The spatio-temporal response of summertime tropospheric ozone to changes in precursor emissions in the Lower Fraser Valley, British Columbia

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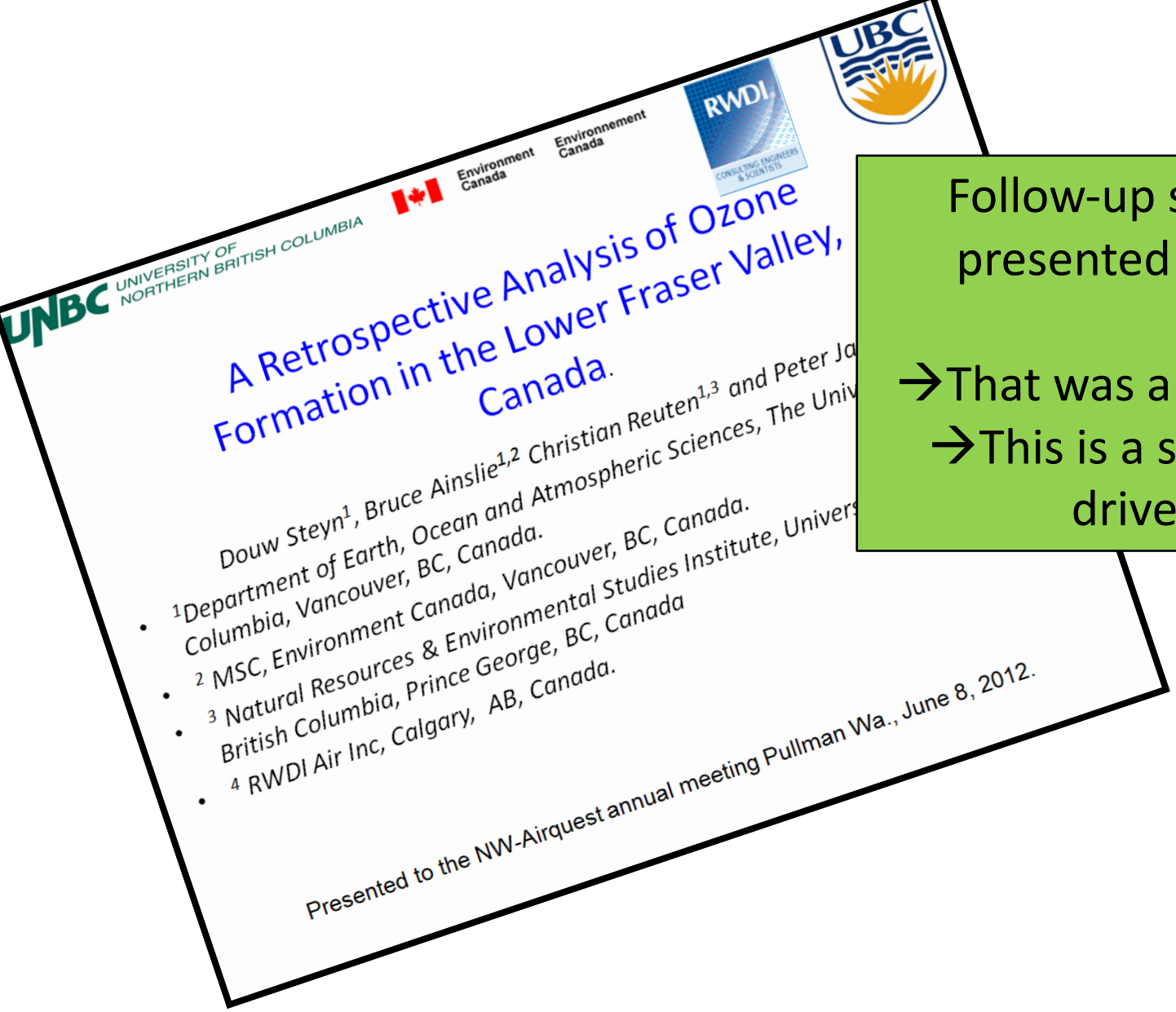
[3]Metro Vancouver

NW-AirQuest Annual Meeting
June 14-16, 2017
Richland WA


UNBC UNIVERSITY OF NORTHERN BRITISH COLUMBIA

Environment Canada Environnement Canada

RWDI CONSULTING ENGINEERS & SCIENTISTS

UBC

A Retrospective Analysis of Ozone Formation in the Lower Fraser Valley, Canada.

Douw Steyn[1], Bruce Ainslie[1,2] Christian Reuten[1,3] and Peter Ja

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- [3] Natural Resources & Environmental Studies Institute, Univers British Columbia, Prince George, BC, Canada
- [4] RWDI Air Inc, Calgary, AB, Canada.

Presented to the NW-Airquest annual meeting Pullman Wa., June 8, 2012.

Follow-up study to work presented here in 2012

→That was a modeling study

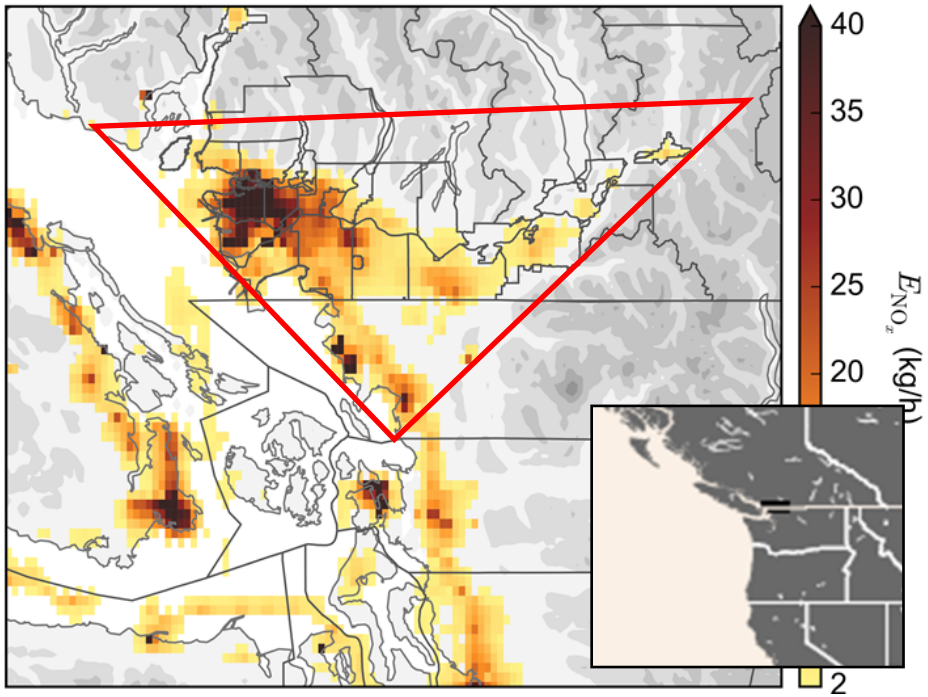
→This is a statistical data-driven study

Then, as now, the research question is:

How have summertime O_3 concentrations changed in the LFV over the last 26 years, given large scale changes in local emissions?

Explored through an examination of:

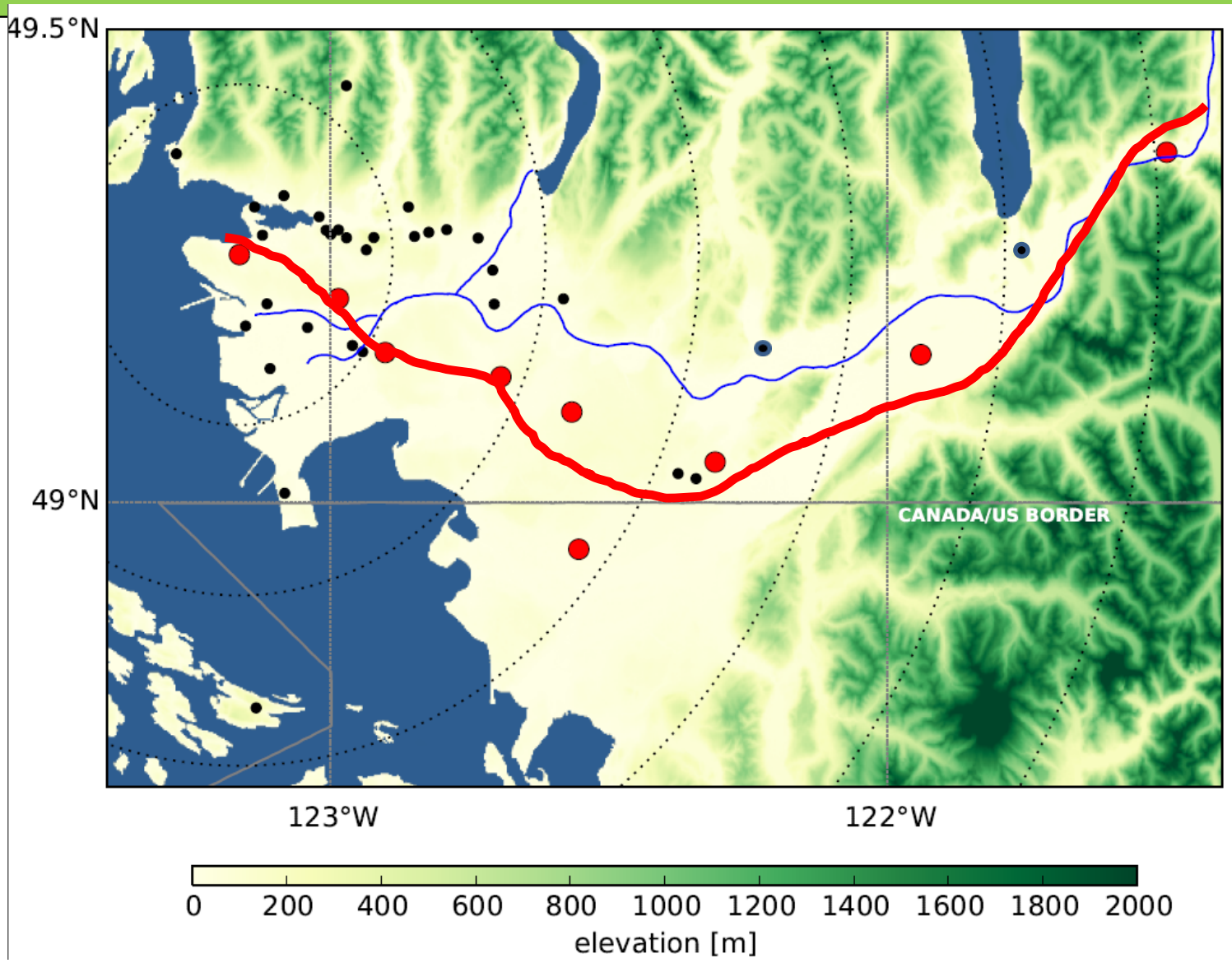
1. Trends in emissions
2. Trends in summer [NOx], [VOC] at key stations
3. Trends in summer [O3] at different levels at key stations



LFV

- Triangular coastal valley
- ~2 million people
- Straddles US-Canada border

Spatio-temporal analysis using monitoring data along an east-west transect of stations



Statistical Models:

Daily summertime (JJA) data from 9 monitors across 26 years (1990-2015) [Potentially 92x26x9 = 21528 data points]

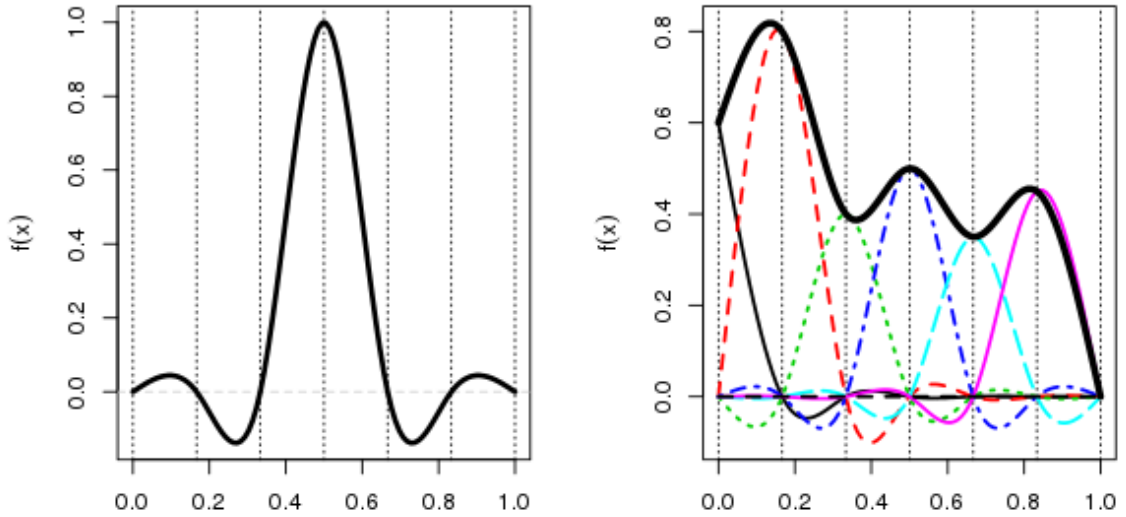
Pollutant	Description
NOx	Daytime (0600-1800) average
VOC	24-hour average
Ozone - **Background**	10^{th} percentile and below of lowest variance MD8A
Ozone – **Fair weather**	Sunny fair weather (roughly 50-96^{th} percentile) MD8A
Ozone – **CAAQS**	Summer time four highest MD8A
Others	fraction of OH reacting with NO_2

General Additive Models (GAM):
response of variable to predictor is not always linear

