From: Justine Stansen
To: Fox, Chris (AU); "Heffernan, Emily (AU)"
Subject: Hazelwood Mine Fire Inqiury
Date: Wednesday, 30 September 2015 8:39:00 PM
Attachments: Letter to KWM 30.9.15.pdf
Excel spreadsheets.msg
Updated analysis.msg
Hazelwood Mine Fire Inquiry.msg
RE Hazelwood Mine Fire Inquiry.msg
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RE Hazelwood Mine Fire Inquiry.msg
image002.jpg

Dear Chris/Emily

Please see attached letter.

Kind regards

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry
[redacted]

30 September 2015

By email: [redacted]

Mr Chris Fox
King & Wood Mallesons
[redacted]

Dear Mr Fox

Hazelwood Mine Fire Inquiry

I refer to Term of Reference 6 and the recent public hearings held on 1-3 and 9 September 2015. During the course of those hearings two reports prepared by Associate Professor Barnett were tendered.

On 11 September 2015, Associate Professor Adrian Barnett contacted the Secretariat and indicated that he was undertaking further analysis of the daily death data provided to him prior to the hearing and that he intended to produce a further report that he wished to publish.

On 15 September 2015, Associate Professor Barnett provided that third report to the Board. On 17 September 2015, the Board sought the views of Professor Armstrong concerning the third report of Associate Professor Barnett. Professor Armstrong's comments in relation to the third report were emailed to the Board on 18 September 2015 and were forwarded to Associate Professor Barnett by the Board in an email dated 24 September 2015.

On 25 September 2015, Associate Professor provided a fourth report to the Inquiry.

Copies of the correspondence described above and the third and fourth reports of Associate Professor Barnett are **attached**. Copies of the reports and the correspondence will also be provided to all experts who gave evidence at the hearing in relation to Term of Reference 6.

The Board will holding a short further hearing to consider this additional evidence held on **15 October 2015 from 9.00 am** in Melbourne. The hearing will take place on level 11, 222 Exhibition St Melbourne. Associate Professor Barnett, Professor Armstrong, Dr Flander and Professor Gordon will be called as witnesses as a panel and will be questioned about this new material by Counsel Assisting. Any party who wishes to question the witnesses about this new material should inform Counsel Assisting by email no later than COB on Tuesday 13 October 2015 in accordance with the Practice Note. The Board will consider any such request in accordance with the Practice Note.

All parties will be entitled to submit brief final written submissions in relation to the evidence given at the further hearing by **12pm, 19 October 2015**.

Please contact me by email at [redacted] or by phone on [redacted] if you have any questions.

Yours faithfully

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry

From: Adrian Barnett
To: Justine Stansen
Subject: Excel spreadsheets
Date: Friday, 11 September 2015 2:47:54 PM

Dear Justine

I've had time to look at the Excel spreadsheets on the death data from the Latrobe valley. The daily data are more detailed than previous monthly estimates. There is the chance to do an improved analyses as the period of the fire (in days) would be more accurate compared with the previous analyses based simply on February and March 2014.

I'd like to do this analysis and publically release the results as I have done with my previous two analyses. Would this be allowable considering both any restrictions that were reported to you when you received the data, and any restrictions that you may have?

Regards,

Adrian
[redacted]

From: Adrian Barnett
To: Monica Kelly
Subject: Updated analysis
Date: Tuesday, 15 September 2015 11:41:35 AM
Attachments: Death.Analysis.3.pdf

Hi Monica

I spoke with Ruth on the phone earlier and she suggested that I send my updated analysis to you.

Attached is an analysis based on the daily data that I received during the expert conclave. I'm happy for this analysis to be shared with all members of the inquiry, and I'm willing to discuss the results any time. I would like to make my results public at some time, but am happy to give the inquiry time to examine the results first.

Regards,

Adrian
QUT
[redacted]

Analysis of daily death data during the Morwell mine fire

Summary

This latest analyses gives a 99% probability of an increase in deaths during the 45 days of the fire, with an estimated 23 additional deaths. This is larger than the 79% to 89% probability and 10 to 14 additional deaths from my two previous analysis. This increase in probability and deaths occurred because this analysis used daily data whereas the previous analyses used monthly data. Using days instead of months reduces the measurement error between exposure and death, and an increased statistical significance and risk is entirely expected based on the theory of measurement error [1]. This analysis also had a better control for the potential confounder of temperature, as temperature was also modelled on a daily time scale.

Introduction

This document contains my third analysis of the Morwell mine fire data. This is an updated analysis using daily death data for four postcodes for the years 2009 to 2014.

Methods

Data

The death data were daily numbers from 1 January 2009 to 31 December 2014, which is 2191 days. The deaths were split by four postcodes (3840-Morwell, 3842-Churchill, 3825-Moe, 3844-Traralgon) according to usual place of residence. There were 3,414 deaths in total.

I used population data from the Australian Bureau of Statistics for each postcode over time. This is a further improvement on my previous analyses which used overall population data for the Latrobe Valley.

The temperature data came from the Bureau of Meteorology weather station at Morwell (station number: 85280), which provided daily maximum temperature. Two days were missing and I imputed the missing temperature using the mean temperature for the days either side of the missing day. I used maximum temperature rather than mean or minimum temperature because previous research found that most common temperature measures are highly correlated and perform equally well when predicting daily death rates [2].

Statistical methods

I used a regression model to examine the key hypothesis of whether deaths rates were higher during the 45 days of the fire.

I give the model as an equation below and then explain each line of the equation.

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\begin{aligned}
d_{i,t} &\sim \text{Poisson}(\mu_{i,t}), \qquad i = 1, \ldots, 4,\ t = 1, \ldots, 2191, \\
\log(\mu_{i,t}) &= \log(\text{pop}_{i,t}/10000) + \alpha_0 + \text{postcode}_i + \text{trend}_t + \text{season}_t + \text{weekday}_t \\
&+ \text{temperature}_t + \text{fire}_t, \\
\text{postcode}_i &\sim N(0, \sigma^2) \\
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The index i is for postcode and the index t is for time. I used a Poisson model as the data are daily counts of deaths. The trend was fitted as a natural spline (ns) with two degrees of freedom which allowed the underlying death rate to change slowly during 2009 to 2014 due to factors such as an ageing population. Season was fitted as an annual sinusoid and f is the fraction of the year from 0 (1 January) to 1 (31 December) [3]. I modelled the expected small difference in death rates by day of the week using an independent effect on each day with Sunday as a the reference day.

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To check the adequacy of the model I examined the residuals (difference between observed and predicted) using a histogram and autocorrelation plot.

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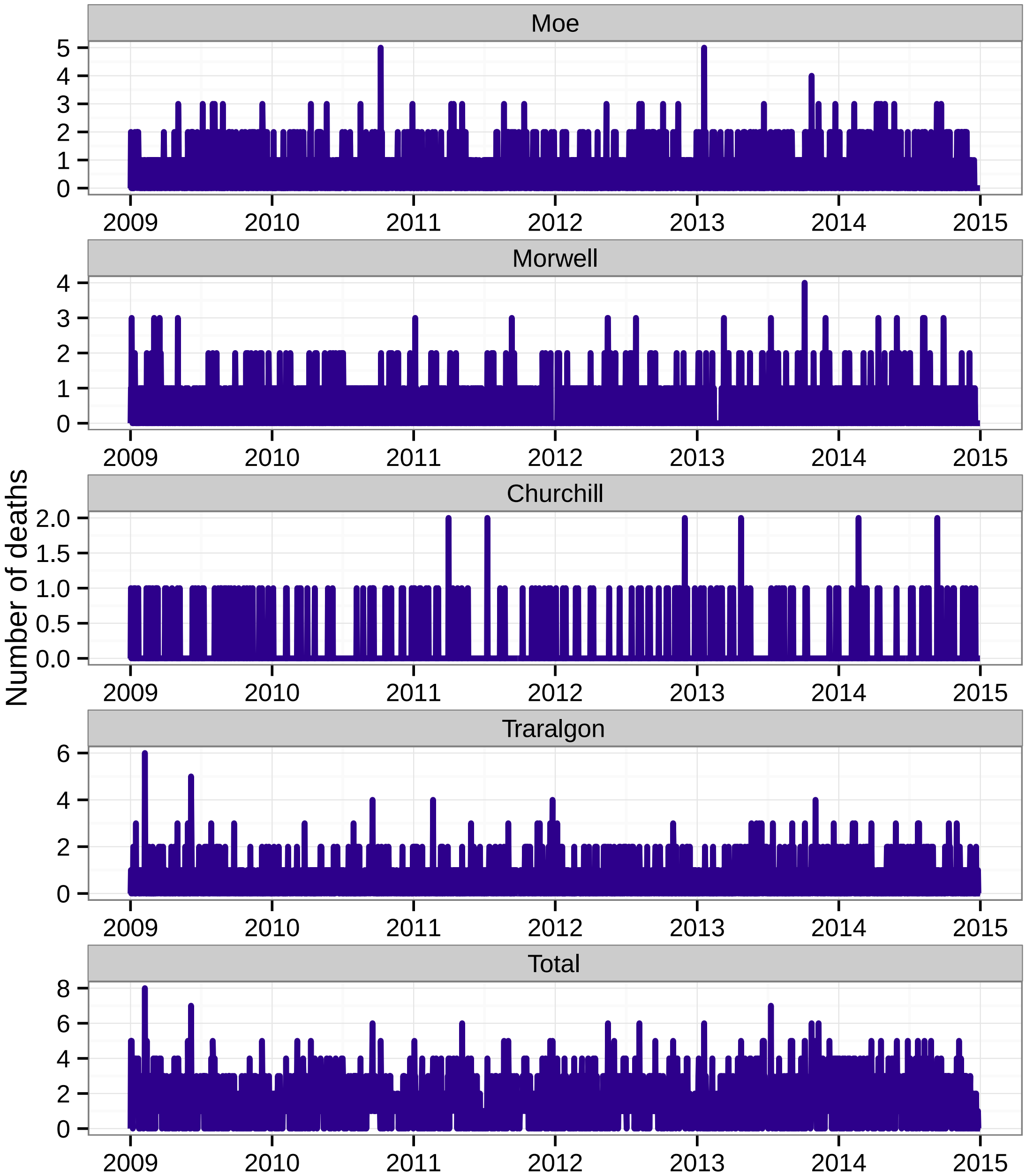
Table 1 shows a higher mean number of daily deaths in all four postcodes during the period of the fire compared with all other times. These crude figures do not adjust for the seasonal pattern in deaths, and the regression model below should give a truer picture of any increase in death rates.

