Spatial and Temporal Patterns of Ozone at Great Smoky Mountains National Park and Implications for Plant Responses

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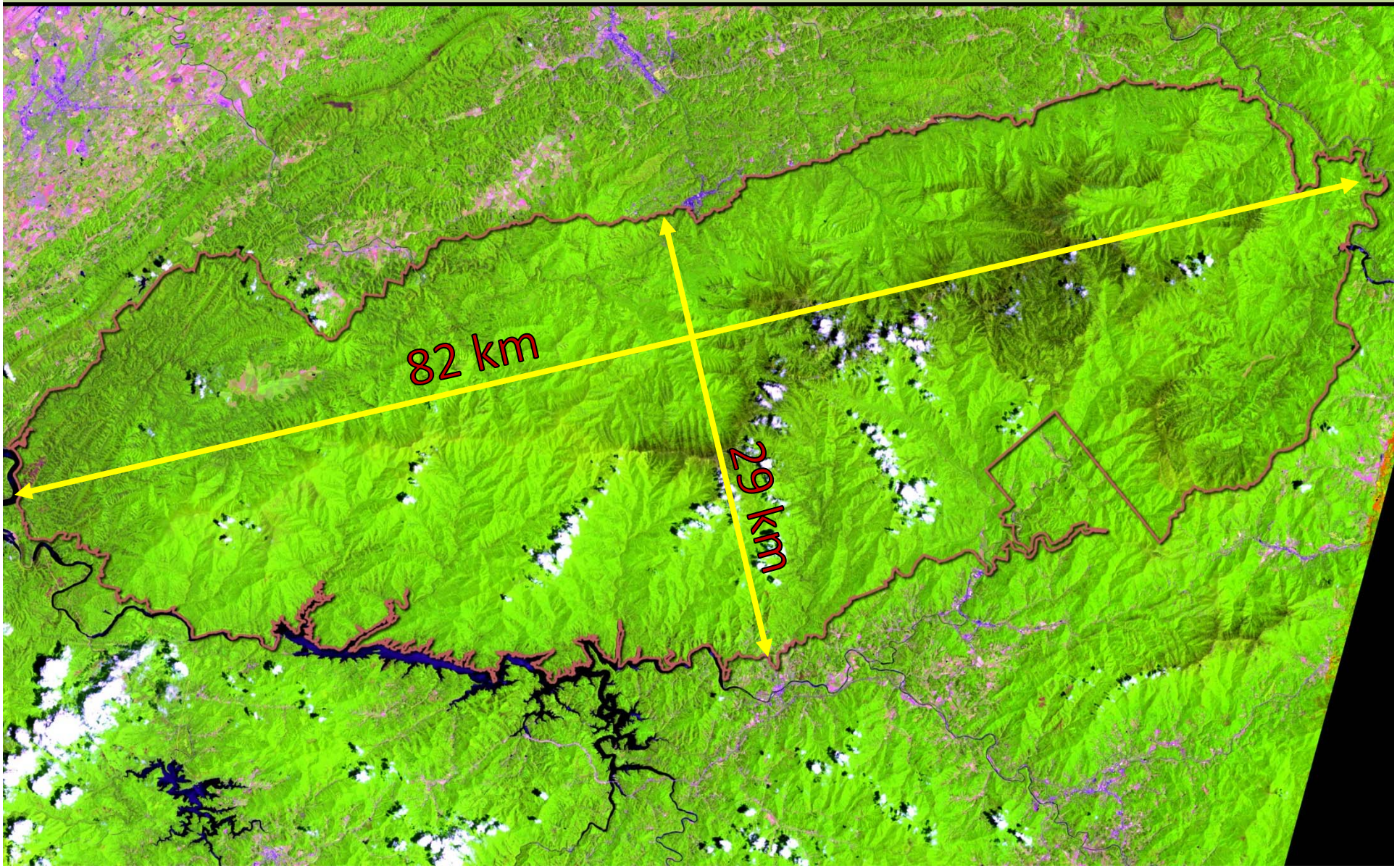
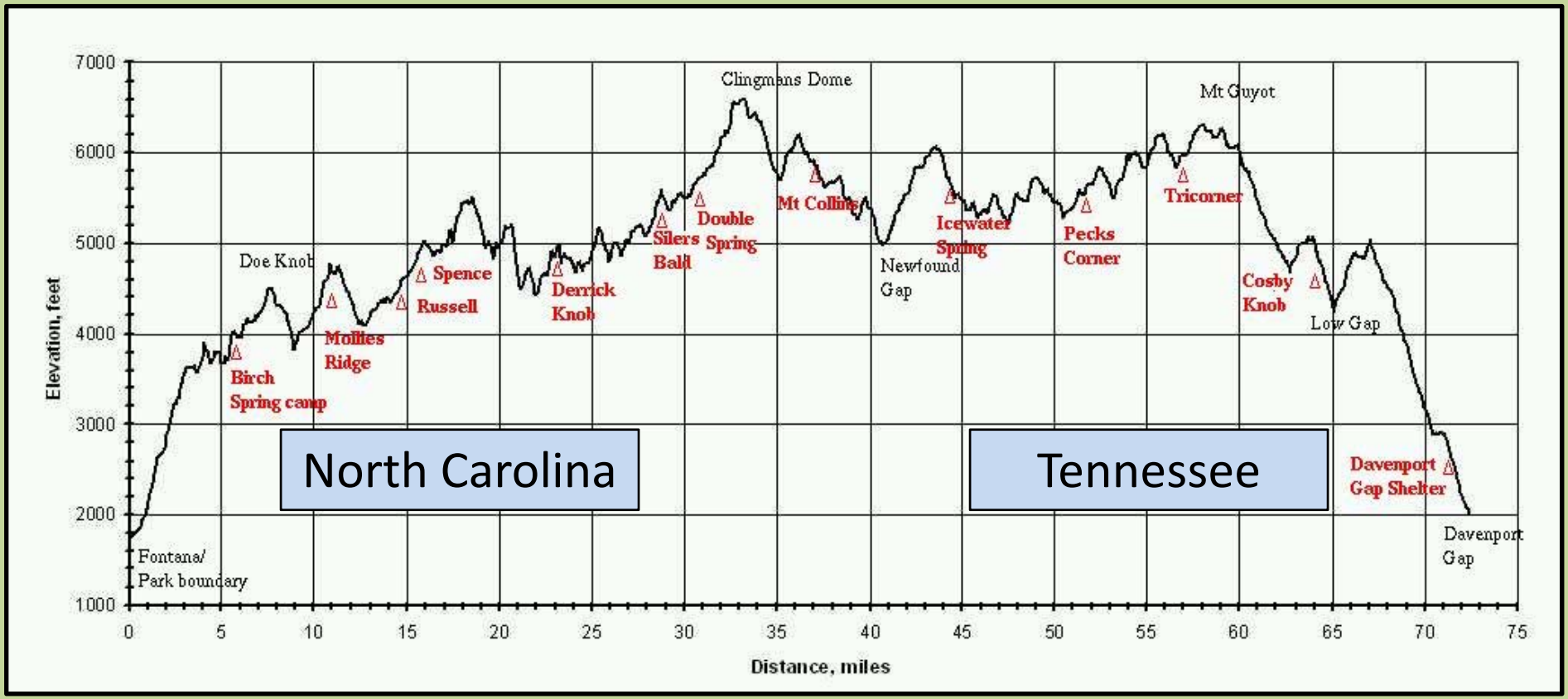
Great Smoky Mountains National Park Science Colloquium
Park Vista Hotel, Gatlinburg, TN
Thursday, March 22, 2018


GREAT SMOKY
MOUNTAINS
NATIONAL PARK
AN INTERNATIONAL BIOSPHERE RESERVE

Landsat Image of
Great Smoky Mountains National Park



Elevational Profile of Great Smoky Mountains National Park

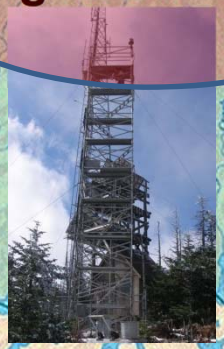


Park elevations range from 267 m to 2025 m

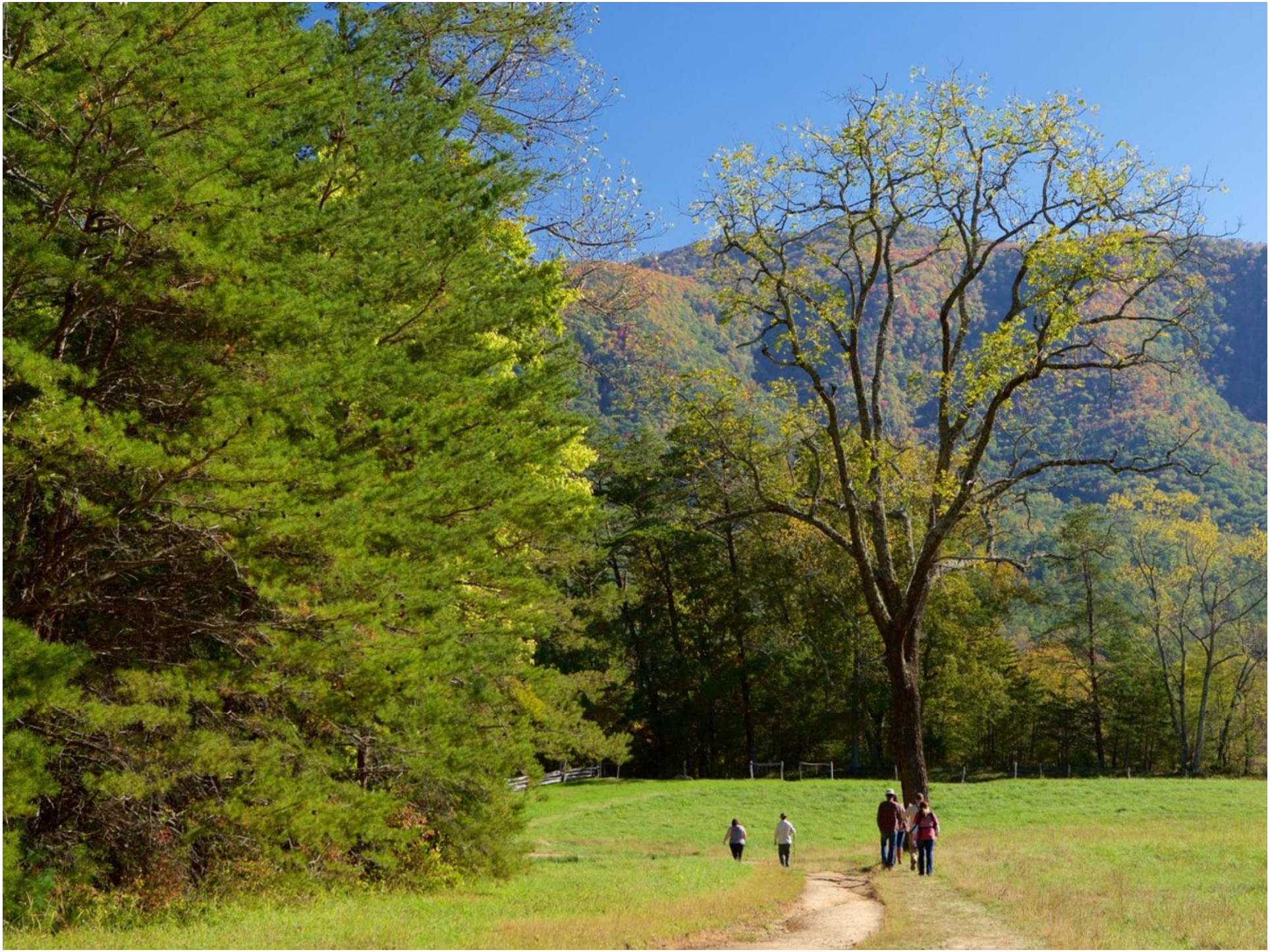
Figure courtesy Univ. TN

Air Quality and Climate Monitoring Stations

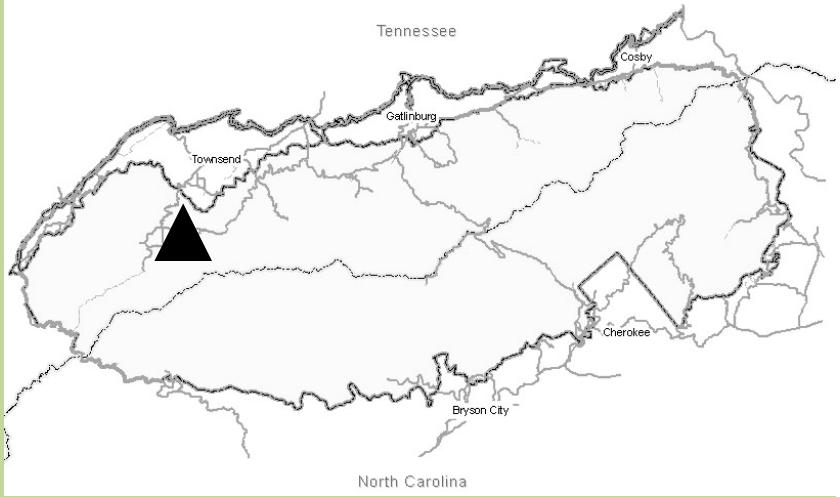
Air Quality Climate



Cove Mtn
HQ
Elkmont
Look Rock
Abrams Creek
Cades Cove
Clingmans Dome
Twin Creeks
Mt. LeConte
Newfound Gap
Noland Divide
Purchase Knob
Barnett Knob
Oconaluftee
Bryson City
Waynesville
Cosby
Big Creek
Smokemont
Twentymile
Fontana Village
CHEROKEE INDIAN RESERVATION
TN
NC
0 5 10 15 miles



Cades Cove, TN



- Low-elevation open valley
- 564 m
- Monitored since 1994
- Year-round
- NPS, TDEC


Photo by NPS

Look Rock, TN

- Pine-Oak Ridgetop
- 823 m
- Since 1984
- Year-round
- NPS, TVA, TDEC

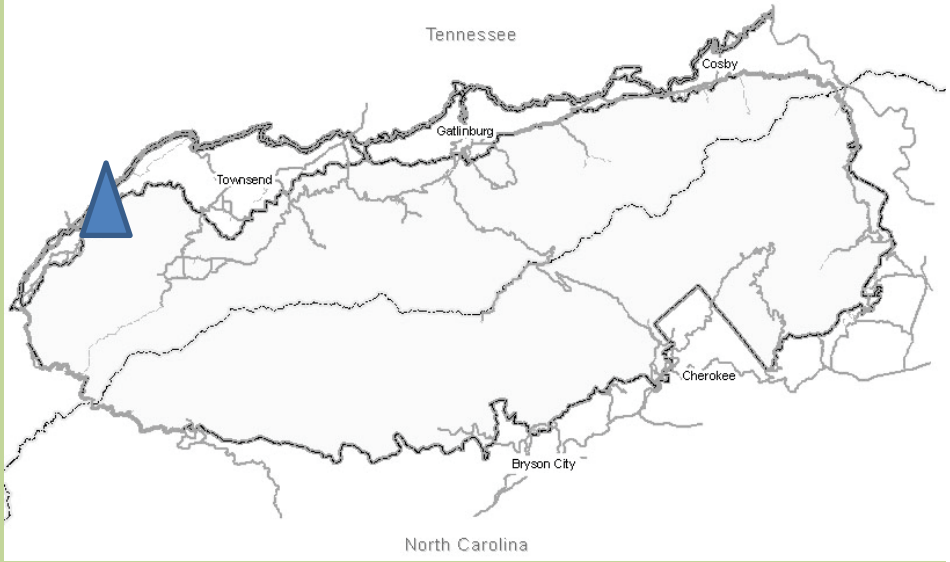
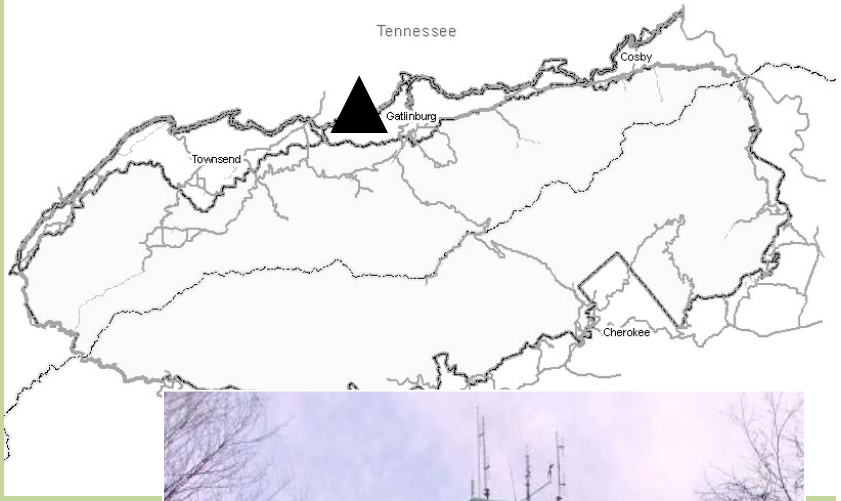