Fit Y using some unknown but potentially non-linear function of X

$$y_i = f(x_i) + \epsilon_i,$$

How to choose f? – Use basis of spline curves

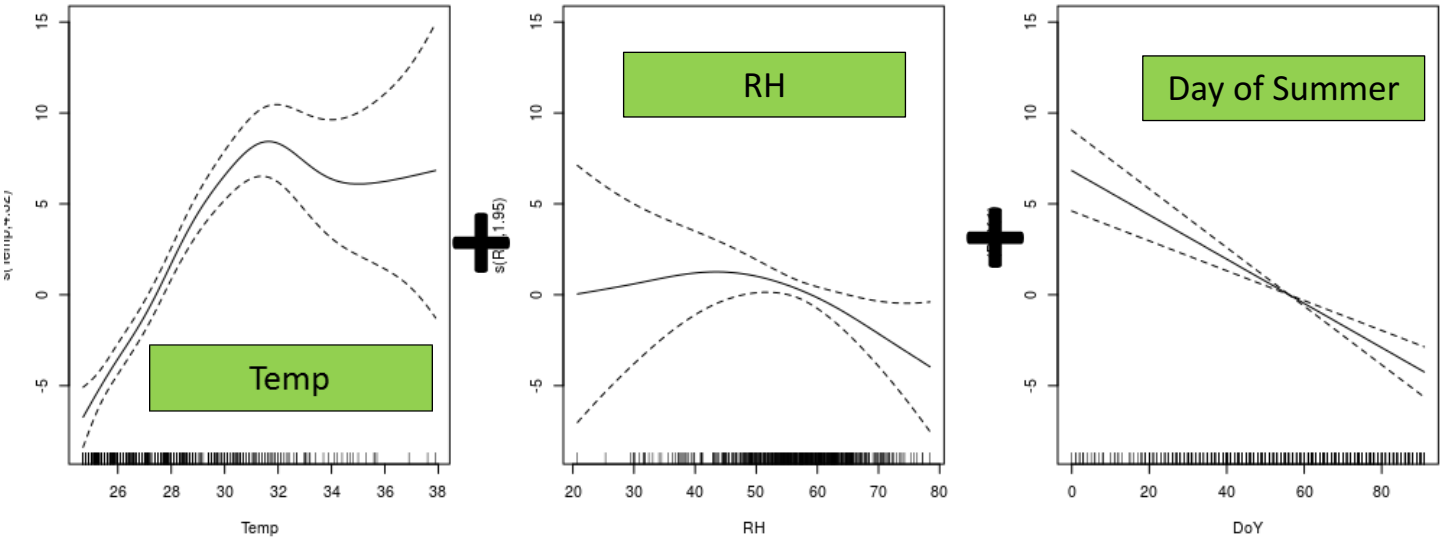


http://www.fromthebottomoftheheap.net/2014/05/09/modelling-seasonal-data-with-gam/

$$f(x) = \sum_{i=1}^{q} b_i(x)\beta_i,$$

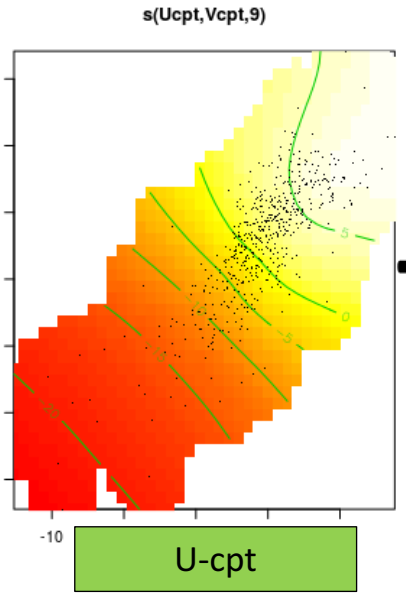
$$[O_3] \sim s(Temp) + s(RH) + s(DoY) + s(Ucpt, Vcpt) + s(Year) + \epsilon$$

$[O_3]$ = Const +

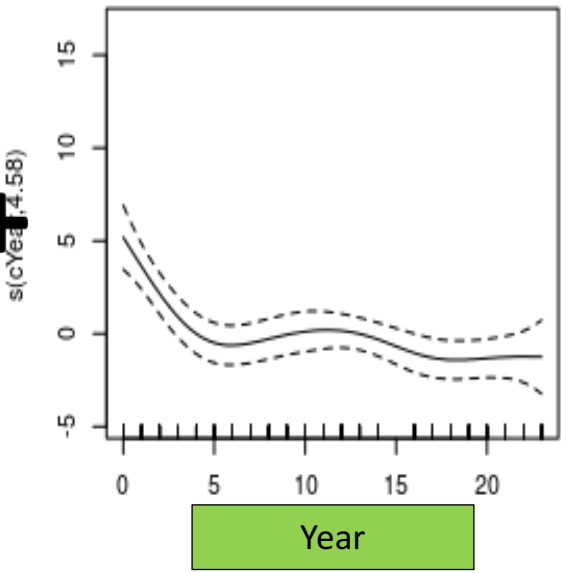


+

V-cpt



+



+ ε

Typical Model formulation

Long term network response

Cultural effects (e.g. weekend/weekday effect)

Pollutant

$$[O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) \times ti(Dist, Year) + \epsilon$$

Meteorological effects

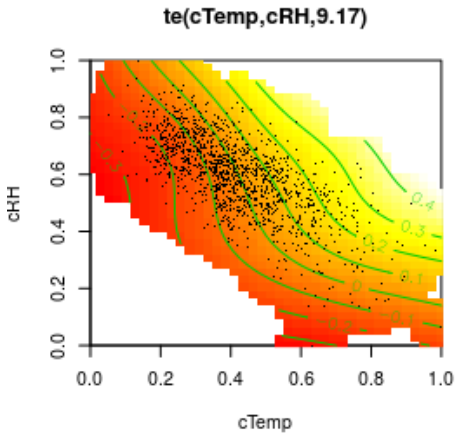
Local station temporal response

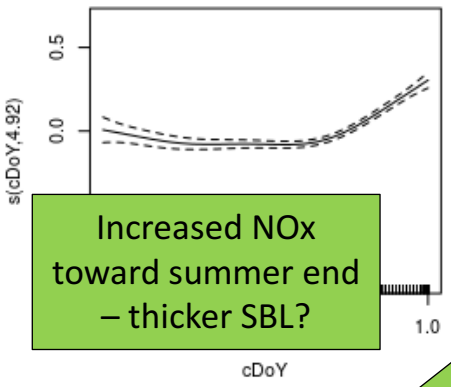
Canonical Footprint

Variable	Description
Temp	Daily maximum temperature
RH	Daytime average RH
ETot	Daytime total incoming SW radiation from T09
DoY	JJA day number (1-92)
Ucpt, Vcpt	Average daytime wind cpts from YVR or YXX
Weekday	Day of week
Dist	Distance from T02
Year	1990 to 2015

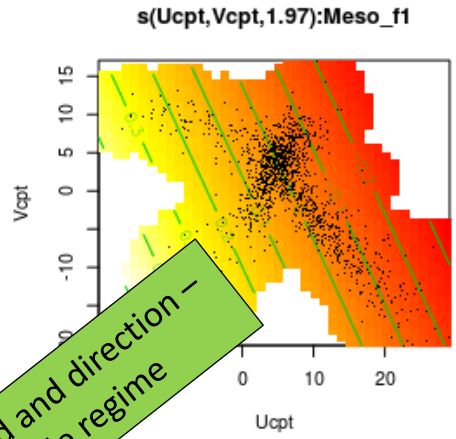
We are after the yellow boxes - the other factors used to isolate the trend

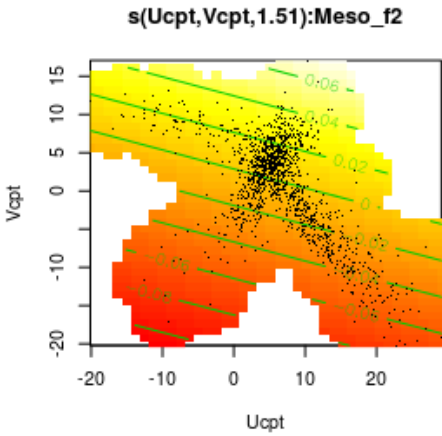
NOx Results



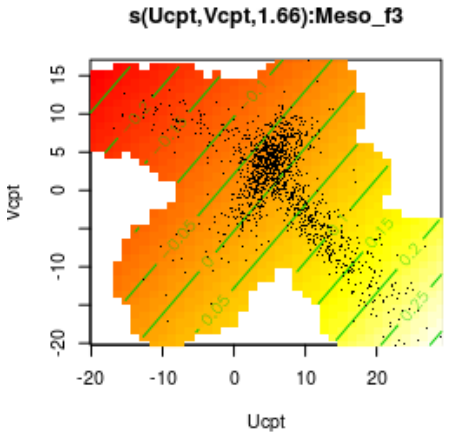


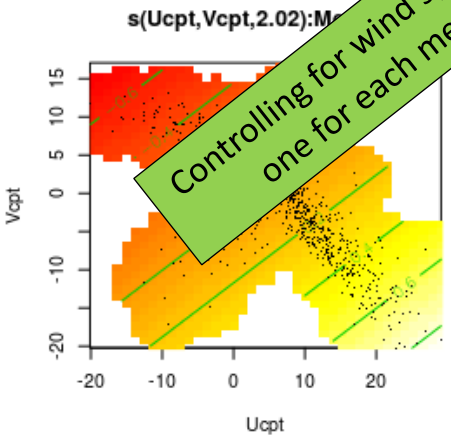
Increased NOx toward summer end – thicker SBL?