Table 1: Summary statistics on daily deaths by postcode and the time of the fire using data for 1 January 2009 to 31 December 2014

			Deaths			
Postcode	Fire	N	Mean	SD	Min	Max
Churchill	No	2145	0.075	0.27	0	2
	Yes	46	0.130	0.40	0	2
Moe	No	2145	0.558	0.74	0	5
	Yes	46	0.717	0.81	0	3
Morwell	No	2145	0.396	0.63	0	4
	Yes	46	0.413	0.62	0	2
Traralgon	No	2145	0.522	0.73	0	6
	Yes	46	0.652	0.87	0	3
All	No	8580	0.388	0.65	0	6
	Yes	184	0.478	0.73	0	3

Plots of daily deaths over time



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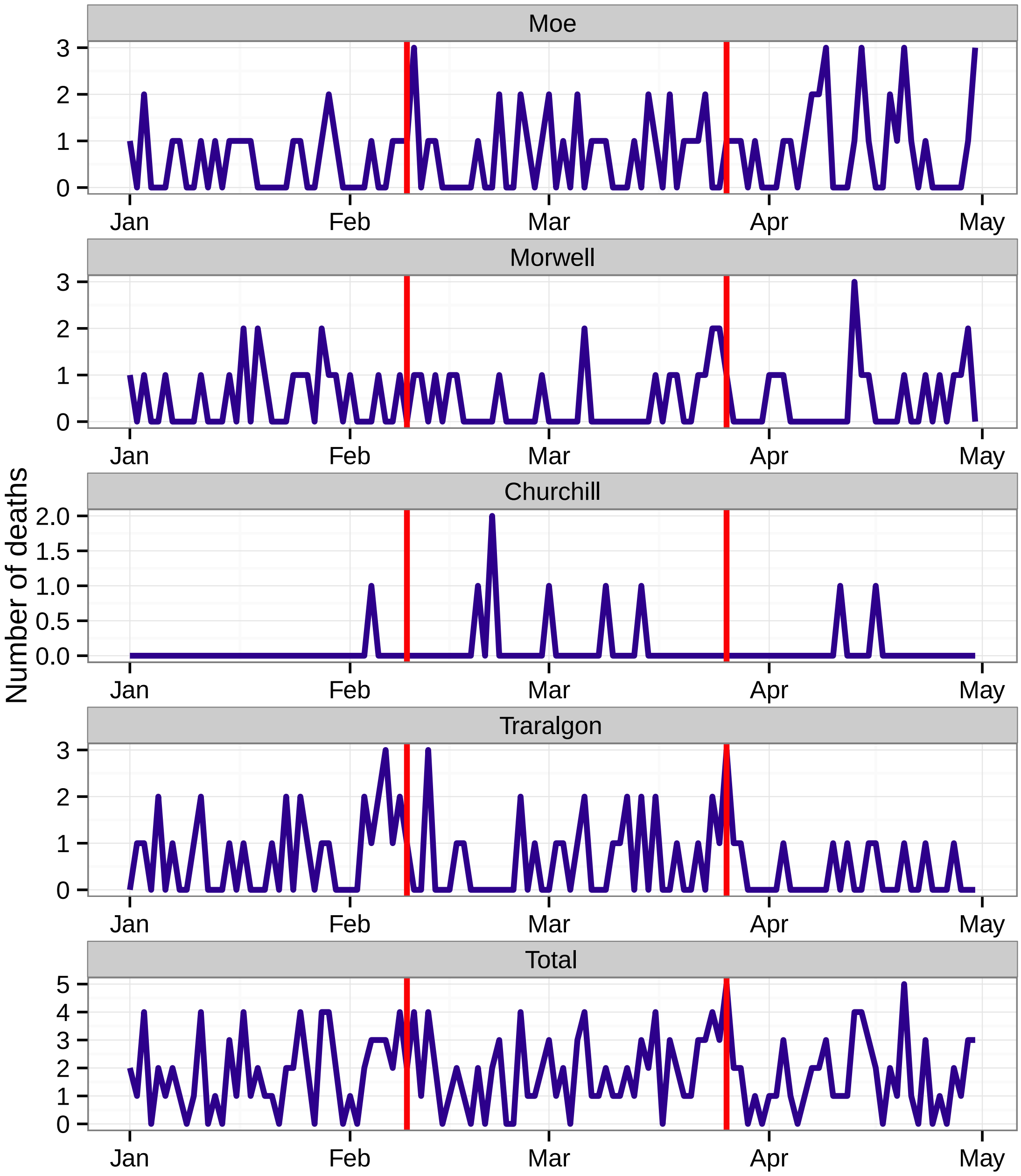

Figure 2: Daily death numbers in each postcode and the total number of deaths across the four postcodes for 1 January 2014 to 30 April 2014. The start and end of the fire are shown by vertical red lines.

Statistical model results

Table 2: Model of daily deaths. Statistics are the mean and lower and upper 95% credible interval. Estimates are on a log scale except for the relative risk and absolute number of deaths.

	Mean	Lower	Upper
Intercept	−1.601	−1.732	−1.475
Trend, 1	−0.125	−0.346	0.096
Trend, 2	0.137	0.016	0.258
Postcode, 3825	0.285	0.225	0.346
Postcode, 3840	0.129	0.062	0.194
Postcode, 3842	−0.310	−0.426	−0.196
Postcode, 3844	−0.104	−0.165	−0.042
Season, cos	0.105	−0.057	0.269
Season, sin	0.059	−0.033	0.153
Monday	−0.069	−0.196	0.056
Tuesday	−0.096	−0.223	0.031
Wednesday	−0.042	−0.165	0.083
Thursday	−0.060	−0.186	0.064
Friday	0.049	−0.074	0.172
Saturday	0.008	−0.114	0.131
Fire, relative risk	1.324	1.034	1.656
Additional deaths during fire, 3825	8.271	0.860	16.731
Additional deaths during fire, 3840	5.848	0.608	11.830
Additional deaths during fire, 3842	1.124	0.117	2.273
Additional deaths during fire, 3844	7.733	0.804	15.642
Additional deaths, all postcodes	22.976	2.388	46.476

The probability that the death rate was higher than the average during the fire is 0.99. This means that the probability that the death rate was not higher than the average during the fire is 0.01. The mean increase in deaths is 1.32 as a relative risk, or 32 as a percentage. The 95% credible interval for the relative risk does not include 1, indicating that the risk was higher than average during the fire. The mean estimated number of extra deaths during the fire over the four postcodes is 23.

Effect of temperature

The effect of temperature in Figure 3 is exactly as expected. It shows a steep rise in risk for high temperatures on the day of exposure, and smaller but longer lasting risk for low temperatures [4].

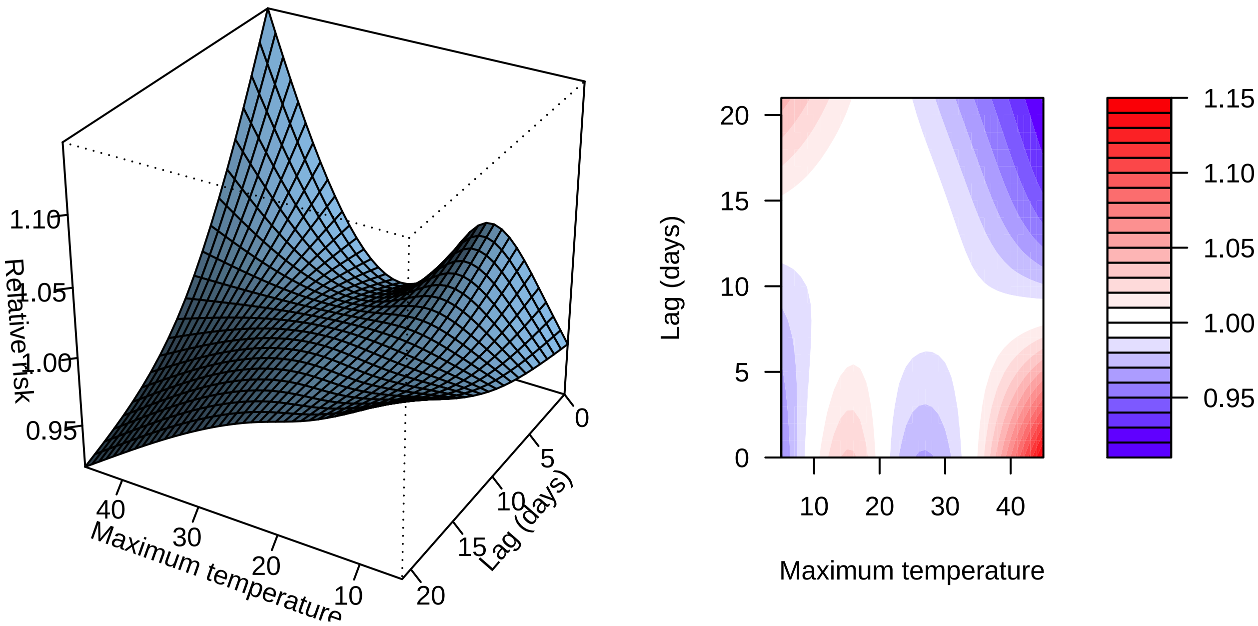

Figure 3: Estimated relative risk of maximum temperature (°C) by temperature and lag using a surface plot (left) and contour plot (right).