Photo by Brian Stansbury

Cove Mountain, TN

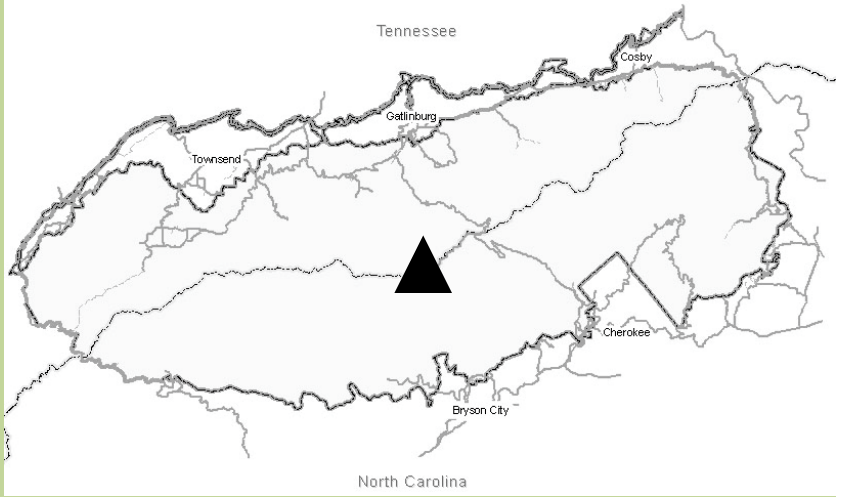


- High-elevation mountaintop
- Hardwood forest
- 1265 m
- Monitored since 1988
- Year-round
- NPS, TDEC, TVA

View of Cove Mountain from Wear's Valley

Photo by Jay Fradd

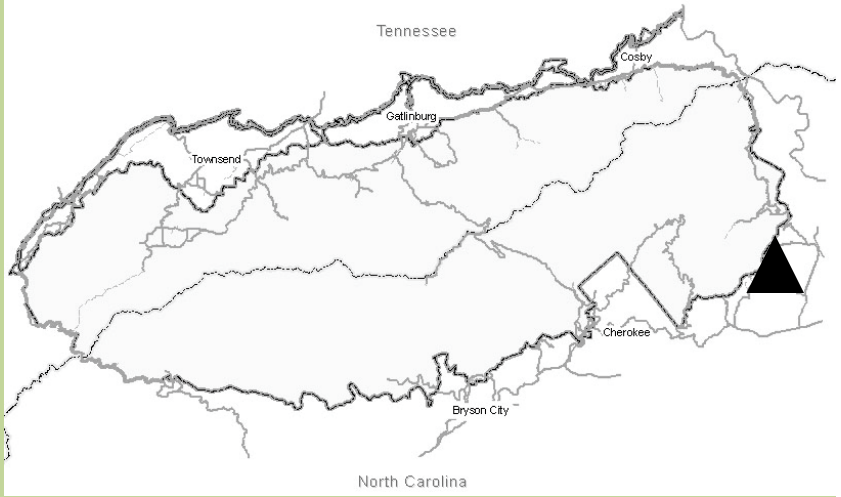
Clingmans Dome, TN/NC



- Highest Point in Park
- 2030 m
- Since 1993
- Seasonal
- NPS, TVA, EPA, TDEC

View from Clingmans Dome courtesy of PBS

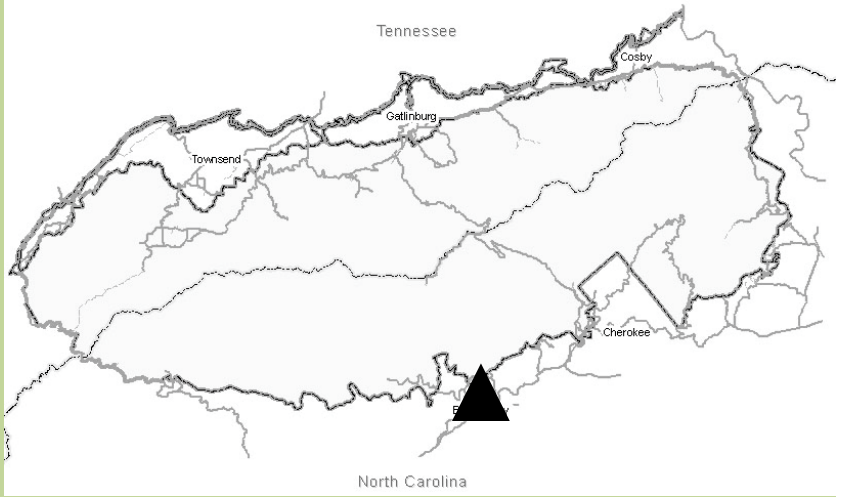
Purchase Knob, NC



- High-elevation ridgetop
- Northern hardwoods
- Since 1995
- Year-round
- NPS, NCDENR, NOAA

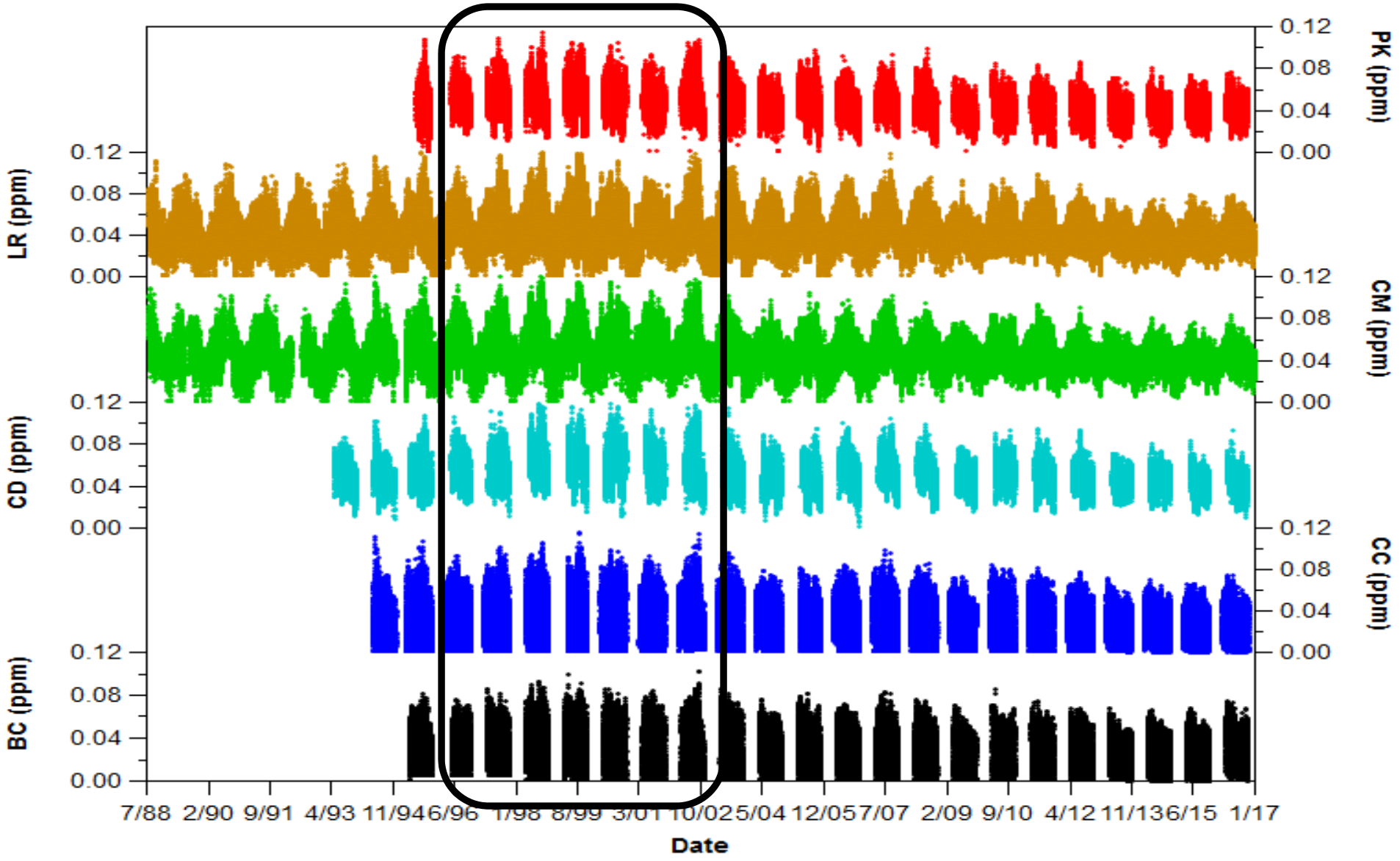
View from Purchase Knob

Bryson City, NC

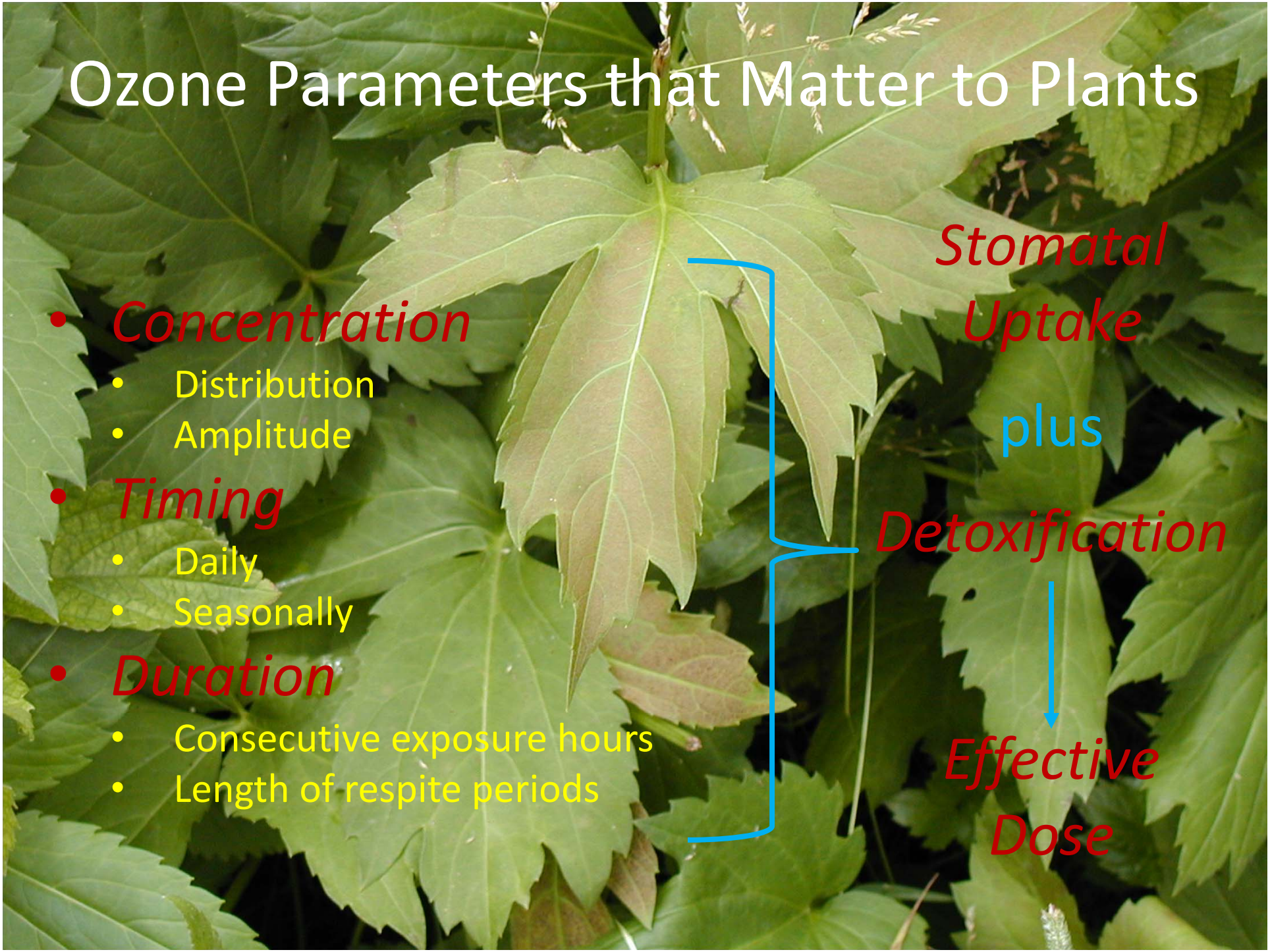


- Low-elevation meadow
- Northern hardwoods
- Since 1995
- Year-round
- NPS, NCDENR, NOAA

Ozone Trends at Six Sites in or Near Great Smoky Mountains National Park



Ozone Parameters that Matter to Plants



Environmental Interactions Affecting Plant Responses to Ozone

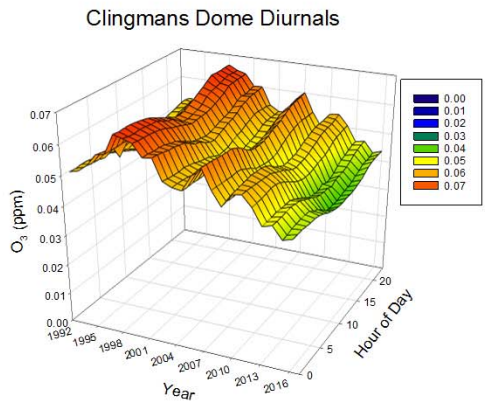
- *Spatial Variation*
  - Elevation is main factor contributing to variation in:
    - *Species Distributions*
    - *Phenological Timing*
    - *Forest Structure*
    - Weather -
      - *Temperature*
      - *Relative Humidity*
      - *Precipitation*
      - *Nitrogen Deposition*

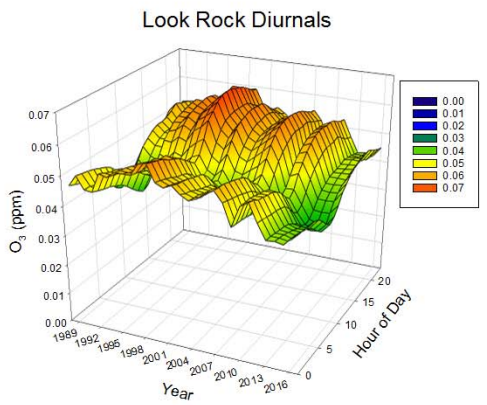
All of these affected by global climate change

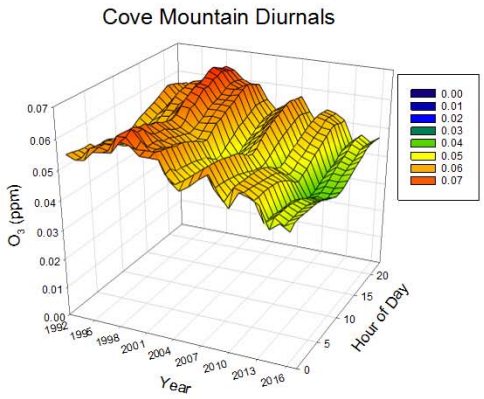
Diurnal Ozone Patterns Over the Years in GRSM