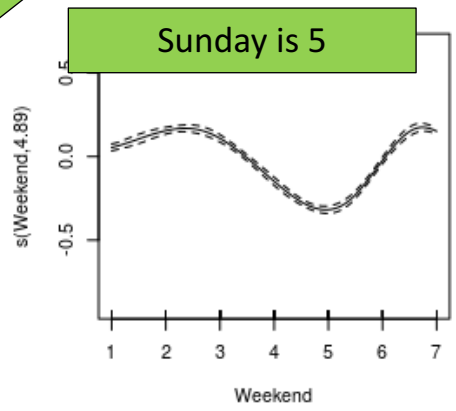


Controlling for wind speed and direction – one for each meso-scale regime

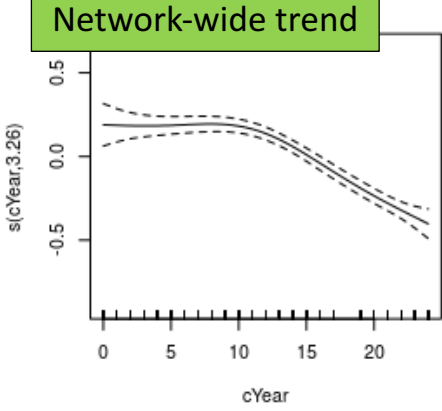




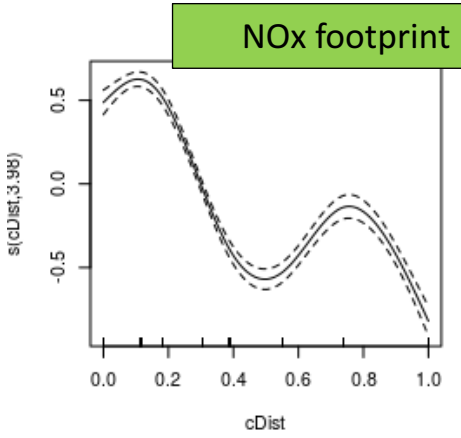
Sunday is 5

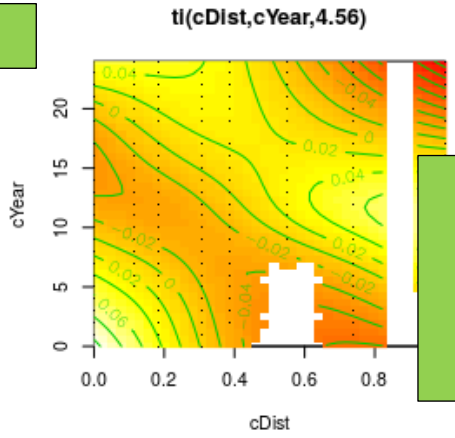


Network-wide trend



NOx footprint

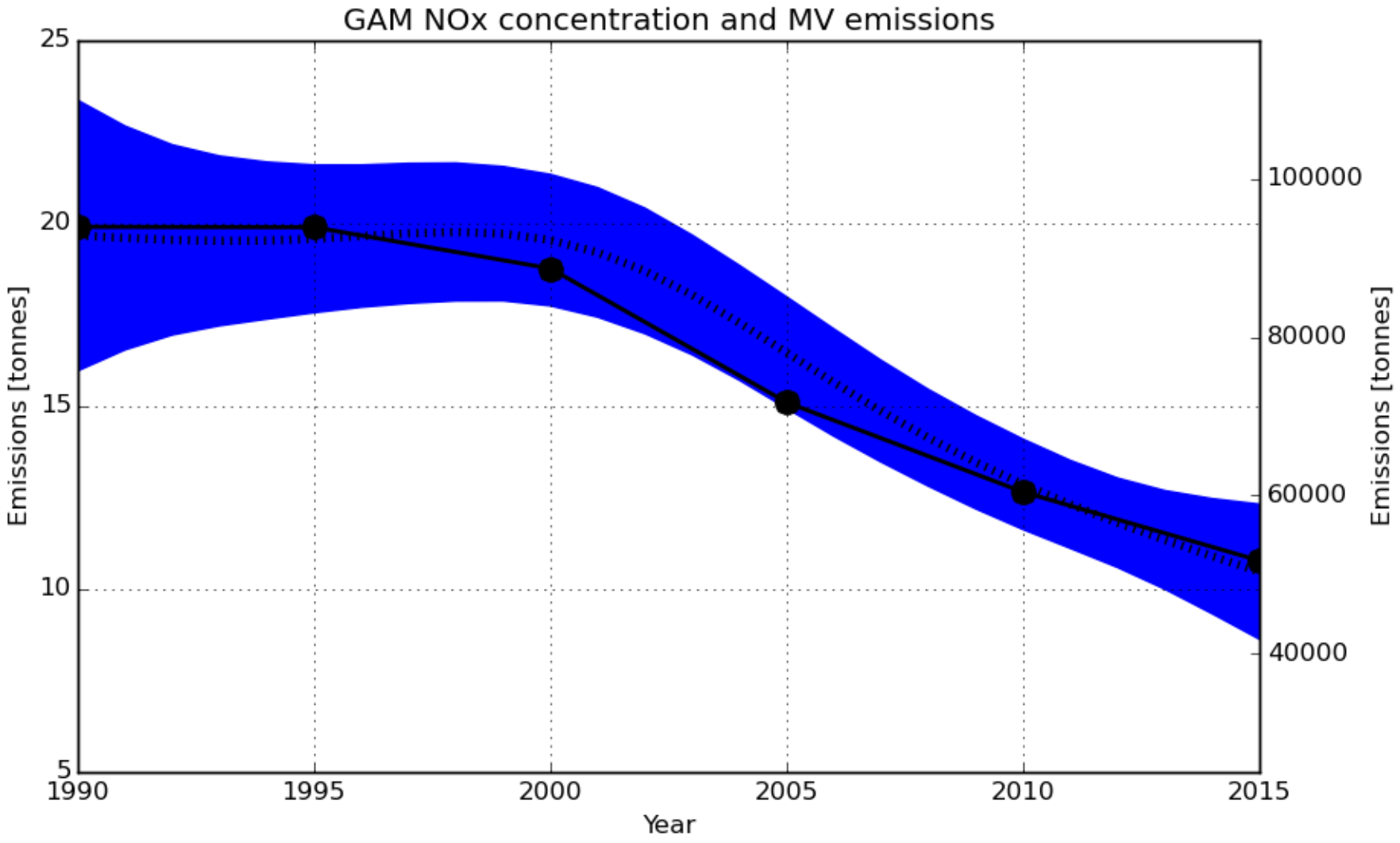




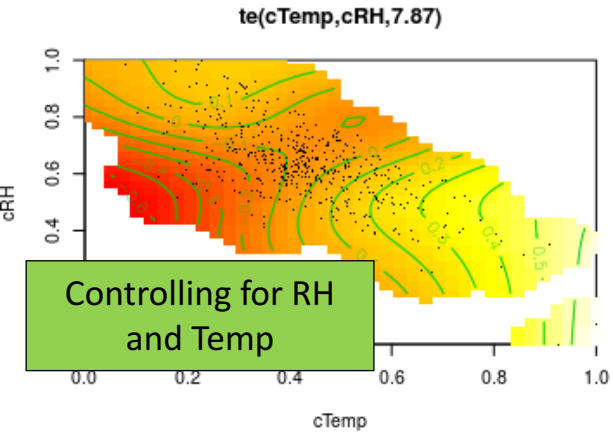
Local changes in NOx over time – above and beyond canonical footprint and network-wide trend – not uniform!

GAM NOx Smooths

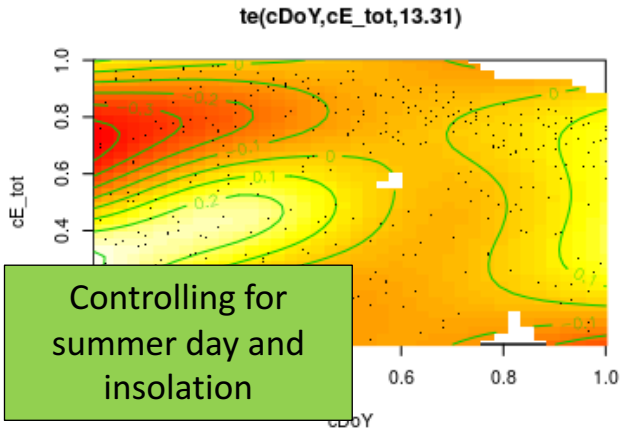
GAM-predicted networked averaged NOx versus MV emissions totals



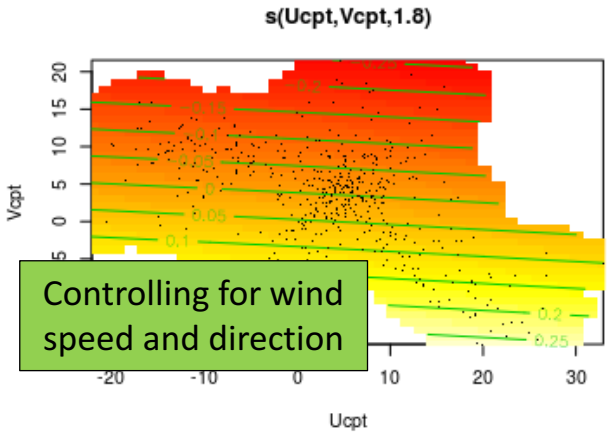
VOC Results



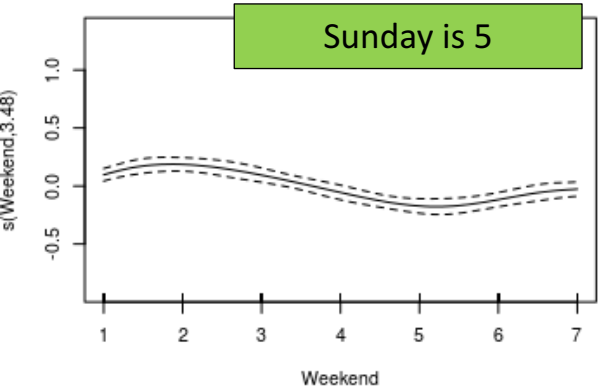
Controlling for RH and Temp



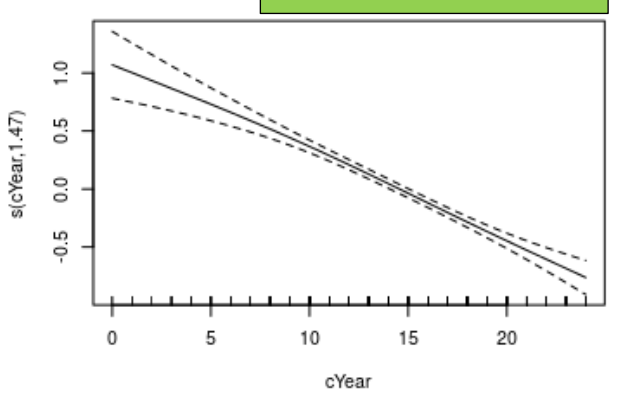
Controlling for summer day and insolation



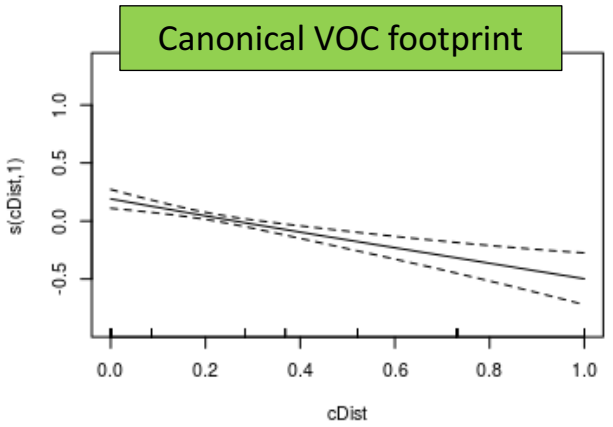
Controlling for wind speed and direction