Residual plots

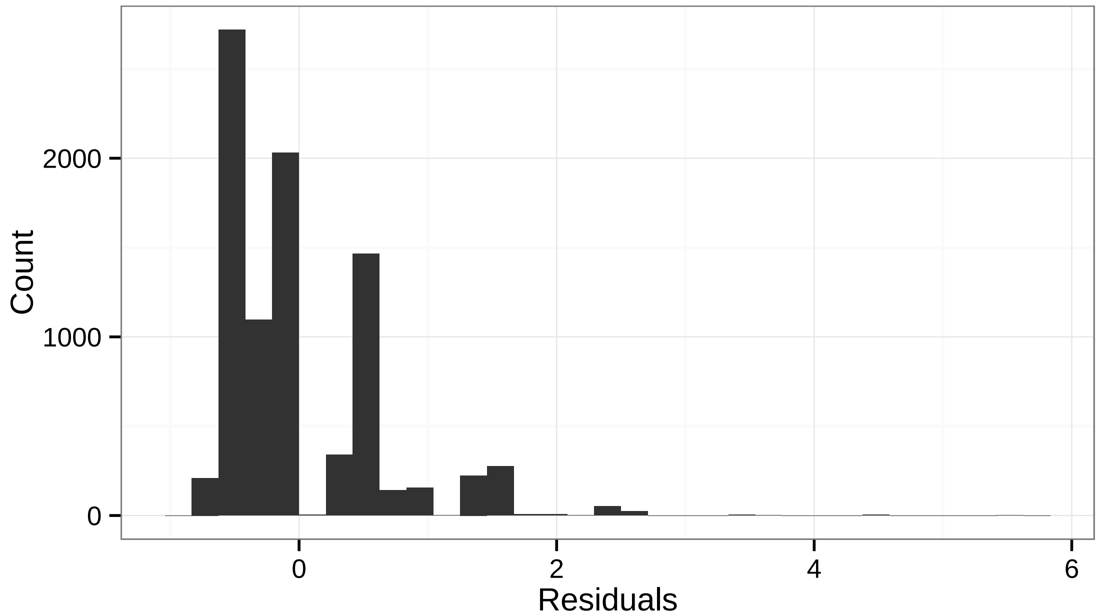

Figure 4: Residual histogram from the model of daily deaths.

The histogram of residuals are centred on zero but with a positive skew which is as expected when modelling small counts (Figure 4). There were four relatively large residuals over 4 as shown in Table 3. The large residual in Traralgon on 7/Feb/2009 may be the Black Saturday bushfires.

Table 3: Four large residuals where the model greatly under-predicted the number of deaths.

Date	Postcode	Deaths	Predicted	Residual	Pearson residual
08/Oct/2010	Moe	5	0.60	4.40	5.66
19/Jan/2013	Moe	5	0.51	4.49	6.27
07/Feb/2009	Traralgon	6	0.57	5.43	7.22
06/Jun/2009	Traralgon	5	0.58	4.42	5.78

The Pearson goodness of fit statistic is 8749 which is smaller than test limit of 8958, which is the 95th percentile of a chi-squared distribution [5]. This indicates that the model is an adequate fit to the data.

The autocorrelation plots of the residuals show no residual autocorrelation in any postcode as the correlations are small and close to zero (Figure 5). This means there is unlikely to be any residual confounding by other short-term environmental factors (e.g., humidity).

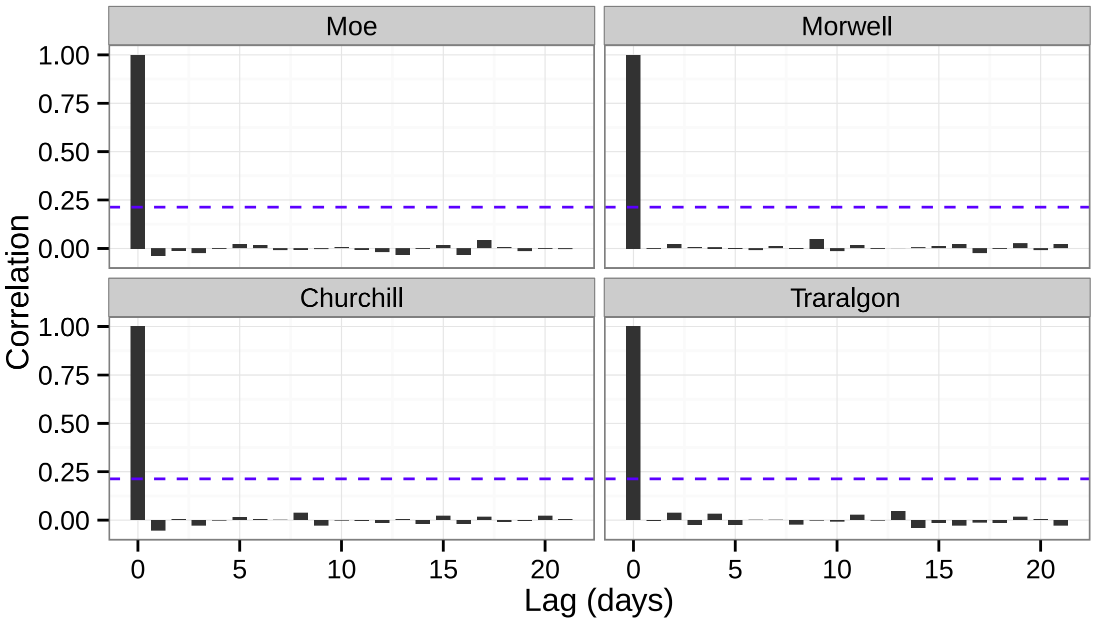

Figure 5: Autocorrelation of residuals from the model of daily deaths by postcode. The dotted horizontal blue line is the limit for assessing significant autocorrelation.

References

[1] Jennifer A Hutcheon, Arnaud Chiolero, and James A Hanley. Random measurement error and regression dilution bias. *BMJ*, 340, 2010.

[2] A. Barnett, S Tong, and ACA Clements. What measure of temperature is the best predictor of mortality? *Environmental Research*, 110(6):604–611, 2010.

[3] Adrian G Barnett and Annette J Dobson. *Analysing Seasonal Health Data*. Springer, Berlin, Heidelberg, 2010.

[4] Antonio Gasparrini and et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet*, 386(9991):369–375, 2015.

[5] Annette J Dobson and A.G̃. Barnett. *An Introduction to Generalized Linear Models*. Texts in Statistical Science. Chapman & Hall/CRC, Boca Raton, FL, 3rd edition, 2008.

[6] Martyn Plummer. *rjags: Bayesian graphical models using MCMC*, 2013. R package version 3-11.

Appendix

JAGS Code

This is the code using the JAGS software that runs the Bayesian regression model of daily deaths [6].

```
model{
# likelihood
for (i in 1:N){
deaths[i] ~ dpois(mu[i]);
log(mu[i]) <- log.pop[i] + alpha + weekday[i] + trend[i] + gamma*fire[i]
+ delta.c[pcode[i]] + season[i] + temp[i];
weekday[i] <- inprod(dow[i,1:6], phi[1:6]);
trend[i] <- inprod(time[i,1:n.time], beta[1:n.time]);
season[i] <- theta[1]*cosw[i] + theta[2]*sinw[i];
temp[i] <- inprod(temperature[i,1:n.temp], zeta[1:n.temp]);
}
# priors
alpha ~ dnorm(0, 0.001) # intercept
for (k in 1:n.time){
beta[k] ~ dnorm(0, 0.001) # time trend
}
gamma ~ dnorm(0, 0.001) # fire
for (k in 1:6){
phi[k] ~ dnorm(0, 0.001) # week day
}
for (k in 1:n.temp){
zeta[k] ~ dnorm(0, 0.001) # temperature
}
for (k in 1:n.pcode){
delta[k] ~ dnorm(0, tau.delta); # random intercept for postcode
delta.c[k] <- delta[k] - mu.delta;
# absolute numbers
```

```
    absolute[k] <- mu.deaths[k]*(rr-1)
}
absolute[5] <- sum(absolute[1:4]) # total deaths
tau.delta ~ dgamma(1,1)
for (k in 1:2){
theta[k] ~ dnorm(0, 0.001); # season
}
## scalars
mu.delta <- mean(delta[1:n.pcode])
p.gamma <- step(gamma) # p-value for positive risk
rr <- exp(gamma) # relative risk
}
```

From: Justine Stansen
To: "Bruce Armstrong"
Subject: Hazelwood Mine Fire Inquiry
Date: Thursday, 17 September 2015 11:28:00 AM
Attachments: image001.jpg
Death.Analysis.3.pdf

Dear Bruce

I trust you are well. We have received some further analysis undertaken by Associate Professor Adrian Barnett since the Hazelwood Inquiry hearings held earlier this month which is based on daily death data rather than monthly data. I was wondering whether you could consider the **attached** analysis and contact me to discuss your thoughts about it. The Board would be grateful for your additional input in relation to this issue.

I look forward to hearing from you.

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry
[redacted]

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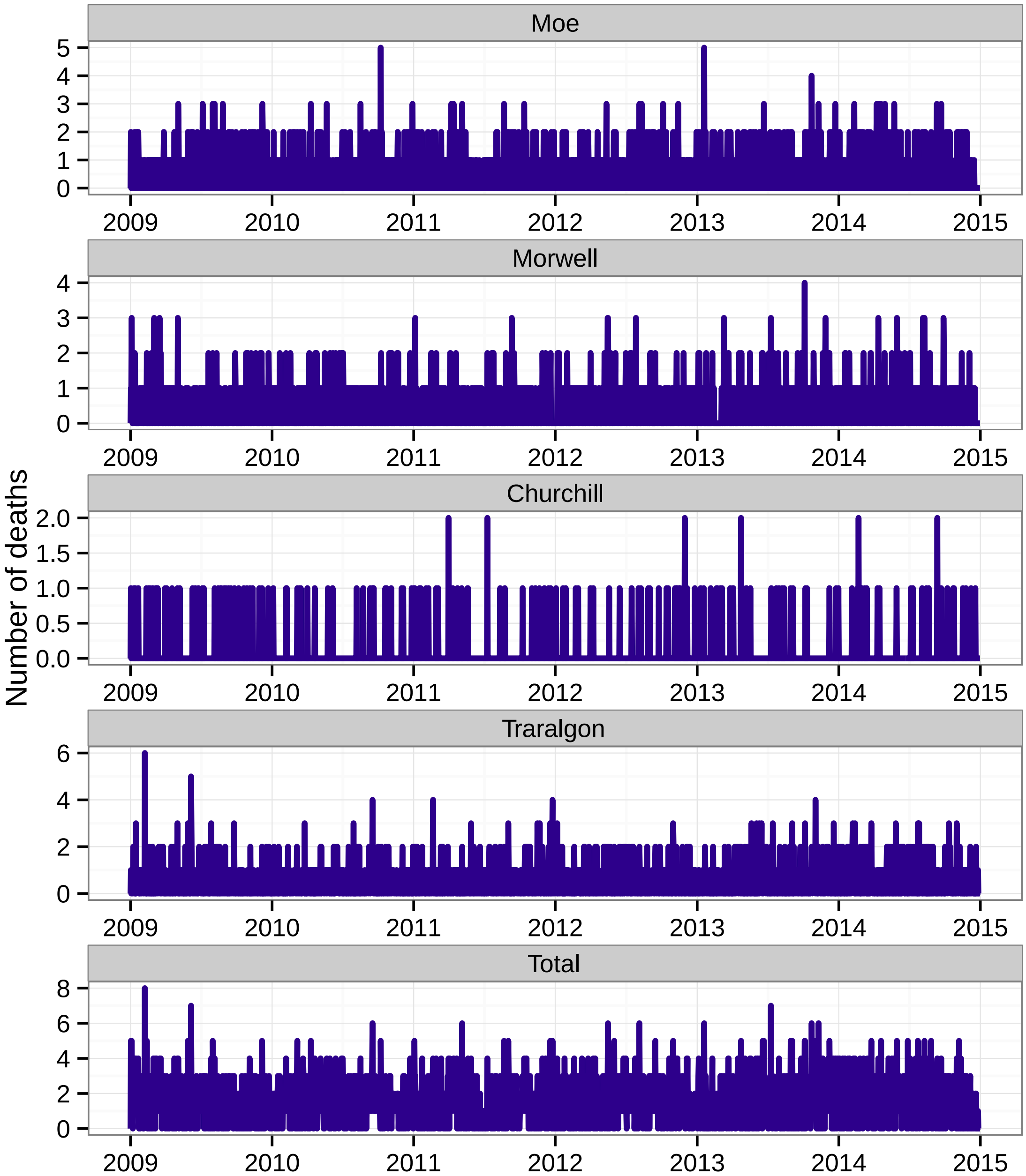

