1992 to 2005 Meteorological Factors Conducive to Ozone Formation in the Portland-Vancouver Area (ODEQ, April 2006)

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Abstract
Elevated ground level ozone concentrations in the Portland/Vancouver airshed have slightly decreased in the period between 1992 and 2005. In the same period, ozone precursor VOCs and NOx levels went down slightly while maximum summer time temperatures rose. Population and vehicle miles traveled also increased. When comparing similar temperature episodes between years the ozone levels declined slightly. Temperature episodes are defined as three or more days with maximum temperatures above 90ºF, average wind speeds less than 10 mph, and solar radiation above 1.0 langley/hr.

Introduction:
Ozone is a secondary pollutant produced by a mixture of Nitrogen dioxide and Oxygen under strong ultraviolet radiation (*hv*). This reaction is driven by the creation of more Nitrogen dioxide from the reaction of volatile organic carbons under ultraviolet radiation and free radicals (See ozone chemistry following this report). The highest ozone levels occur during the summer months, during clear, hot days with poor ventilation

Meteorological parameters which affect ozone formation:
Temperature:
In Portland/Vancouver the ozone levels start to approach Air Quality Index levels of "Unhealthy For Sensitive Groups" and the National Ambient Air Quality Standards (NAAQS) when temperatures are near or above 90ºF for three consecutive days or more with poor ventilation.

Ventilation:
Ventilation refers to the amount of vertical mixing in the atmosphere. With good ventilation the dirty ground level air is transported up and replaced with cleaner air. In short, good ventilation reduces the ground level volatile organic carbon levels and the resulting ozone. The rule of thumb is for good ventilation to occur the average horizontal wind speed should be greater than 10 mph.

Solar radiation (ultraviolet radiation):
The time of year is important because the angle of the sun and duration of the day determine the ultraviolet radiation intensity and duration.

Portland and Vancouver have many programs designed to lower the emissions of the ozone precursor pollutants of Volatile Organic Carbon and Nitrogen dioxide. One way to determine the efficacy of these programs is by analyzing the ozone trends while considering the trends for ozone precursors, vehicle miles traveled, and population growth. This analysis would not be complete, however, without accounting for variations in meteorological conditions such as temperature and ventilation. These parameters must be considered to place ozone levels in context. Once the meteorological conditions are identified a better comparison of ozone trends can be made using ozone episodes with similar weather conditions.

Results

1. Ozone

The NAAQS for ozone is calculated by averaging three consecutive years of the fourth highest daily eight hour average ozone. This level must be below 0.8 ppm or it is a violation. The eight hour ozone standard replaced the one hour standard in 1997 and since that time the Portland/Vancouver Air Quality Maintenance Area has remained in compliance. However, the Portland/Vancouver area has had four exceedances (any eight hour daily max above 0.08 ppm)[1]. Figure 1 illustrates the exceedances both before and after the 1997 standard took effect.

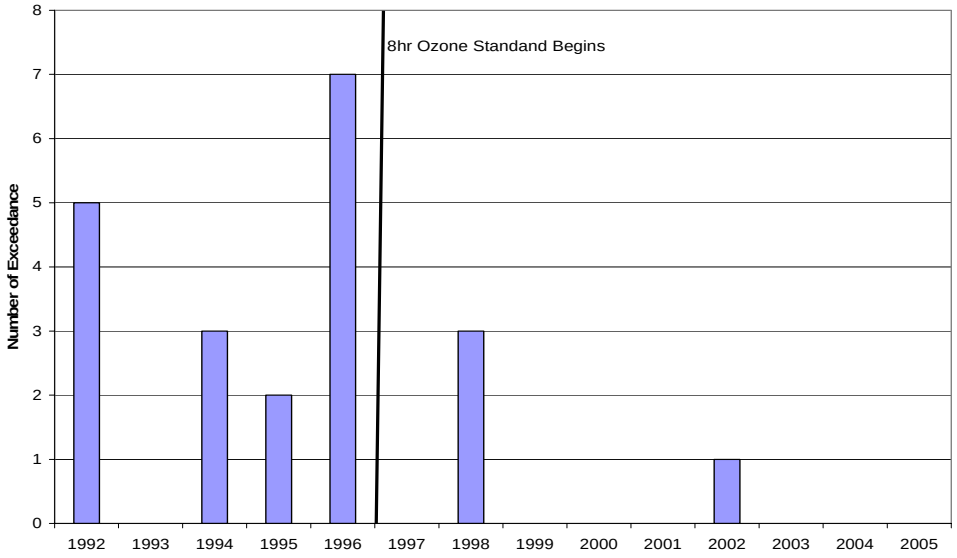

Figure 1. Portland/Vancouver number of exceedances of eight hour standard [1].

In Figure 2, the three year average of the fourth highest maximum daily eight hour average trends down slightly with a slope of -0.001.

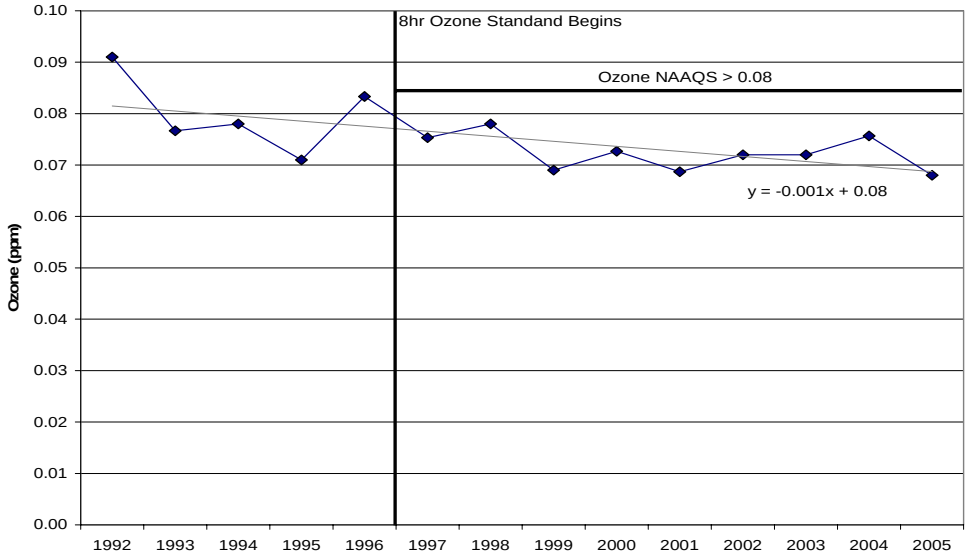

Figure 2. Portland/Vancouver three year average of fourth highest daily maximum eight hour average. Eight hour standard begins in 1997.

2. Vehicle Miles Traveled (VMT) and Population

In Figure 3 the Portland/Vancouver VMT[2] and Population[3] have slopes of +0.08 and +0.04 respectively. The three year average of the fourth highest eight hour average Ozone value has a trend with a slope of -0.002 which is relatively flat.