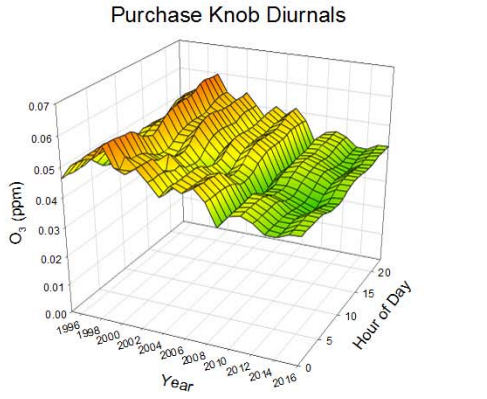
High and Mid-Elevation Sites

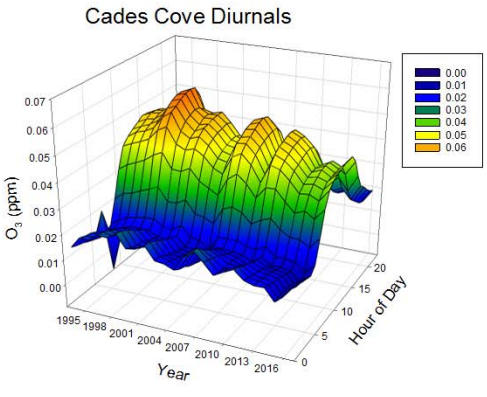
Low Elevation Sites

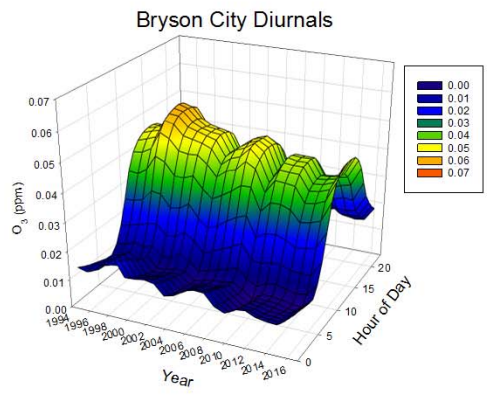




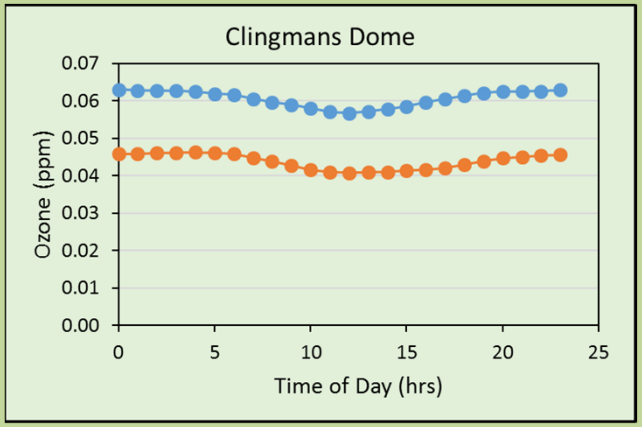


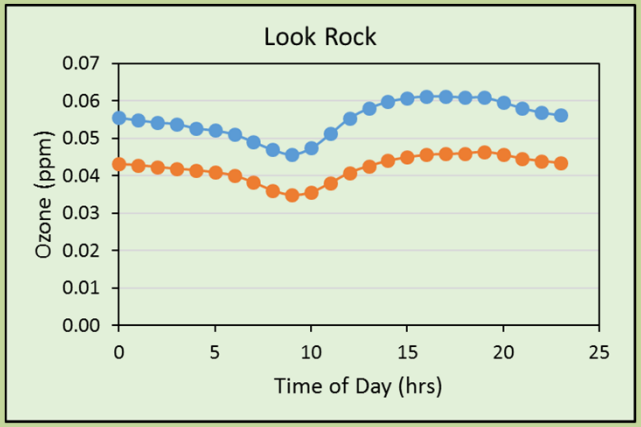






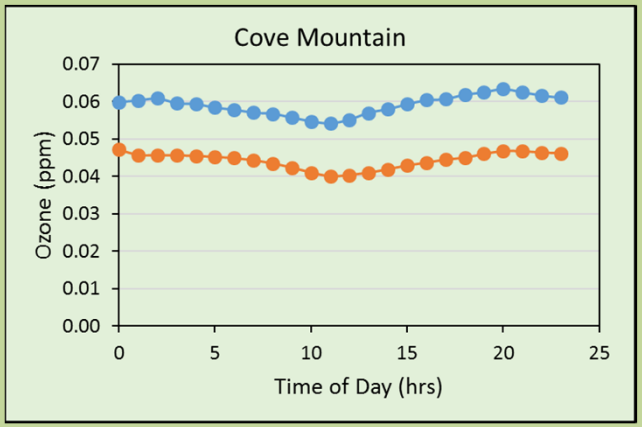
Δ 18 ppb

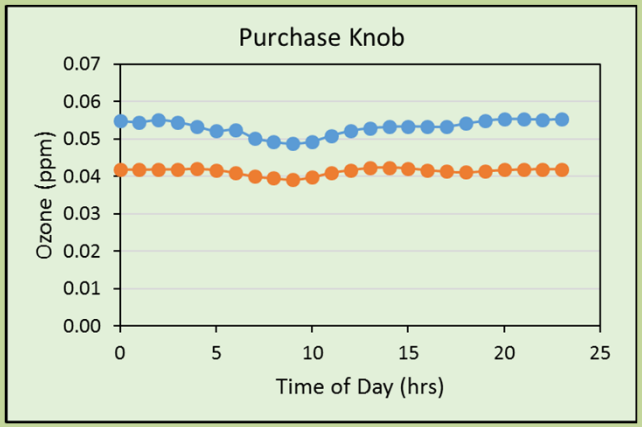




Δ 16 ppb

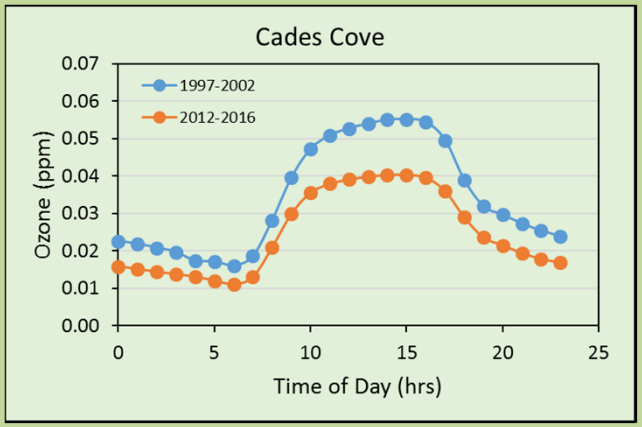
Δ 17 ppb

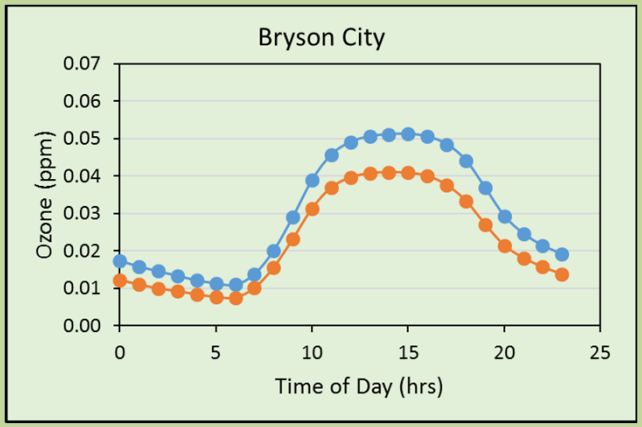




Δ 14 ppb

Δ 15 ppb





Δ 11 ppb

W126 Index

$$W126 = \sum[O_3] * w_i$$

Where:

$[O_3]$ = hourly ozone concentration

w_i is a weighting factor and,

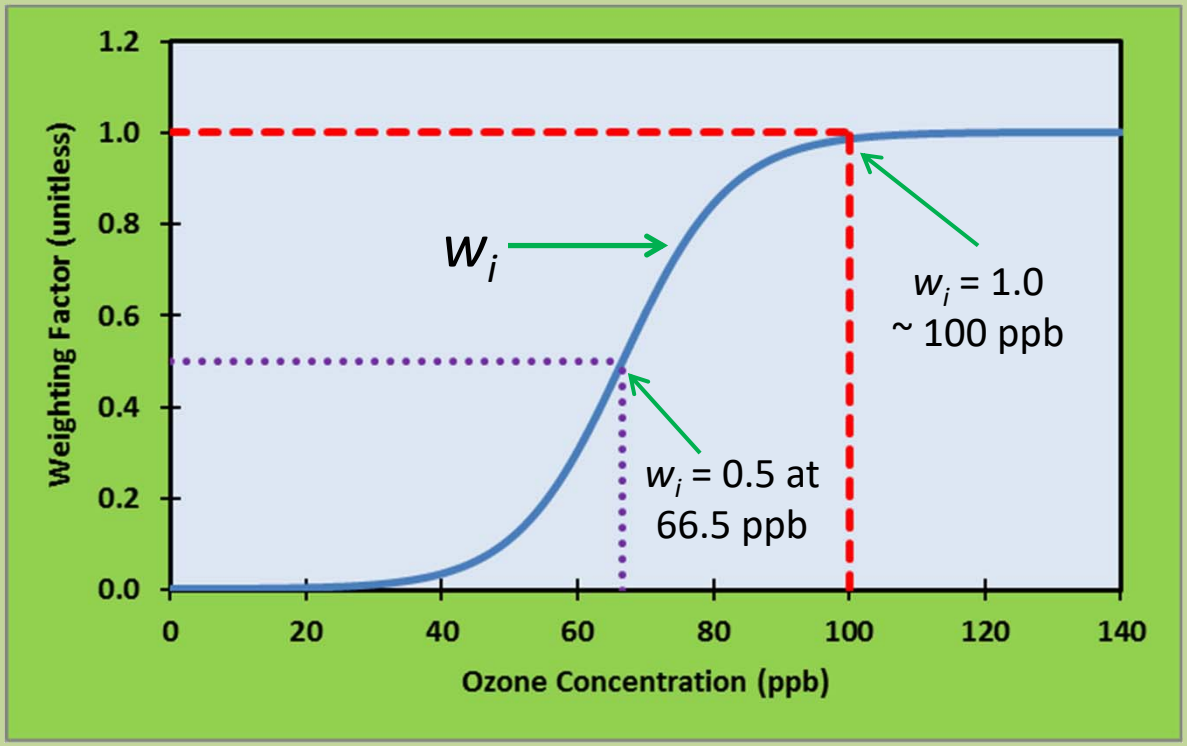
ranges from 0.0 when $[O_3]$ = 0 to 1.0 when $[O_3]$ ~ 100 ppb

$$w_i = \frac{1}{\left[1 + M * e^{-([O_3] * c_i)}\right]}$$

where:

M = 4403

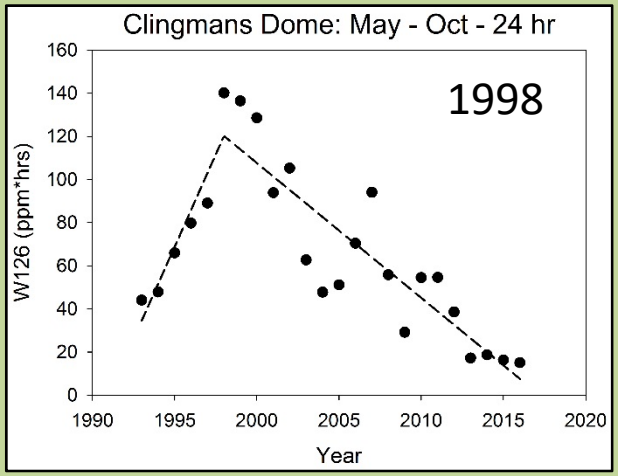
c_i = 0.126 ppm

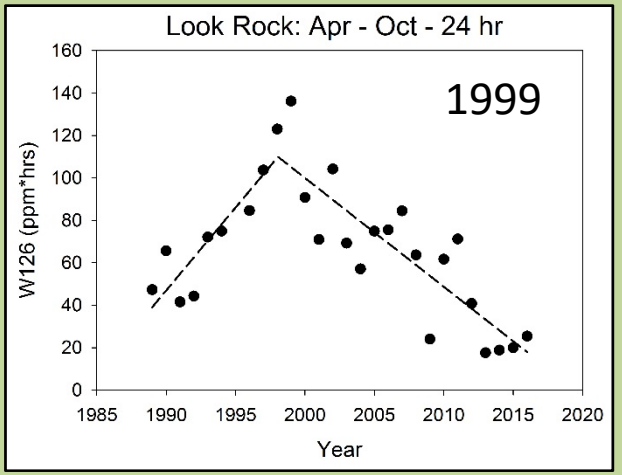


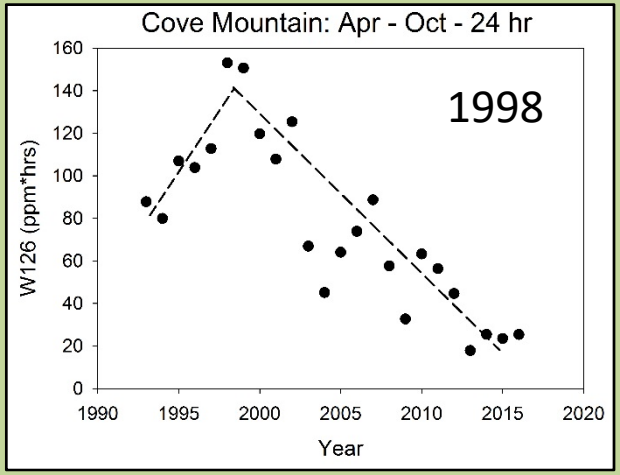
Piecewise Regressions show inflection points for ozone trends between 1998-1999

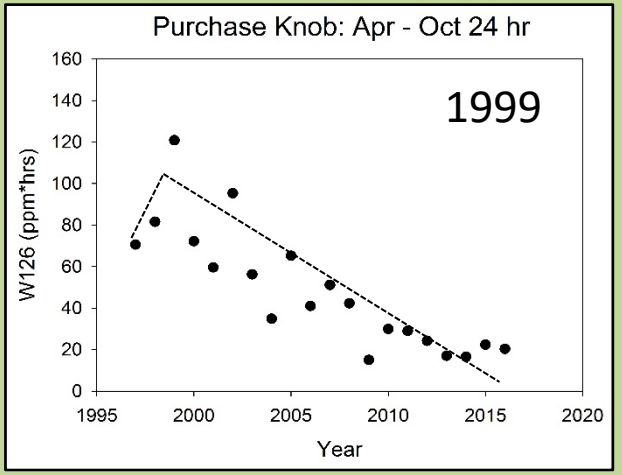
Mann-Kendall analyses show highly significant increasing trends (except for PK) up to 1999 and decreasing trends (all sites) after 1999

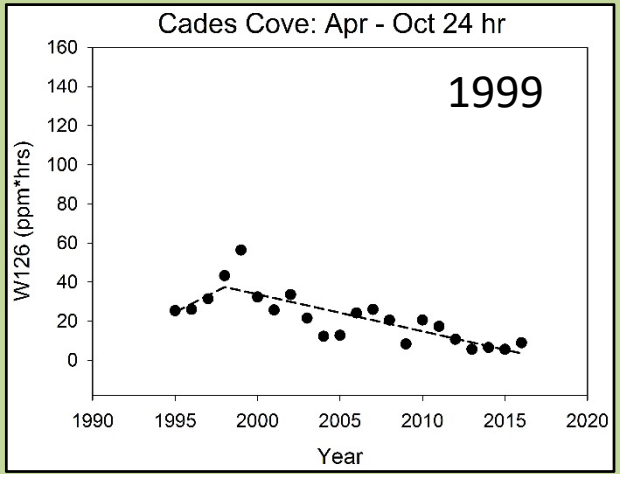
Thanks to Montana Eck for doing the Mann-Kendall analyses