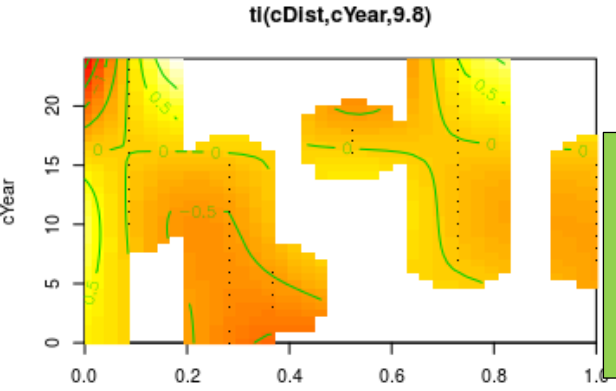
Sunday is 5



Network-wide trend



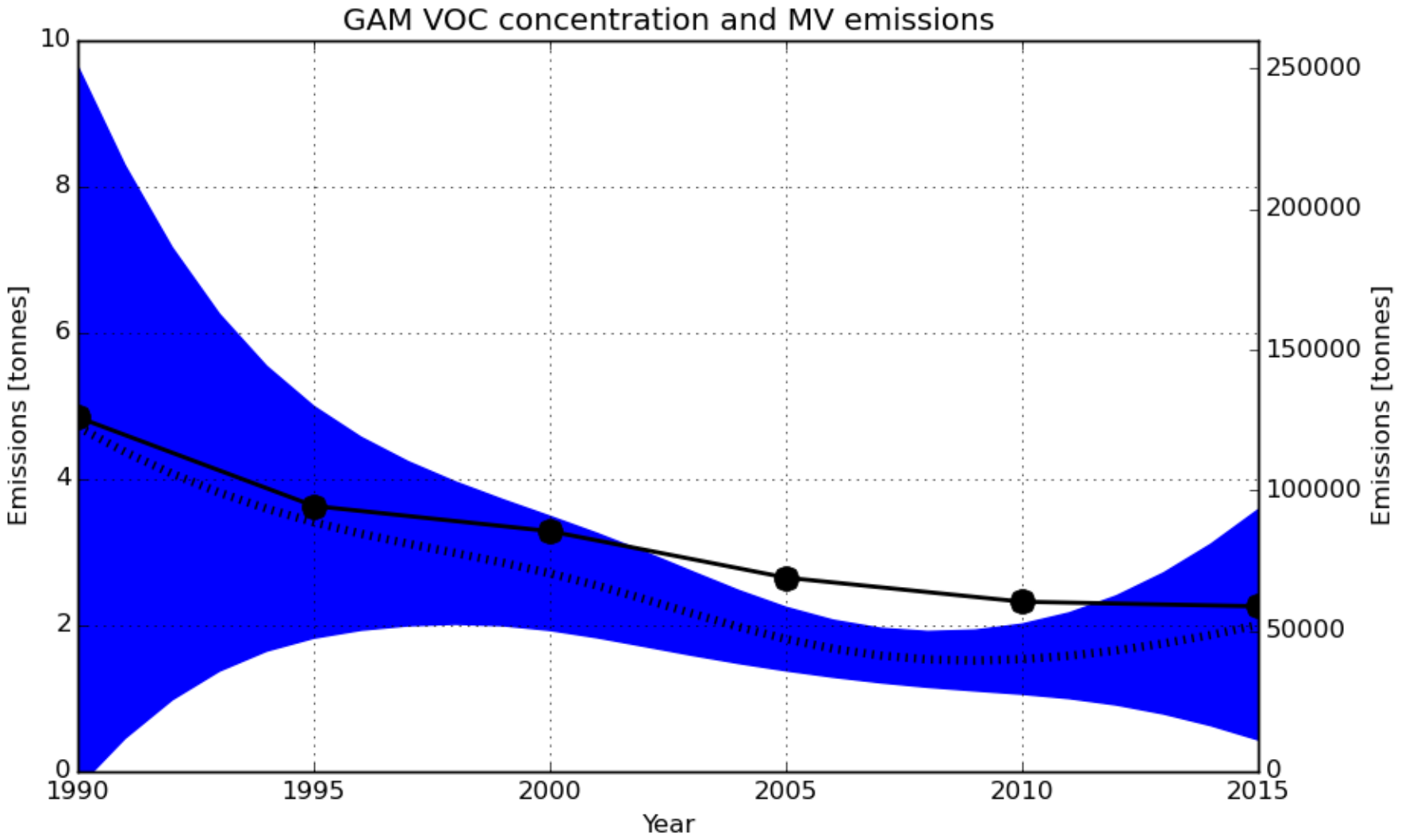
Canonical VOC footprint

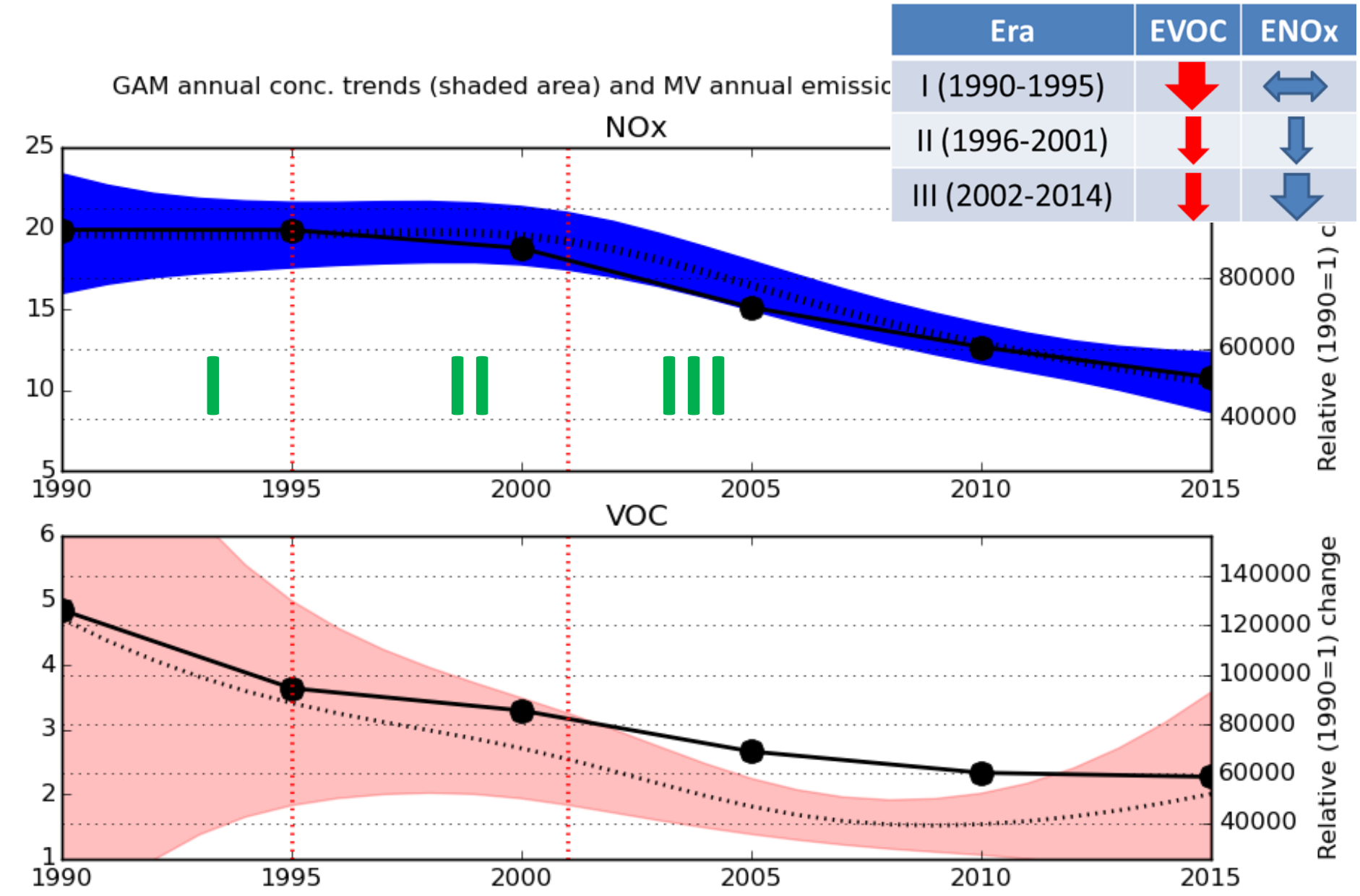


Local changes in VOC over time – above and beyond canonical footprint and network-wide trend
Not great coverage

GAM VOC Smooths

GAM-predicted networked averaged VOC versus MV emissions totals



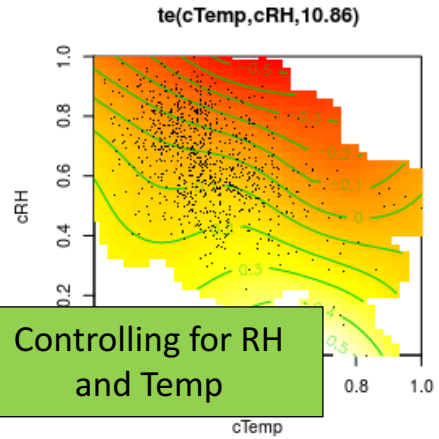


Era	EVOC	ENOx
I (1990-1995)	↓	↔
II (1996-2001)	↓	↓
III (2002-2014)	↓	↓

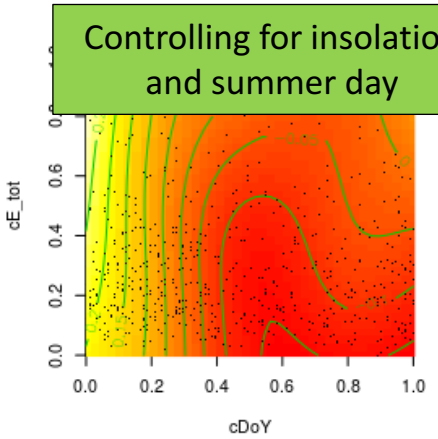
Precursor Summary

- GAM annual average concentration trends consistent with MV annual emissions trends
- VOC results are more uncertain – likely due to limited sampling on the GAM-side and difficulty quantifying fugitive and evaporative emissions on the MV-side
- VOC and NOx annual trends are not linear
- Rate of VOC reductions (emissions or concentrations) have **not** occurred at the same rate as NOx reductions

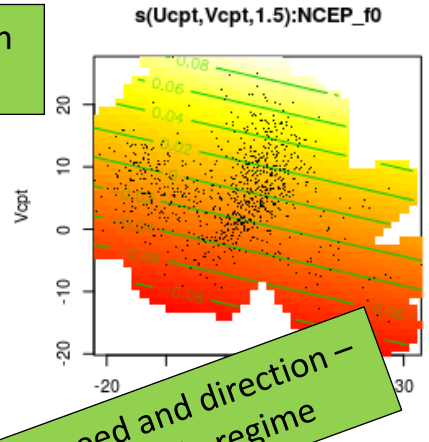
Ozone Results
Background days

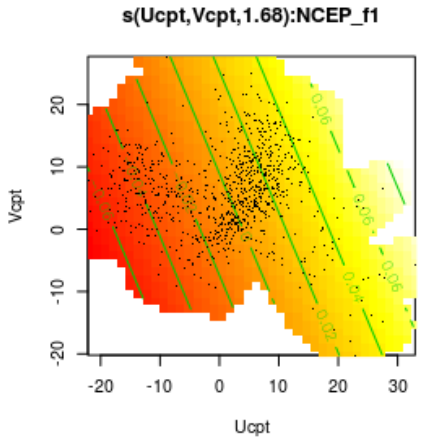


Controlling for RH and Temp

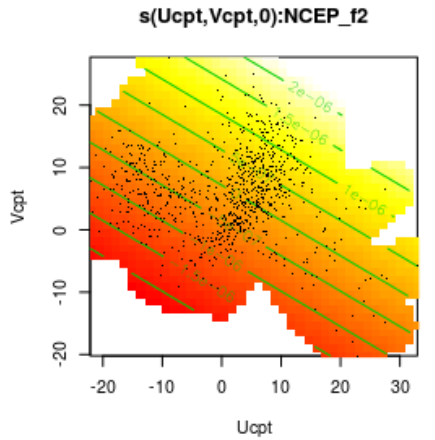


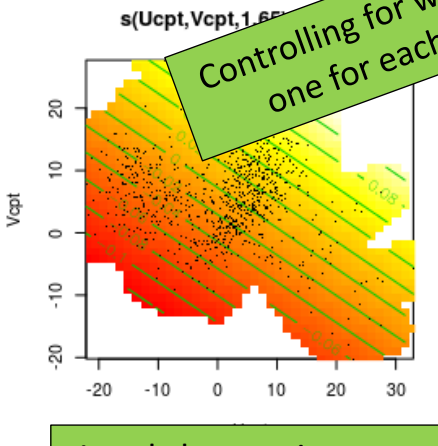
Controlling for insolation and summer day

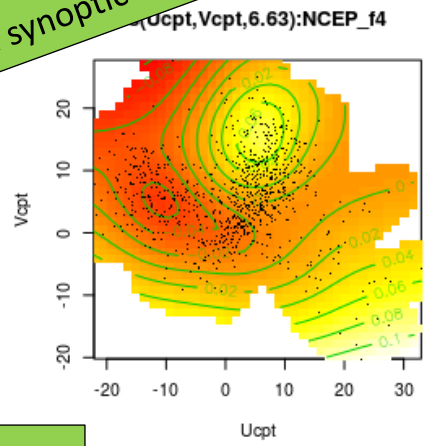




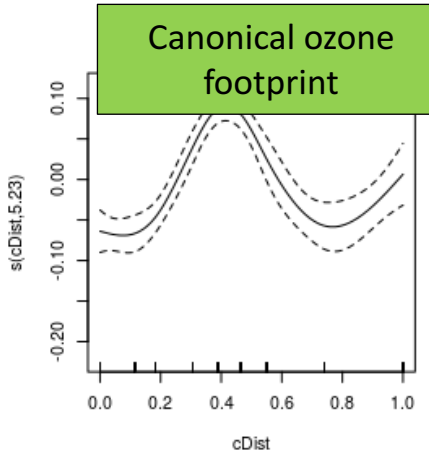
Controlling for wind speed and direction – one for each synoptic-scale regime



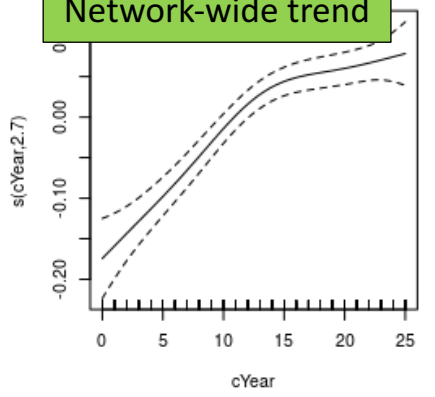




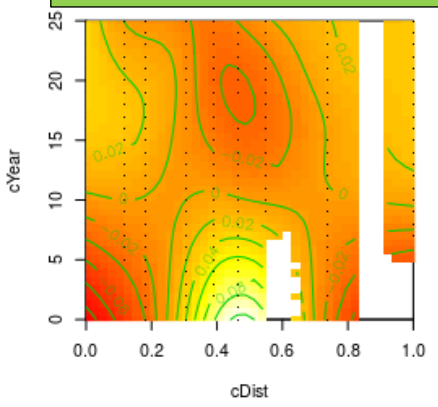
Canonical ozone footprint



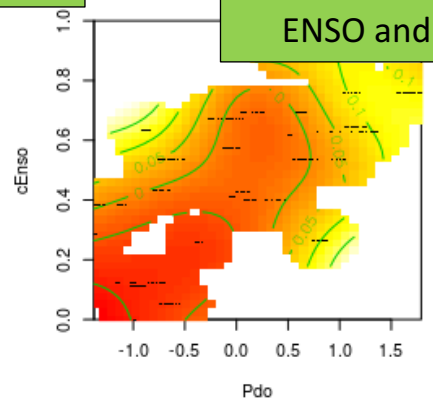
Network-wide trend



Local changes in ozone– not uniform!



Controlling for ENSO and PDO



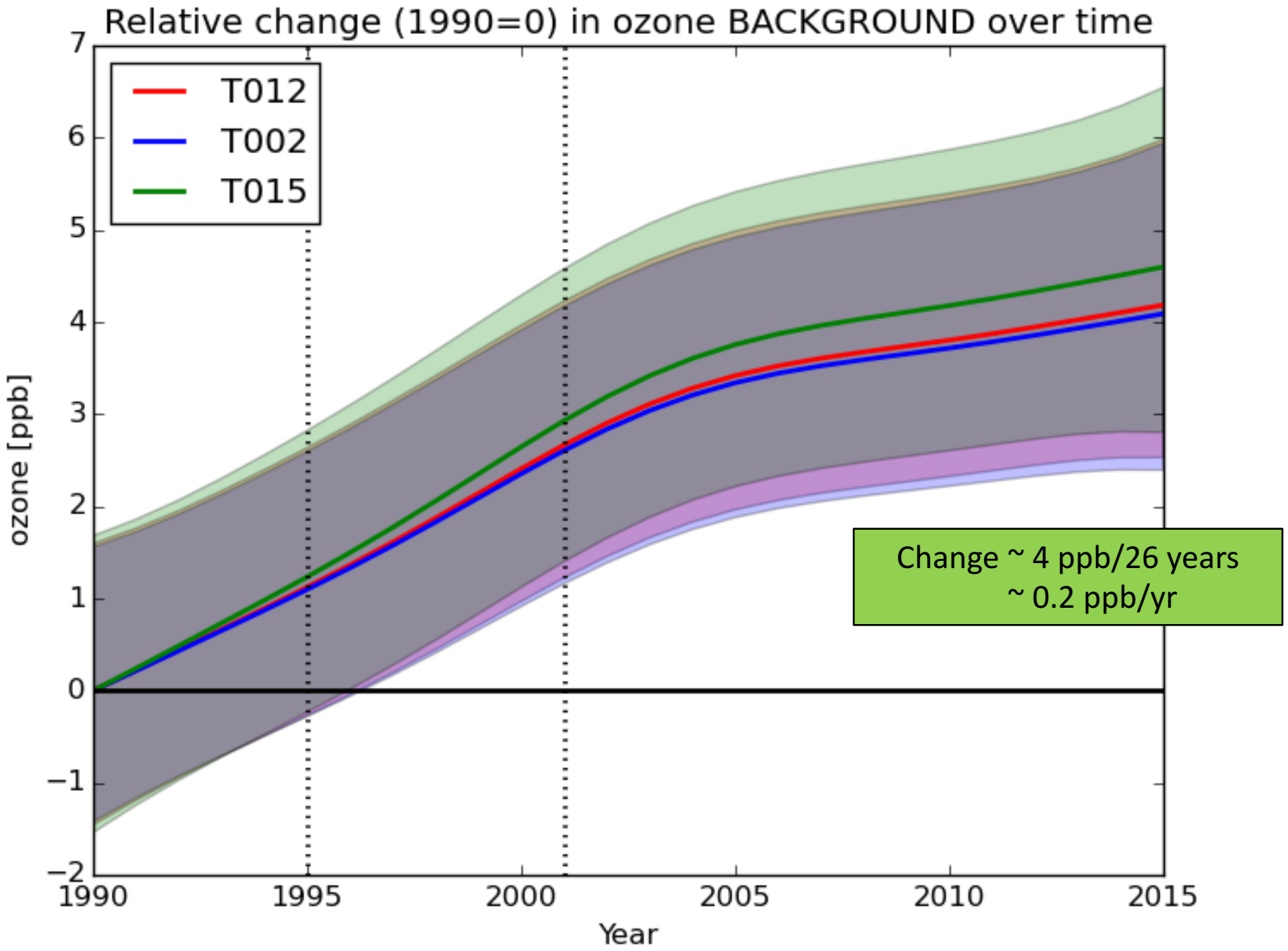
Have all monitors responded equally to changing background?
(after accounting for location and meteorology)

$$H_0 : [O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) \times ti(Dist, Year) + \epsilon$$