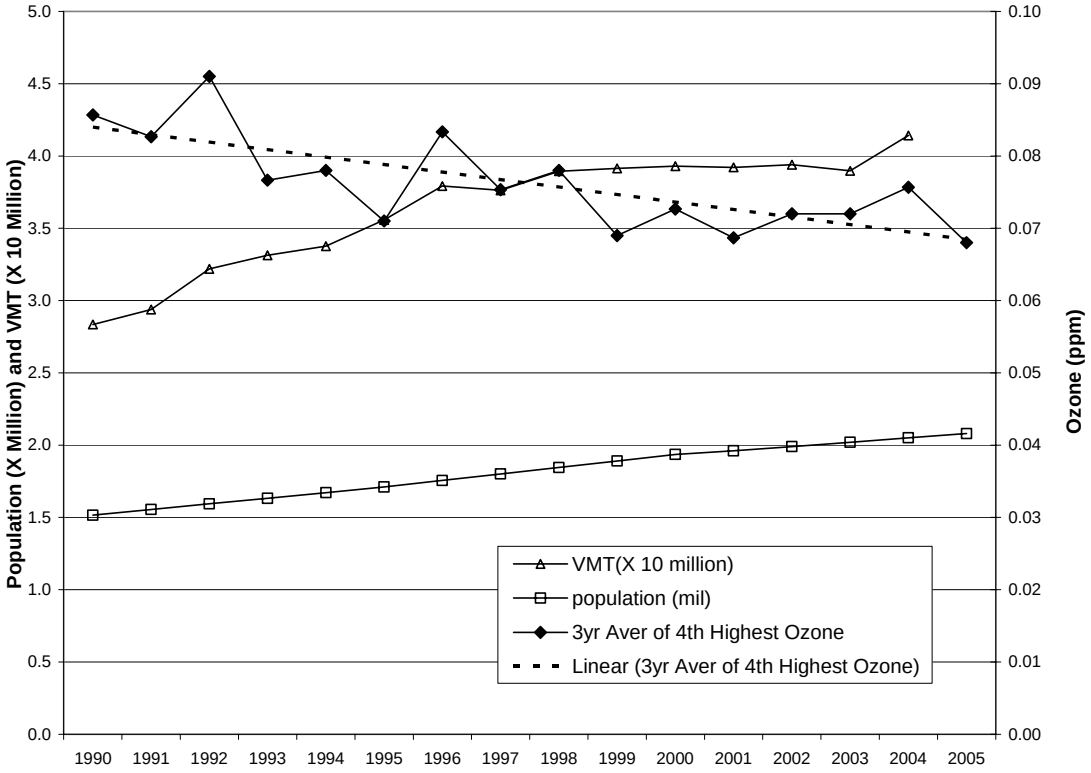

Figure 3. 3yr average of 4th highest 8hr average Portland/Vancouver 1979-2004 [2,3]

3. Precursors:

The Portland/Vancouver area ozone precursors are Nitrogen dioxide and volatile organic carbons (VOCs). Portland/Vancouver is VOC limited which means that reduction of VOCs reduces ozone levels more effectively than a reduction in NOx. TheVOCs that contribute most readily to ozone formation are aldehydes, alkanes, alkenes, and to a lesser extent aromatics. ODEQ has been measuring these compounds in Portland on a consistent basis from 2000 to 2005 (the time of this paper)[4]. Figures 4 and 5 contain the May through September average concentrations measured by ODEQ in North Portland for Formaldehyde, Acetaldehyde, Propionaldehyde, and Acetone (some of the more common aldehydes). In all cases there is a negative slope as concentrations trend down over the six year period. Formaldehyde levels spiked in 2003 which also had three multi-day $\geq 90^{o}$F episodes. Acetone levels dropped at a much steeper rate. Maximum Nitrogen dioxide, Nitric oxide, and Nitrogen oxides concentrations have also been declining as shown in Figure 6. Seasonal average Nitrogen dioxide, Nitric oxide, and Nitrogen oxides concentrations have been stable since 1995 with relatively flat slopes (Figure 7).

2. Horowitz D., 001_Portland-National-DMVT.xls, Portland Metro
3. Population Research Center, College of Urban and Public Affairs, Portland State University.
4 ODEQ measured VOCs at N. Roselawn, Portland and NOx measured at SE Lafayette, Portland.

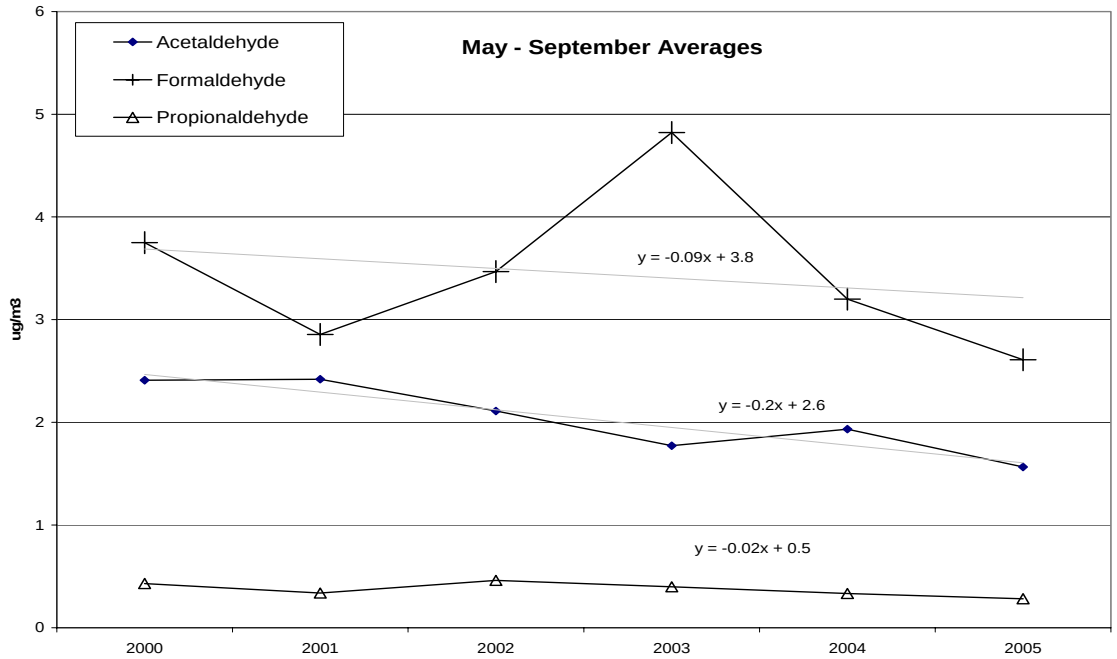

Figure 4. May through September 2000 to 2005 average Acetaldehyde, Formaldehyde, and Propionaldehyde concentrations in North Portland[4].

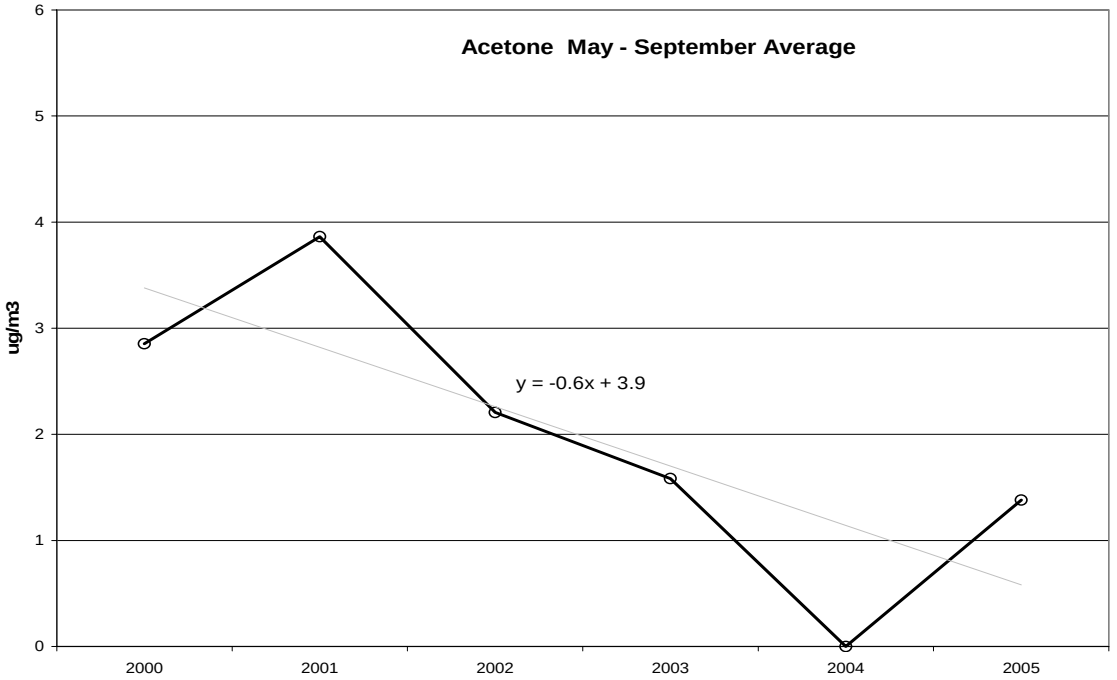

Figure 5. May through September 2000 to 2005 average Acetone concentrations in North Portland[4].