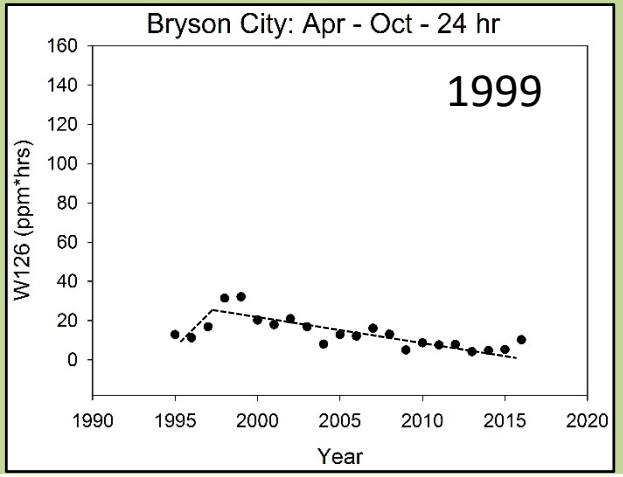


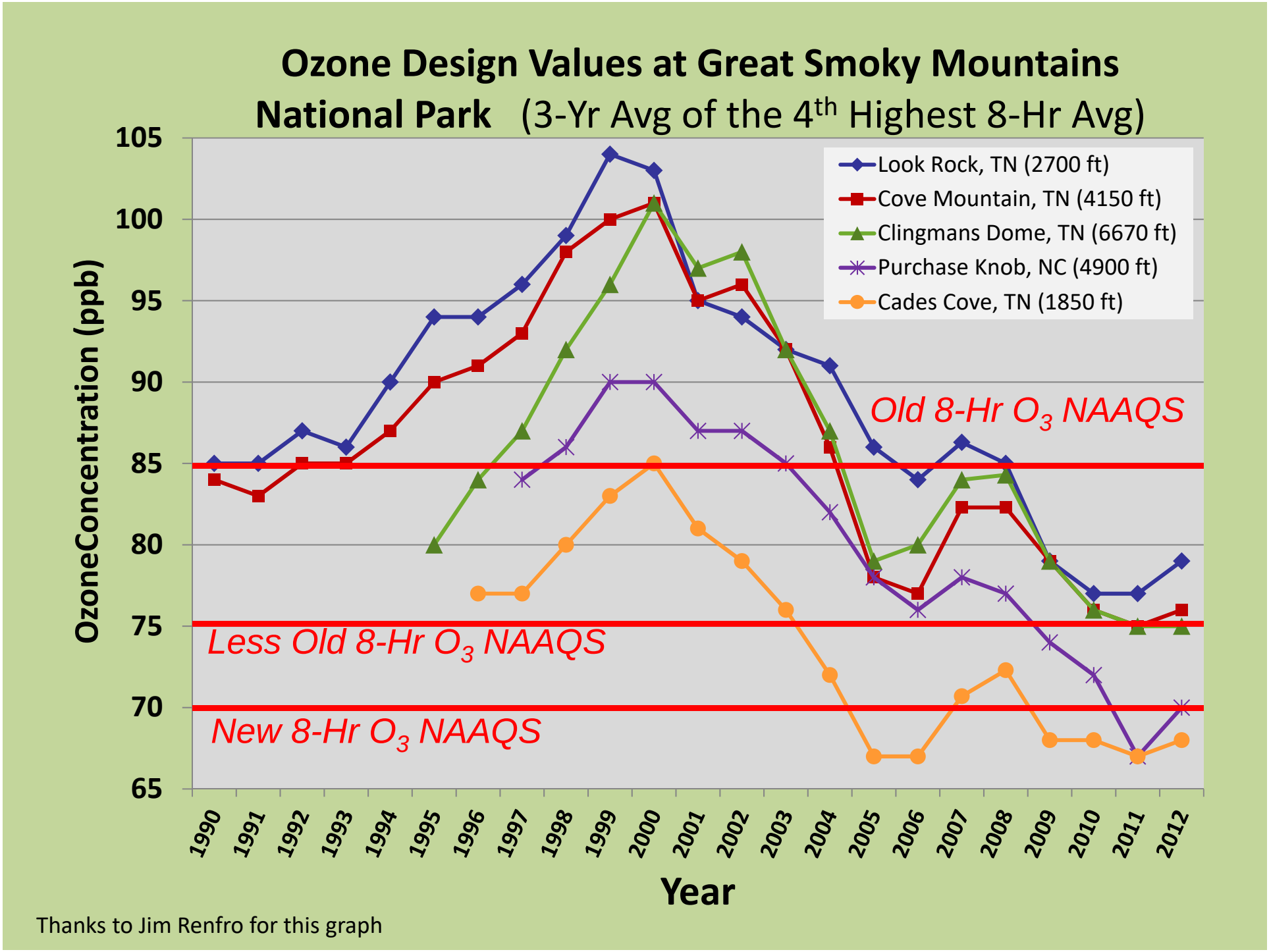












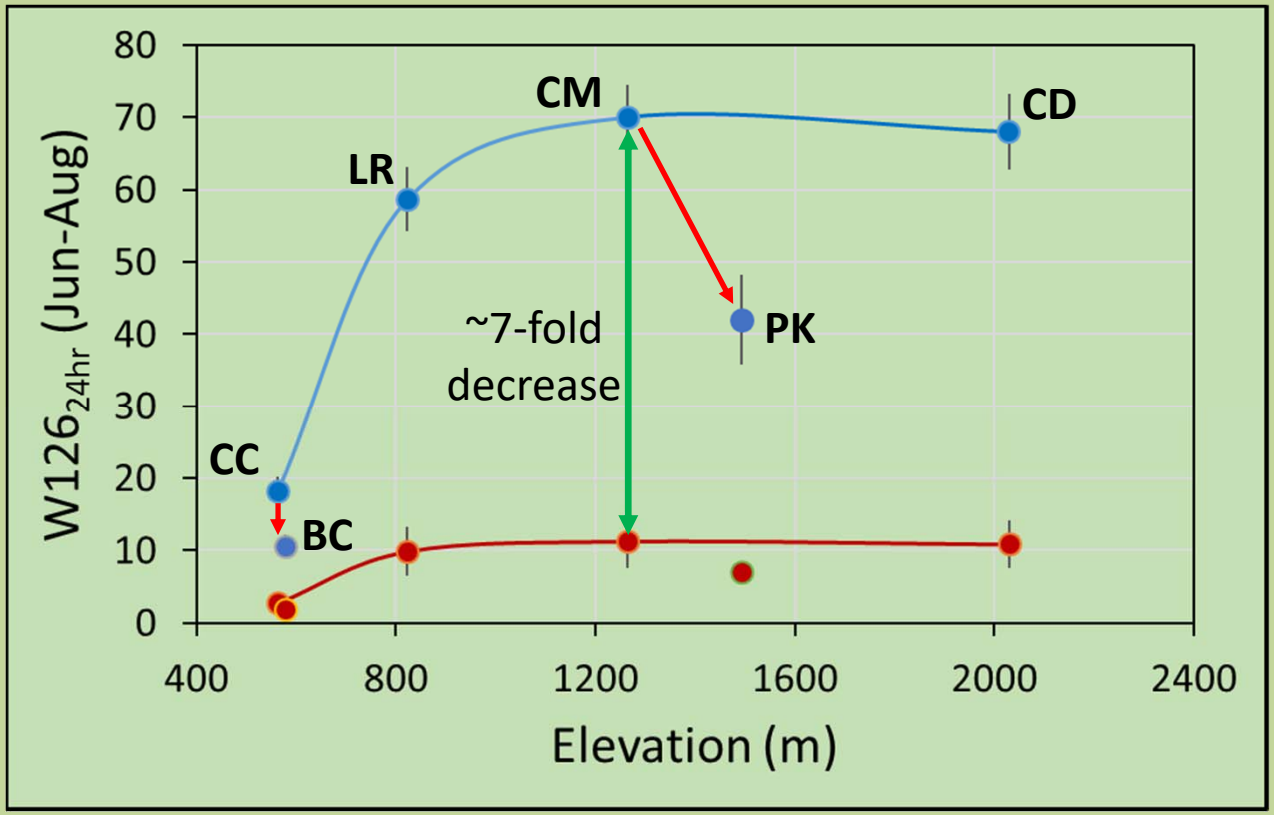
Thanks to Jim Renfro for this graph

$W126_{24hr}$ (Jun-Aug)

Exposures increase up to ~850 m and then plateau

Exposures lower at NC sites (BC and PK)

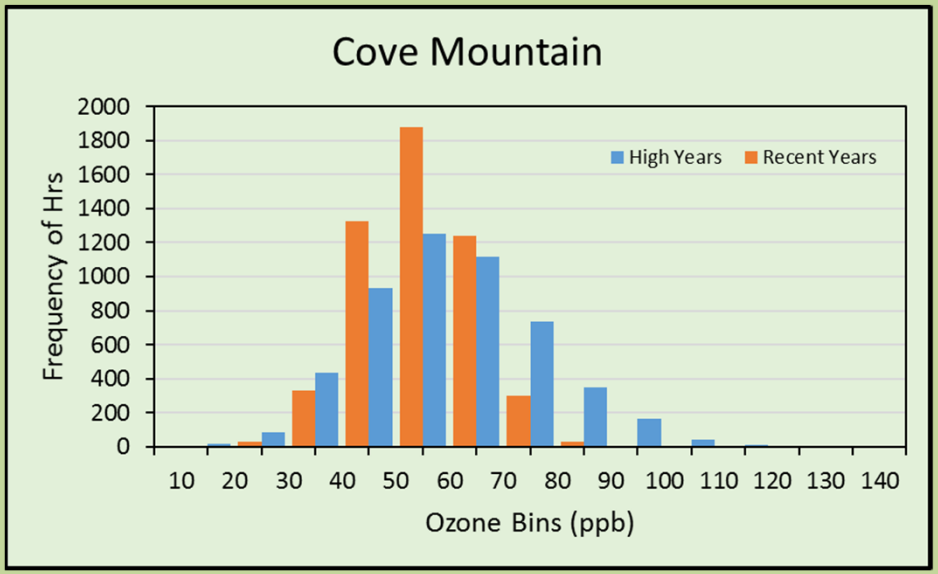
Exposures ~7x lower in recent years

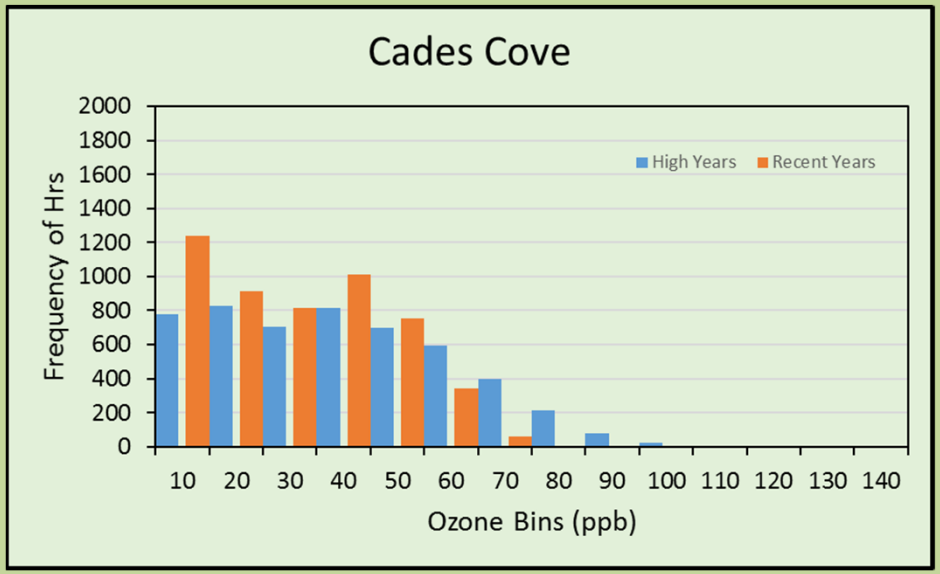


1997-2002

2012-2016

Changes in Frequency Distributions for Ozone at Low and High Elevations in GRSM



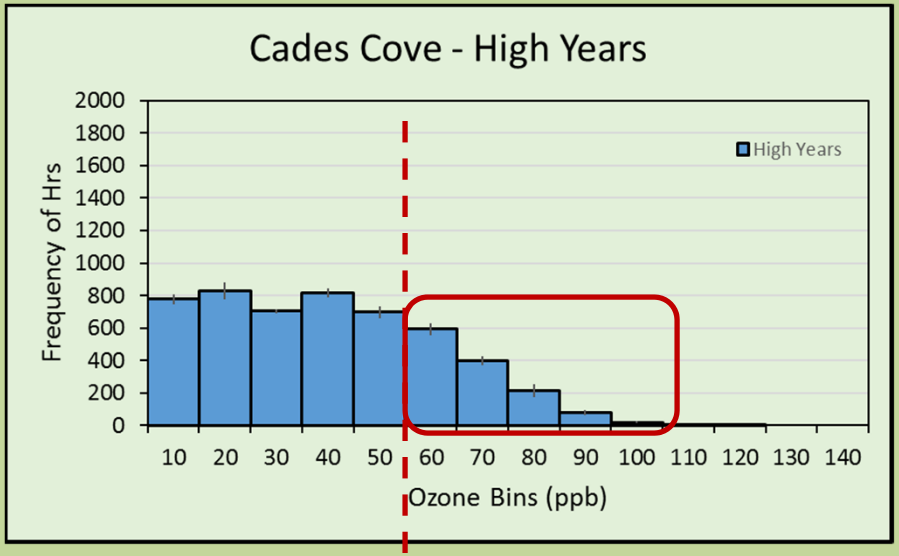


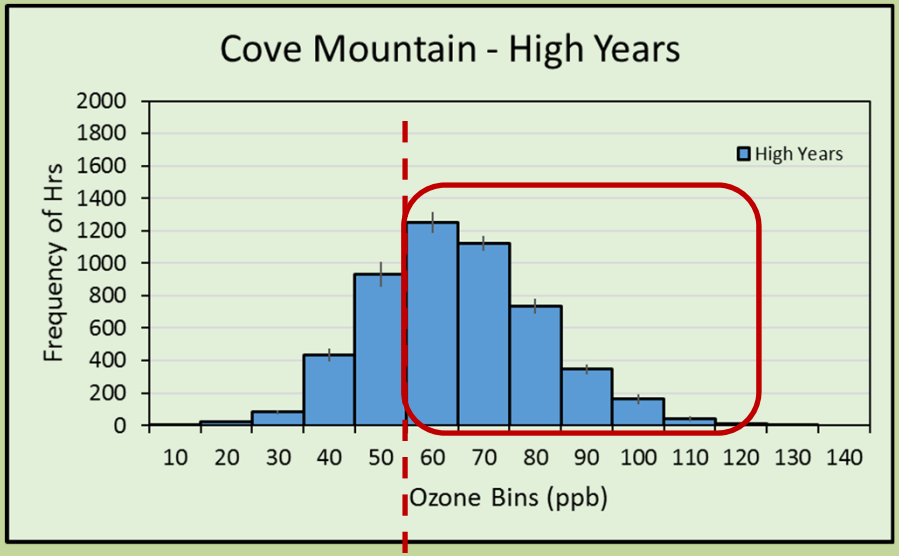
From high years (1997-2002) to recent years (2012-2016), $[O_3] \geq 60$ ppb decrease substantially

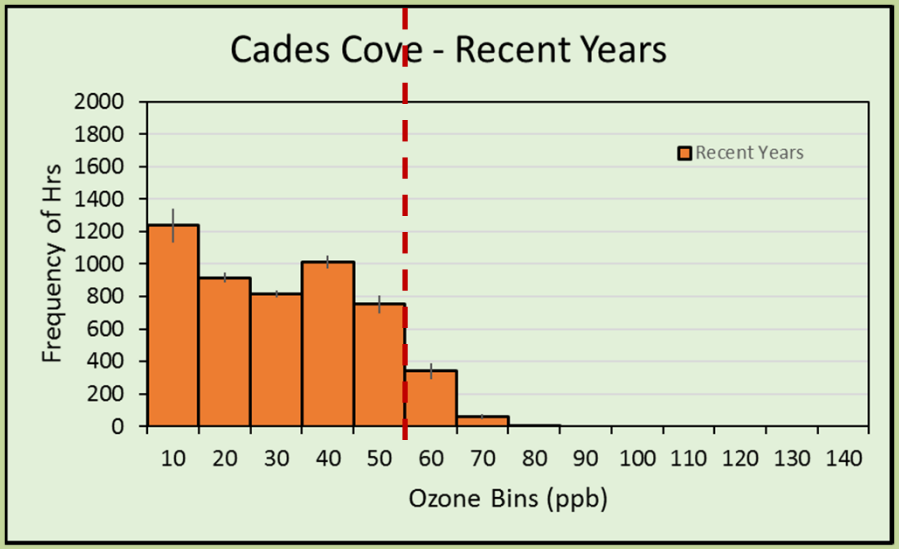
High Years: 1997-2002 (without 2001)

