Forecasting brown haze in Auckland

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Abstract

Brown haze is a visual indicator of poor urban air quality. In Auckland, brown haze typically occurs on cold winter days during the weekday morning commute. There is large interannual variability in the number of brown haze events observed in the region. Recent research identified a clear link between brown haze and poor respiratory health outcomes in Auckland.

This paper analyses the meteorological characteristics of 23 brown haze events in Auckland (as identified from camera images) and proposes a simple Numerical Weather Prediction (NWP) forecast scheme that doesn't explicitly model pollutants, but instead predicts weather conditions historically conducive to brown haze.

Results showed a distinctive atmospheric profile associated with the development of brown haze conditions. A forecast scheme was designed to capture this specific meteorology, and was subsequently validated against camera imagery during a pilot phase lasting three months during the winter of 2017, both at the 30-hour and 54-hour forecast validity period. Results showed 97% forecast accuracy for both 30- and 54-hour forecasts, and a probability of detection of 89% and 78% respectively.

One limitation of the current forecast scheme is that it does not forecast local emissions, and so does not differentiate between weekdays and weekends. Human assessment would still be required before forecasts could be released to the public. Another limitation is that validating the scheme is subjective (brown haze is a visual indicator). Future work will validate the forecast scheme against quantitative measurements of surface air pollution concentrations over a longer period (3 winters), since initial relationships between the forecast index and observed air pollution concentrations looked promising.

1. Introduction

Many cities around the world run operational air quality forecast and alerting schemes. The schemes vary significantly from country to country. Two contrasting examples are New Delhi (India), which regularly experiences extremely poor air quality and ranks as the most polluted capital in the world (WHO 2018), and Melbourne Australia, which records air quality generally considered to be good by international standards (EPA 2018).

The operational air quality systems in India versus Australia are also very different. The Air Quality Index

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in India is effectively a nowcast (BBC, 2015), with alerting colours (red through green) based on 8 observed pollutants averaged over 24 hours. In contrast, the Australian Air Quality Forecasting System (AAQFS) forecasts the following day's air quality in Melbourne, Sydney and Adelaide (Hess, 2000). Both meteorological Numerical Weather Prediction (NWP) and emissions data are entered into the AAQFS model, which produces hour-by-hour air quality forecasts. The forecasting method uses historical weather and air quality data, and watches for particular weather conditions known to be associated with poor air quality. Statistical forecast techniques are used in the Australian method.

The scheme created for the Auckland region uses high resolution Numerical Weather Prediction (NWP) output to forecast the vertical state of the atmosphere over central Auckland for the coming 2 days. The Auckland forecast scheme doesn't ingest or model air pollution concentrations at all, but rather predicts weather conditions that historically have been conducive to capturing available pollution.

The Auckland scheme was tuned on historical significant (dark) brown haze events in the region, selected via visual camera imagery.

Brown haze is a visual indicator of poor urban air quality. In Auckland, brown haze has been correlated with increased levels of specific surface atmospheric pollutants (NO, NO2, CO and PM10), which, in turn, have been statistically linked to increased respiratory hospital admissions in the region (Dirks et al., 2017).

The use of brown haze to tune the forecast scheme, as a surrogate pollution marker instead of direct surface observations of air pollution concentrations, is unusual, even in the international context. But it appears to have paid off. While this was a pilot study set up to investigate whether forecasting severe brown haze in Auckland was even possible, initial analysis of the relationship between the forecast Pollution Score and observed air pollution concentrations look promising (see Results section).

Given the relationship between brown haze and poor respiratory health outcomes in Auckland, there is a need for a robust forecasting tool for the region, which could assist in the management and mitigation of the social and economic consequences of haze events. For example, a reliable forecasting scheme could alert District Health Boards (DHB) and the general public of likely poor air quality events. This would enable DHB staff to respond appropriately to changes in expected respiratory hospital admissions and raise public awareness prompting changes in behaviour (such as choosing not to walk to work during high air pollution events). The ability to predict high air pollution days could also be utilised as a promotional tool to promote public transport on high air pollution days.

Earlier analyses (e.g. Salmond et al., 2016) highlighted the wide range of surface weather situations that can yield brown haze in Auckland. Another complexity was the link to weekday rush-hour traffic and domestic heating, meaning that meteorological factors alone may not explain haze occurrence or non-occurrence. Instead, this forecast scheme aims to predict when the meteorological situation is conducive to trapping air pollution, rather than focusing on the available levels of pollution.