4 ODEQ measured VOCs at N. Roselawn, Portland and measured NOx at SE Lafayette, Portland.

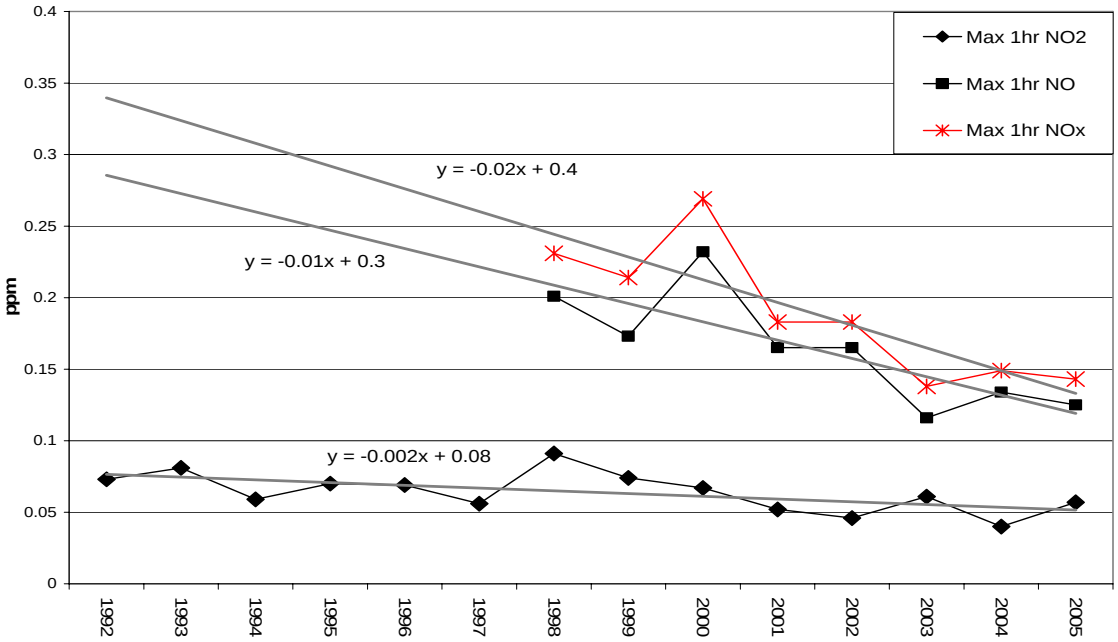

Figure 6. SE Portland, May through September 1992 to 2005 maximum one hour average concentrations of Nitrogen dioxide, Nitric oxide, and Nitrogen oxides[4].

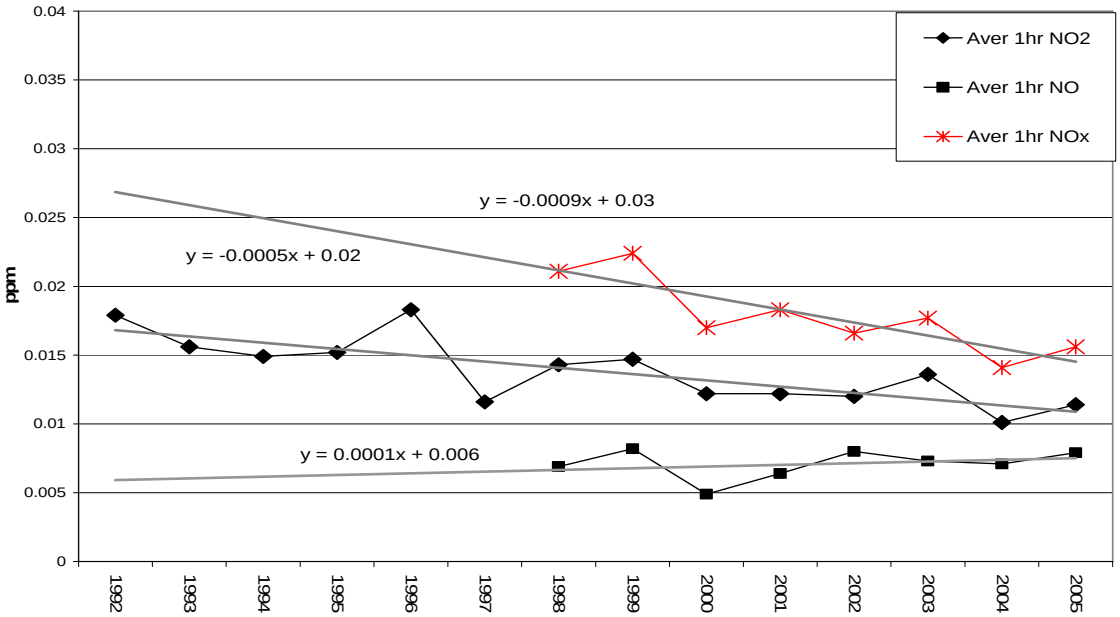

Figure 7. SE Portland, May through September 1992 to 2005 Seasonal average concentrations of Nitrogen dioxide, Nitric oxide, and Nitrogen oxides[4].

4 ODEQ measured VOCs at N. Roselawn, Portland and measured NOx at SE Lafayette, Portland.

4. Temperature

The Portland/Vancouver temperatures have been trending up from at least 1992 to 2005 as measured by ODEQ at SE Lafayette. The number of days ≥ 90ºF have gone up in the last 14 years as shown in Figure 8. There also have been numerous multi-day episodes of maximum temperatures ≥ 90ºF. The years 1993-1996, 1998, 2000, and 2003-2005 all had three plus consecutive day episodes ≥ 90ºF. Of these, 1996 and 2003-2005 had the greatest number of consecutive hot days.

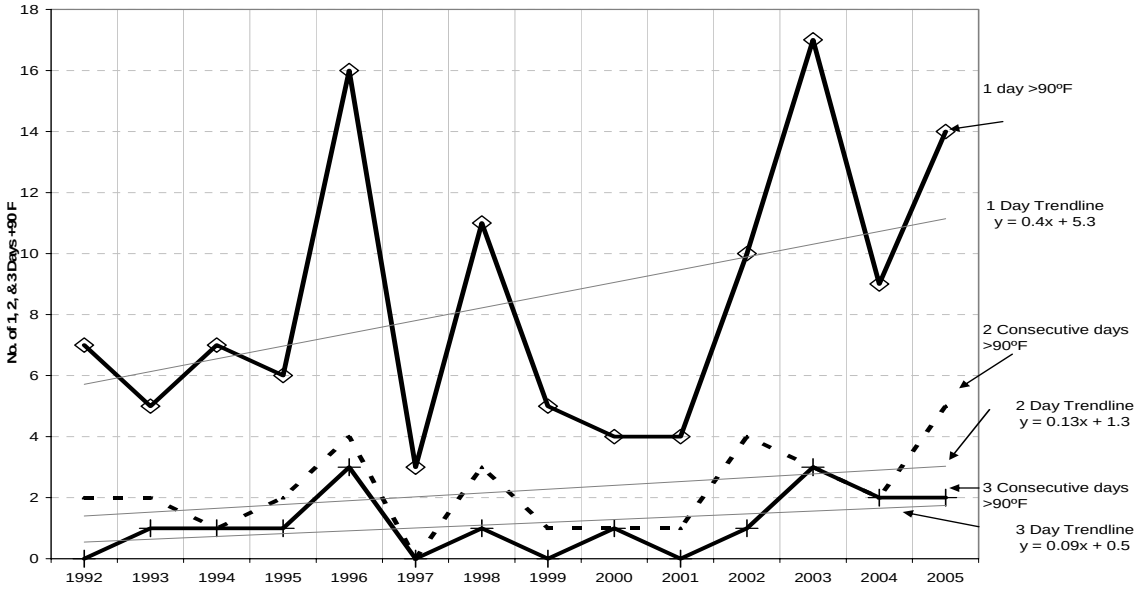

Figure 8. Number of consecutive days ≥ 90ºF for one, two, and three day episodes as measured by Oregon DEQ at SE Lafayette[5].