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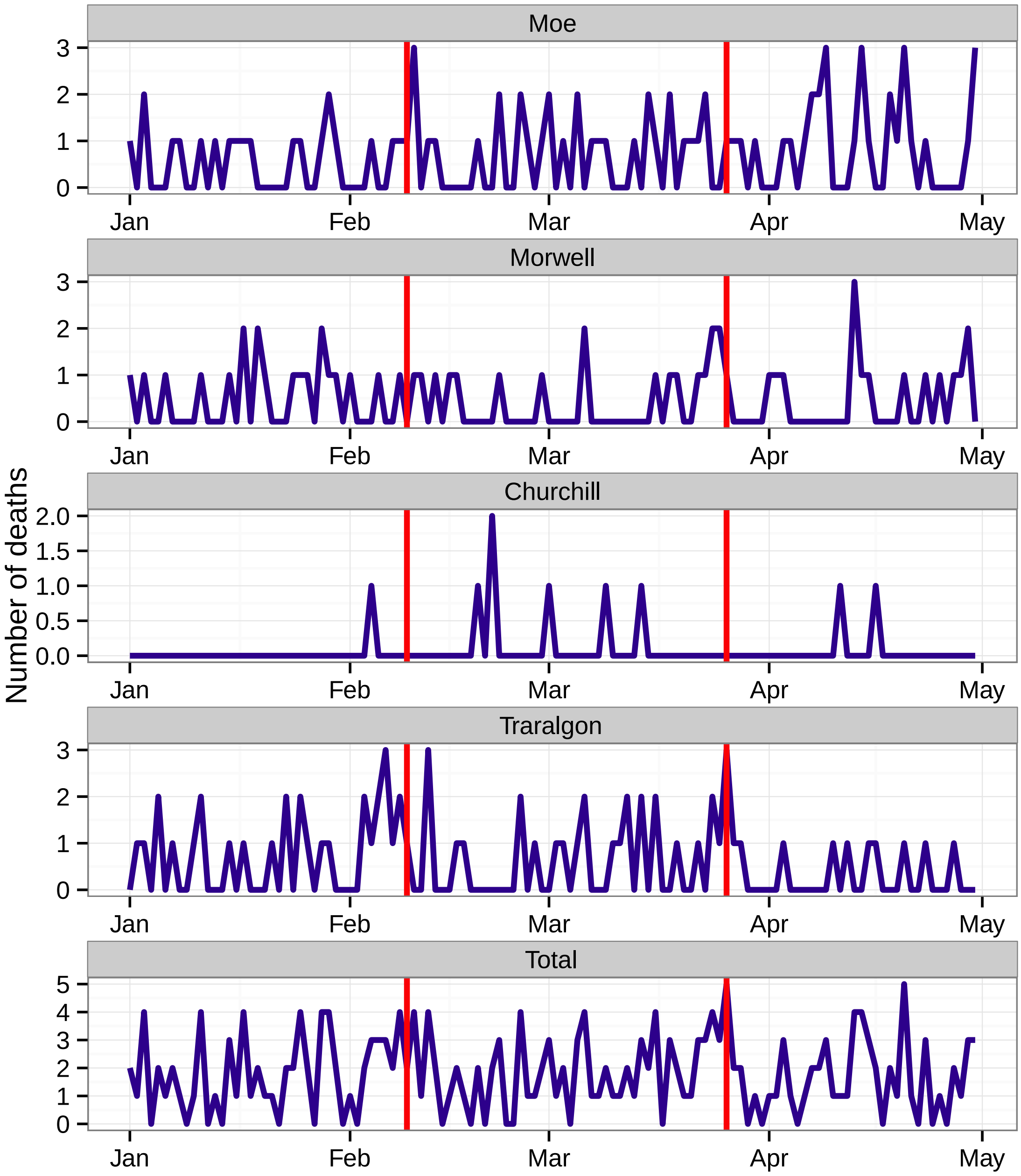

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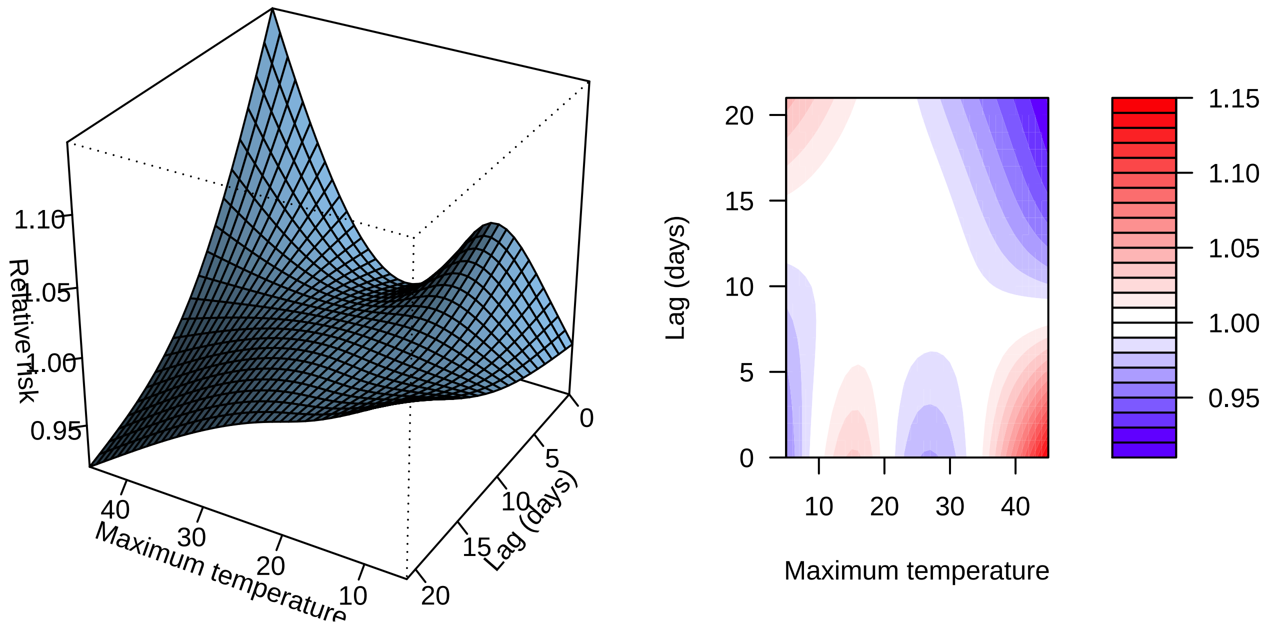

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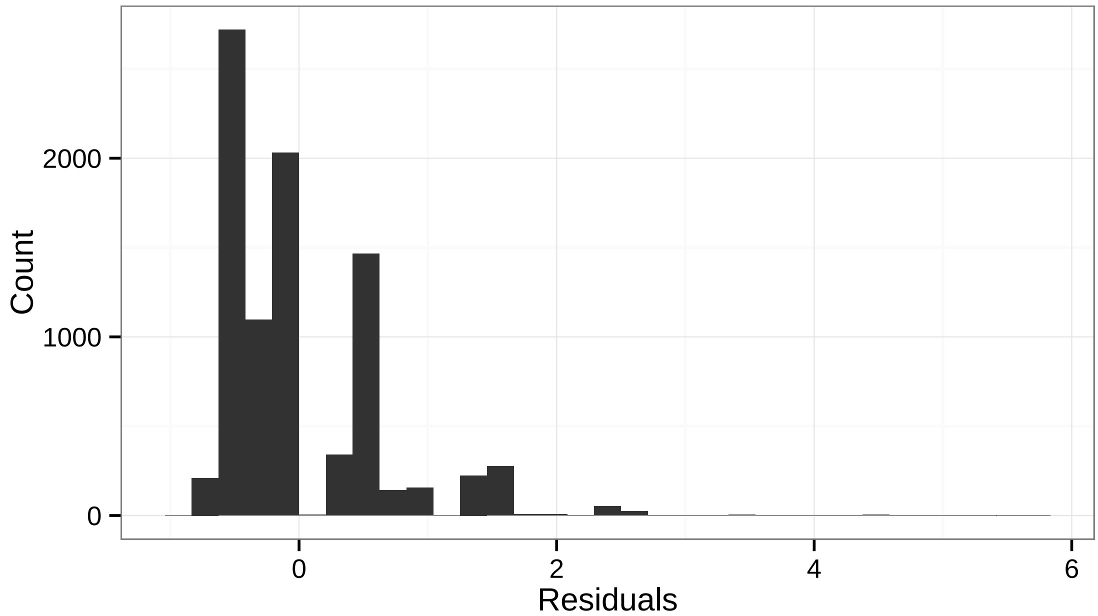

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The Pearson goodness of fit statistic is 8749 which is smaller than test limit of 8958, which is the 95th percentile of a chi-squared distribution [5]. This indicates that the model is an adequate fit to the data.

