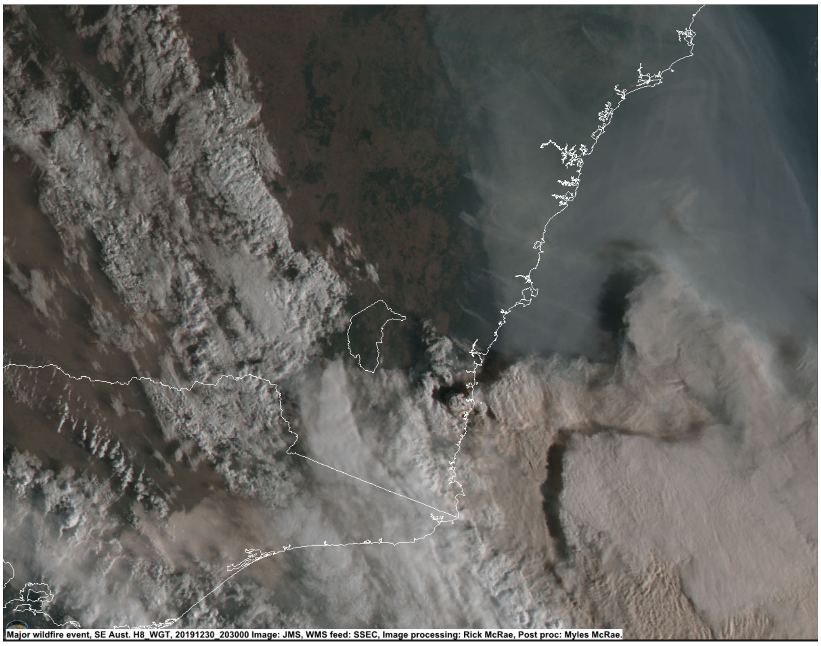
BELOW: The aerological diagram for Wagga from 4 Jan 2020. [BoM]



Himawari-8

The Himawari-8 geostationary earth observation satellite provides imagery in 16 bands every ten minutes. Value-added products, such the fire imagery or the real-colour imagery are essential for tracking fire dynamics. At times Super Rapid Scan mode was activated for the fires, providing 2 minute imagery.

BELOW: The image that shocked atmospheric researchers. The first glimpse of the smoke on the morning of 30 Dec 2019. The image spans from Melbourne to Newcastle. Four forms of smoke are seen: thin white smoke in the north is from distant fires; uniform brown smoke on the Gippsland Coast is moske in a sea breeze system; heavily textured brown smoke has been lofted to the top of the troposphere; and smooth brown-grey smoke is pushing into the stratosphere. Various type of cloud are seen in white. This scale of convective activity had never been seen before. Approximately 10,000,000 cubic kilometres of the atmosphere have been heavily affected by the large plumes.



Sentinel 2

Sentinel 2 is a European earth observation satellite that provides an image equivalent to a linescan. Due to its higher resolution on the ground, its image swathe is narrow, and a repeat occurs only after a few days. It is more useful for post-analysis than for real-time operations.

BELOW: Three Sentinel-2 images from a fire in the Victorian High Country at Timbarra on Jan 20,23 & 25, 2019. First a fire is seen spreading outwards from lightning ignition, then some parts of its perimeter have been suppressed but the fire still spreads, and finally a backburn from a fire trail is underway as an essential strategy. Part of the fire trail is downwind of the fire – a challenge at the best of times. The arrow points to a spot-over due to the fire crossing the fire trail in a number of places. This difficulty of control was a feature of Black Summer.