Operational forecasters can bring significant benefit to atmospheric analyses, since they routinely view the atmosphere 'in the vertical'. This is important, in that the surface situation (meteorological or pollutant) is connected to what happens higher up in the atmosphere.

In this study, forecasters examined the meteorology associated with 22 historical brown haze events selected by imagery from a camera installed in Takapuna in Auckland's North Shore, looking southwards towards Auckland's CBD. This camera field of view was optimal for morning light absorption and scatter, enabling good

Figure 1: The view from the Takapuna (North Shore, Auckland) camera looking south towards the Auckland CBD, during a major brown haze event. The Sky Tower (1,076 ft or 328m amsl) is a useful height indicator. In this example, significant brown haze was evident up to about half the height of the Sky Tower, with lesser haze extending to the top of the Sky Tower.

visibility of brown haze formation over central Auckland (Figure 1).

In addition to the 22 events, a major brown haze event occurred during the analysis period, allowing forecasters to assimilate valuable real-time and vertical awareness of the underlying weather situation. In total, 23 brown haze case studies were used to define the forecast scheme.

2.Meteorological analysis

2.1 Mean sea level pressure analyses

A dominant synoptic sequence was easily identified from the mean sea level pressure analyses. Of the 23 brown haze events, 70% showed the classic signature of a strong, cold winter southerly outbreak, followed by hard ridging at latitudes south of Auckland. The coldest air typically affected the eastern North Island, often with an active cold front rounding East Cape (Figure 2).

Following the passage of the cold air, strong surface ridging and upper subsidence occurred. This typically resulted in a large, slow-moving anticyclone centred over central New Zealand, meaning that many of the 'classic' brown haze events in Auckland extended over several days.

Seven events (30%) differed from the classic sequence described above. Instead, the dominant synoptic weather feature on the weather map was a low pressure system or a trough located immediately to the east of the North Island (Figure 3).

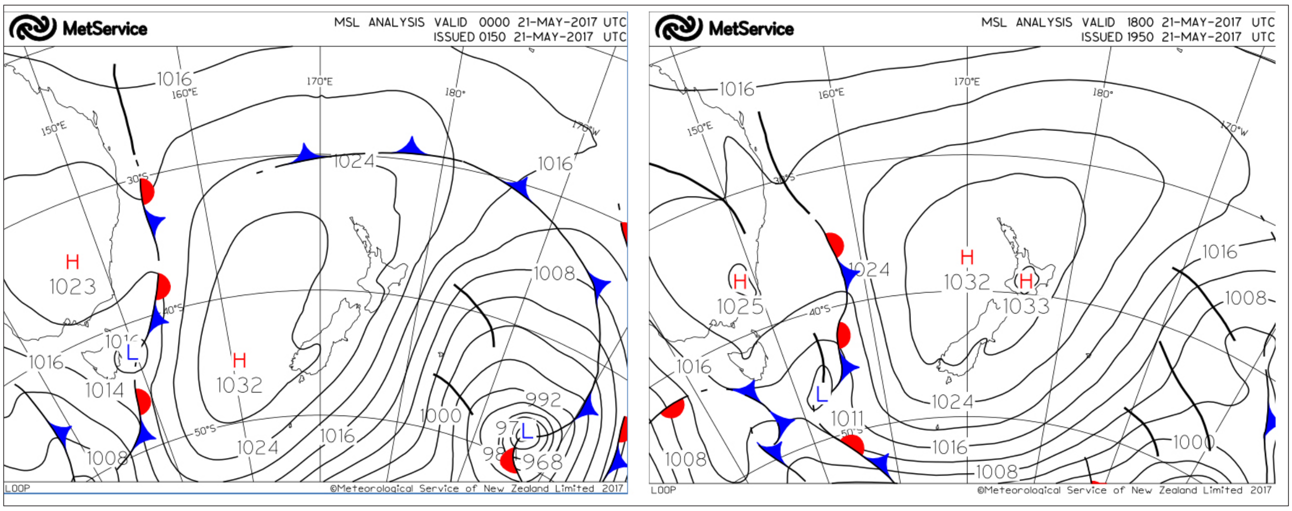

Figure 2: Mean sea level pressure analyses: Midday Sunday 21 May 2017 (left map) and 6am Monday 22 May 2017 (right map). These maps show the classic sequence of a strong, cold outbreak spreading across the North Island, with High pressure subsequently building over central New Zealand.