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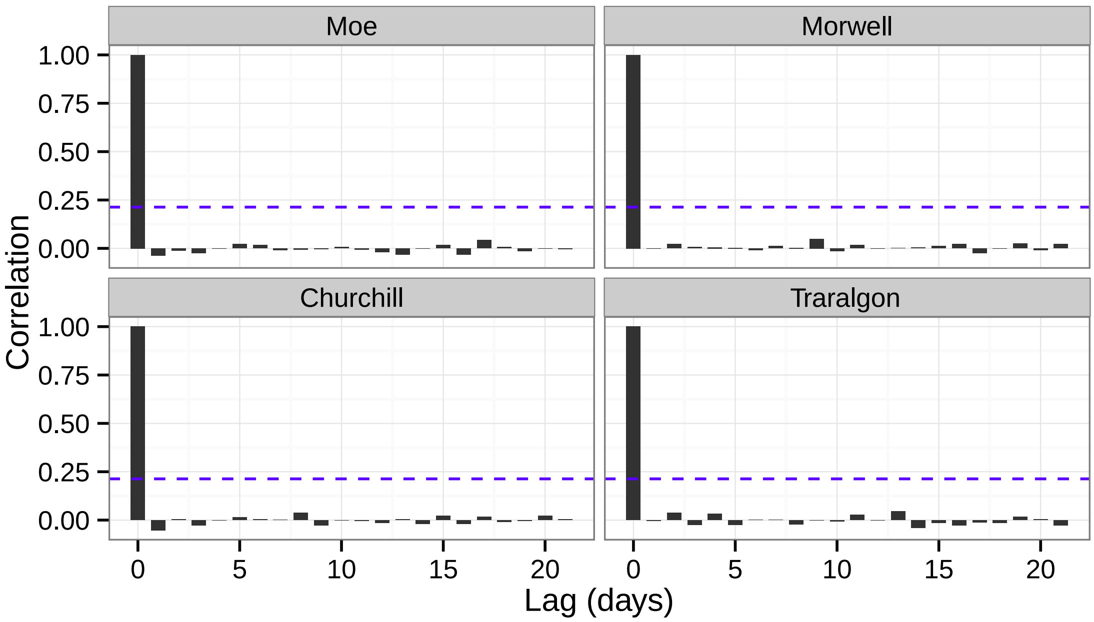

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[4] Antonio Gasparrini and et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet*, 386(9991):369–375, 2015.

[5] Annette J Dobson and A.G̃. Barnett. *An Introduction to Generalized Linear Models*. Texts in Statistical Science. Chapman & Hall/CRC, Boca Raton, FL, 3rd edition, 2008.

[6] Martyn Plummer. *rjags: Bayesian graphical models using MCMC*, 2013. R package version 3-11.

Appendix

JAGS Code

This is the code using the JAGS software that runs the Bayesian regression model of daily deaths [6].

```
model{
# likelihood
for (i in 1:N){
deaths[i] ~ dpois(mu[i]);
log(mu[i]) <- log.pop[i] + alpha + weekday[i] + trend[i] + gamma*fire[i]
+ delta.c[pcode[i]] + season[i] + temp[i];
weekday[i] <- inprod(dow[i,1:6], phi[1:6]);
trend[i] <- inprod(time[i,1:n.time], beta[1:n.time]);
season[i] <- theta[1]*cosw[i] + theta[2]*sinw[i];
temp[i] <- inprod(temperature[i,1:n.temp], zeta[1:n.temp]);
}
# priors
alpha ~ dnorm(0, 0.001) # intercept
for (k in 1:n.time){
beta[k] ~ dnorm(0, 0.001) # time trend
}
gamma ~ dnorm(0, 0.001) # fire
for (k in 1:6){
phi[k] ~ dnorm(0, 0.001) # week day
}
for (k in 1:n.temp){
zeta[k] ~ dnorm(0, 0.001) # temperature
}
for (k in 1:n.pcode){
delta[k] ~ dnorm(0, tau.delta); # random intercept for postcode
delta.c[k] <- delta[k] - mu.delta;
# absolute numbers
```

```
    absolute[k] <- mu.deaths[k]*(rr-1)
}
absolute[5] <- sum(absolute[1:4]) # total deaths
tau.delta ~ dgamma(1,1)
for (k in 1:2){
theta[k] ~ dnorm(0, 0.001); # season
}
## scalars
mu.delta <- mean(delta[1:n.pcode])
p.gamma <- step(gamma) # p-value for positive risk
rr <- exp(gamma) # relative risk
}
```

From: Bruce Armstrong
To: Justine Stansen
Subject: RE: Hazelwood Mine Fire Inquiry
Date: Thursday, 17 September 2015 2:44:06 PM
Attachments: image001.jpg

Thanks Justine. I will be happy to give the Board my opinion. You should have it by Monday.

Bruce

BRUCE ARMSTRONG
Emeritus Professor, School of Public Health
THE UNIVERSITY OF SYDNEY
Senior Adviser
THE SAX INSTITUTE
Chairman
BUREAU OF HEALTH INFORMATION

CONTACT INFORMATION
[redacted]

From: Justine Stansen [redacted]
Sent: Thursday, 17 September 2015 11:29 AM
To: Bruce Armstrong
Subject: Hazelwood Mine Fire Inquiry

Dear Bruce

I trust you are well. We have received some further analysis undertaken by Associate Professor Adrian Barnett since the Hazelwood Inquiry hearings held earlier this month which is based on daily death data rather than monthly data. I was wondering whether you could consider the **attached** analysis and contact me to discuss your thoughts about it. The Board would be grateful for your additional input in relation to this issue.

I look forward to hearing from you.

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry
[redacted]

From: Adrian Barnett
To: Justine Stansen
Cc: Monica Kelly
Subject: Re: Hazelwood Mine Fire Inquiry
Date: Thursday, 24 September 2015 5:56:32 PM
Attachments: image001.jpg

Dear Justine

Thanks. I'll look at this very soon. Regards,

Adrian

Sent from my iPhone

On 24 Sep 2015, at 15:55, "Justine Stansen" [redacted] wrote:

> Dear Adrian
>
> I **enclose** below an email from Bruce Armstrong in relation to your additional analysis based on the daily death data. The Board would be grateful if you could consider the comments by Bruce and let us know whether you can provide responses to the issues raised? The Board would be grateful to receive your feedback as soon as possible.
>
> Thank you in advance.
>
> Kind regards
>
> Justine Stansen
> **Principal Legal Advisor**
> **Hazelwood Mine Fire Inquiry**
> [redacted]
>
> <image001.jpg>
>
>
>
> ---
>
> **From:** Bruce Armstrong [redacted]
> **Sent:** Friday, 18 September 2015 10:18 PM
> **To:** Justine Stansen

Cc: Monica Kelly
Subject: RE: Hazelwood Mine Fire Inquiry

Justine

I have now read Adrian Barnett's Analysis of daily death data during the Morwell mine fire (version of September 2015).

His analysis of deaths is, from a technical point of view, an improvement on his previous analyses because it uses daily death data (referenced to the postcode of residence) and Australian Bureau of Statistics population data. It also restricts the analysis to the four postcode areas of greatest interest – Churchill, Moe, Morwell and Traralgon. From this analysis he reports a relative risk of death from the days of the fire (9th February 2015 to 26th March 2014) of 1.32 (95% credible interval of 1.03 to 1.66; p value 0.01). He also estimates the number of additional deaths in the four postcode areas from the period of the fire to be 23, 1 in Churchill, 8 in Moe, 6 in Morwell and 8 in Traralgon.

These estimates take account of the time trend in mortality in these four postcodes from 2009 to 2014, the underlying differences in mortality in the four postcodes, the seasonal variation in mortality, the weekly variation in mortality and the maximum daily temperature. Therefore, on the face of it, the observed relative increase in mortality risk during the period of the mine fire was independent of these other variables.

These results are reasonably coherent with, but suggest a greater increase in mortality in the period of the mine fire than, the other mortality analyses. For example, the table below compares Adrian Barnett's latest result with my result for the period February to March 2014 (Table 2 of my report) based on the Flander et al 2015 analysis.

Years	February-June			February-March			Notes
	Rate ratio	95% CI	p-value	Rate ratio	95% CI	p-value	
Deaths from all causes							
2014	1			1			
2009-2013[b]	0.90	0.80-1.00	0.04	0.83	0.68-1.02	0.08	As in Table 2 of my report
2009-2013				1.20	0.98-1.47	0.08	Inverted to be in the same form as Barnett's latest result
2009-2013				1.32	1.03-1.66	0.01	Barnett's latest result

The greater increase in mortality in the period of the mine fire could be due, perhaps, to the more precise definition of the period of the fire or to effects of one or more of the variables newly added to Barnett's statistical model for this analysis (time trend in mortality, weekly variation in mortality and maximum daily temperature). Whether it was any of the latter could be tested by removing each in turn from Barnett's statistical model and observing the change in the mine fire result consequent on the removal.

It is worth noting that Barnett's latest analysis shows an excess of deaths during the period of the mine fire in all four postcodes, Morwell included. In his second previous analysis there was an apparent deficit of deaths in Morwell (relative risk 0.8, 95% CI 0.55-1.28; Table 3 of the relevant report). Barnett does not describe how he arrived at the estimated number of extra deaths during the mine fire in the four postcodes.

Bruce

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THE UNIVERSITY OF SYDNEY
Senior Adviser
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Chairman
BUREAU OF HEALTH INFORMATION

CONTACT INFORMATION
[redacted]

From: Bruce Armstrong
Sent: Thursday, 17 September 2015 2:42 PM
To: 'Justine Stansen'
Subject: RE: Hazelwood Mine Fire Inquiry

Thanks Justine. I will be happy to give the Board my opinion. You should have it by Monday.

Bruce

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CONTACT INFORMATION
[redacted]

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To: Bruce Armstrong
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I look forward to hearing from you.

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry
[redacted]

<image001.jpg>

From: Adrian Barnett
To: Justine Stansen
Cc: Monica Kelly
Subject: RE: Hazelwood Mine Fire Inquiry
Date: Friday, 25 September 2015 7:42:46 PM
Attachments: image001.jpg
Death.Analysis.3.pdf

Dear Justine

Thank you for passing on Professor Armstrong's comments on my analysis. I have expanded my original analysis to answer his questions. I am happy to answer further questions from Prof Armstrong or The Board.