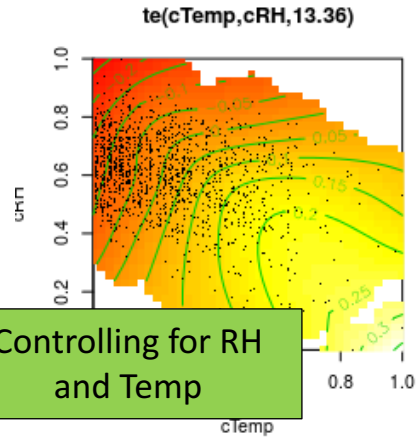
$$H_1 : [O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) + \epsilon$$

Model	df	BIC	AIC
H0	19	-348	-452
H1	16	-363	-450

Hard to say!
BIC score for model without Dist+Year interaction (H_1) is more negative
But AIC slight favours H_O

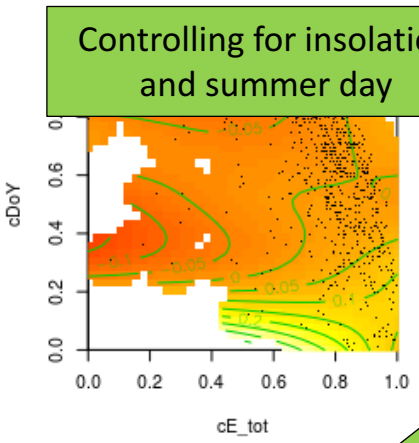

Relative change (1990=0) in ozone BACKGROUND over time
T012
T002
T015
ozone [ppb]
Year
7
6
5
4
3
2
1
0
−1
−2
1990
1995
2000
2005
2010
2015
Change ~ 4 ppb/26 years
~ 0.2 ppb/yr

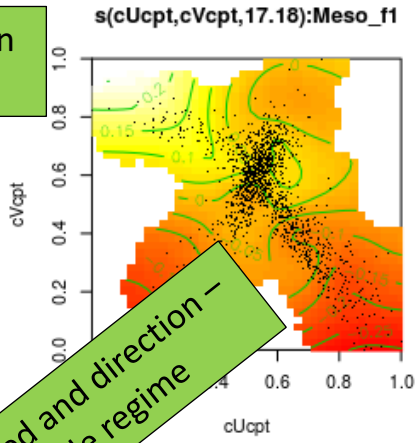
Ozone Results
Fair weather days

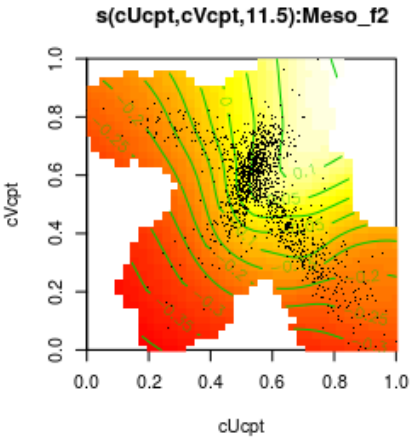


Controlling for RH and Temp

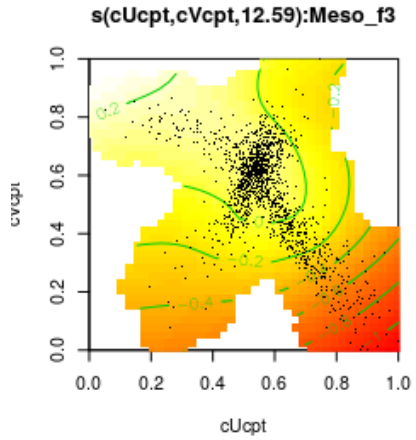
Controlling for insolation and summer day

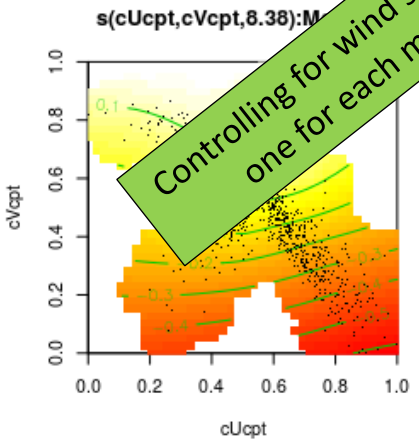




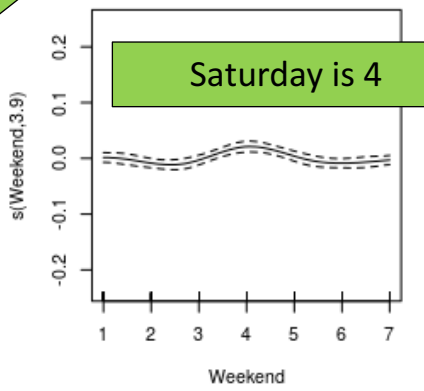


Controlling for wind speed and direction – one for each meso-scale regime

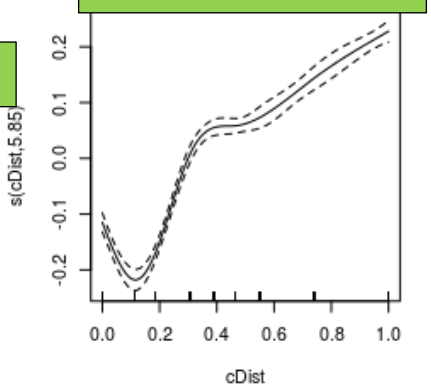




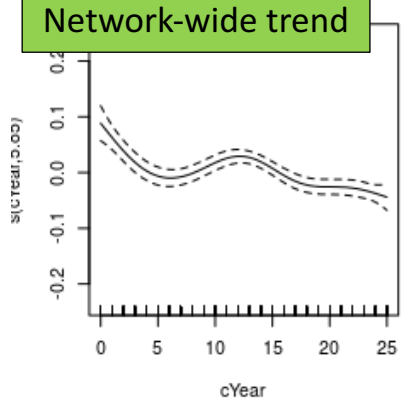
Saturday is 4

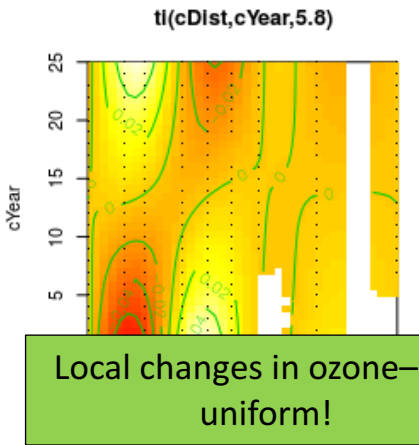


Canonical ozone footprint



Network-wide trend





Local changes in ozone– not uniform!

GAM Ozone – ‘fair weather days’ Smooths

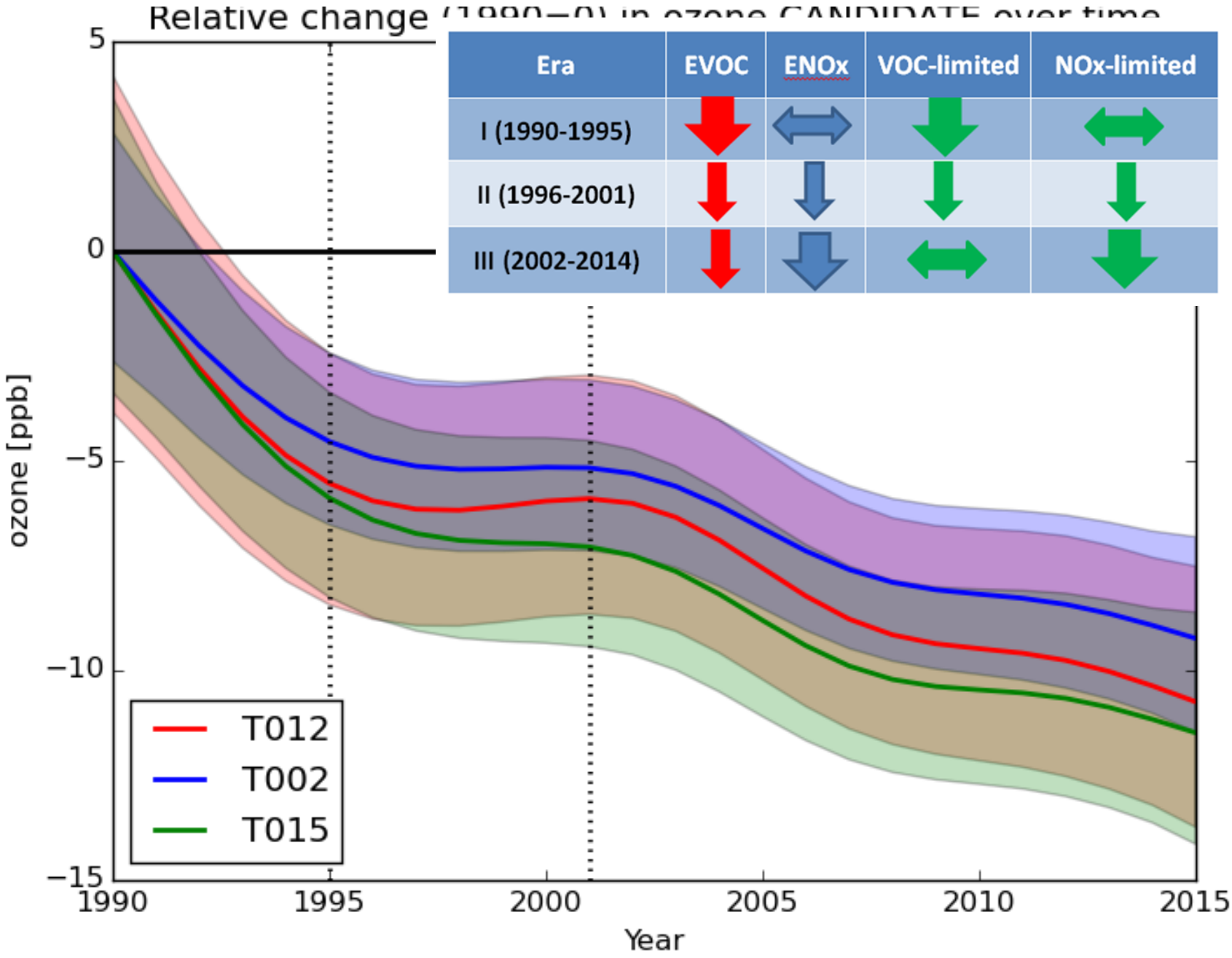
Have all monitors responded equally to changing emissions?
(after accounting for location and meteorology)

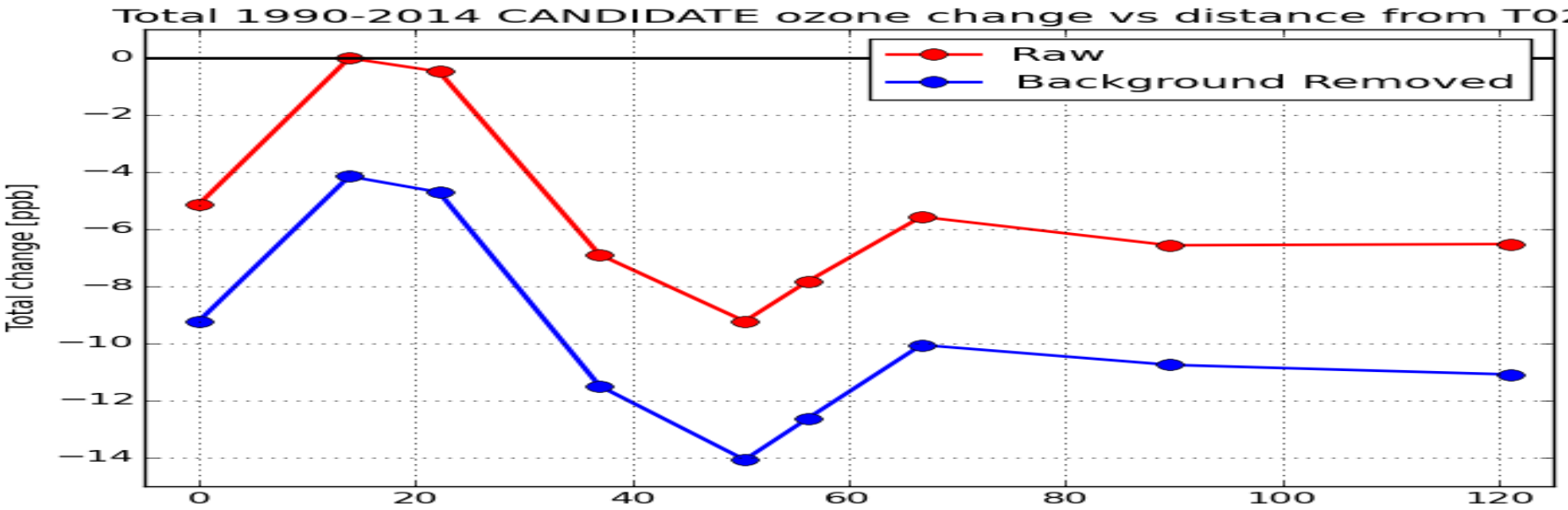
$$H_0 : [O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) \times ti(Dist, Year) + \epsilon$$