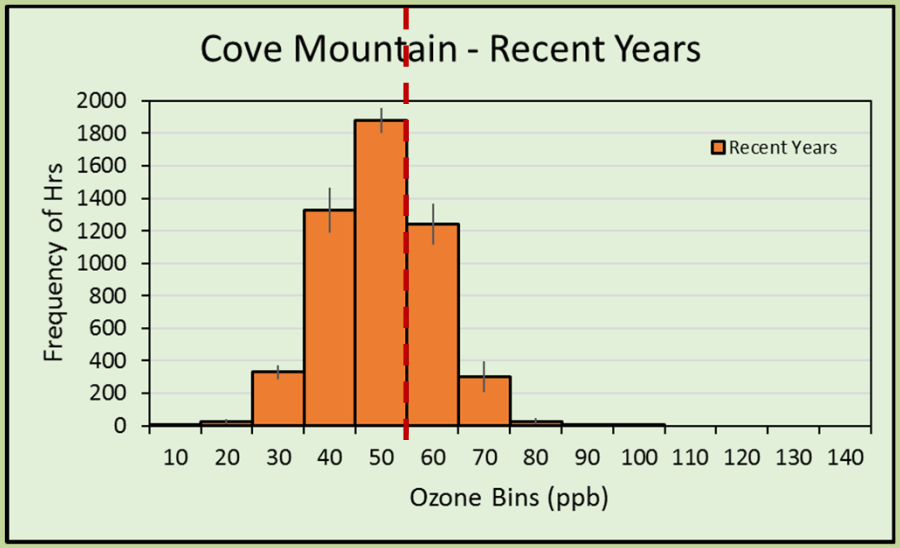
Recent Years: 2012-2016

Changes in Frequency Distributions for Ozone at Low and High Elevations in GRSM

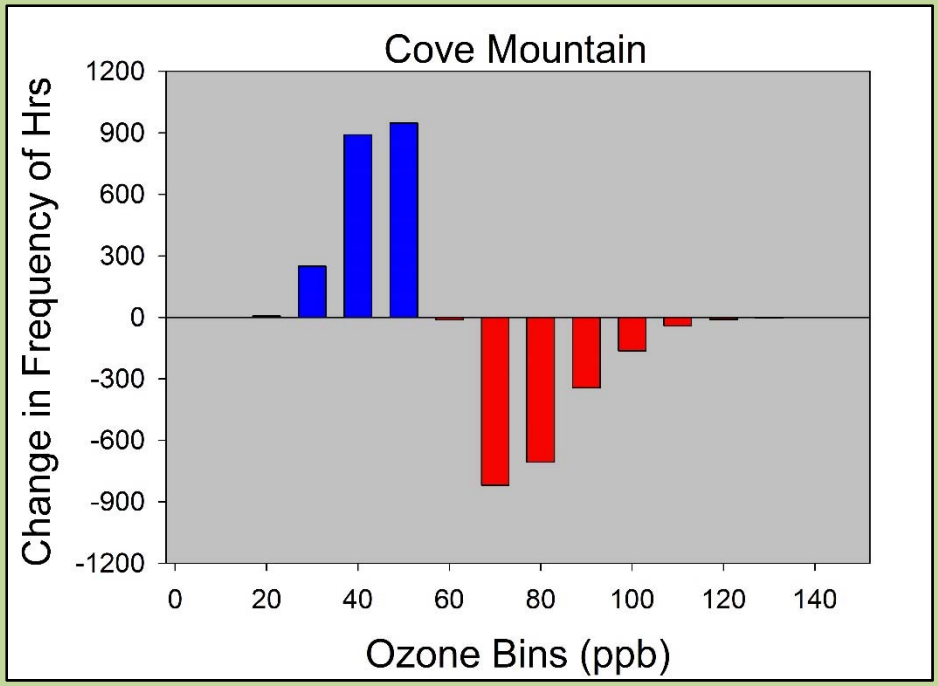


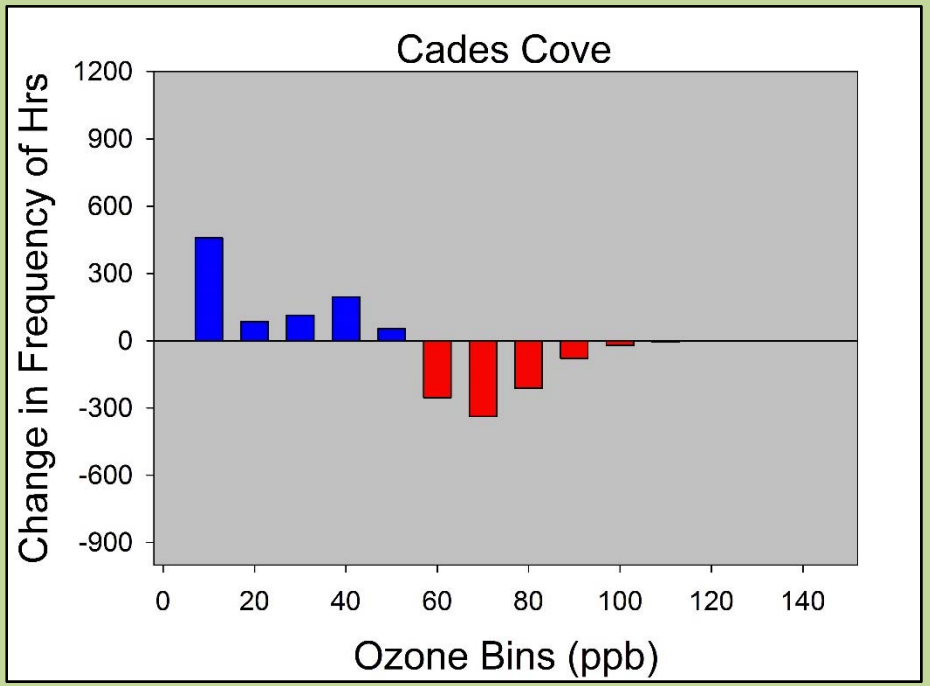






Changes in Frequency Distributions for Ozone at Low and High Elevations in GRSM

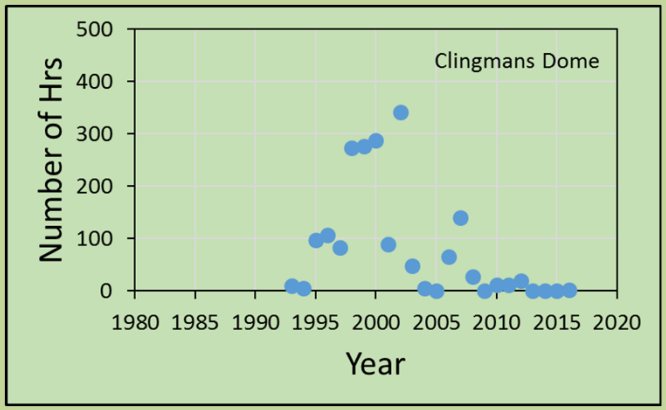


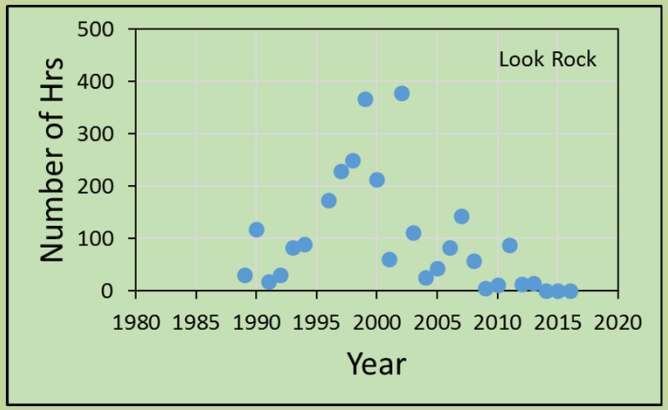


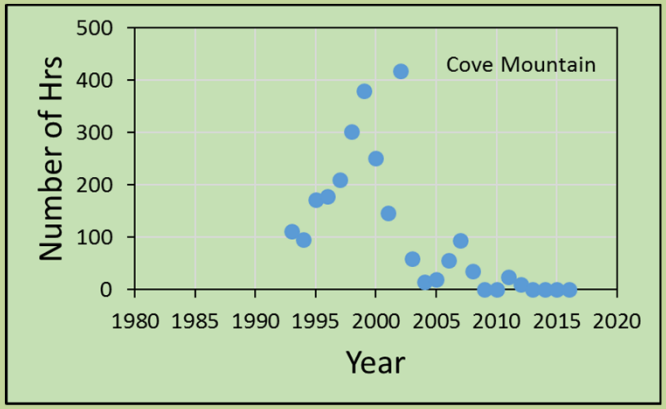
For both high and low elevation sites, there has been a substantial decrease in the frequency of $[O_3] \geq 60$ ppb

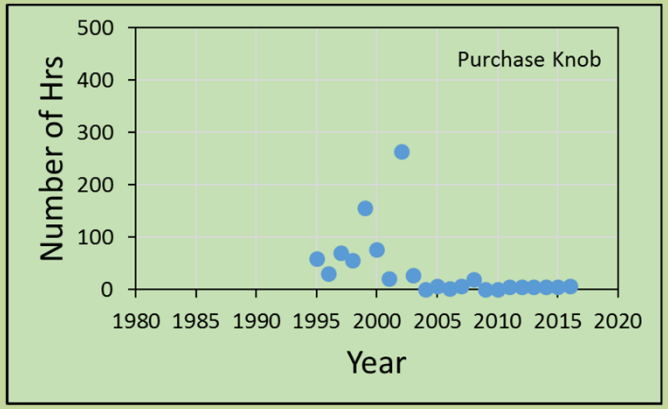
Values are mean frequencies for (2012-2016) – (1997-2002; exclusive of 2001)

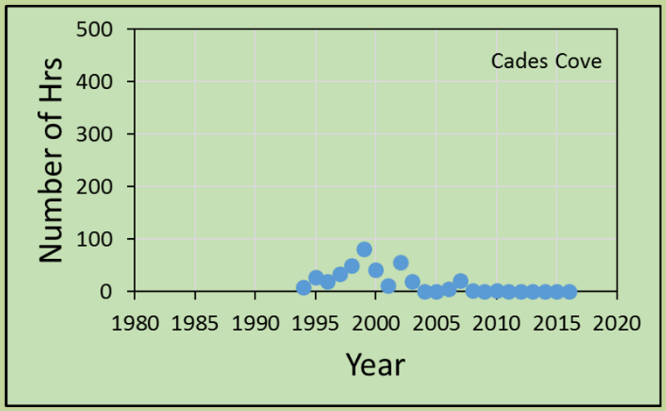
Changes in N80 Index (Jun-Aug, 24 hr) at Low and High Elevations in GRSM

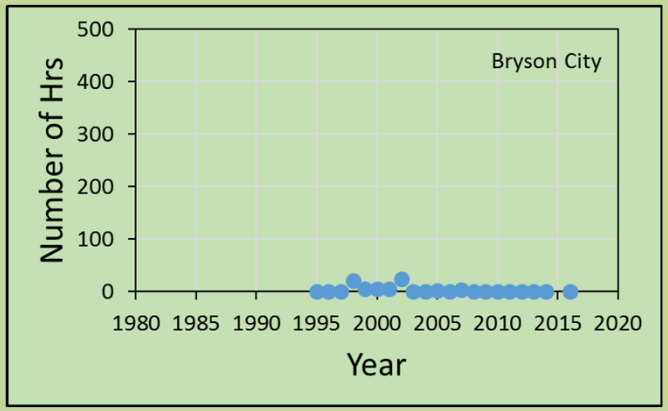












How an Ozone Episode is Characterized:
3 or more consecutive hrs with $[O_3] \geq 60$ ppb interspersed with 2 or fewer hrs < 60 ppb

Episode Length: 10 hrs

65	70	85	90	85	75	70	65	63	60

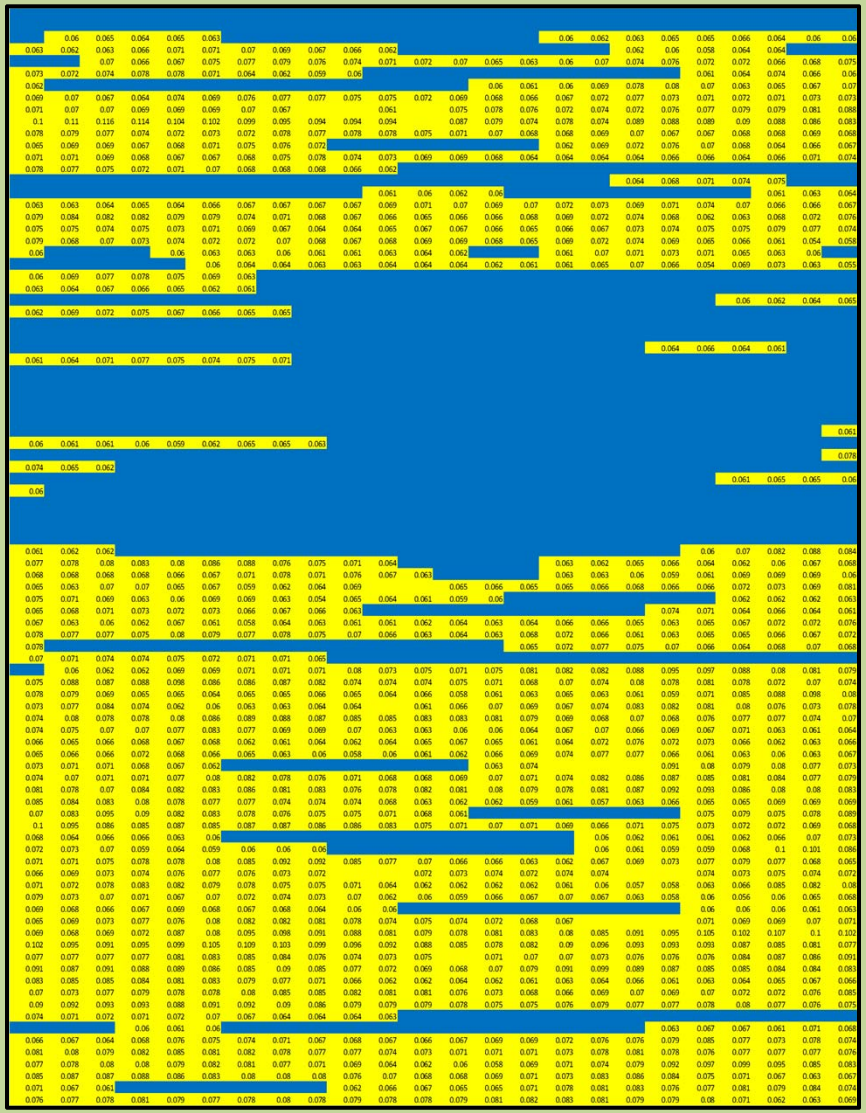
Episode Length: 10 hrs, because respite period is not greater than 2 hrs

65	70	70	65	60	58	59	63	67	70

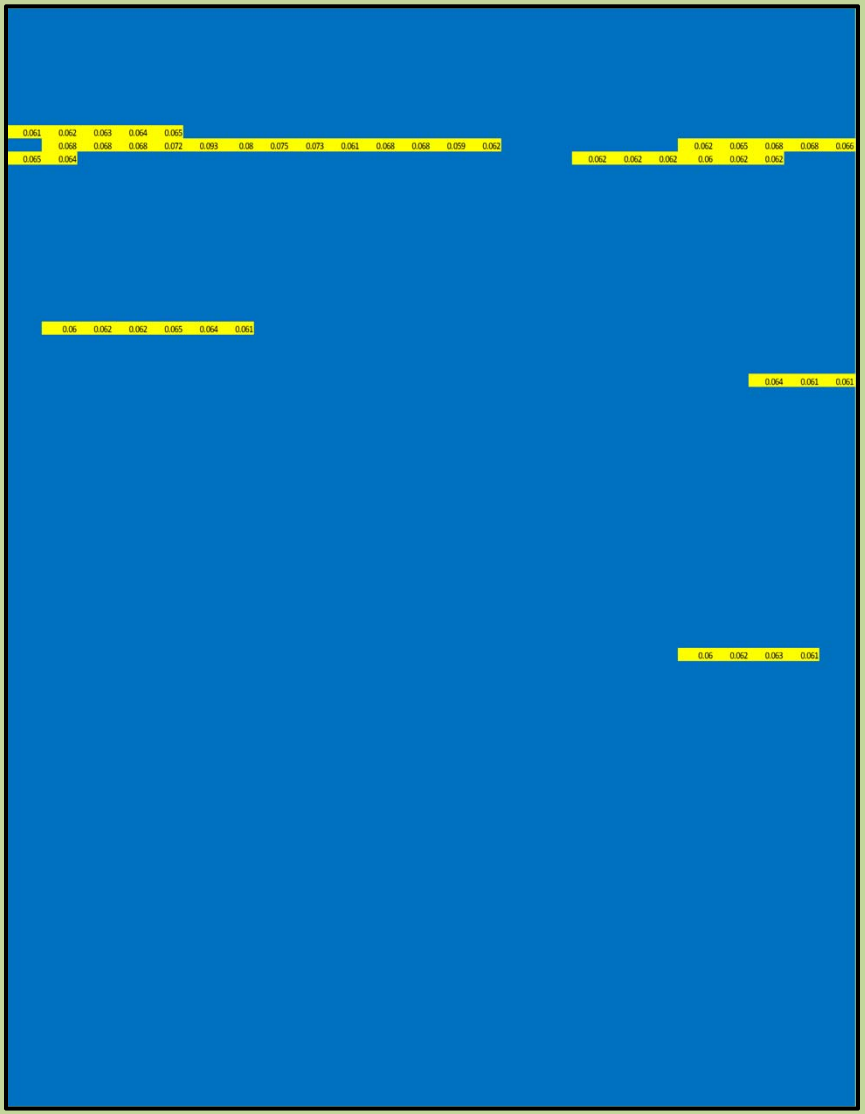
Episode Lengths: 3 hrs and 4 hrs; Respite period is 3 hrs