I would like to make this analysis public at some time, but am happy to wait to hear from you before doing that.

Regards,

Adrian

From: Justine Stansen [redacted]
Sent: Thursday, 24 September 2015 3:55 PM
To: Adrian Barnett
Cc: Monica Kelly
Subject: FW: Hazelwood Mine Fire Inquiry

Dear Adrian

I **enclose** below an email from Bruce Armstrong in relation to your additional analysis based on the daily death data. The Board would be grateful if you could consider the comments by Bruce and let us know whether you can provide responses to the issues raised? The Board would be grateful to receive your feedback as soon as possible.

Thank you in advance.

Kind regards

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry
[redacted]

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CONTACT INFORMATION
[redacted]

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To: 'Justine Stansen'
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Sent: Thursday, 17 September 2015 11:29 AM
To: Bruce Armstrong
Subject: Hazelwood Mine Fire Inquiry

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I look forward to hearing from you.

Justine Stansen
Principal Legal Advisor
Hazelwood Mine Fire Inquiry
[redacted]

Analysis of daily death data during the Hazelwood mine fire

Summary

This latest analyses gives a 99% probability of an increase in deaths during the 45 days of the fire, with an estimated 23 additional deaths. This is larger than the 79% to 89% probability and 10 to 14 additional deaths from my two previous analysis. This increase in probability and deaths occurred because this analysis used daily data whereas the previous analyses used monthly data. Using days instead of months reduces the measurement error between exposure and death, and an increased statistical significance and risk is entirely expected based on the theory of measurement error [1]. This analysis also had a better control for the potential confounder of temperature, as temperature was also modelled on a daily time scale. Model checks show that there is unlikely to be any confounding with time and that there are no important influential observations. Overall the model is an adequate fit to the data.

Introduction

This document contains my third analysis of the Hazelwood mine fire data. This is an updated analysis using daily death data for four postcodes for the years 2009 to 2014.

Methods

Data

The death data were daily numbers from 1 January 2009 to 31 December 2014, which is 2191 days. The deaths were split by four postcodes (3840-Morwell, 3842-Churchill, 3825-Moe, 3844-Traralgon) according to usual place of residence. There were 3,414 deaths in total.

I used population data from the Australian Bureau of Statistics for each postcode over time. This is a further improvement on my previous analyses which used overall population data for the Latrobe Valley.

The temperature data came from the Bureau of Meteorology weather station at Morwell (station number 85280), which provided daily maximum temperature. Two days were missing and I imputed the missing temperature using the mean temperature for the days either side of the missing day. I used maximum temperature rather than mean or minimum temperature because previous research found that most common temperature measures are highly correlated and perform equally well when predicting daily death rates [2].

Statistical methods

I used a regression model to examine the key hypothesis of whether deaths rates were higher during the 45 days of the fire.

I give the model as an equation below and then explain each line of the equation.

$$\begin{aligned}
d_{i,t} &\sim \text{Poisson}(\mu_{i,t}), \qquad i = 1, \dots, 4,\ t = 1, \dots, 2191, \\
\log(\mu_{i,t}) &= \log(\text{pop}_{i,t}/10000) + \alpha_0 + \text{postcode}_i + \text{trend}_t + \text{season}_t + \text{weekday}_t \\
&+ \text{temperature}_t + \text{fire}_t, \\
\text{postcode}_i &\sim N(0, \sigma^2) \\
\text{trend}_t &= \text{ns}(\alpha_{1:2}, t, 2), \\
\text{season}_t &= \alpha_3 \cos\left[2\pi f(t)\right] + \alpha_4 \sin\left[2\pi f(t)\right], \\
\text{weekday}_t &= \alpha_{5:10}\mathbf{D}_t, \\
\text{temperature}_t &= \text{ns}(\alpha_{11:19}, \text{maximum temperature}_t, 3 \times 3), \\
\text{fire}_t &= \begin{cases} \alpha_{20}, & \text{if date}_t \in \{\text{9-Feb-2014}, \text{10-Feb-2014}, \dots, \text{26-Mar-2014}\}, \\ 0, & \text{otherwise.} \end{cases}
\end{aligned}$$

The index i is for postcode and the index t is for time. I used a Poisson model as the dependent variable is daily counts of deaths. The trend was fitted as a natural spline (ns) with two degrees of freedom which allowed the underlying death rate to change slowly during 2009 to 2014 due to factors such as an ageing population. Season was fitted as an annual sinusoid and $f(t)$ is the fraction of the year from 0 (1 January) to 1 (31 December) [3]. I modelled the expected small difference in death rates by day of the week using an independent effect on each day with Sunday as a the reference day.

Temperature was modelled as a non-linear variable to allow for increased risks in low and high temperatures [4]. To allow for the known delay between exposure to temperature and death I also included a lag with a delay up to 21 days. Both temperature and lag were fitted using a natural spline with three degrees of freedom which is large enough to model a non-linear association.

To check the adequacy of the model I examined the residuals (difference between observed and predicted) using a histogram and autocorrelation plot. To check for influential observations I used Cook's distance [5].

The estimated additional number of deaths due to the fire in each postcode were calculated using:

$$45 \times \overline{d}_i \times [\exp(\alpha_{20}) - 1],$$

where $\overline{d}_i$ is the mean number of daily deaths in postcode i and $\exp(\alpha_{20})$ is the relative risk of death during the fire. The daily estimate is multiplied by 45 to give an estimate for the period of the fire.

Results

Simple table

Table 1: Summary statistics on daily deaths by postcode and the time of the fire using data for 1 January 2009 to 31 December 2014

			Deaths			
Postcode	Fire	N	Mean	SD	Min	Max
Churchill	No	2145	0.075	0.27	0	2
	Yes	46	0.130	0.40	0	2
Moe	No	2145	0.558	0.74	0	5
	Yes	46	0.717	0.81	0	3
Morwell	No	2145	0.396	0.63	0	4
	Yes	46	0.413	0.62	0	2
Traralgon	No	2145	0.522	0.73	0	6
	Yes	46	0.652	0.87	0	3
All	No	8580	0.388	0.65	0	6
	Yes	184	0.478	0.73	0	3

Table 1 shows a higher mean number of daily deaths in all four postcodes during the period of the fire compared with all other times. These crude figures do not adjust for the seasonal pattern in deaths or changes over time in population size, and the regression model below should give a truer picture of any increase in death rates.

Plots of daily deaths over time

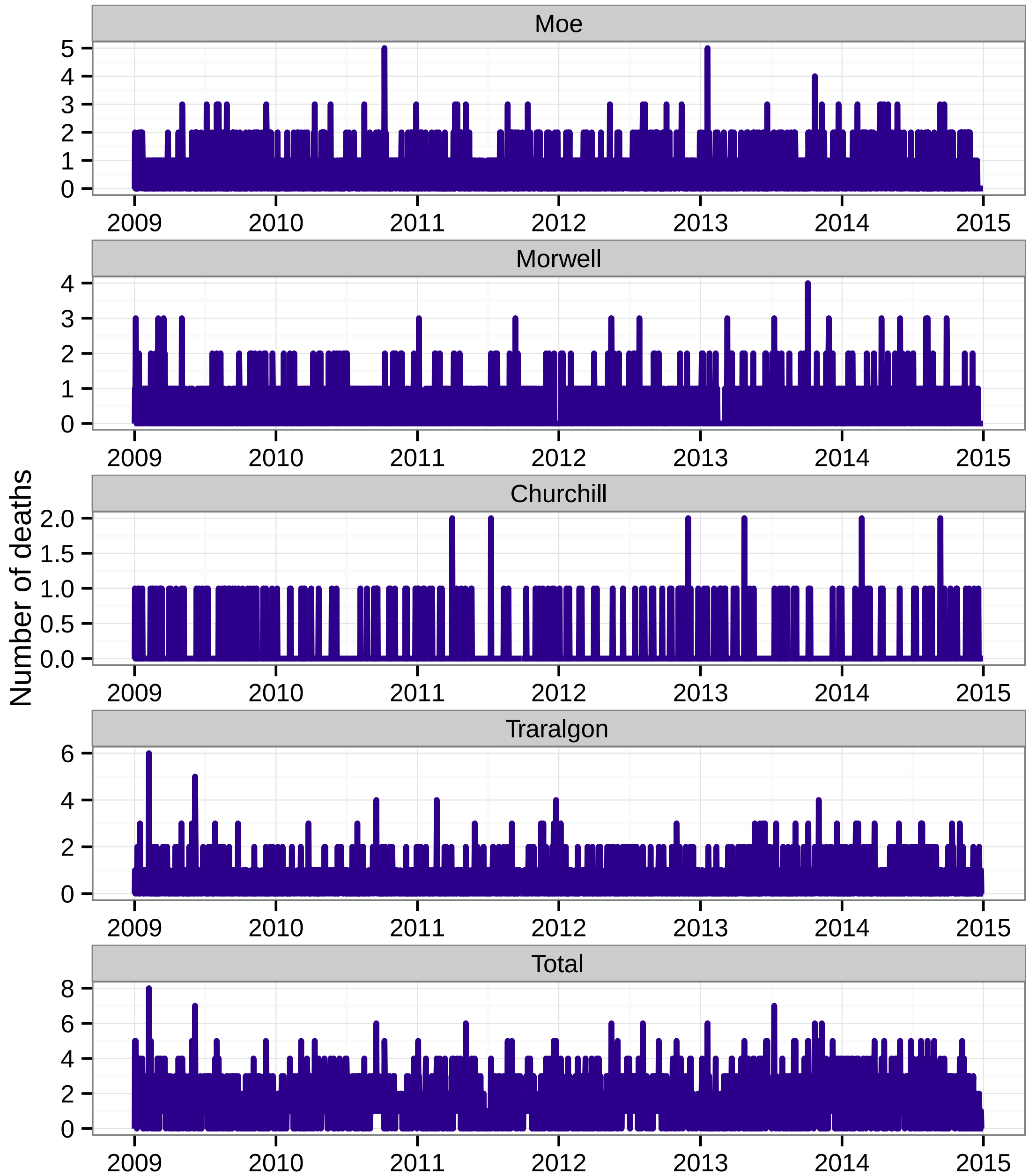

Figure 1: Daily death numbers in each postcode and the total number of deaths across the four postcodes for 1 January 2009 to 31 December 2014.