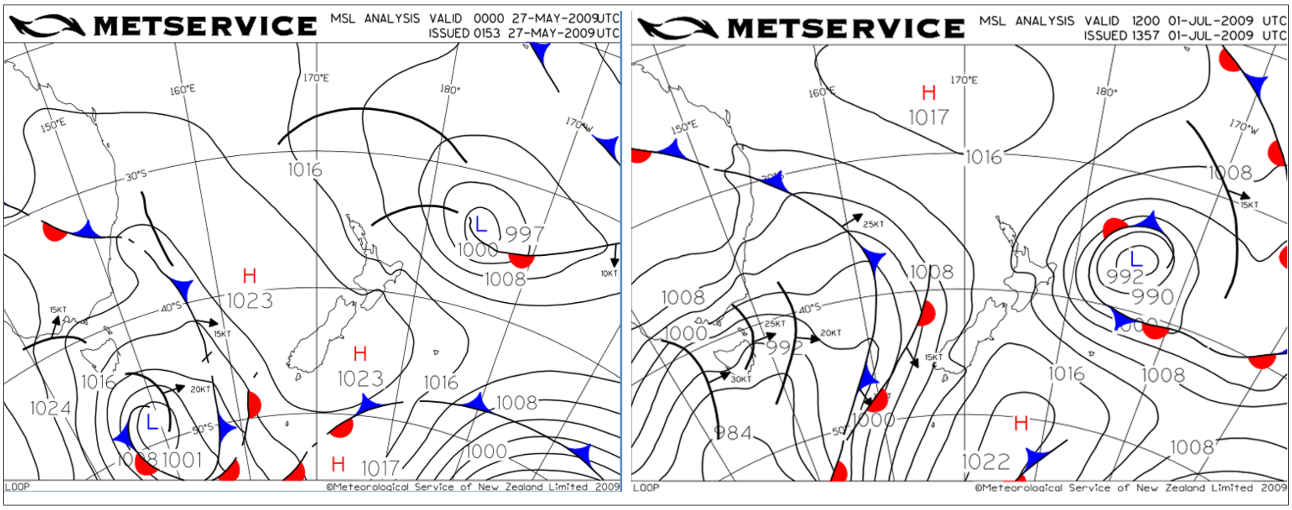

Figure 3: Two examples of the "trough or low to east" synoptic type. Mean sea level pressure analyses from midday 27 May 2009 (left map) and midnight 1 July 2009 (right map) illustrate the considerable variation in surface weather maps during brown haze events.

The common denominator for both synoptic types was low-level southeast quarter winds over Auckland. This result was also supported by raw surface data extracted from the National Climate Database (not shown), and from raw and graphical weather balloon data from Whenuapai (Section 2.2).

2.2 Weather balloon (tephi) analysis

Weather balloon data from Whenuapai (west Auckland) were analysed (Griffiths, 2017) and showed a clear-cut vertical atmospheric profile evident during the 23 brown haze events in Auckland.

As expected, a strong near-surface temperature inversion was necessary to trap pollutants.

In the lower atmosphere, the temperature normally decreases with height. Any point where the temperature increases with height is called an inversion. In winter, on a clear, calm night, the ground cools faster than the air. The ground subsequently cools the layer of air closest to it. This means that a layer of colder near-surface air lies underneath relatively warmer air, creating a near-surface inversion (usually in the lowest 50-350 ft (15-100 m)). This inversion forms a lid, or stable layer, underneath which pollutants can become trapped.

In addition, southeast winds and an associated dry, clear-sky layer at between 1,000 to 3,000 ft (300-900 m) were evident in the brown haze events (Figure 4). This drier layer was consistent with down-slope (warming, drying) southeast winds coming off the nearby Coromandel, Kaimai and Hunua Ranges, ensuring a clear sky recipe to promote the formation of a stronger near-surface temperature inversion during winter nights.