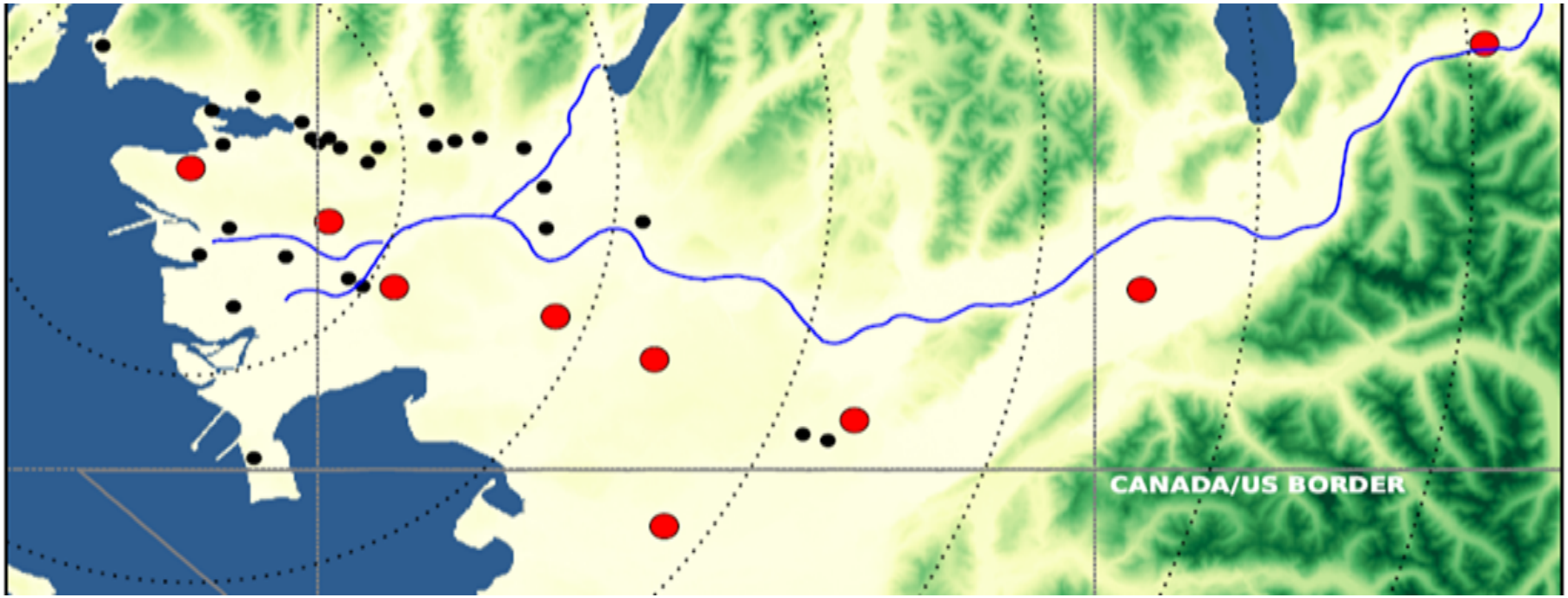
$$H_1 : [O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) + \epsilon$$

Model	df	BIC	AIC
H0	33	-3516	-3733
H1	31	-3506	-3710

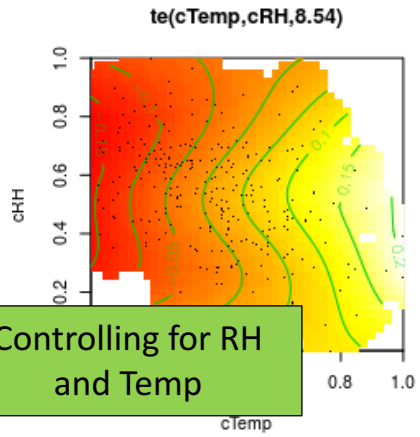
NO!
Both BIC and AIC scores support (are more negative) the H_o model with Dist+Year interaction term.


Relative change (1990=0) in ozone CANDIDATE over time
Era
EVOC
ENOx
VOC-limited
NOx-limited
I (1990-1995)
II (1996-2001)
III (2002-2014)
ozone [ppb]
5
0
−5
−10
−15
1990
1995
2000
2005
2010
2015
Year
T012
T002
T015

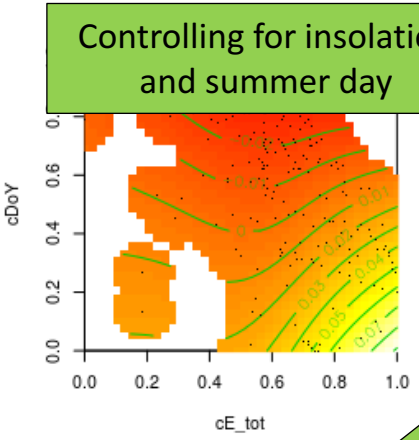

Total 1990-2014 CANDIDATE ozone change vs distance from T02
Raw
Background Removed
Total change [ppb]
0
−2
−4
−6
−8
−10
−12
−14
0
20
40
60
80
100
120


CANADA/US BORDER

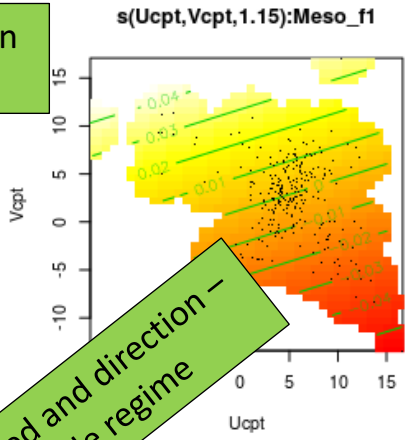
Ozone Results
CAAQS days

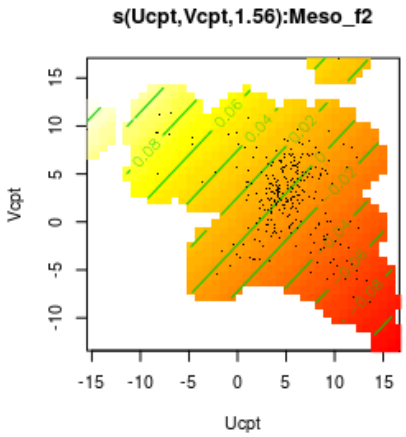


Controlling for RH and Temp

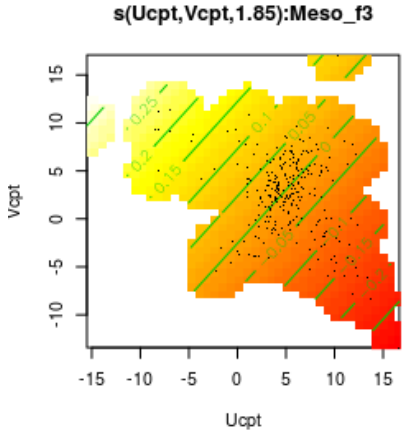


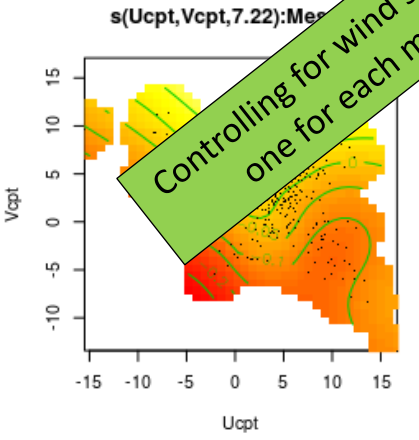
Controlling for insolation and summer day



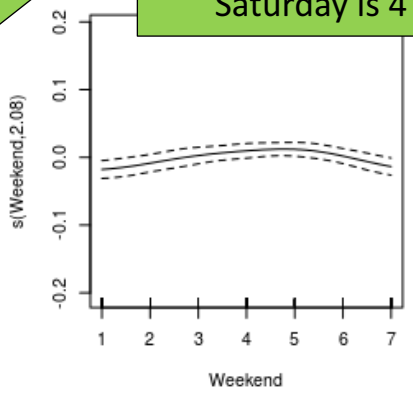


Controlling for wind speed and direction – one for each meso-scale regime

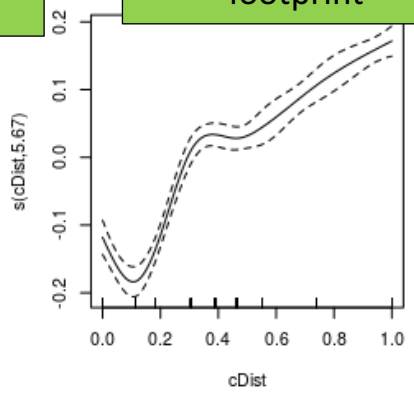




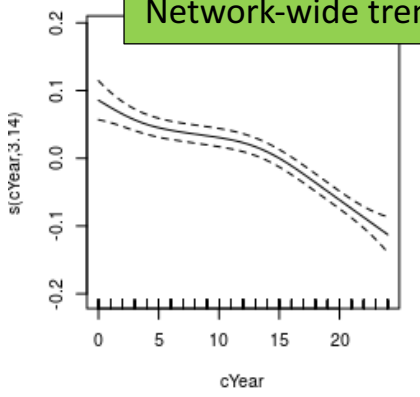
Saturday is 4

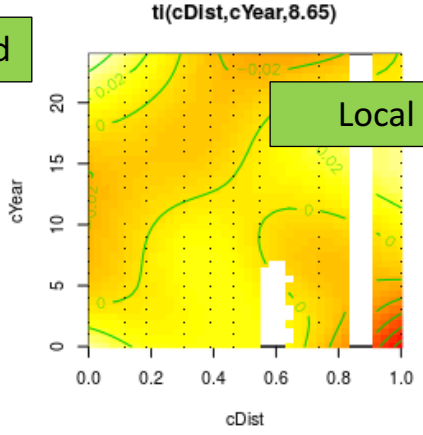


Canonical ozone footprint



Network-wide trend





Local changes in ozone

GAM Ozone – ‘CAAQO days’ Smooths

Have all monitors responded equally to changing emissions?
(after accounting for location and meteorology)

$$H_0 : [O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) \times ti(Dist, Year) + \epsilon$$

$$H_1 : [O_3] \sim s(Temp, RH) \times s(ETot, DoY)) \times s(Ucpt, Vcpt) \times s(WeekDay) \times s(Dist) \times s(Year) + \epsilon$$

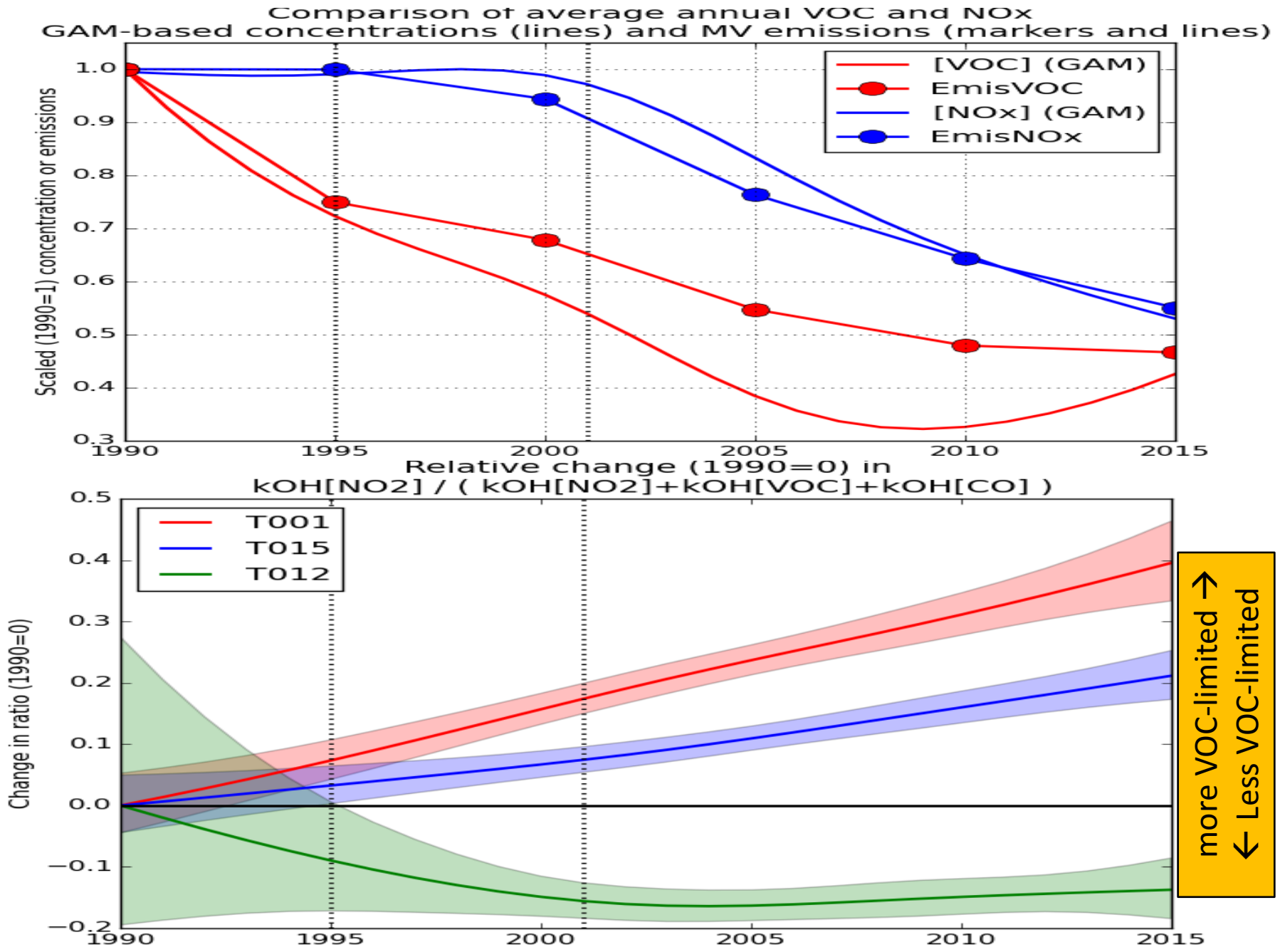
Model	df	BIC	AIC
H0	17	-1047	-1125
H1	15	-1060	-1128

It appears so!
Both BIC and AIC scores **do not** support the more complex H_o model (with Dist+Year interaction term).