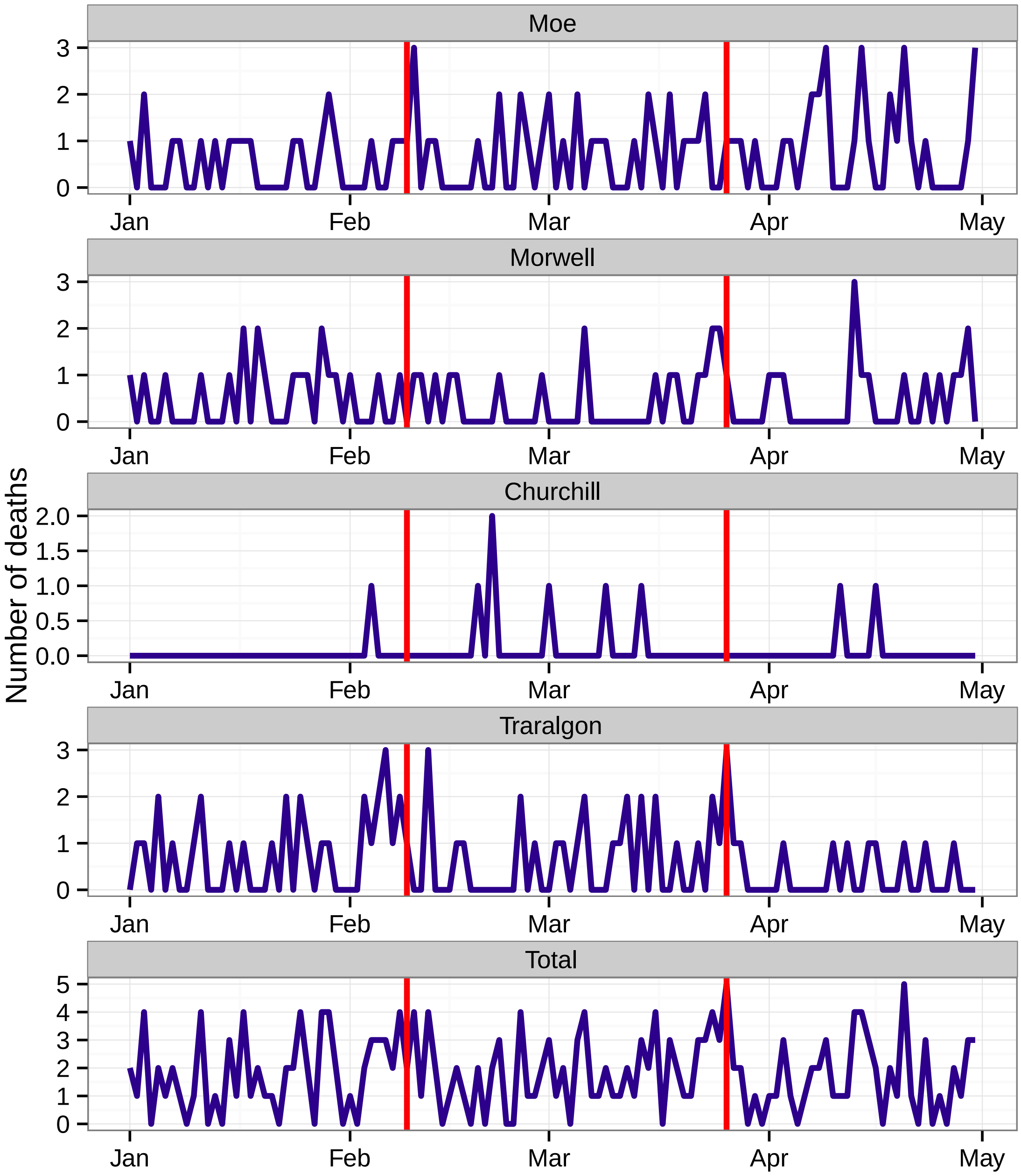

Figure 2: Daily death numbers in each postcode and the total number of deaths across the four postcodes for 1 January 2014 to 30 April 2014. The start and end of the fire are shown by vertical red lines.

Statistical model results

Table 2: Model of daily deaths. Statistics are the mean and lower and upper 95% credible interval. Estimates are on a log scale except for the relative risk and absolute number of deaths.

	Mean	Lower	Upper
Intercept	−1.601	−1.732	−1.475
Trend, 1	−0.125	−0.346	0.096
Trend, 2	0.137	0.016	0.258
Postcode, 3825	0.285	0.225	0.346
Postcode, 3840	0.129	0.062	0.194
Postcode, 3842	−0.310	−0.426	−0.196
Postcode, 3844	−0.104	−0.165	−0.042
Season, cos	0.105	−0.057	0.269
Season, sin	0.059	−0.033	0.153
Monday	−0.069	−0.196	0.056
Tuesday	−0.096	−0.223	0.031
Wednesday	−0.042	−0.165	0.083
Thursday	−0.060	−0.186	0.064
Friday	0.049	−0.074	0.172
Saturday	0.008	−0.114	0.131
Fire, relative risk	1.324	1.034	1.656
Additional deaths during fire, 3825	8.271	0.860	16.731
Additional deaths during fire, 3840	5.848	0.608	11.830
Additional deaths during fire, 3842	1.124	0.117	2.273
Additional deaths during fire, 3844	7.733	0.804	15.642
Additional deaths, all postcodes	22.976	2.388	46.476

The probability that the death rate was higher than the average during the fire is 0.99. This means that the probability that the death rate was not higher than the average during the fire is 0.01. The mean increase in deaths is 1.32 as a relative risk, or 32 as a percentage. The 95% credible interval for the relative risk does not include 1, indicating that the risk was higher than average during the fire. The mean estimated number of extra deaths during the fire over the four postcodes is 23 (95% credible interval: 2 to 46).

Effect of temperature

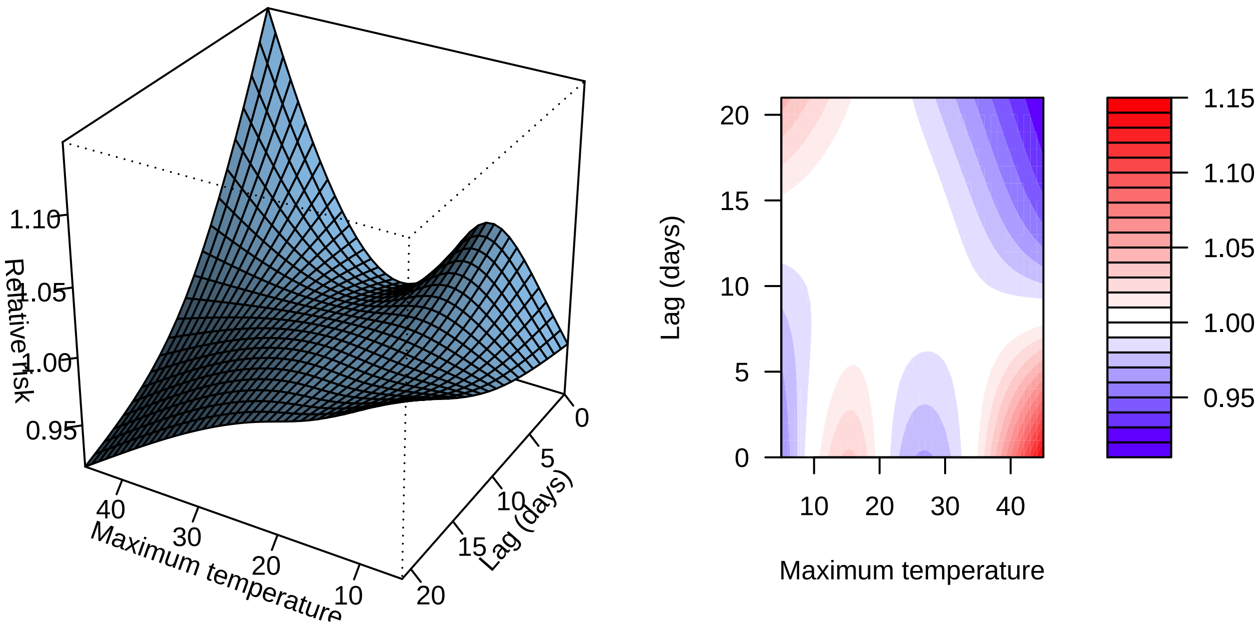

Figure 3: Estimated relative risk of maximum temperature (°C) by temperature and lag using a surface plot (left) and contour plot (right).

The effect of temperature in Figure 3 is exactly as expected. It shows a steep rise in risk for high temperatures on the day of exposure, and smaller but longer lasting risk for low temperatures [4].

Residual plots and model checking

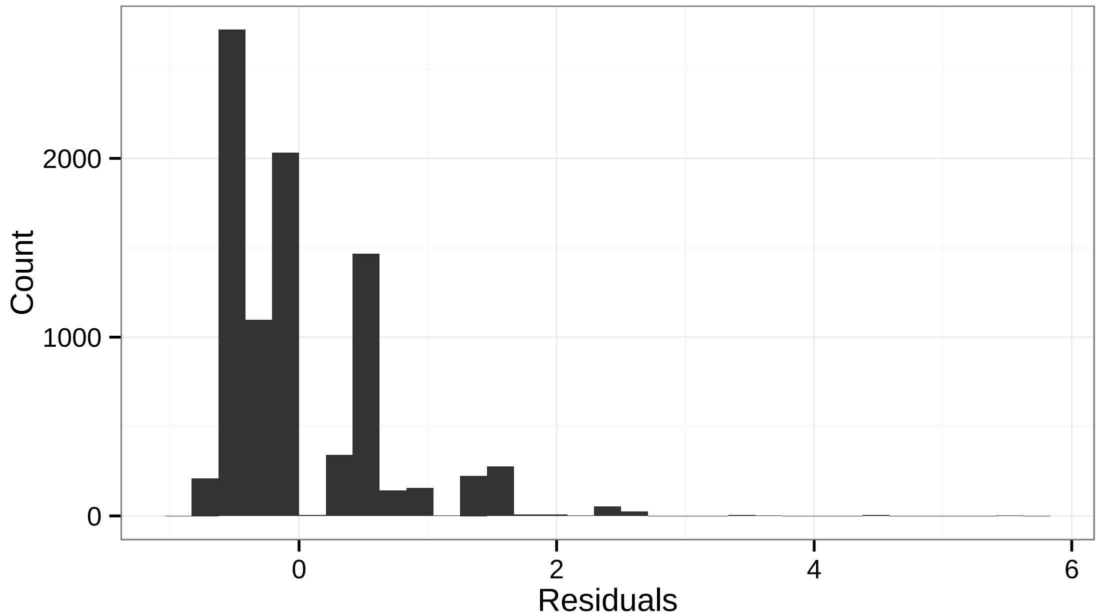

Figure 4: Residual histogram from the model of daily deaths.