3. Producing a forecast scheme

Following on from the meteorological pattern recognition (i.e. identifying the common weather elements of each event) discussed in Section 2, selected surface and vertical pressure, temperature, dewpoint, and wind data for the 23 brown haze events were compiled. Analysis of these data revealed that:

- About 65% of severe brown haze events (15 cases) exhibited 1,000 feet (300m) winds at the preceding midnight at Whenuapai (west Auckland) in the southeast sector (between 090 and 180 degrees). Another six cases

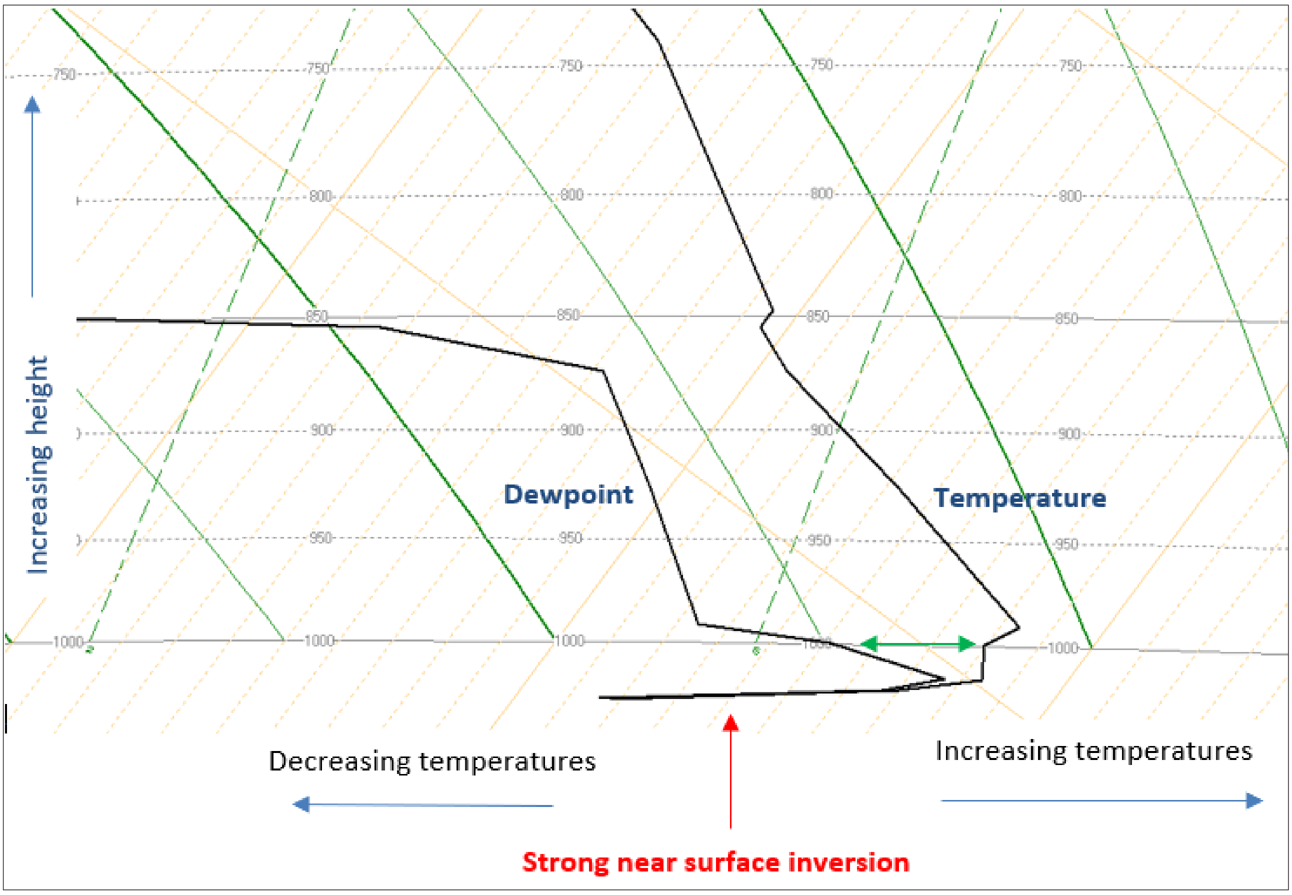

Figure 4: Whenuapai weather balloon data at on 12Z 03 June 2009, during a strong brown haze event. This diagram shows the temperature trace (right hand side) and dewpoint trace (left hand side), with increasing height up the page. This is a clear illustration of wide temperature and dewpoint separation at around the height of the top of the Auckland Sky Tower (indicated by the green arrow), illustrating dry air, clear skies, and a stable "lid" there. This corresponds well to the observed southeast winds at the Sky Tower at the same time. Also note the extremely strong near-surface temperature inversion (shown with red arrow), with both temperature and dewpoint close together but increasing sharply with increased height above ground.