Ratio of

$k_{OH}[NO2]/$

$(k_{OH}[NO2]+k_{OH}[CO]+k_{OH}[VOC])$


Comparison of average annual VOC and NOx
GAM-based concentrations (lines) and MV emissions (markers and lines)
Scaled (1990=1) concentration or emissions
[VOC] (GAM)
EmisVOC
[NOx] (GAM)
EmisNOx
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1990
1995
2000
2005
2010
2015
Relative change (1990=0) in
kOH[NO2] / (kOH[NO2]+kOH[VOC]+kOH[CO])
Change in ratio (1990=0)
T001
T015
T012
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
1990
1995
2000
2005
2010
2015
more VOC-limited →
← Less VOC-limited

Conclusions -- background

- Trends look to be ~ 0.2 ppb/year trend, some suggestion that not uniform
- Not much inter-station variability

Conclusions – fair weather

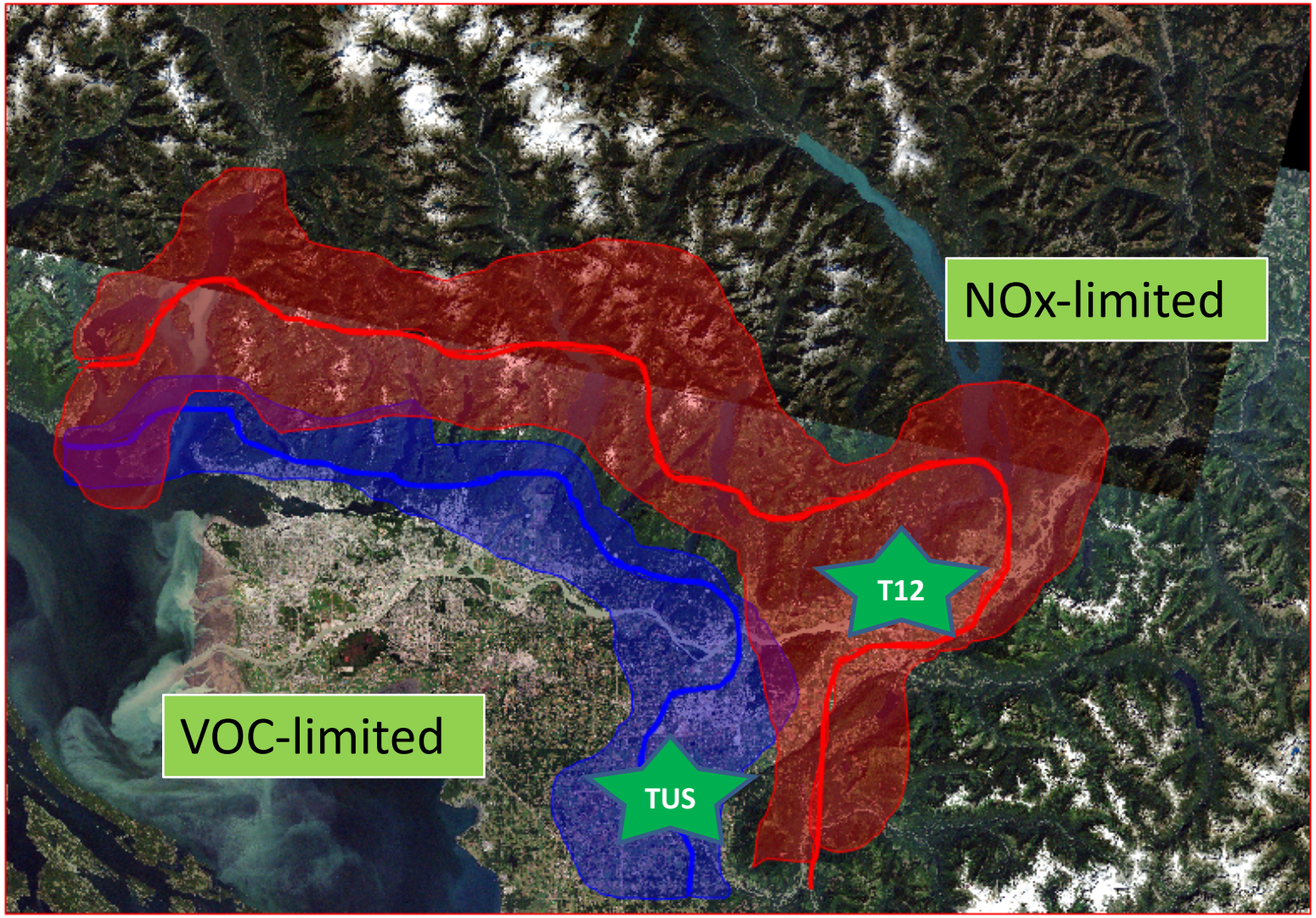
- Trends **not** uniform/linear
- Trends best understood after removing background
- A lot of inter-station variability

Conclusions -- CAAQS

- Results similar to FAIR WEATHER but with bigger trends. Why?
- No inter-station variability. Why?

Future Work

- Are these results consistent with the earlier modeling work?



Hand drawn VOC-to-NOx transition regions based on CMAQ model output

Coloured regions give estimated extent of variability from varying meteorological conditions

Red colours for CMAQ output using 1985 emissions

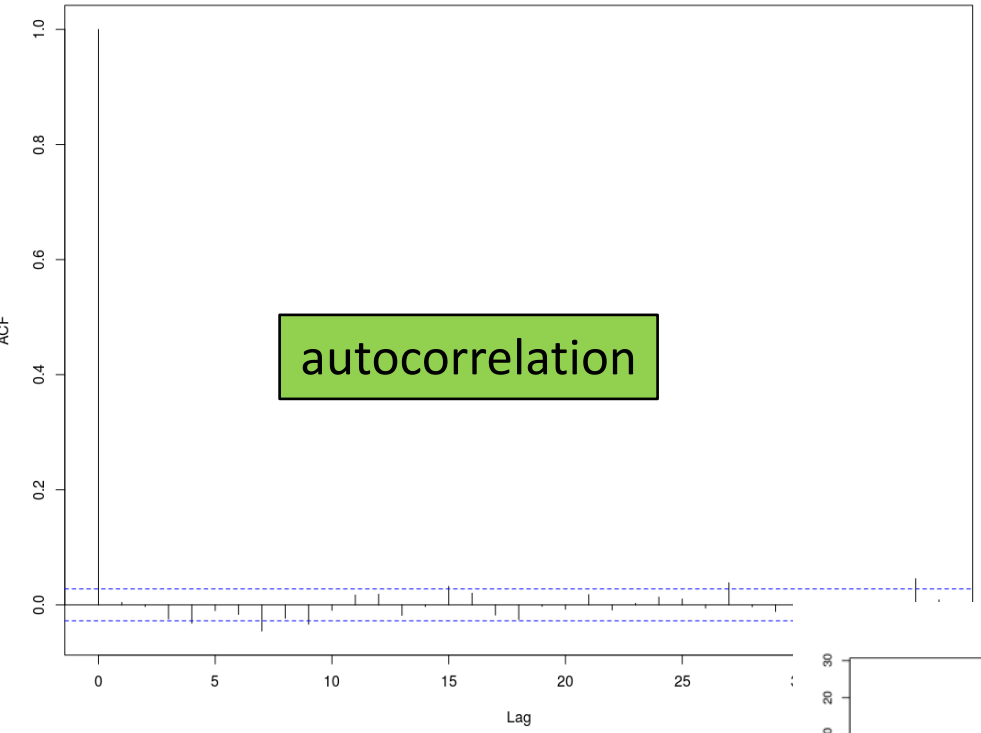
Blue colours for CMAQ output using 2005 emissions

Questions?

Thanks !

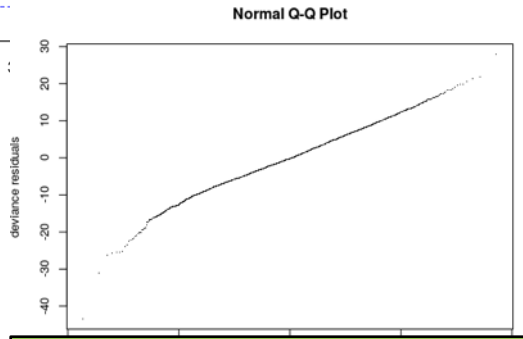
Previous LFV Trend analysis

Reference	Timeframe	Comments
Joe et al. (1996)	1978-1990	1-hr ozone; isotonic regression; 2 stations
Pryor (1998)	1984-1991	1-hr ozone; trends in declimatized ozone; 8 stations
Vingarzan and Taylor (2003)	1985-2000	1-hr ozone; GLS regression; 5 stations
Chan (2009)	1997-2006	8-hr ozone; GLMM; 4 stations (as part of larger analysis)
This study (2017)	1990-2014	8-hr ozone; GAM; 9 stations

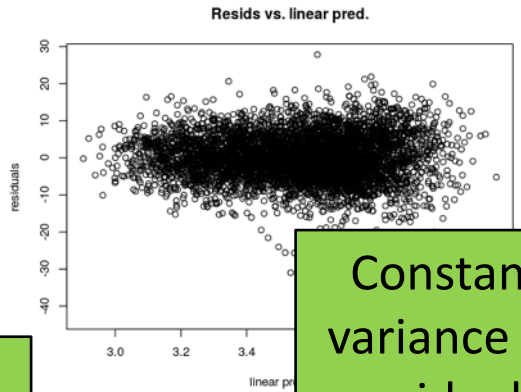


autocorrelation

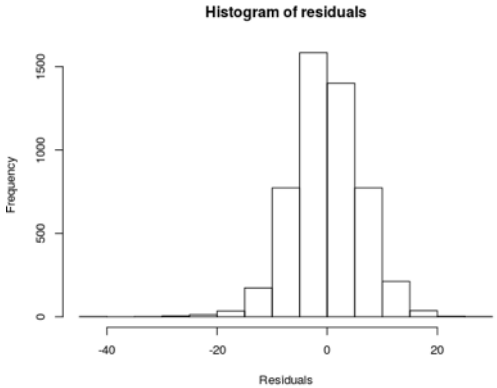
Summary of GAM fit to ozone candidate days