65	70	70	55	45	57	60	65	70	75

Clingmans Dome - Episodes

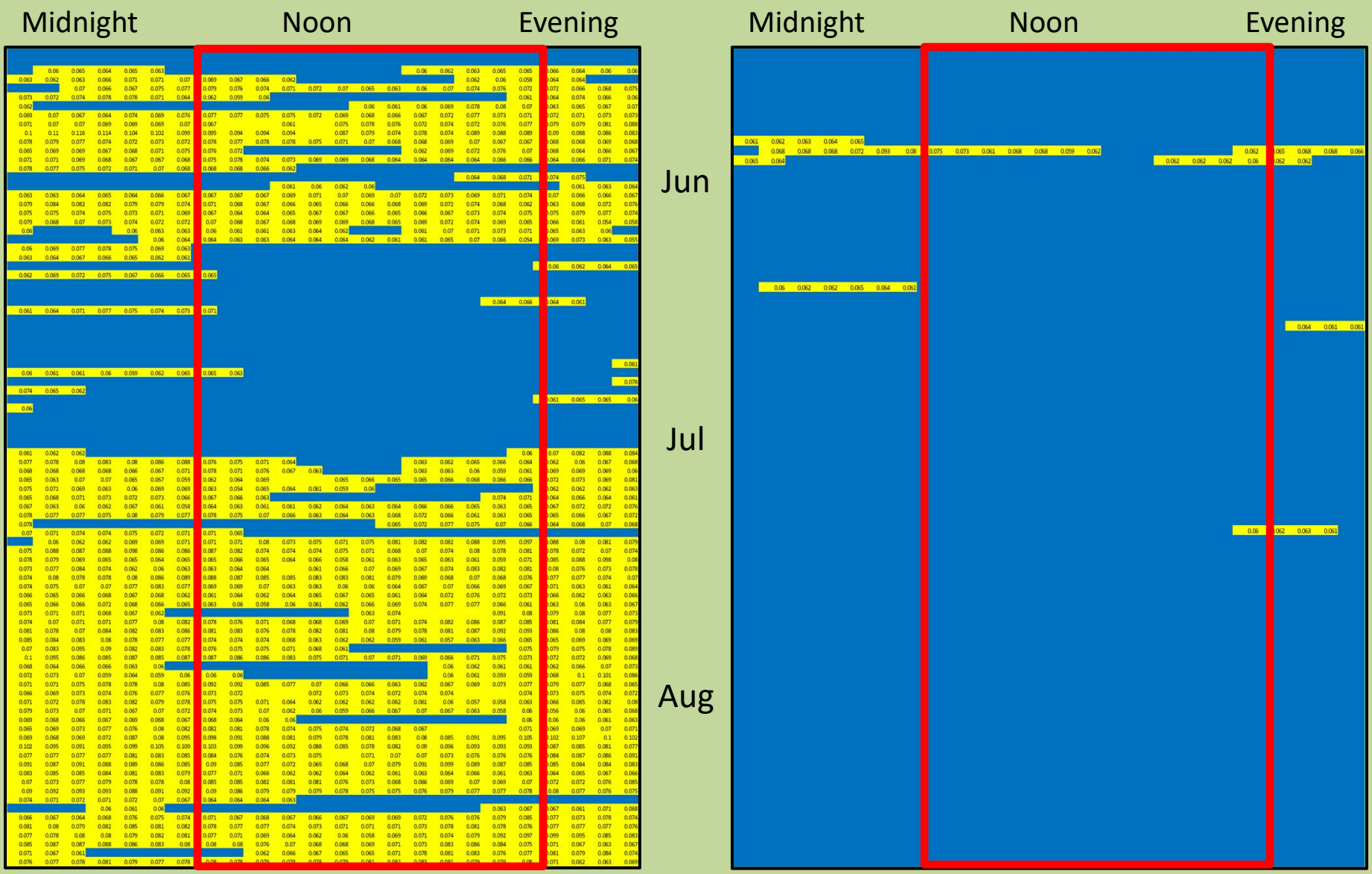


Jun – Aug 1999
Percent Hrs in Episodes: 64%



Jun – Aug 2016
Percent Hrs in Episodes: 2%

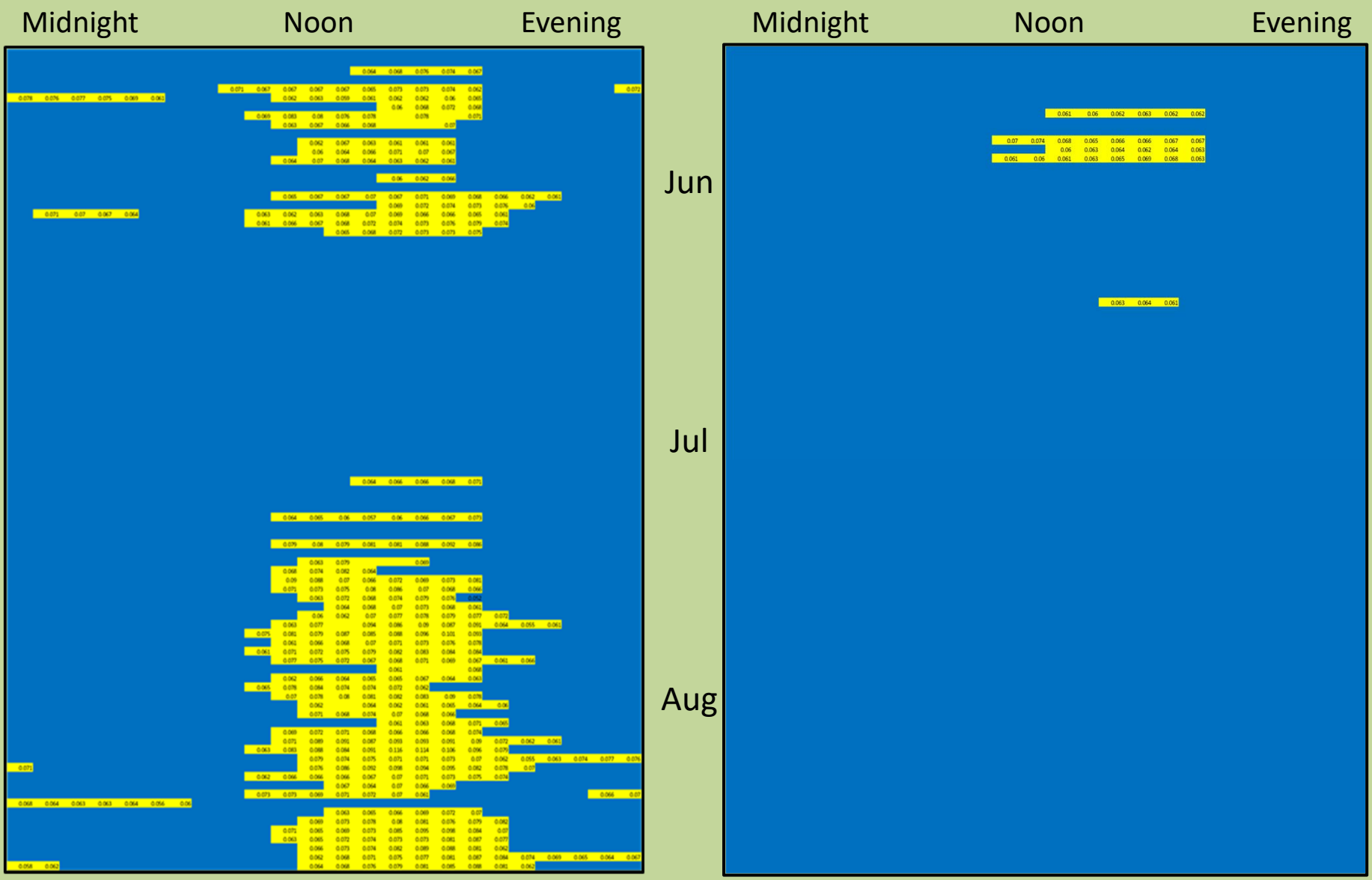
Clingmans Dome - Episodes



Jun – Aug 1999
Percent Hrs in Day Episodes: 44%

Jun – Aug 2016
Percent Hrs in Day Episodes: 27%

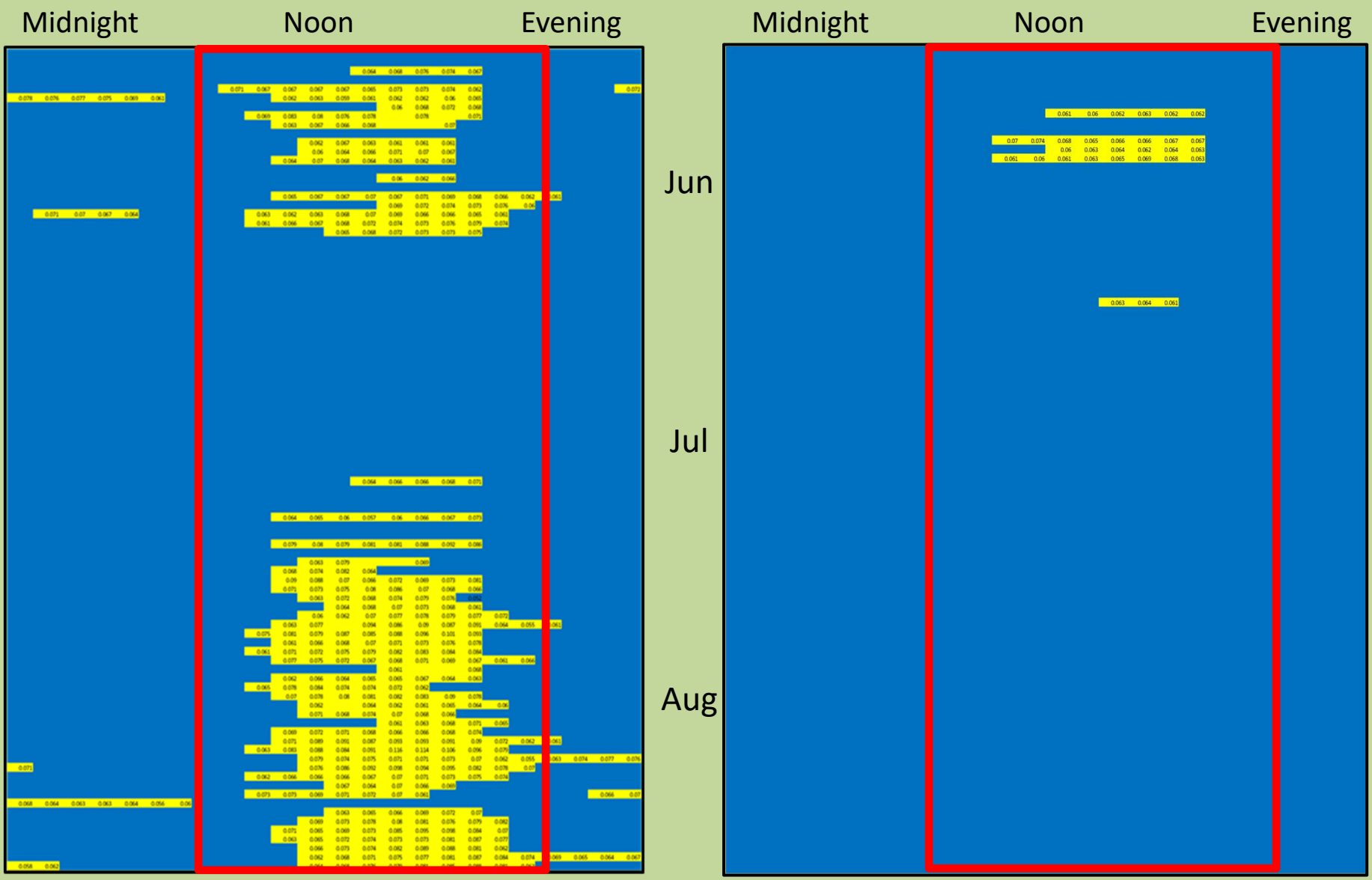
Cades Cove - Episodes



Jun – Aug 1999
Percent Hrs in Episodes: 19%

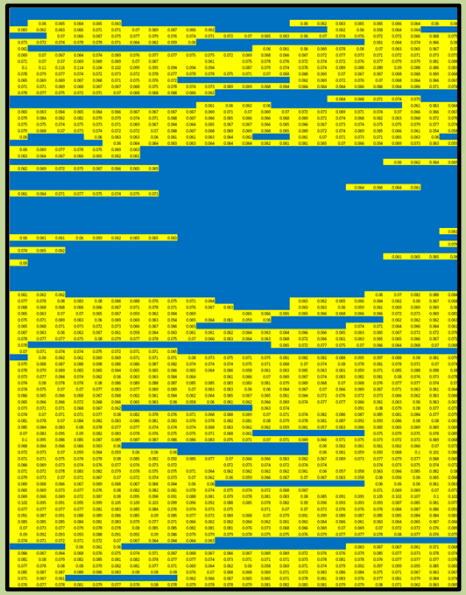
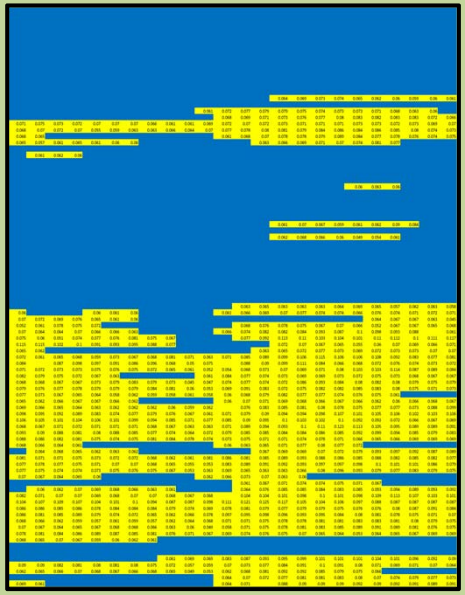
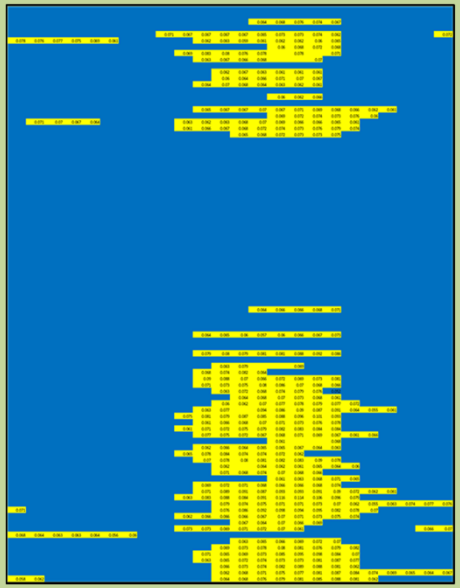
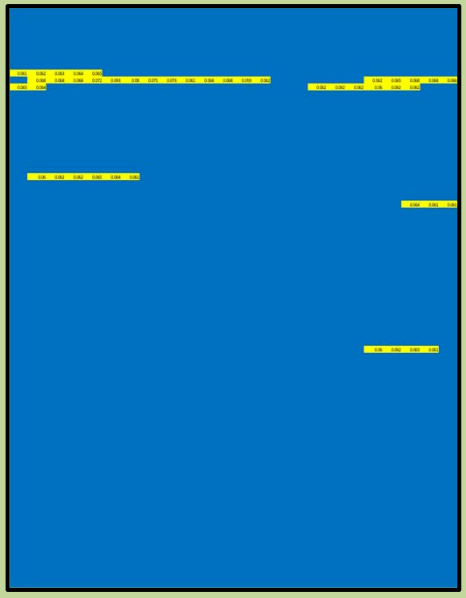
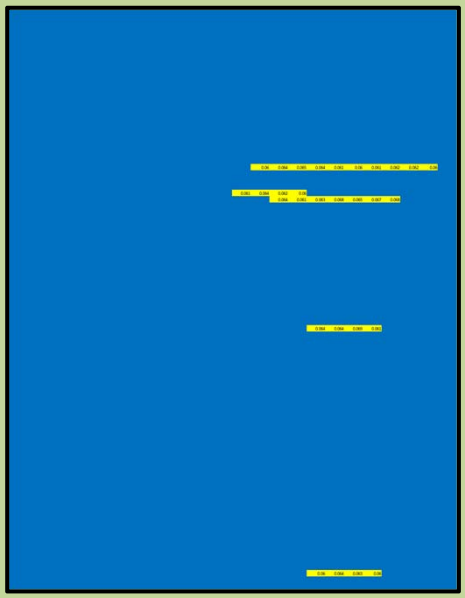
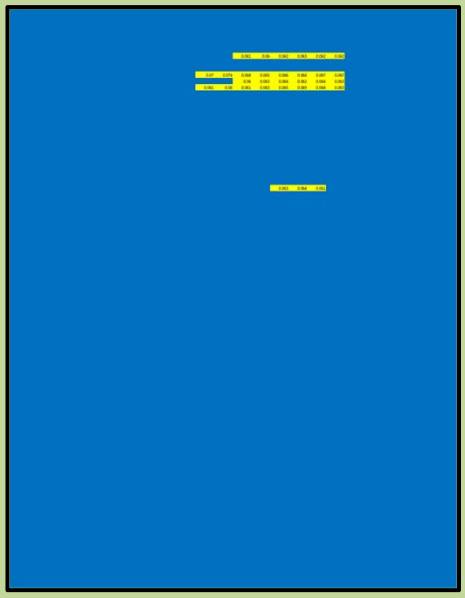
Jun – Aug 2016
Percent Hrs in Episodes: 1%

Cades Cove - Episodes



Jun – Aug 1999
Percent Hrs in Day Episodes: 92%

Jun – Aug 2016
Percent Hrs in Day Episodes: 100%

	Clingmans Dome	Look Rock	Cades Cove
1999			
2016			

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ENVIRONMENTAL POLLUTION
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Assessing the risk of foliar injury from ozone on vegetation in parks in the U.S. National Park Service's Vital Signs Network

Robert Kohut

Boyce Thompson Institute for Plant Research, Cornell University, Ithaca, NY 14853, USA

Received 18 April 2007; accepted 24 April 2007

An assessment of the risk of foliar ozone injury on plants was conducted for 269 parks in support of the U.S. National Park Service's Vital Signs Monitoring Network Program.

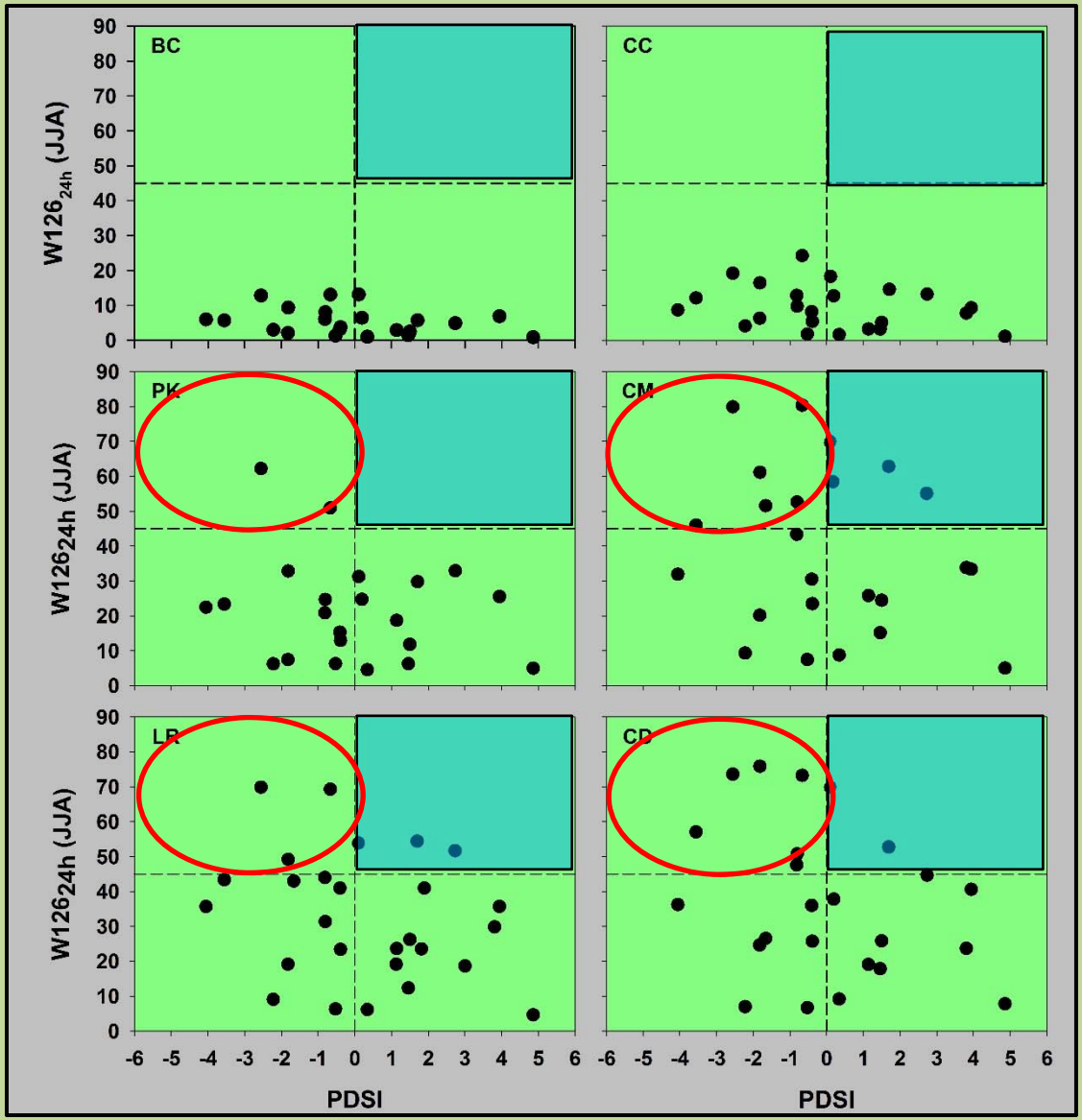
Is there a statistically significant correlation between ozone exposure (W126 Index) and soil water status in GRSM?