(26%) exhibited 1,000ft (300 m) midnight winds at 180 to 210 degrees, and subsequently backing.

- Light winds with height were important but not essential. Half (50%) of the dawn and midnight winds at 1,000 feet (300 m) (using available Sky Tower data, a central Auckland tower 328 metres high) were less than or equal to 5 knots, with another 25% of events recording winds that were less than or equal to 8 knots.

- Surface pressure was consistent with 'classic' high pressures over central New Zealand. At Whenuapai (west Auckland), 70% of the events exhibited surface pressures in excess of 1020 hPa. The proportions for Gisborne (Airport) and Kelburn, Wellington were 65% and 82% of cases, respectively. Notably, Gisborne Airport and Kelburn, Wellington recorded pressure of more than 1030 hPa, during six and five events (26% and 22%), respectively.

- With respect to the dawn minimum temperatures recorded at Whenuapai (west Auckland), 87% of events recorded less than 4°C, with 65% of events recording less than 2°C and 22% measuring air frosts (0°C or below).

Based on these observations, MetService implemented an automated forecast scheme.

The prediction scheme uses high resolution (4km) Numerical Weather Prediction (NWP) output to forecast the vertical state of the atmosphere over central Auckland for the coming 2 days, and the horizontal state of the atmosphere over the entire North Island. The Auckland forecast scheme doesn't ingest or model air pollution concentrations at all, but rather predicts weather conditions that historically have been conducive to air pollution (as defined by visual brown haze).

MetService forecasters select a 'model of the day', based on which of three downscaled models (IFS, UKMO, ECMWF) is initialising best at analysis time, and it is this selected model that generates the calculated Pollutant Score daily.

The automated forecast scheme was issued by email daily, at 1030am. Data from the midnight prior forecast model was used to forecast at the T+30, T+48 and T+54-hour time steps. That is, predicted Pollutant Scores were issued for dawn (6am) the next day, midnight the next night, and dawn the morning after that.

The scheme was designed to robustly predict significant or extended brown haze events since these were most likely to impact most on Aucklanders' health. There was also intent to minimise 'false alarms', even at the expense of some of the brief, weak or unusual brown haze events.

The avoidance of false alarms was deemed important. Not every winter High produces clear skies leading to cold mornings, strong near surface temperature inversions and brown haze events. The forecasters observed that Highs centred to the west of Auckland often resulted in marine stratocumulus advecting across the city in the southwest flow. This cloudiness kept minimum temperatures in Auckland from falling too far and prevented strong near-surface inversions from forming.

The forecast scheme was designed to be a sum of conducive parameters, with a higher 'Pollutant Score' indicating a stronger forecast for atmospheric conditions conducive to brown haze.

The Pollutant Score was intended to be a continuous score, rather than a discrete 'yes/no' score. This is so that after ground-truthing in subsequent pilot studies, Auckland Council could continue to use it, even if there

Table 1: Parameters contributing to the forecast Auckland Pollutant Score

Parameter	Details
Whenuapai surface pressure (hPa)	Points for every hPa > 1020hPa
Gisborne surface pressure (hPa)	Points for every hPa > 1020hPa
Kelburn surface pressure (hPa)	Points for every hPa > 1020hPa
Whenuapai surface air temperature (C) at 12Z	Points for every degree < 8C
Whenuapai surface air temperature (C) at 18Z	Points for every degree < 4C
Whenuapai surface wind speed (kt)	5 points for every knot < 5 knots
Sky Tower 1,000 foot/300m wind speed (kt)	5 points for every knot < 8 knots
Sky Tower 1,000 foot/300m wind direction (deg)	5 points 161-210, 10 points <=160
Whenuapai 250m wind direction (deg)	5 points 161-210, 10 points <=160
Whenuapai 500m wind direction (deg)	5 points 161-210, 10 points <=160
Whenuapai 750m wind direction (deg)	5 points 161-210, 10 points <=160
Whenuapai 1000hPa temperature minus surface temperature (C)	Points for every degree C