A break down of the three plus day episodes (Figure 9) reveals the number of three, four, five, and six consecutive day events each year. Of days ≥ 90ºF, 1993, 1994, 1996, 2003, and 2004 all had episodes of four days or longer. 1996 was the worst with the only six day episode and two three day episodes. More recently 2003 and 2004 had three and four day episodes.

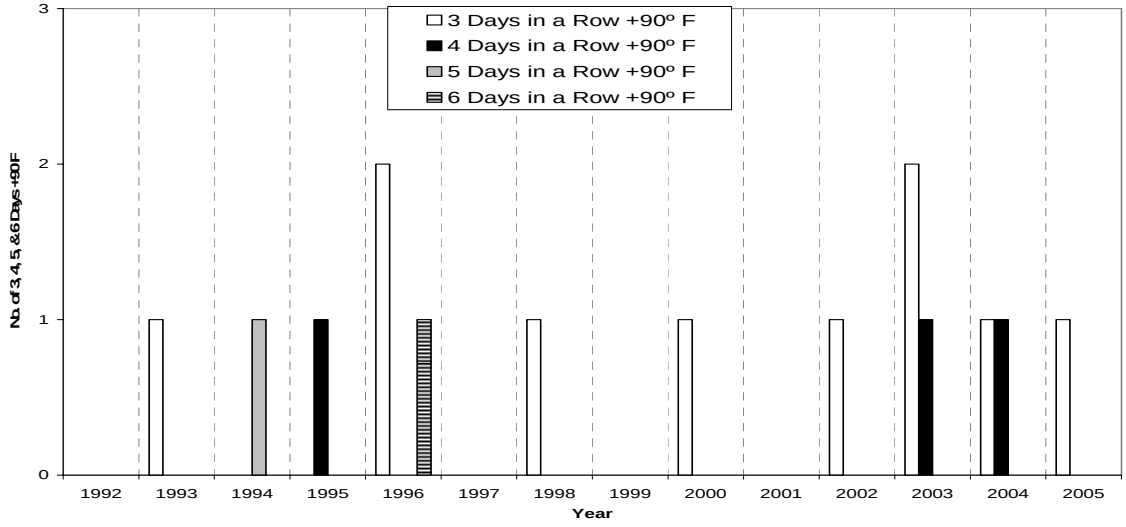

Figure 9. Three, four, five, and six day episodes of consecutive days ≥ 90ºF [5].

5 ODEQ measured temperature at SE Lafayette, Portland.

5. Ventilation

The ventilation can be represented using the ventilation index which is calculated by multiplying the wind speed and the mixing height. The mixing height is the elevation below which all ground level mixing occurs. The lower the ventilation index the poorer the mixing. The ventilation index for days with the highest one hour ozone values from 1977 to 1996 were presented in the *1996 Meteorological Factors Conducive to Ozone Formation in the Portland/Vancouver Area*[6]. This graph is reproduced in Figure 10 below.

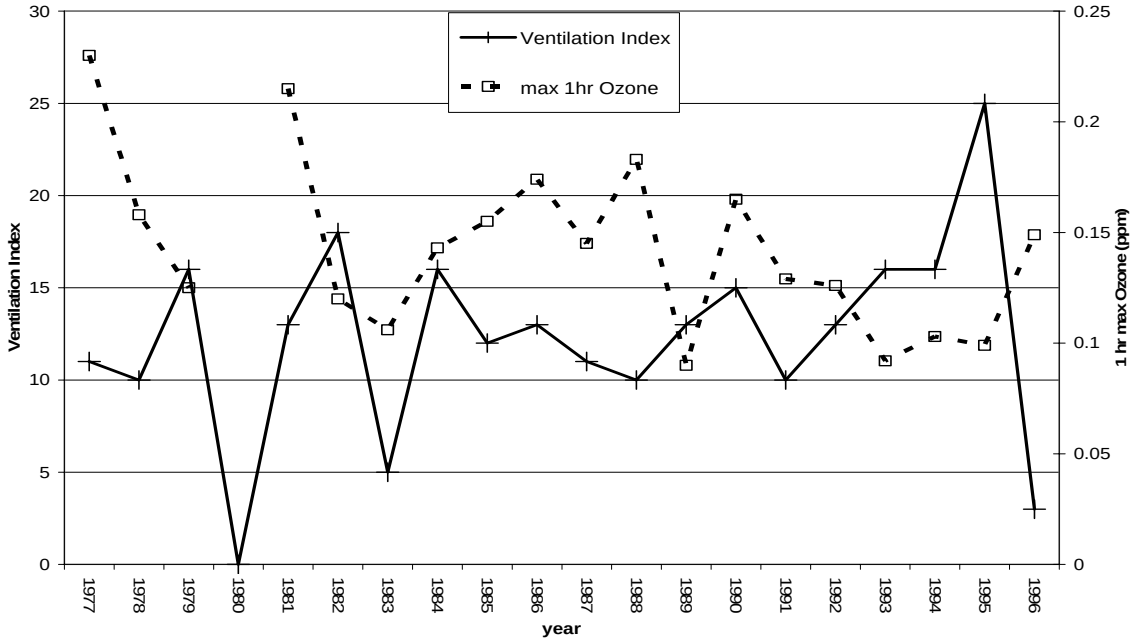

Figure 10. Ventilation index on the maximum one hour ozone day 1979-1996 [6].

The ventilation index for eight hour average ozone from 1998 to 2004[7] is shown in Figure 11. Not surprisingly, the ventilation index is poor for both one hour and eight hour average maximums ozone levels.

For reference, the Washington Department of Ecology displays the ventilation index categories in Table 1 for air stagnation levels on their web site. http://www.ecy.wa.gov/programs/air/aginfo/MM5Instructions.htm . Jackson County, Oregon uses a ventilation index of level of 400 to ban woodstove burning in winter.

6. Ventilation indices 1977 to 1996 provided by ODEQ 1996 Meteorological Factors Conducive to Ozone Formation in the Portland/Vancouver Area.