The histogram of residuals are centred on zero but with a positive skew which is as expected when modelling small counts (Figure 4). There were four relatively large residuals over 4 as shown in Table 3. The large residual in Traralgon on 7th February 2009 may be the Black Saturday bushfires.

Table 3: Four large residuals where the model greatly under-predicted the number of deaths.

Date	Postcode	Deaths	Predicted	Residual	Pearson residual
08/Oct/2010	Moe	5	0.60	4.40	5.66
19/Jan/2013	Moe	5	0.51	4.49	6.27
07/Feb/2009	Traralgon	6	0.57	5.43	7.22
06/Jun/2009	Traralgon	5	0.58	4.42	5.78

The Pearson goodness of fit statistic is 8749 which is smaller than test limit of 8958, which is the 95th percentile of a chi-squared distribution [5]. This indicates that the model is an adequate fit to the data.

The autocorrelation plots of the residuals show no residual autocorrelation in any postcode as the correlations are small and close to zero (Figure 5). This means there is unlikely to be any residual confounding by other short-term environmental factors (e.g., humidity).

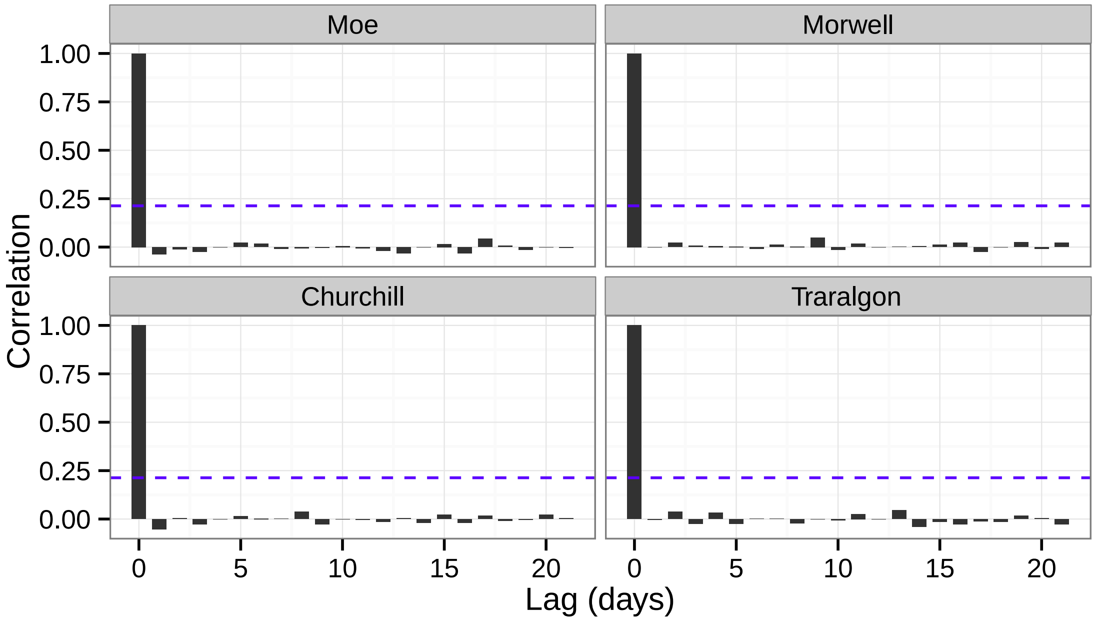

Figure 5: Autocorrelation of residuals from the model of daily deaths by postcode. The dotted horizontal blue line is the limit for assessing significant autocorrelation.

Cook's distance

There is one relatively large influential value in Figure 6, which was the six deaths in Traralgon on the 7th February 2009 possibly due to the Black Saturday bushfires. To check if this impacts on the results I removed this day and re-ran the model.

Table 4: Mean relative risk and 95% credible interval with and without influential day.

model	mean	lower	upper	p.value
Complete data	1.324	1.036	1.655	0.988
Influential observation excluded	1.344	1.048	1.681	0.990

The results in Table 4 show that excluding the influential day from Traralgon had little impact on the mean relative risk or probability that deaths increased during the period of the fire.

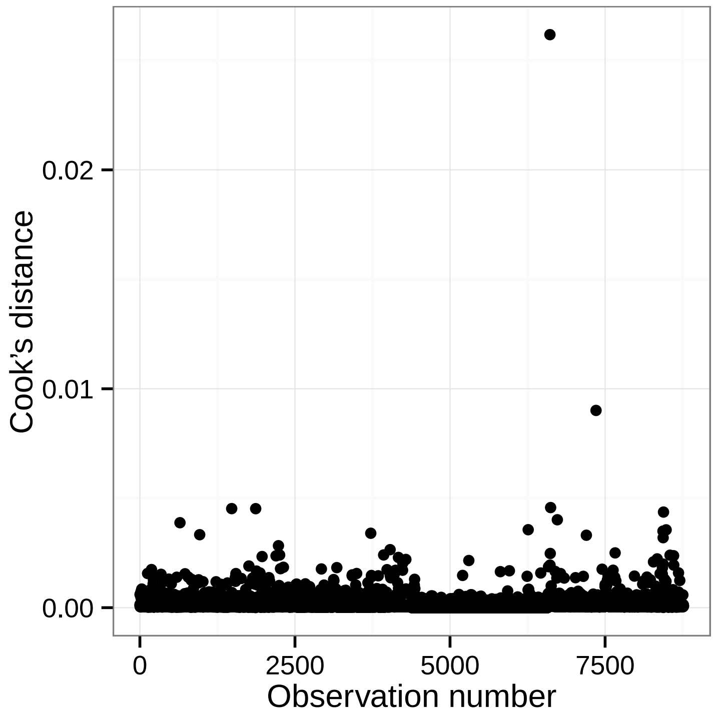

Figure 6: Cook's distance to identify influential observations.

Alternative models

In this section I examine the effect of three new variables from the previous monthly analysis: day of the week, daily temperature and daily trend. The models were as before except without each variable. I compared the relative risk of death, the probability that deaths were increased during the fire, and the model fit using the Pearson goodness of fit statistic. Smaller values for the Pearson goodness of fit statistic indicate a better fit of the model's predictions to the observed data.

Table 5: Estimates of the relative risk of death during the mine fire for alternative models without individual variables. Also shown are the 95% credible intervals and the probability that deaths were higher during the fire. The model fit column is the Pearson goodness of fit statistic.

model	mean	lower	upper	p.value	model.fit
Full model	1.324	1.036	1.655	0.988	8749.1
Without temperature	1.210	0.958	1.496	0.943	8749.7
Without time trend	1.385	1.091	1.719	0.996	8744.5
Without day of the week	1.322	1.033	1.653	0.987	8775.7

The results for the 'Full model' in Table 5 are the same as in Table 2 and are repeated here for ease of comparison.

Not adjusting for daily temperature has a relatively large effect on the mean relative risk as it decreases to 1.21. Temperature is a known confounder of air pollution [6] and has causal biological pathways linked to death that are independent of air pollution (e.g., heat exhaustion). The difference in model fit between a model with and without temperature is small. I prefer to adjust for temperature as this should give a better estimate of the number of deaths independently due to air pollution.

Removing the trend and day of the week had little impact on the relative risk estimates. Removing day of the week had a relatively large detrimental effect on model fit.

References

[1] Jennifer A Hutcheon, Arnaud Chiolero, and James A Hanley. Random measurement error and regression dilution bias. *BMJ*, 340, 2010.

[2] Adrian Barnett, Shilu Tong, and Archie CA Clements. What measure of temperature is the best predictor of mortality? *Environmental Research*, 110(6):604–611, 2010.

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[5] Annette J Dobson and Adrian G Barnett. *An Introduction to Generalized Linear Models*. Texts in Statistical Science. Chapman & Hall/CRC, Boca Raton, FL, 3rd edition, 2008.

[6] Jessie P Buckley, Jonathan M Samet, and David B Richardson. Commentary: Does air pollution confound studies of temperature? *Epidemiology*, 25(2):242–245, 2014.

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Appendix

JAGS Code

This is the code using the JAGS software that runs the Bayesian regression model of daily deaths [7].

```
model{
# likelihood
for (i in 1:N){
deaths[i] ~ dpois(mu[i]);
log(mu[i]) <- log.pop[i] + alpha + weekday[i] + trend[i] + gamma*fire[i]
+ delta.c[pcode[i]] + season[i] + temp[i];
weekday[i] <- inprod(dow[i,1:6], phi[1:6]);
trend[i] <- inprod(time[i,1:n.time], beta[1:n.time]);
season[i] <- theta[1]*cosw[i] + theta[2]*sinw[i];
temp[i] <- inprod(temperature[i,1:n.temp], zeta[1:n.temp]);
}
# priors
alpha ~ dnorm(0, 0.001) # intercept
for (k in 1:n.time){
beta[k] ~ dnorm(0, 0.001) # time trend
}
gamma ~ dnorm(0, 0.001) # fire
for (k in 1:6){
phi[k] ~ dnorm(0, 0.001) # week day
}
for (k in 1:n.temp){
zeta[k] ~ dnorm(0, 0.001) # temperature
}
```

```
for (k in 1:n.pcode){
delta[k] ~ dnorm(0, tau.delta); # random intercept for postcode
delta.c[k] <- delta[k] - mu.delta;
# absolute numbers
    absolute[k] <- mu.deaths[k]*(rr-1)
}
absolute[5] <- sum(absolute[1:4]) # total deaths
tau.delta ~ dgamma(1,1)
for (k in 1:2){
theta[k] ~ dnorm(0, 0.001); # season
}
## scalars
mu.delta <- mean(delta[1:n.pcode])
p.gamma <- step(gamma) # p-value for positive risk
rr <- exp(gamma) # relative risk
}
```