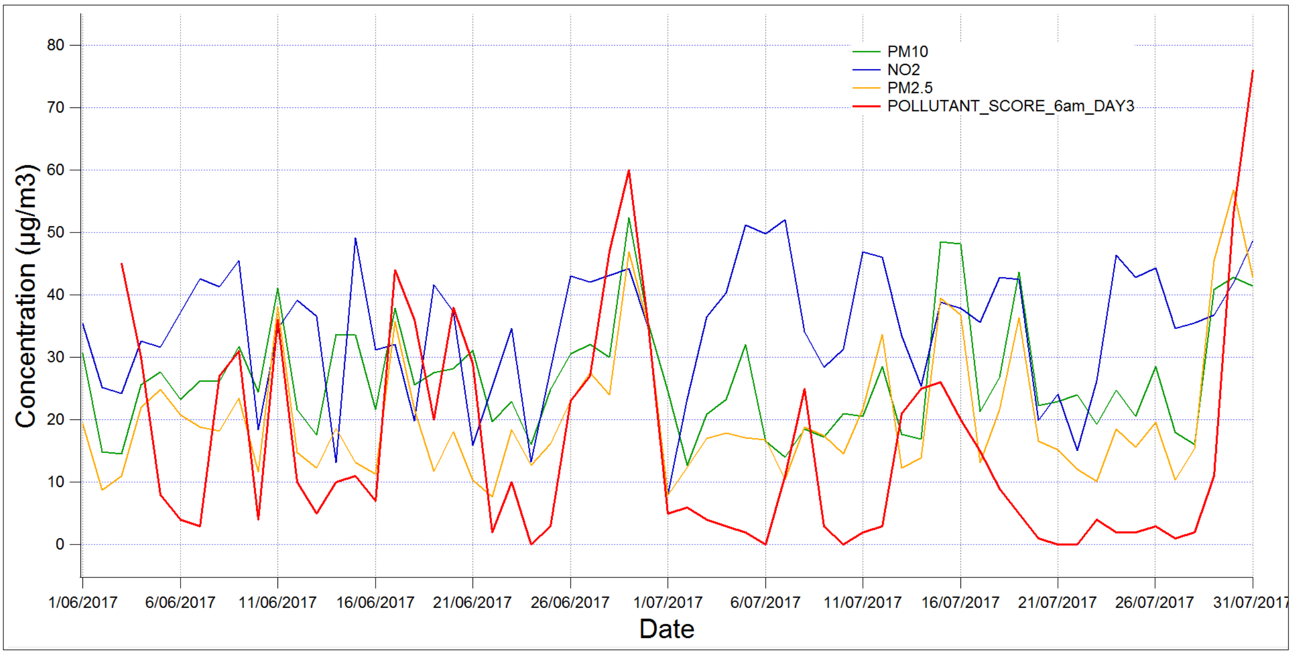

Figure 5: A time series of daily Pollution Score data and daily 95th percentile pollution concentrations at Penrose across June and July 2017. The red line is the forecast Pollutant Score at T+54 hours (dawn day 3). This illustrates that the larger predicted Pollutant Scores (for example, 29 June 2017 and 31 July 2017) typically correspond to elevated measurements of surface pollution. (The blue line is NO2, the green line is PM10, and the yellow line is PM2.5).

was considerable over-forecasting or under-forecasting of brown haze events. A 'sliding' threshold of interest (above which brown haze events were observed and then forecast for) could easily be adjusted.

In the 23 brown haze case studies, 82% calculated a hindcast Pollutant Score of 40 or more, with about half of the events recording a pollutant score of 70 or more. Due to significant amounts of missing Sky Tower data, the hindcast Pollutant Scores for several events were likely too low, with no component added in for missing wind data from Sky Tower.

The Pollution Score was weighted to 'easily forecast' prediction parameters and focused on the known influential factors to form brown haze in Auckland (Table 1), namely high pressure over central New Zealand, cold mornings in Auckland, light winds in Auckland, vertical southeast winds with height over Auckland (forecasting for both Whenuapai and Sky Tower locations), and strong near-surface temperature inversions.

4. Validating the forecast scheme during an initial pilot study

The forecast scheme was operational for a three-month pilot study, carried out from June to August 2017. A continuous Pollutant Score was used, as described in the previous section. The Pollutant Score threshold employed during the pilot study for brown haze formation was > 40, based on the lower bound of the majority of hindcasts for the 23 historical brown haze events.

The validation of the Pollutant Score was subjective, based on a visual assessment of brown haze occurrence using camera data from Takapuna (North Shore, Auckland).