7. Ventilation indices 1998 to 2004 provided by Oregon Dept. of Ag. using Salem soundings.

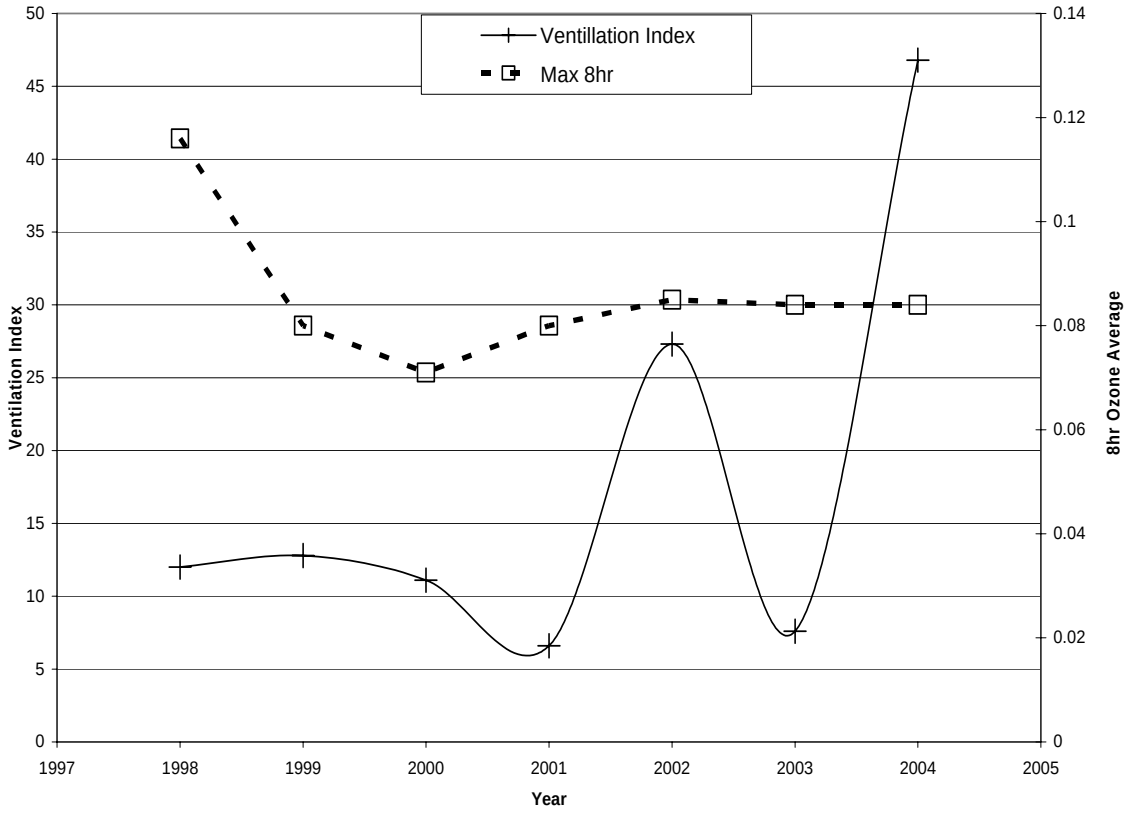

Figure 11. Ventilation index on the maximum 8hr ozone day 1998-2004 [7].

Table 1. Ventilation Index categories used for smoke management.

Ventilation Index	Dispersion
0-50	Very poor
50-2350	Poor
2350-4700	Marginal-Fair
> 4700	Good

6. Ventilation indices 1977 to 1996 provided by ODEQ 1996 Meteorological Factors Conducive to Ozone Formation in the Portland/Vancouver Area.
7. Ventilation indices 1998 to 2004 provided by Oregon Dept. of Ag. using Salem soundings.

6. Wind Speed

The horizontal wind speed impacts the ventilation index as well as the location of the ozone plume. The wind speeds for the maximum eight hour ozone for each year were below six miles per hour as shown in Figure 12. A low wind speed is one of the elements for poor ventilation the other being low mixing heights.

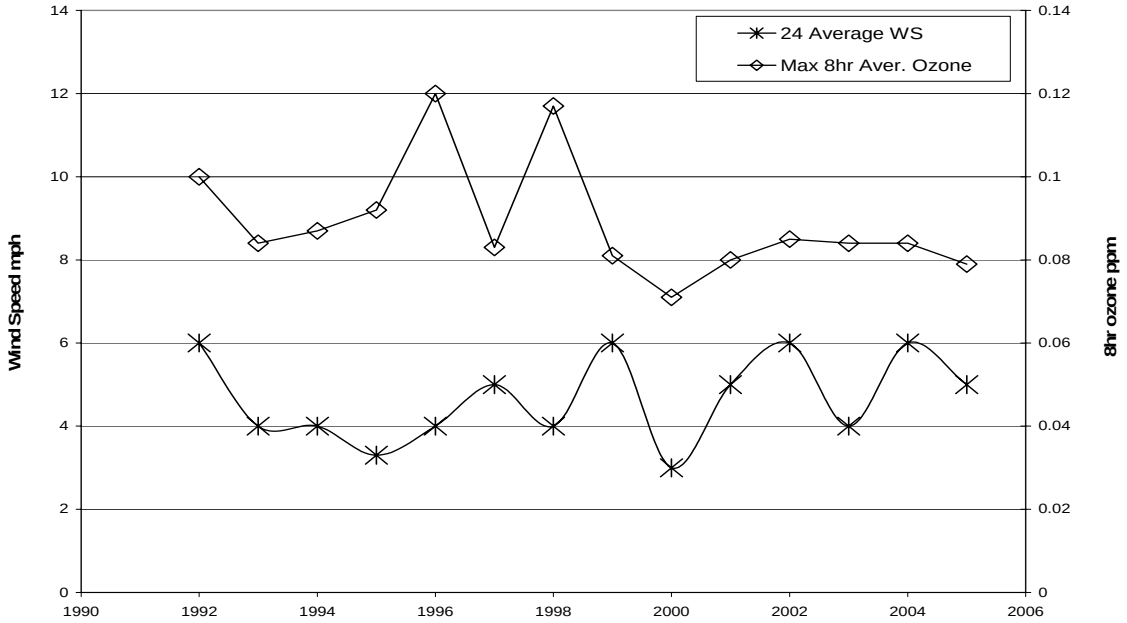

Figure 12. Wind speed on the maximum eight hour average ozone day 1992-2005[8].

7. High Ozone Episodes

A high ozone episode is defined in this report as a period of three or more consecutive days with maximum temperatures ≥ 90ºF, daily average wind speeds < 10 mph, and maximum solar radiation > 0.1 Langleys/minutes. Episodes are grouped into weekday or weekend events. The weekday episodes occurs entirely within the week. The weekend events end on Saturday.

Episode Identifying Method

To find episodes, the maximum daily temperatures at ODEQ's SE Lafayette, Portland site were identified and plotted from May through September. Figure 13 provides an example plot done for 1996 maximum temperatures. After these high temperature days were identified, the maximum daily eight hour ozone levels at all the Portland and Vancouver WA sites were retrieved. The wind speed, wind direction, solar radiation, and days of the week were also compiled. The dates with average wind speeds above 10 mph were removed from consideration. Days occurring in mid to late September were also not considered because their solar radiation levels were to low. The resulting three consecutive day episodes were compiled in Table 2. These days were grouped into weekday episodes and weekend episodes. One three episode per year was used for comparison between years. The episodes were selected based on similarities in the time of year, solar radiation, three day temperature trend, and low average wind speed.