"Some of the better-known parks at which this inverse relationship [*between high ozone exposure and drought*] *exists for one or both of the indices of exposure include Great Smoky Mountains,…."*

Relationship Between PDSI and $W126_{24hr}$ (Jun - Aug)

Statistically significant correlations between W126 O_3 exposures and Palmer Drought Index occur only at Clingmans Dome

Highest W126 exposures occur only during dry years (red circles)



When Do Maximum Ozone Exposures Occur?

April 2018

W	S	M	T	W	T	F	S
14	1	2	3	4	5	6	7
15	8	9	10	11	12	13	14
16	15	16	17	18	19	20	21
17	22	23	24	25	26	27	28
18	29	30					

May 2018

W	S	M	T	W	T	F	S
18			1	2	3	4	5
19	6	7	8	9	10	11	12
20	13	14	15	16	17	18	19
21	20	21	22	23	24	25	26
22	27	28	29	30	31		

June 2018

W	S	M	T	W	T	F	S
22						1	2
23	3	4	5	6	7	8	9
24	10	11	12	13	14	15	16
25	17	18	19	20	21	22	23
26	24	25	26	27	28	29	30

May 2018

W	S	M	T	W	T	F	S
18			1	2	3	4	5
19	6	7	8	9	10	11	12
20	13	14	15	16	17	18	19
21	20	21	22	23	24	25	26
22	27	28	29	30	31		

June 2018

W	S	M	T	W	T	F	S
22						1	2
23	3	4	5	6	7	8	9
24	10	11	12	13	14	15	16
25	17	18	19	20	21	22	23
26	24	25	26	27	28	29	30

July 2018

W	S	M	T	W	T	F	S
27	1	2	3	4	5	6	7
28	8	9	10	11	12	13	14
29	15	16	17	18	19	20	21
30	22	23	24	25	26	27	28
31	29	30	31				

June 2018

W	S	M	T	W	T	F	S
22						1	2
23	3	4	5	6	7	8	9
24	10	11	12	13	14	15	16
25	17	18	19	20	21	22	23
26	24	25	26	27	28	29	30

July 2018

W	S	M	T	W	T	F	S
27	1	2	3	4	5	6	7
28	8	9	10	11	12	13	14
29	15	16	17	18	19	20	21
30	22	23	24	25	26	27	28
31	29	30	31				

August 2018

W	S	M	T	W	T	F	S
31				1	2	3	4
32	5	6	7	8	9	10	11
33	12	13	14	15	16	17	18
34	19	20	21	22	23	24	25
35	26	27	28	29	30	31	

July 2018

W	S	M	T	W	T	F	S
27	1	2	3	4	5	6	7
28	8	9	10	11	12	13	14
29	15	16	17	18	19	20	21
30	22	23	24	25	26	27	28
31	29	30	31				

August 2018

W	S	M	T	W	T	F	S
31				1	2	3	4
32	5	6	7	8	9	10	11
33	12	13	14	15	16	17	18
34	19	20	21	22	23	24	25
35	26	27	28	29	30	31	

September 2018

W	S	M	T	W	T	F	S
35							1
36	2	3	4	5	6	7	8
37	9	10	11	12	13	14	15
38	16	17	18	19	20	21	22
39	23	24	25	26	27	28	29
40	30						

August 2018

W	S	M	T	W	T	F	S
31				1	2	3	4
32	5	6	7	8	9	10	11
33	12	13	14	15	16	17	18
34	19	20	21	22	23	24	25
35	26	27	28	29	30	31	

September 2018

W	S	M	T	W	T	F
35						
36	2	3	4	5	6	7
37	9	10	11	12	13	14
38	16	17	18	19	20	21
39	23	24	25	26	27	28
40	30					

October 2018

W	S	M	T	W	T	F	S
40		1	2	3	4	5	6
41	7	8	9	10	11	12	13
42	14	15	16	17	18	19	20
43	21	22	23	24	25	26	27
44	28	29	30	31			

When Do Maximum Ozone Exposures Occur?

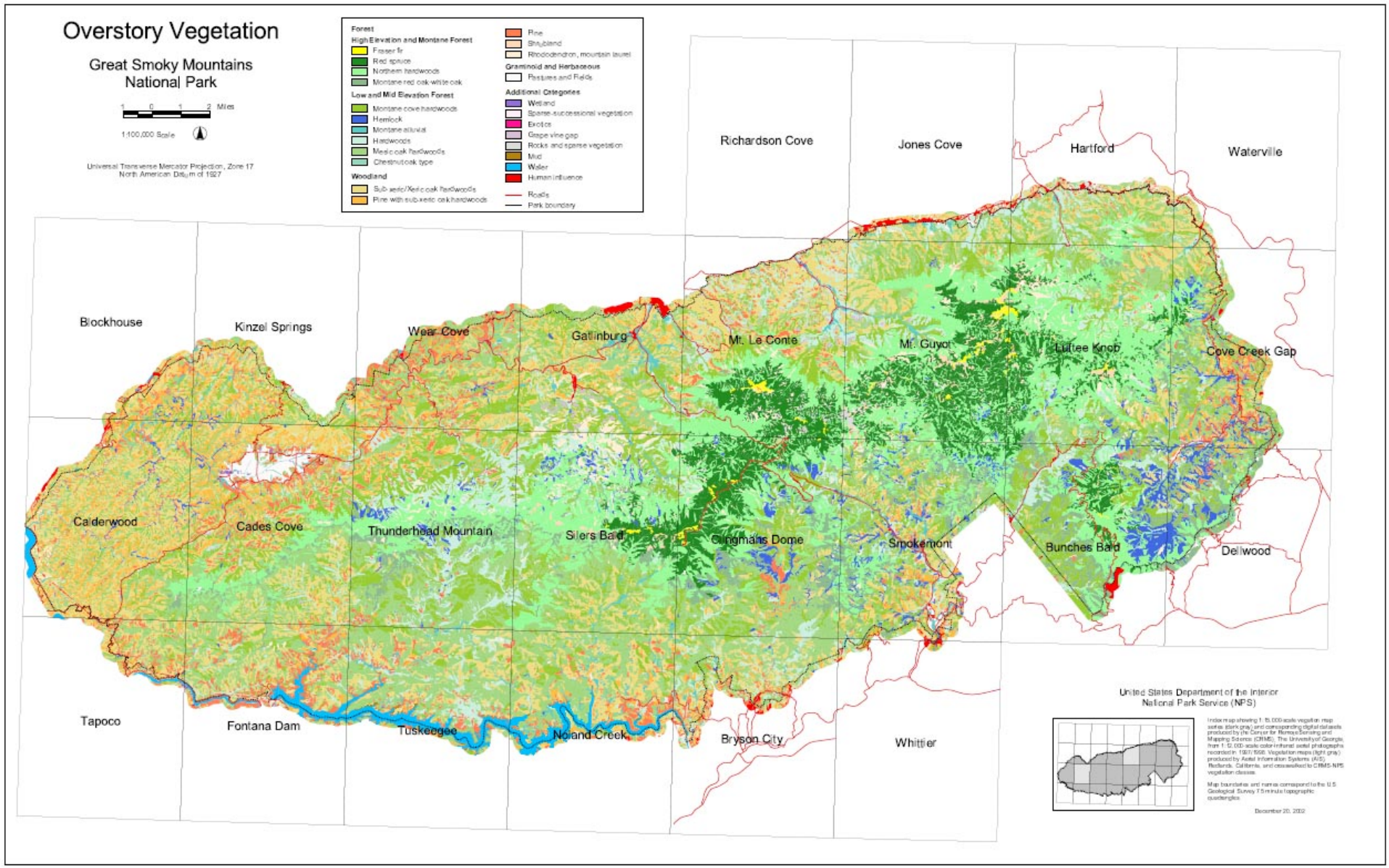
Cades Cove

Year	AMJ	MJJ	JJA	JAS	ASO
1994		12.12777	7.81657	5.421686	4.668028
1995	12.44801	13.85864	12.78497	12.20597	6.861225
1996	16.51463	15.68986	14.45259	8.402852	5.180502
1997	12.82932	12.9424	13.17881	16.71684	13.33507
1998	18.65626	17.31336	18.24273	22.14591	19.90209
1999		18.91852	24.14295	31.17636	29.42654
2000	16.19168	18.06745	16.50163	13.05466	9.92023
2001	17.14571	13.62006	9.749828	7.053673	6.105412
2002	14.48217	15.78141	19.07417	18.55652	13.96181
2003	14.10798	10.49636	9.230839	7.306719	6.471568
2004	6.704068	5.546671	5.101638	4.41325	3.262528
2005	9.748379	6.550993	3.239157	3.968501	3.820104
2006	15.13492	13.21745	12.82598	8.178581	5.114247
2007	14.36426	11.8581	12.11417	10.30167	9.830179
2008	13.22789	12.40392	8.660627	6.357942	4.555269
2009	6.091489	3.811938	3.190684	1.960402	0.960334
2010	12.24616	7.198928	6.284972	6.522308	5.545772
2011	10.77922	8.101752	8.042028	5.558221	5.200778
2012	7.014997	6.053536	5.352522	3.130401	2.312053
2013	4.460312	2.237897	1.111915	0.792047	0.856009
2014	4.858682	2.707694	1.616076	1.21166	1.193984
2015		3.535638	1.748436	1.250953	1.145426
2016	6.750287	4.200009	2.835854	1.368354	1.58068

Cove Mountain

Year	AMJ	MJJ	JJA	JAS	ASO
1993	38.04196	47.20577	50.96222	44.38867	31.48154
1994	49.5455	41.8493	34.34698	28.01574	25.89572
1995	42.62719	53.13474	58.16907	57.96127	41.76589
1996	49.73264	56.54124	62.96831	48.80795	40.08548
1997	36.48641	49.61565	55.20201	68.48079	51.2125
1998	54.96014	61.43873	69.12239	88.40607	77.58127
1999	49.32391	61.68362	78.99982	92.79637	77.12936
2000	48.6708	55.87782	60.87937	47.99138	52.70812
2001	57.56204	59.30118	52.61895	42.83319	32.50499
2002	48.33846	61.51766	79.89744	73.73388	53.28484
2003	31.04072	29.02705	33.35303	31.10873	25.69543
2004	18.98523	22.40513	24.46142	21.91431	16.1628
2005	27.72811	24.82435	25.79841	32.49837	28.59796
2006	40.02248	41.73912	43.38507	31.28057	19.39747
2007	43.26879	42.15263	46.03942	42.14732	37.8928
2008	27.75689	32.14541	31.84681	26.02236	18.25959
2009	19.16013	14.65682	15.14515	11.99813	8.499927
2010	30.07903	20.79443	20.13632	23.95696	25.15798
2011	28.72205	28.63192	30.523	23.55232	20.25863
2012	22.47173	23.24801	23.37414	15.65559	9.527497
2013	11.69473	7.496636	5.226453	4.826843	4.974646
2014	16.28583	11.24696	8.888412	7.289575	7.258469
2015	14.86842	13.03967	7.724365	7.392685	7.111419
2016	16.35502	12.72441	9.262134	6.221921	6.797353

Overstory Vegetation in GRSM



Differences in Phenology Due to Elevation

Hopkins Law: Leafing delayed 3-4 days/100 m in elevation

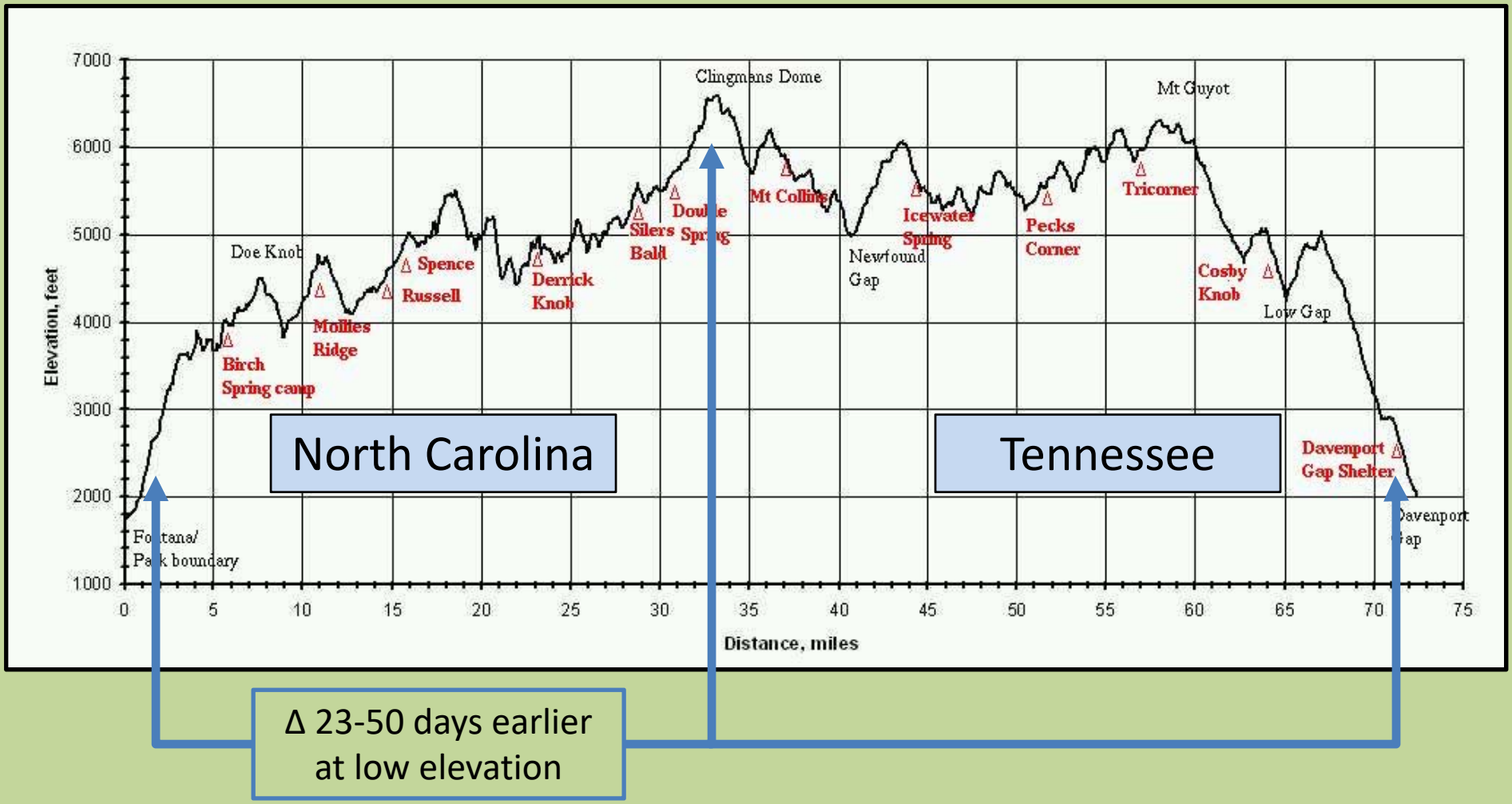


Figure courtesy Univ. TN


Variation in Phenology Within Cove Hardwood Forests
Aesculus flava can leaf out up to 33 days before *Magnolia fraseri*