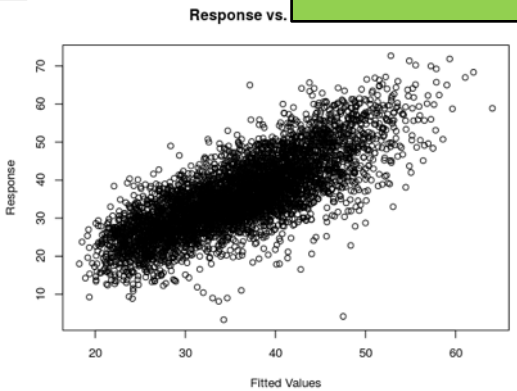


Normality of residuals



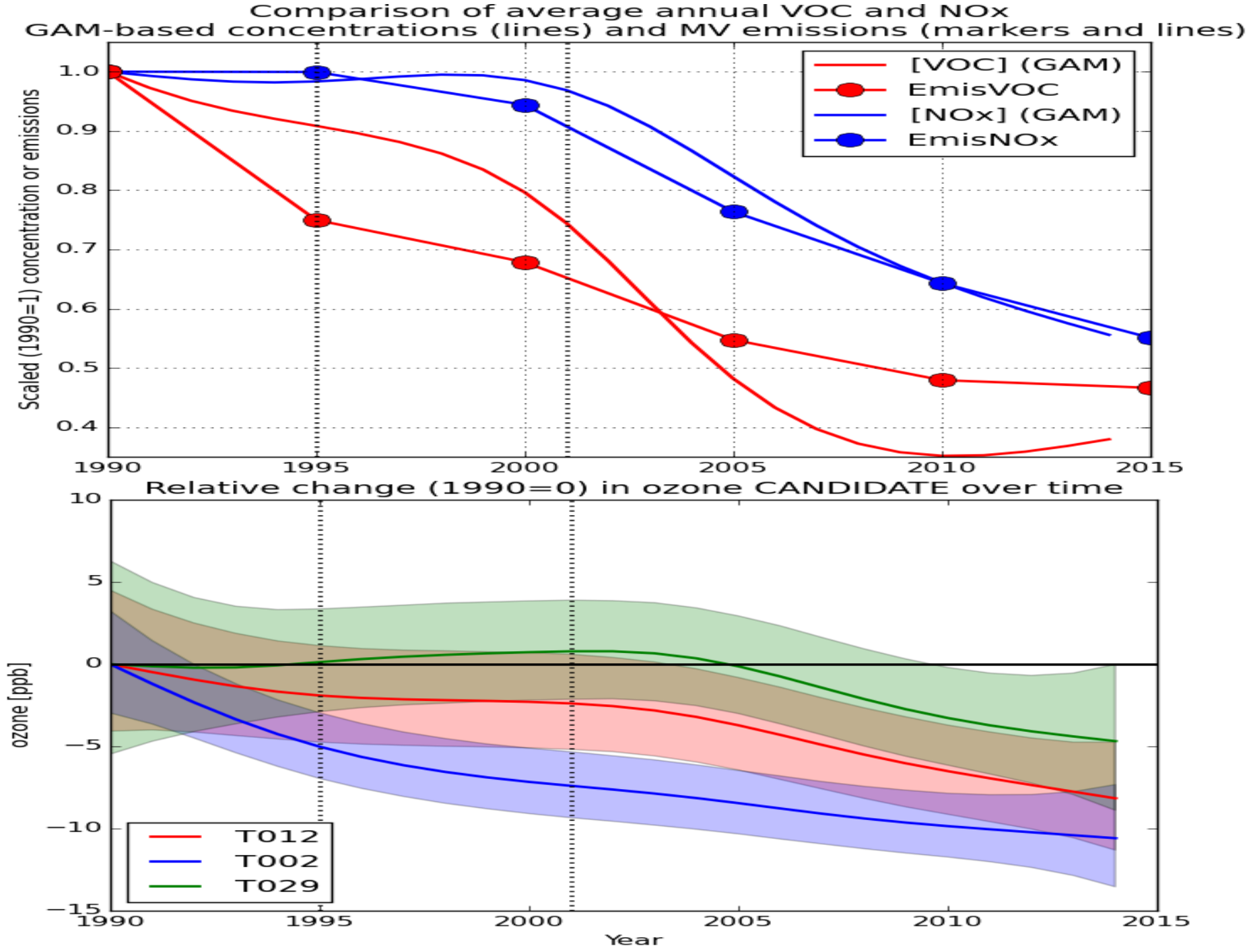
Constant variance of residuals

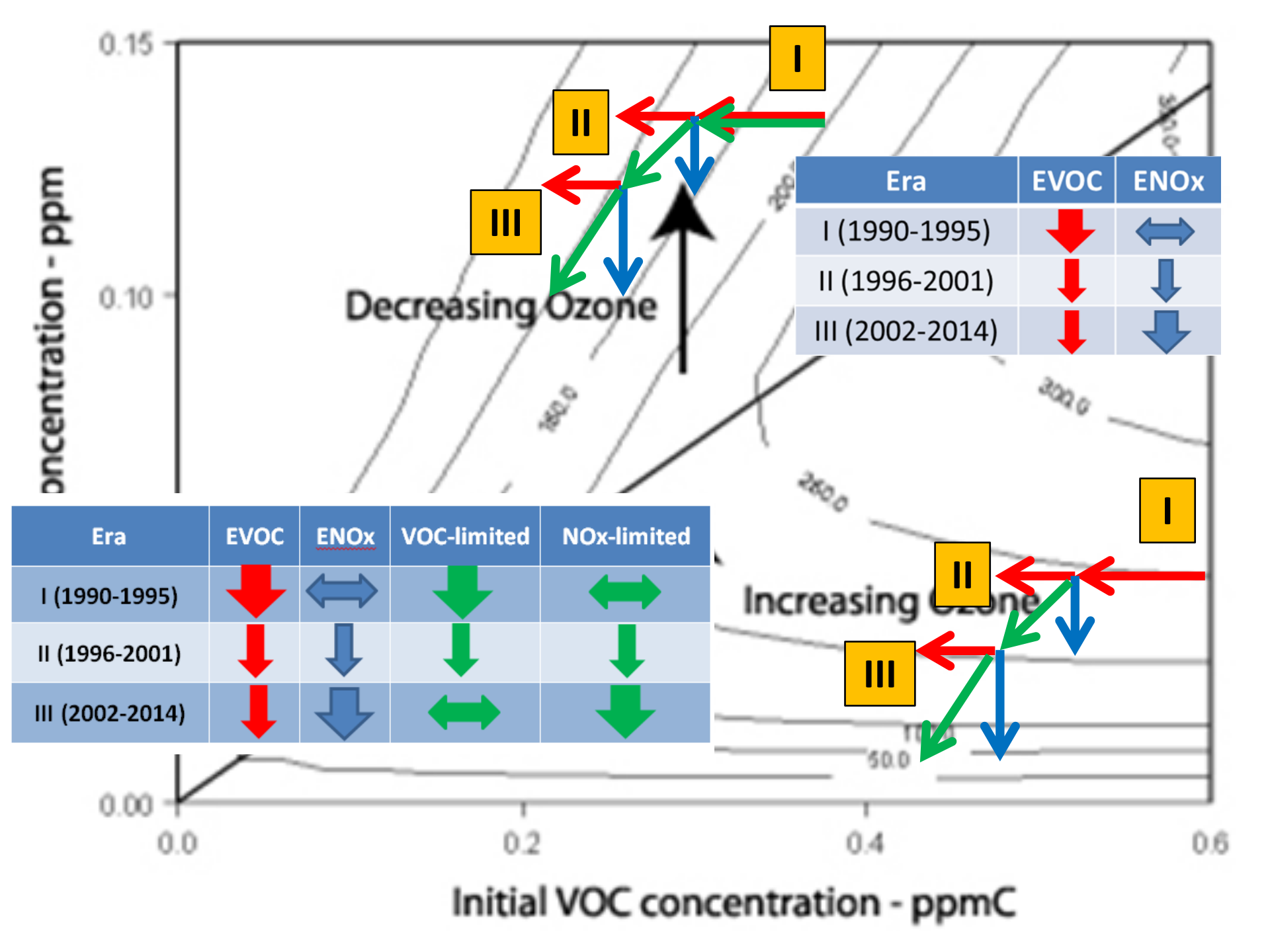


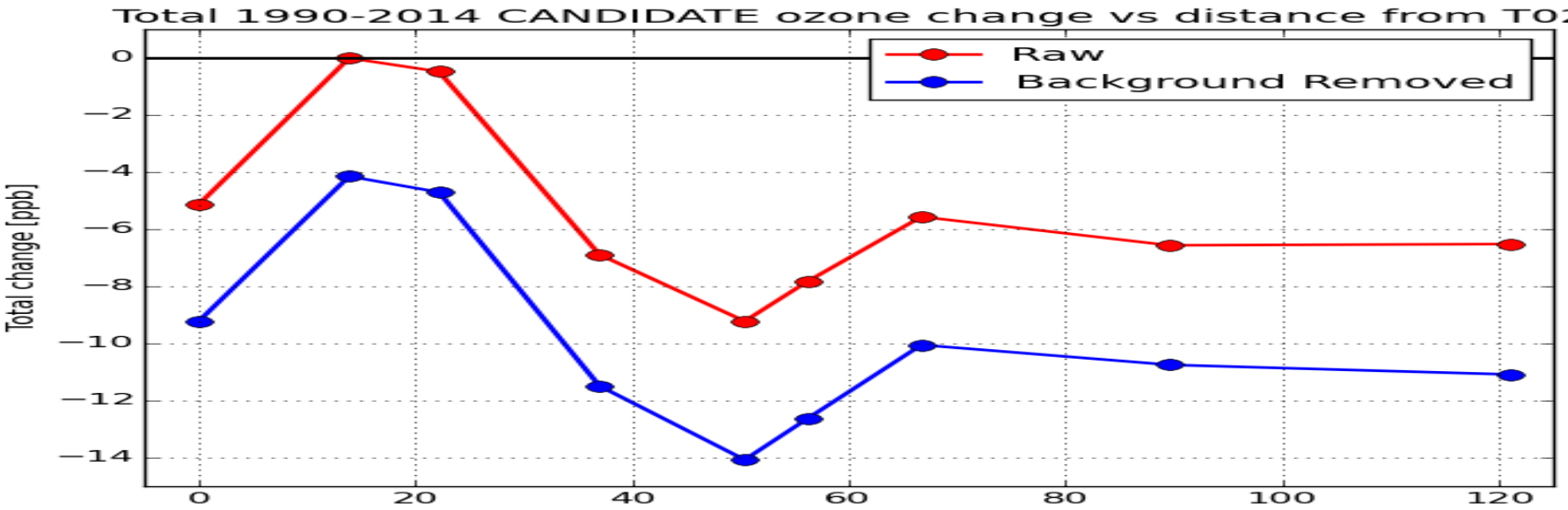


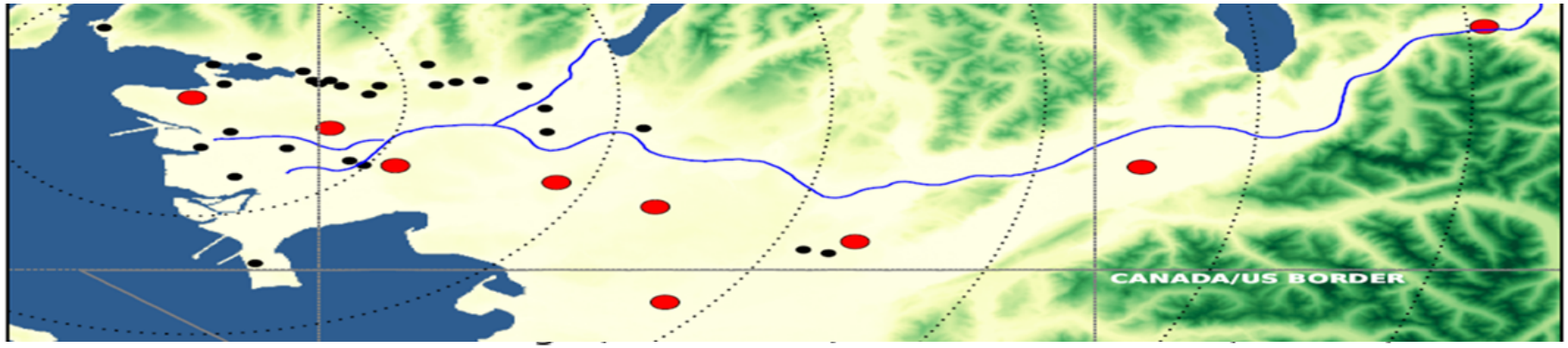
GAM Model summary

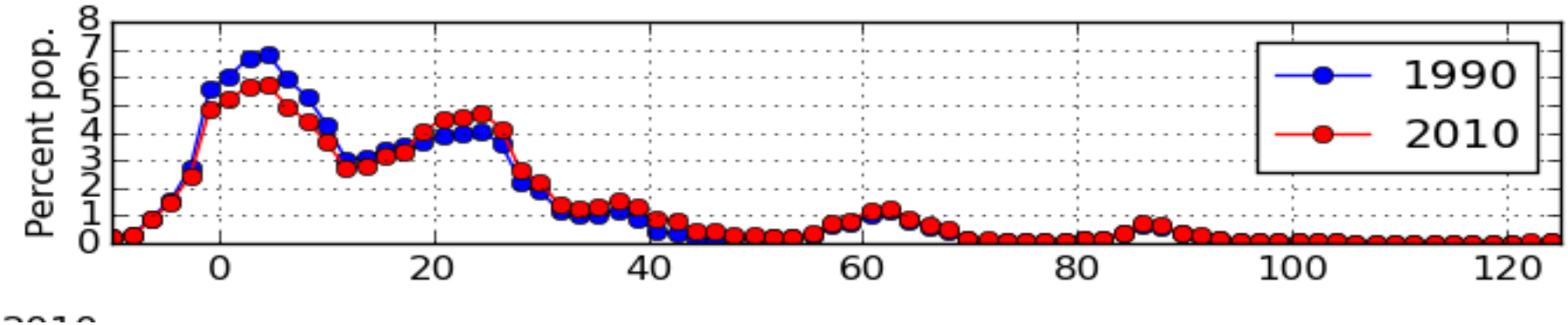
```
> summary(gammobjLAC$gam)

Family: gaussian
Link function: log

Formula:
Ozone ~ te(cTemp, cRH) + te(cE_tot, cDoY) + s(cUcpt, cVcpt, by = Meso_f) +
    s(Weekend, bs = "cc", k = 7) + s(cDist, k = 7, bs = "ts") +
    s(cYear, k = 10, bs = "ts") + ti(cDist, cYear, k = c(7, 10))

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 3.528496   0.008138   433.6   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                          edf Ref.df      F  p-value
te(cTemp,cRH)          13.683 13.683 95.785  < 2e-16 ***
te(cE_tot,cDoY)        11.420 11.420 20.549  < 2e-16 ***
s(cUcpt,cVcpt):Meso_f1 16.097 16.097 15.604  < 2e-16 ***
s(cUcpt,cVcpt):Meso_f2  9.573  9.573 19.150  < 2e-16 ***
s(cUcpt,cVcpt):Meso_f3 16.824 16.824 16.982  < 2e-16 ***
s(cUcpt,cVcpt):Meso_f4 11.591 11.591 31.778  < 2e-16 ***
s(Weekend)              3.871  5.000  5.110 9.87e-06 ***
s(cDist)                5.636  6.000 90.730  < 2e-16 ***
s(cYear)                3.545  9.000  2.662 9.30e-06 ***
ti(cDist,cYear)         5.292  5.292  2.522    0.027 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.603
  Scale est. = 40.967    n = 5009
```


Comparison of average annual VOC and NOx
GAM-based concentrations (lines) and MV emissions (markers and lines)
Scaled (1990=1) concentration or emissions
1.0
0.9
0.8
0.7
0.6
0.5
0.4
1990
1995
2000
2005
2010
2015
[VOC] (GAM)
EmisVOC
[NOx] (GAM)
EmisNOx
Relative change (1990=0) in ozone CANDIDATE over time
ozone [ppb]
10
5
0
−5
−10
−15
T012
T002
T029
Year


0.15
0.10
0.00
0.0
0.2
0.4
0.6
oncentration - ppm
Initial VOC concentration - ppmC
Decreasing Ozone
Increasing Ozone
I
II
III
I
II
III
Era
EVOC
ENOx
I (1990-1995)
II (1996-2001)
III (2002-2014)
Era
EVOC
ENOx
VOC-limited
NOx-limited
I (1990-1995)
II (1996-2001)
III (2002-2014)


Total 1990-2014 CANDIDATE ozone change vs distance from T02
Raw
Background Removed
Total change [ppb]
0
−2
−4
−6
−8
−10
−12
−14
0
20
40
60
80
100
120


CANADA/US BORDER


Percent pop.
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100
120
1990
2010