8. Temperature collected by ODEQ at SE Lafayette.

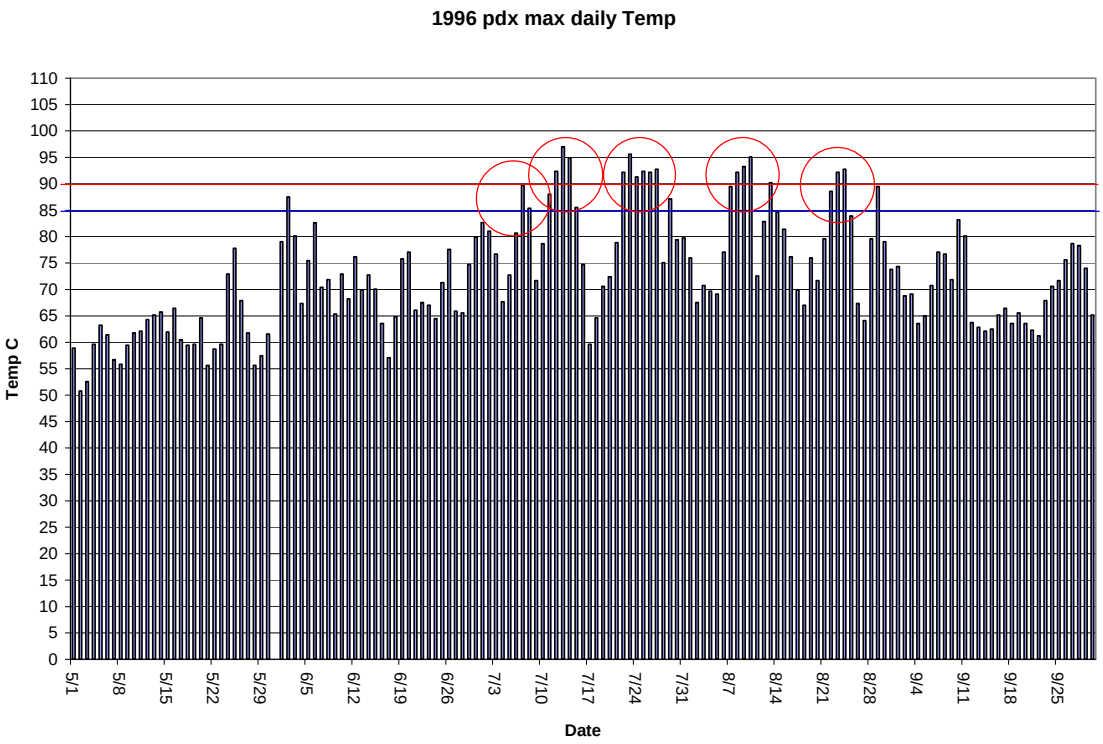

Figure 13. Maximum daily temperatures for 1996 in Portland[8].

8. Temperature collected by ODEQ at SE Lafayette.

Table 2. Three day ozone episodes with maximum temperatures ≥ 90ºF, average ws <10 mph, average solar radiation > 1 Langley/hr

Date	Day	SPR O3 max daily 8hr ave	MHS/ MSJ O3 max daily 8hr ave	SIS O3 max daily 8hr ave	WA O3 max daily 8hr ave	Max Temp	max SR	Aver WS mps	aver SR	max WS MPS
7/28/92	Tuesday	0.051	0.033	0.036	void	87	1.30	6.2	0.47	10.6
7/29/92	Wednesday	0.064	0.043	0.051	0.048	91	1.30	7.0	0.46	10.8
7/30/92	Thursday	0.082	0.078	0.066	0.097	100	1.30	4.4	0.46	8.1
8/2/93	Monday	0.057	0.047	0.060	0.053	93	1.23	8.0	0.44	13.2
8/3/93	Tuesday	0.047	0.045	0.065	0.041	98	1.23	8.1	0.39	13.9
8/4/93	Wednesday	0.074	0.073	0.072	0.078	97	1.20	3.9	0.42	6.6
9/6/93	Monday	0.058	0.053	0.043	0.043	90	1.03	5.3	0.30	9.7
9/7/93	Tuesday	0.057	0.038	0.062	0.051	89	1.02	4.2	0.32	7.0
9/8/93	Wednesday	0.058	0.051	0.054	0.048	90	1.05	4.2	0.33	6.6
6/28/95	Wednesday	0.046	0.046	void	0.050	89	1.28	9.7	0.47	18.7
6/29/95	Thursday	0.057	0.053	0.051	0.057	92	1.28	9.7	0.47	17.8
6/30/95	Friday	0.083	0.063	0.062	0.069	97	1.29	7.1	0.46	12.1
7/11/96	Thursday	0.067	0.054	0.059	0.057	88	1.33	8.2	0.49	14.3
7/12/96	Friday	0.074	0.063	0.062	0.067	92	1.35	7.7	0.50	13.2
7/13/96	Saturday	0.106	0.085	0.069	0.081	97	1.34	6.6	0.49	11.7
8/7/96	Wednesday	0.051	0.038	0.053	0.048	89	1.27	6.9	0.45	12.1
8/8/96	Thursday	0.073	0.057	0.066	0.067	92	1.26	6.9	0.44	12.3
8/9/96	Friday	0.079	0.061	0.069	0.066	93	1.26	6.7	0.44	12.1

9. Ozone measured by ODEQ and Southwest Washington Clean Air Agency, Meteorological data measured at SE Lafayette, Portland.

8/22/96	Thursday	0.048	0.036	0.040	0.046	89	1.21	6.9	0.40	10.3
8/23/96	Friday	0.065	void	0.059	0.056	92	1.18	7.8	0.39	11.9
8/24/96	Saturday	0.073	0.063	0.065	0.067	93	1.10	6.0	0.35	10.3
7/26/98	Sunday	0.116	0.100	0.073	0.070	98	1.26	3.9	0.43	6.2
7/27/98	Monday	0.088	void	0.077	0.078	97	1.27	4.0	0.38	7.7
7/28/98	Tuesday	0.098	0.074	0.062	0.075	99	1.25	5.3	0.45	11.7
6/26/00	Monday	0.056	0.049	0.054	0.054	91	1.28	7.3	0.48	11.2
6/27/00	Tuesday	0.061	0.057	0.066	0.058	96	1.28	5.2	0.47	9.8
6/28/00	Wednesda	0.067	0.048	0.040	0.045	92	1.29	5.3	0.48	10.2
8/8/01	Wednesday	0.049	0.040	0.047	0.046	86	1.24	8.0	0.43	14.4
8/9/01	Thursday	0.081	0.067	0.055	0.063	96	1.25	4.7	0.43	6.4
8/10/01	Friday	0.077	0.066	0.068	0.071	90	1.21	4.6	0.42	7.8
7/22/04	Thursday	0.058	0.054	0.058	0.056	98	1.23	7.0	0.44	12.8
7/23/04	Friday	0.051	0.051	0.061	0.049	102	1.24	6.5	0.45	9.5
7/24/04	Saturday	0.084	0.077	0.058	0.065	100	1.22	6.1	0.44	11.9

9. Ozone measured by ODEQ and Southwest Washington Clean Air Agency, Meteorological data measured at SE Lafayette, Portland.

Three Day Episode Results

Figure 14 shows weekday ozone episodes from 1992 to 2005. Figure 15 displays weekend ozone episodes from 1996 and 2004.

Ozone on the weekday episodes exhibit a slight negative trend with a slope of -0.004. The maximum temperatures for these episodes dropped more significantly -0.01. This temperature drop only refers to the episodes selected and is not reflective of the temperature trends in Portland/Vancouver. The maximum temperatures in the episodes selected were lower toward the end of the 14 year period and could explain in part why the ozone levels in this graph were also lower. The weekend episode data shown in Figure 15 closely track the meteorological parameters.