Camera imagery was assessed between dawn and 10am for each of the 93 days that the pilot study was operational. On most days, no haze was observed. If a significant brown haze was present, it was very obvious by eye, both on the camera imagery and also independently observed by MetService forecasters, as well as Auckland

Council and University of Auckland staff, enroute to work. The days with weak haze were harder to classify, and the forecaster necessarily employed some subjective judgement (is it fog, is it haze, is it brown?).

Although the subjectivity seems to undermine the scheme, in actual fact on the days with a strong brown haze event (in other words, the events that the public likely care about), there was consensus by all authors assessing the haze.

Lastly, a preliminary (subset) analysis of the relationship between the forecast Pollution Score and observed air pollution concentrations at a single location look promising (Figure 5). On days that the Pollutant Score was predicted to be extremely high (for example, Pollutant Score of 60 on 29 June 2017 or Pollutant Score of 74 on 31 July 2017), elevated 95th percentile PM2.5 concentrations were recorded at Penrose. This effect was not so obvious with lower forecast Pollutant Scores.

However, it did serve as a good litmus test, indicating that further analysis of the relationship between the prediction scheme and quantitative air pollution concentration data would be informative as a next step.

Two full data validations against camera imagery were undertaken, one for the 30-hour time step (dawn the next day, also known as 'Dawn Day 2') and the other for the 54-hour time step ('Dawn Day 3'). Since the camera was a visual source of validation information, no validation was performed for the 48-hour (midnight) time step due to darkness.

For both of the camera validations, the following verification metrics were calculated:

- **Probability of Detection (POD) = (hits)/(hits + missed events):** This metric defines the fraction of "yes" events that were correctly forecast.
- **False Alarm Rate (FAR) = (false alarms)/(hits + false alarms):** This metric defines the fraction of "yes" forecasts that did not occur.
- **Accuracy = (hits + correct negatives)/(total):** This metric defines overall fraction of correct forecasts.

Table 2: Verification statistics for T+54 hours (Dawn Day 3).

		Observed	
		Yes	**No**
Forecast	**Yes**	**7 Hits**	**1 False Alarm** (3 June, Queen's birthday weekend)
	No	**2 missed events** (both weak)	**83 correct negatives**

Table 3: Verification statistics for T+30 hours (Dawn Day 2).

		Observed	
		Yes	**No**
Forecast	**Yes**	**8 Hits**	**2 False Alarm** (5 August, T30 Score 43) (20 June, T30 Score 59)
	No	**1 missed event**	**82 correct negatives**

Table 4: Verification metrics for both T+54 and T+30 validity times.

	T 54 hours (dawn day 3)	T 30 hours (dawn day 2)
Accuracy	97%	97%
POD	78%	89%
FAR	13%	20%

5. Conclusions

Brown haze is a visual indicator of poor urban air quality. In Auckland, brown haze typically occurs on cold winter days during the weekday morning commute. Recent research identified a clear link between strong brown haze and poor respiratory health outcomes in Auckland.

Based on a climatological analysis of 23 brown haze events in Auckland identified from camera imagery, a clear-cut atmospheric profile associated with haze formation was identified.

About 70% of the brown haze events showed the classic signature of a strong, cold winter southerly outbreak, followed by High pressure building in over central New Zealand. However, the remainder of the cases showed rather diverse weather maps. The common element with all cases, however, was clear skies that allowed temperatures to drop, and a strong near surface temperature inversion to form.

This work has identified that southeasterly sector winds were key to producing clear skies during winter in Auckland, both at the height of the top of the Sky Tower (around 1,000 ft (300 m)), but also extending up to around 3,000 ft (900 m).

Southeasterly winds over Auckland typically produce clear skies due to downslope warming and drying coming off the Coromandel, Kaimai and Hunua Ranges – even when no High is in play on the weather map. The highest points in the Kaimai and Hunua Ranges are 950m (about 3,100 ft) and 688m (approximately 2,200 ft) in elevation, respectively. Drying and warming – and subsequent clear skies - would be expected below the height of the ranges.

This mechanism explains the 'low or trough to the east' situations which produce brown haze in Auckland, even when surface pressures are not high. It also explains why winter Highs lying over the Tasman Sea are not associated with brown haze events in Auckland, since cloudy southwesterlies typically keep minimum temperatures elevated, such that no strong near-surface temperature inversion forms.

Based on this analysis, MetService designed and implemented an automated forecast scheme that predicted when atmospheric conditions were strongly conducive to trapping air pollution.