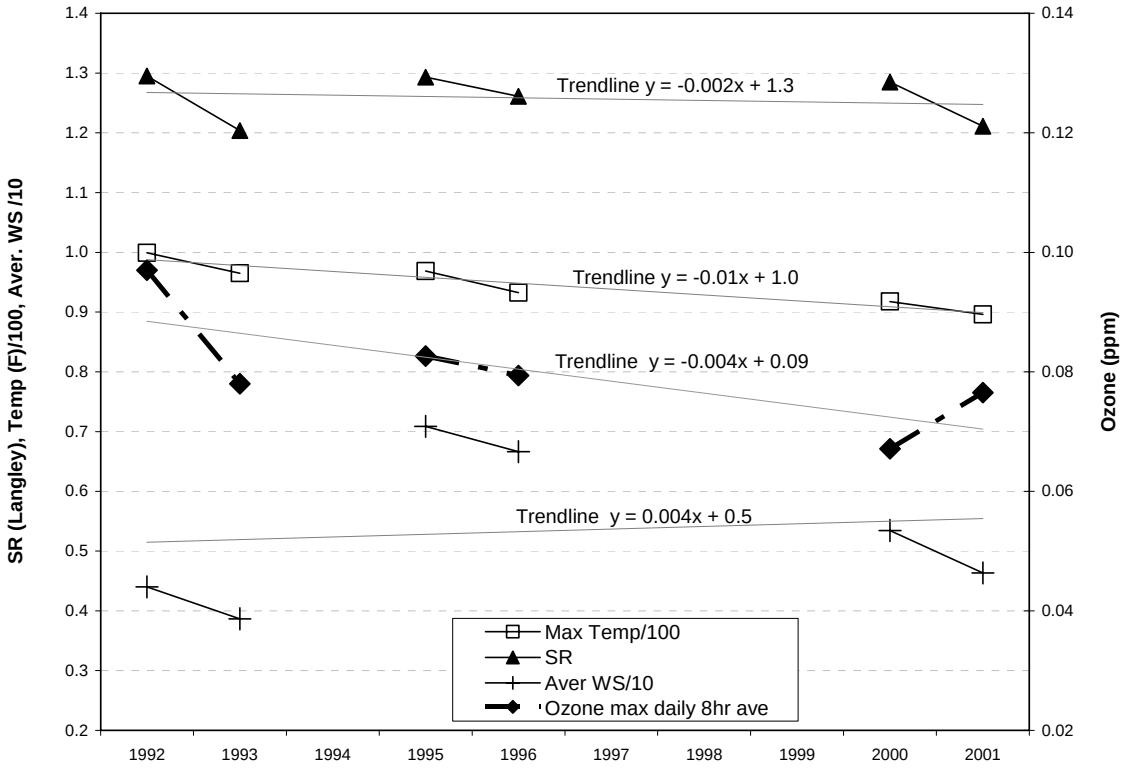

Figure 14: Three day episodes with maximum temperatures ≥ 90ºF, wind speed < 10mph, Solar Radiation >1 Langleys/hr, all weekdays[9].

9. Ozone measured by ODEQ and Southwest Washington Clean Air Agency, Meteorological data measured at SE Lafayette, Portland.

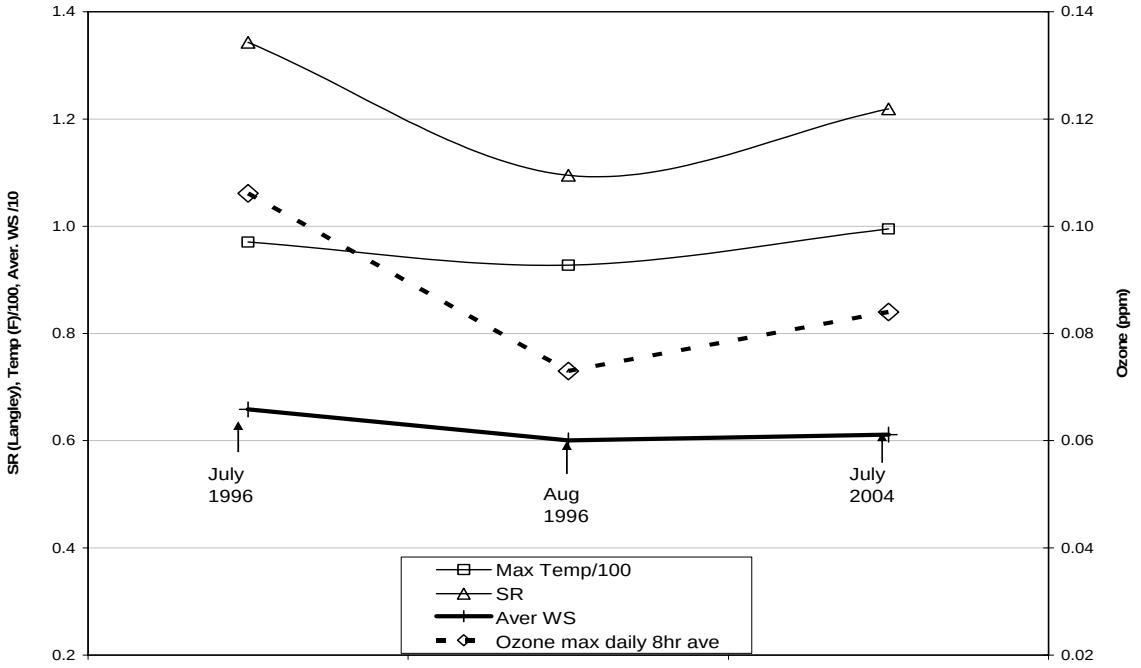

Figure 15: Three day episodes with maximum temperatures ≥ 90ºF, wind speed < 10mph, Solar Radiation >1 Langley/hr with third day on Saturday[9].

1998 and 2003 episode comparison.

In 2003 there were three multi-day episodes with temperatures ≥ 90ºF but the maximum ozone level only reached 0.084 ppm. Conversely, in 1998 there was only one multi-day episode ≥ 90ºF and the maximum level reached 0.116 ppm. If the maximum daily temperature criteria were lowered to ≥ 88ºF, there are more episodes to consider.

Three day episodes

In 1998 there is one three day episode and in 2003 there are two three day episodes ≥ 88ºF (Table 2). These episodes all include at least one weekend day, however, one starts on a Sunday, one ends on Saturday, and one includes both Saturday and Sunday. All three days in the 1998 episode have maximum temperatures in the high 90s and only one day in the 2003 episodes has a temperature in the high 90s. Solar radiation and wind speeds are comparable. Figure 16 compares these three episodes. There is a drop in ozone levels in 2003 from 1998, however, the temperature in the 2003 episodes is also lower and the wind speed are higher. The 1998 maximum ozone level occurs on the first day (Sunday) of the three day episode. The proceeding day had a maximum temperature of 85ºF and a maximum 8 hour ozone of 0.067ppm. The eight hour ozone level had a jump of 0.05 ppm in one day. The first days of the 2003 episode were both only 0.002ppm higher than the proceeding day.

9. Ozone measured by ODEQ and Southwest Washington Clean Air Agency, Meteorological data measured at SE Lafayette, Portland.

Table 2. Three day ozone episodes with maximum temperatures ≥ 88ºF, average ws <10 mph, average solar radiation > 1 Langley/hr[9]

Year	Date	Day	Max O3	Max Temp (X10)	max SR	aver SR	Aver WS mph	max WS MPS
1998	7/26/98	Sun	**0.116**	9.8	1.26	0.43	4	6.2
	7/27/98	Mon	**0.088**	9.7	1.27	0.38	4	7.7
	7/28/98	Tue	**0.098**	9.9	1.25	0.45	5	11.7
2003	6/5/03	Thr	**0.070**	9.0	1.33	0.50	8	13.7
	6/6/03	Fri	**0.071**	9.6	1.31	0.49	6	10.4
	6/7/03	Sat	**0.071**	9.0	1.29	0.47	5	9.3
2003	6/27/03	Fri	**0.046**	8.8	1.29	0.48	7	11.8
	6/28/03	Sat	**0.066**	9.2	1.32	0.47	7	13.1
	6/29/03	Sun	**0.055**	8.9	1.29	0.47	9	14.0

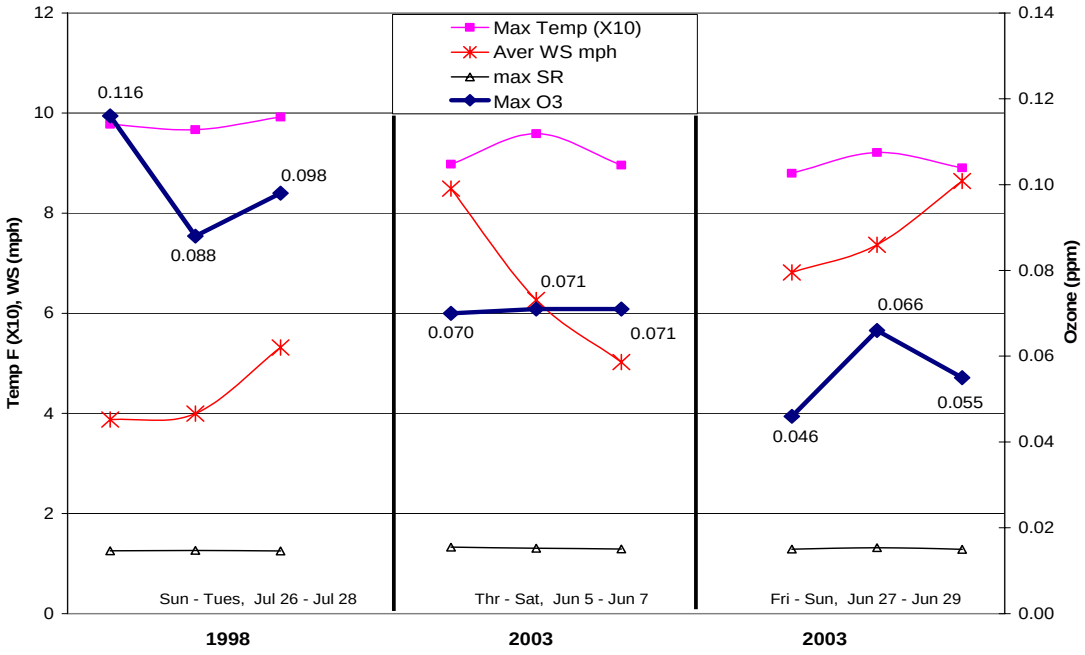

Figure 16. 1998 and 2003 three day episodes with temperatures ≥ 88ºF, ws < 10mph, > 1 Langley/hr[9].

9. Ozone measured by ODEQ and Southwest Washington Clean Air Agency, Meteorological data measured at SE Lafayette, Portland.

Four day episodes

Two four day episodes with similar meteorological patterns occurred in 1998 and 2003 in early September (Table 3). The maximum ozone levels during these two four day episodes were virtually identical and they both occurred in the second day of the four day stretch (Figure 17).

Table 3. Four day ozone episodes with maximum temperatures ≥ 88ºF, average ws <10 mph, average solar radiation > 1 Langley/hr

Year	Date	Day	Max O3	Max Temp (X10)	max SR	aver SR	Aver WS mph	max WS MPS
1998	8/31/98	Mon	0.079	9.6	1.1	0.36	6	9.2
	9/1/98	Tue	0.081	9.1	1.1	0.36	5	9.7
	9/2/98	Wed	0.041	8.8	1.1	0.36	7	11.2
	9/3/98	Thr	0.053	8.9	1.1	0.35	7	11.2
2003	9/2/03	Tue	0.055	9.2	1.0	0.33	5	6.8
	9/3/03	Wed	0.084	9.2	1.0	0.30	4	6.6
	9/4/03	Thr	0.075	9.2	1.0	0.33	4	6.6
	9/5/03	Fri	0.050	9.0	1.1	0.34	4	6.9

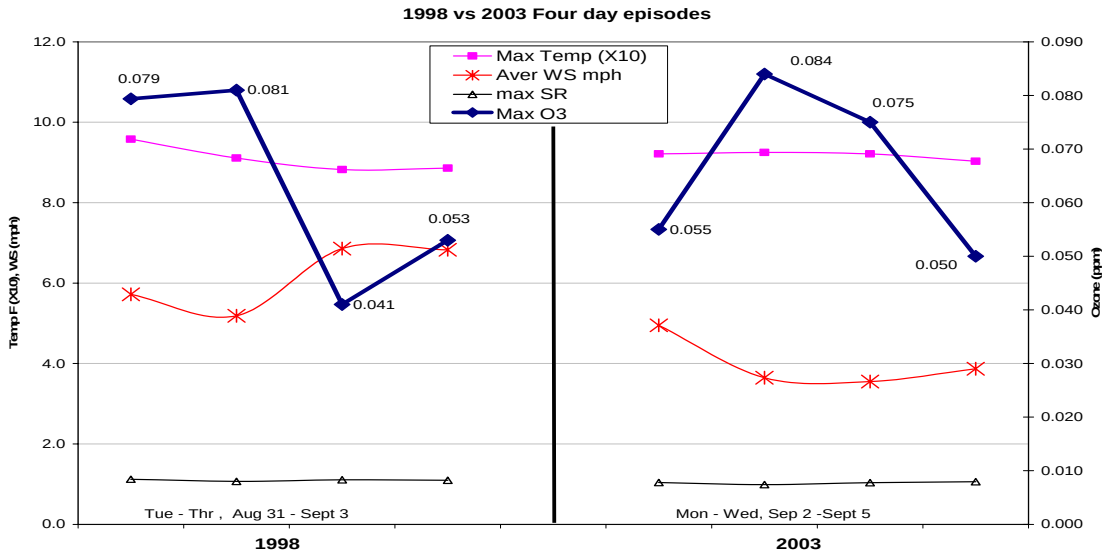

Figure 17. 1998 and 2003 four day early September episodes with temperatures ≥ 88ºF, ws < 10mph, > 1 Langley/hr.

9. Ozone measured by ODEQ and Southwest Washington Clean Air Agency, Meteorological data measured at SE Lafayette, Portland.

Discussion:
In the last 14 years, ozone levels in Portland and Vancouver have been going down slightly while the population and the vehicle miles traveled continued to grow. The number of consecutive days with temperatures over 90ºF went up during the same period. When similar high temperature episodes were compared over the years, ozone trends also were slightly negative. Portland also witnessed a drop in precursor pollutants concentrations which helps explain the lower than expected ozone levels. The wind speed and ventilation on maximum ozone days were typical for stagnant conditions and were not a factor in the ozone trending.

The 2003 episodes were evidence of this. 2003 had more episodes than a similar hot year, 1998, but had a much lower maximum. The 1998 maximum occurred on a Sunday and jumped 0.05 ppm in one day. This is a very large rate of increase for the eight hour average and indicates that there was much more activity on Sunday than usual along with low wind speeds and high temperatures. The 1998 solar radiation levels were actually lower than the 2003 episodes however. The Monday following this event was a Clean Air Action Day and could have helped lower the precursor pollutants levels. The 2003 episodes had lower ozone levels with similar meteorological factors which could mean lower precursor levels were present. The precursor trends shown in Figures 4 through 7 above prove this to be true.

Conclusion:
The slightly negative ozone trend, the upward temperature trends, and the negative precursor trends would indicate that the ozone reduction programs are working. This argument can be made because the Portland/Vancouver population and total vehicle miles traveled continues to grow. However, many of the VOC controls are already in place and Portland/Vancouver could see more ozone with the expected population growth. The Oregon Low Emission Vehicle program is new in 2005-2006 and may result in further reduction in precursors per VMT.

References

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Simplified Ozone Formation

Ozone (O_3) is a secondary pollutant produced by the photolysis of Nitrogen Dioxide (NO_2) to NO and a single oxygen (O). The single Oxygen (O) bonds to Oxygen (O_2) in the presence of any solid material. In summary the reaction is:

$$NO_2 + O_2 + m \xrightarrow{h\nu} NO + O_3 + m$$

Ozone readily reacts with Nitrogen oxide (NO) to return to oxygen when the ultra violet radiation levels drop.

$$NO + O_3 \xrightarrow{nohv} NO_2 + O_2$$

This is an equilibrium which can be driven to produce more ozone by the addition of more NO_2. NO_2 is formed indirectly from the degradation of volatile organic carbons (RHOC) in the presence of free radicals (OH•) and ultraviolet radiation. The RHOC and OH• produce another free radical HO_2• which can react with NO to form NO_2 and another free radical (OH•).

$$OH\bullet + RHOC \xrightarrow{h\nu} NO + HO_2\bullet \longrightarrow NO_2 + OH\bullet$$