The prediction scheme uses high resolution (4km) Numerical Weather Prediction (NWP) output to forecast the vertical state of the atmosphere over central Auckland for the coming 3 days. The scheme doesn't ingest pollution data or model air pollution concentrations at all, as some schemes in other countries do - but rather predicts weather conditions that historically have been conducive to trapping air pollution (as defined by brown haze).

A pilot scheme to forecast significant pollutant days in Auckland was then established in the winter of 2017. The focus of the forecast scheme was to correctly forecast significant or extended brown haze events. The scheme also aimed to minimise 'false alarms', particularly winter Highs lying to the west of Auckland.

The forecast scheme validated well against camera imagery, both at the 30-hour and 54-hour validity period. There were only small differences in validation metrics between the two validity periods, and as such, the 54-hour forecast could be preferentially used to enable a longer (two-day) lead time.

The Pollutant Score was robust in that it accurately identified brown haze events in the region, with a good probability of detection and without significant over-alerting bias. The only false alarm during the pilot study at the 54-hour validity period occurred during a long weekend (Queen's birthday), highlighting the known impact of emissions associated with Auckland's rush hour on brown haze formation.

Pollutant Scores of around 40 tended to be associated with absent, partial or weak events, and with this knowledge, a slightly higher working threshold of 45 was adopted in an operational scheme that subsequently ran through the winter of 2018 and winter 2019.

The full validation undertaken here was based on the subjective identification of haze from camera imagery. An exploratory analysis of forecast Pollutant Score against quantitative air pollution concentration data recorded at a single site showed potential, with a relationship evident between large Pollutant Score and elevated concentrations of PM2.5.

Future work will include analysis of the forecast scheme against quantitative measurements of surface air pollution concentrations over a longer period (all three winters that the scheme has now been operating).

If the Auckland Pollutant Score is continually found to validate well against surface pollutants through subsequent winters, the next (ultimate) step will be to initiate a 'live' Air Pollution forecast for Auckland during the winter period, complete with Auckland Council alerting of predicted high air pollution events to both the public and to District Health Boards.

Acknowledgements

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Addendum

Subjective assessment via camera imagery

The use of camera imagery to identify brown haze is subjective.

The validation was performed daily, in near real-time whenever possible. Visual checks of state of the sky were routinely undertaken by MetService staff as part of their morning observation, in conjunction with checking the camera imagery. These observations also noted whether cloud was present in the region, and this could be checked using Himawari-8 satellite data. On days when brown haze was forecast, or identified by MetService staff as visible (even on days that were not forecast), University of Auckland and Auckland Council staff were notified to employ independent visual checks enroute to work.

Sometimes the visual check results varied between different areas of Auckland, with only part of the region affected by brown haze, or varied between time of day (with brown haze sometimes more obvious slightly later in the morning, when the boundary layer was deepening, and the brown haze was lifting).

In addition, classifying a day as either brown haze present, (including a description of strong or weak brown haze), or no haze present, remained subjective between the observers. MetService staff are trained observers who routinely observe the state of the sky, whereas the other observers are not.

Fog layers, white haze/suspended sea salt, and cloud layers all cause optical effects that are not defined as brown haze, but visually, can be difficult to differentiate.

An example of strong brown haze present is shown below:

1. Brown haze is obvious to the southeast (to left) and southwest (to right) of the Auckland CBD. A layer of stratocumulus is also present above the haze layer:

2. Weak brown haze is observed across the image, possibly being of slightly darker hue to the southeast (to the left) of the Auckland CBD. Note that this lowest-level was confirmed not to be cloud by both satellite data and from observation from the MetService Stanley Street office. There were, however, two very thin strips of cloud above the haze layer.

Forecast Pollutant Score for T+54 hours, listed if > 40 or haze observed

Date	Pollutant Score T+54hrs	Haze on camera?	Validation Status
3-Jun-17	45	No haze	False alarm (long weekend)
17-Jun-17	44	Brown haze	Hit
18-Jun-17	36	Weak brown haze	Missed event (elevated NO^2 only)
28-Jun-17	47	Strong brown haze	Hit (elevated NO^2)
29-Jun-17	60	Strong brown haze	Hit (elevated levels all pollutants)
30-Jul-17	53	Brown haze	Hit
31-Jul-17	76	Weak brown haze	Hit
4-Aug-17	48	Brown haze	Hit
22-Aug-17	39	Weak brown haze	Missed event
23-Aug-17	61	Strong brown haze	Hit