Variation in Phenology Within Cove Hardwood Forests

Aesculus flava can leaf out up to 33 days before *Magnolia fraseri*

Differences in Phenology Due to Elevation

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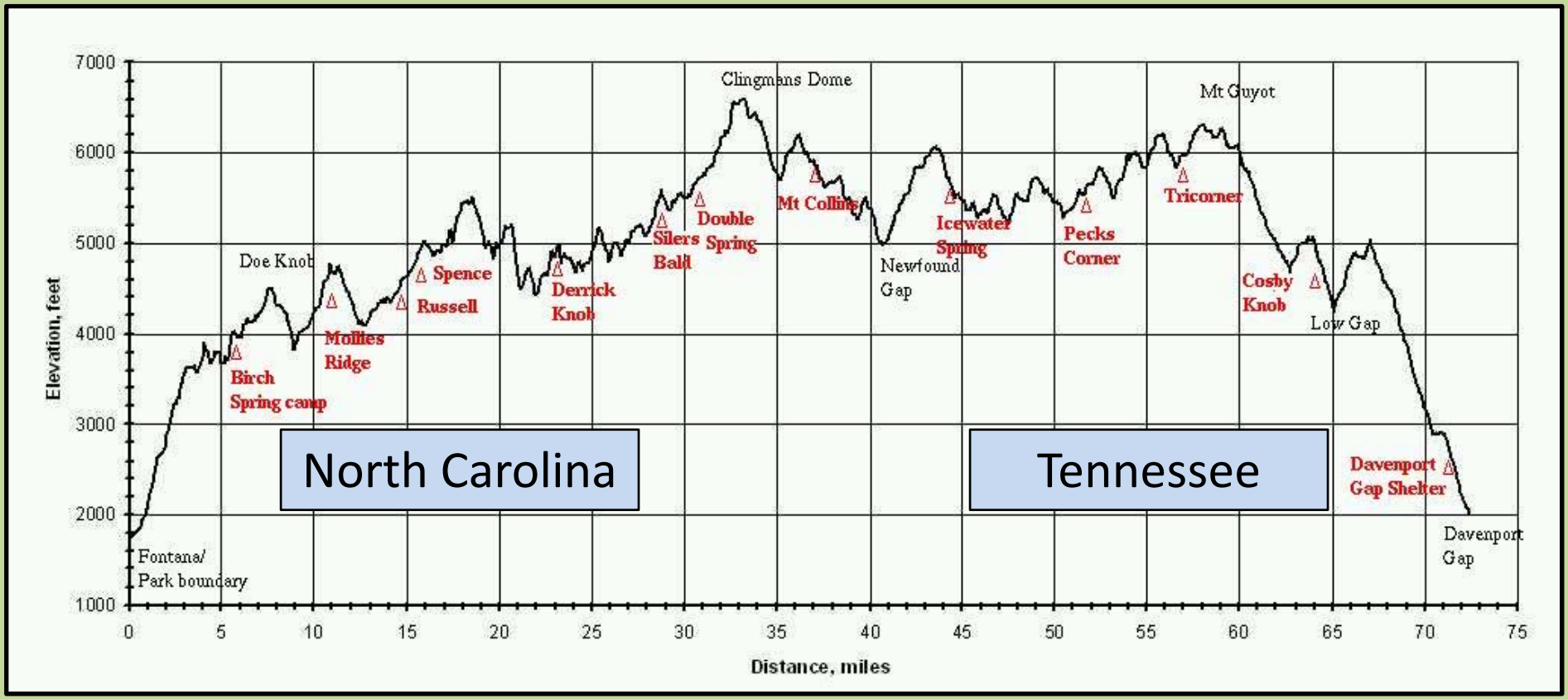
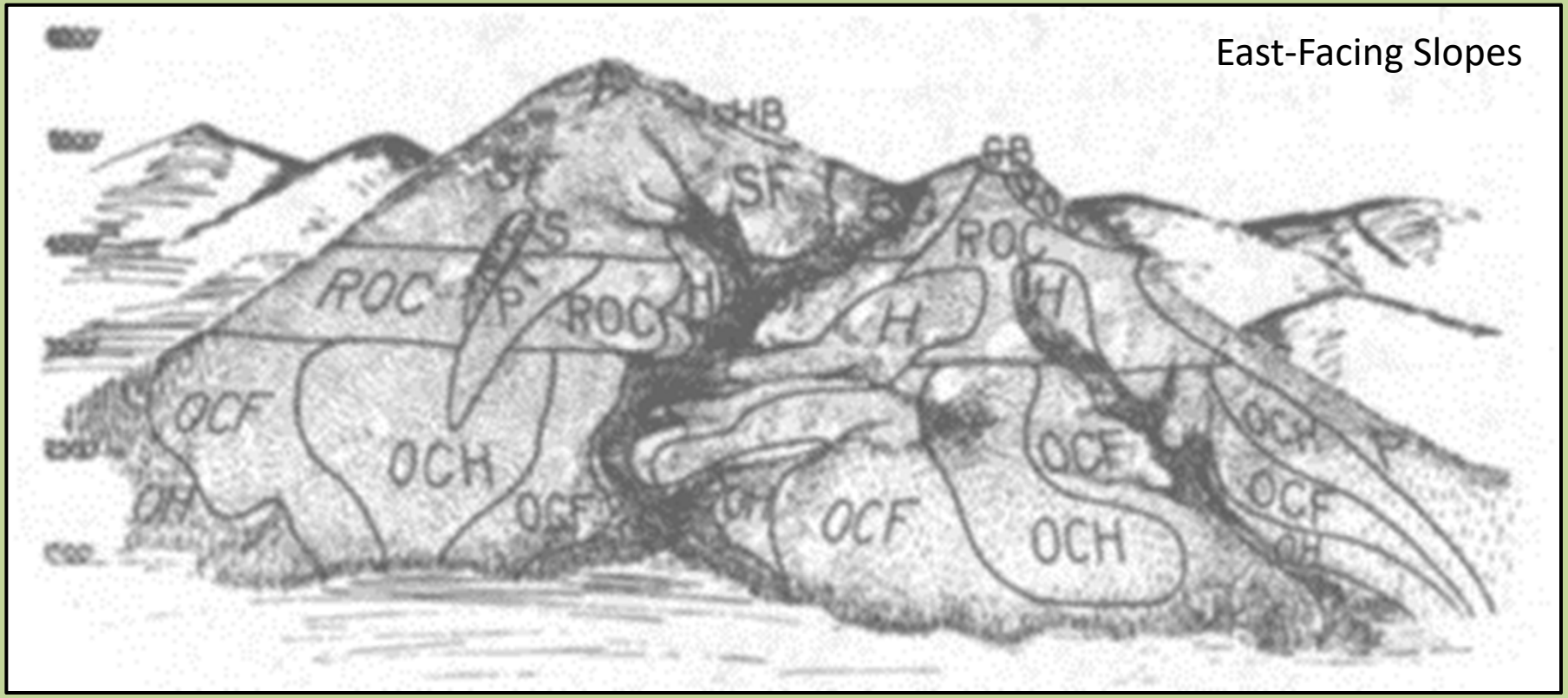


Ozone Lower on NC side of Park

Ozone Higher on TN side of Park

Figure courtesy Univ. TN

Topographic Dispersion of Vegetation Types in Great Smoky Mts National Park

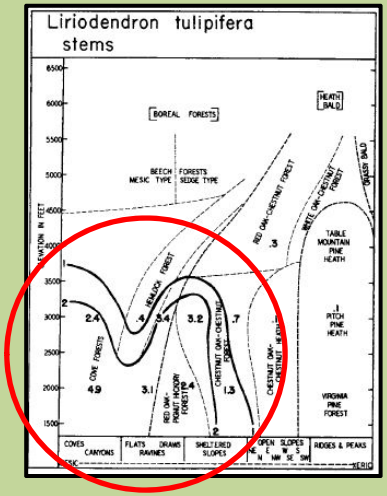


OCF: Chestnut Oak-Chestnut
OCH: Chestnut Oak-Chestnut Heath
OH: Oak-Hickory

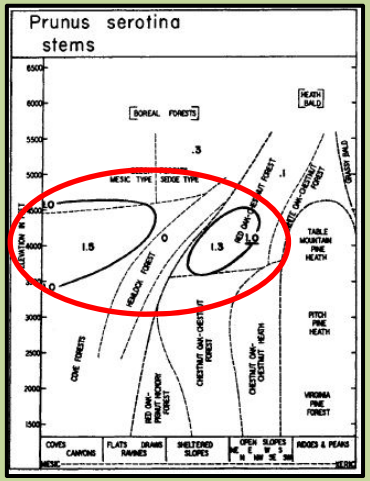
ROC: Red Oak-Chestnut
P: Pine
SF: Spruce-Fir

Whittaker, R.H. 1956. Vegetation of the Great Smoky Mountains. Ecological Monographs 26:1-80.

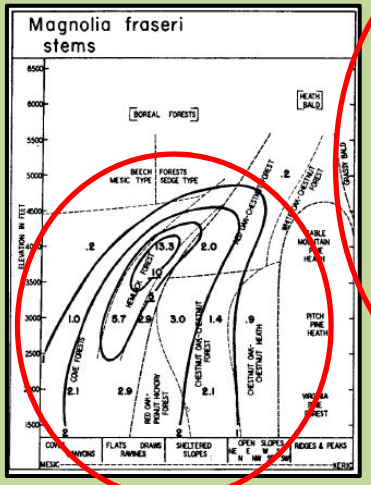
Topographic Dispersion of Species in Great Smoky Mts National Park



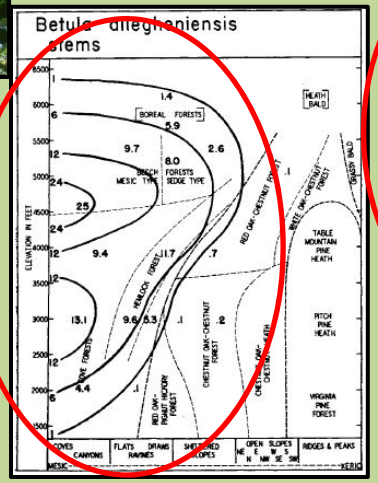
Moderately Sensitive



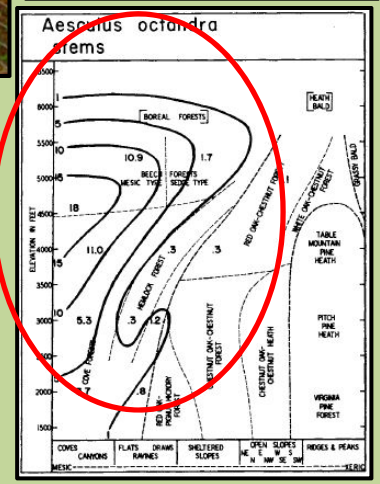
Very Sensitive



Unknown Sensitivity



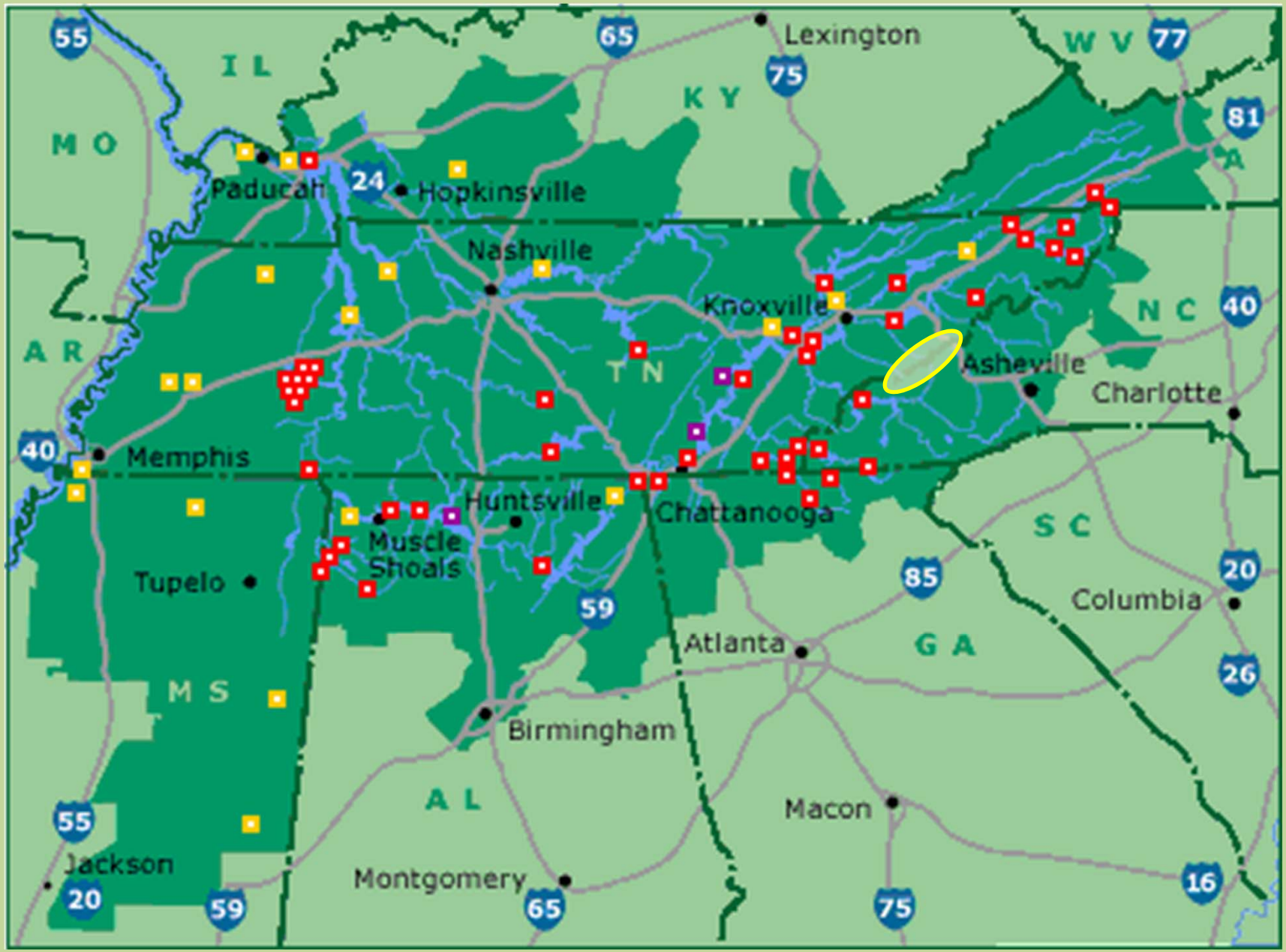
Moderately Sensitive

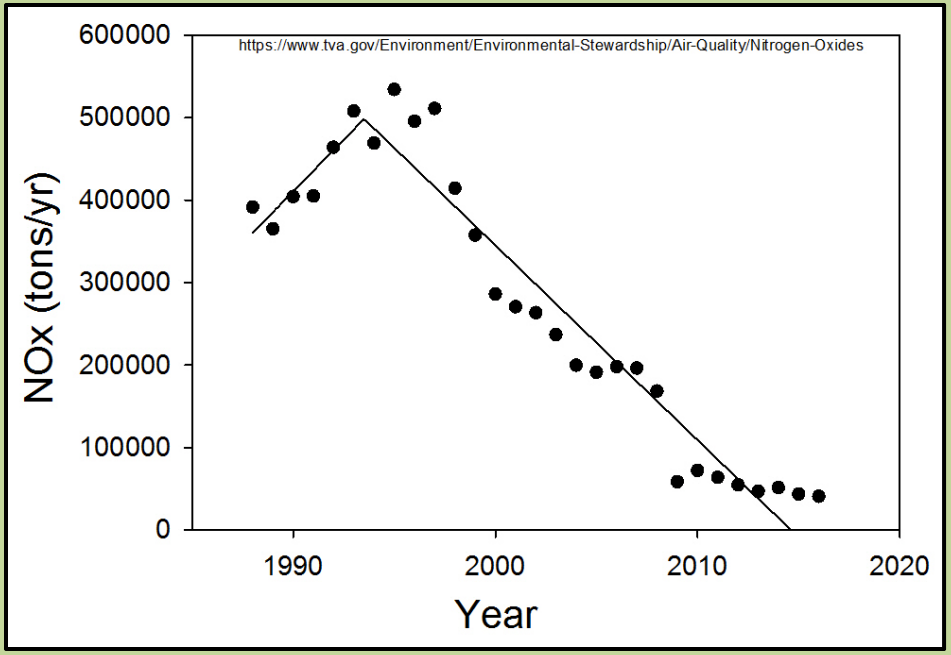


Unknown Sensitivity

Whittaker, R.H. 1956. Vegetation of the Great Smoky Mountains. Ecological Monographs 26:1-80.

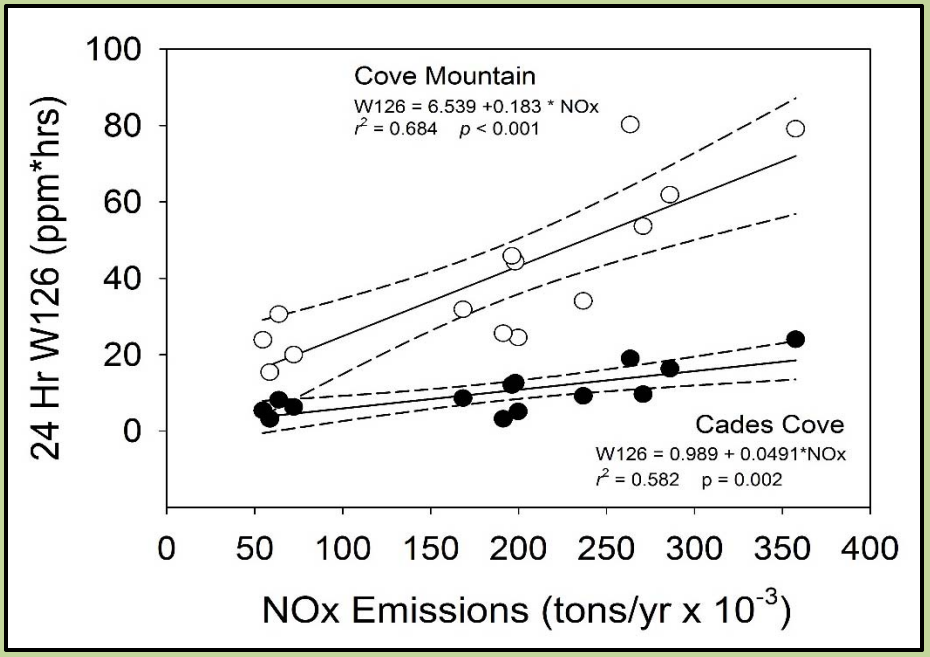
Location of TVA Power Generating Units





Reductions in NOx Emissions by 58 Generating Units of the TVA around Great Smoky Mountains National Park Declines begin in 1994-1995

Reduced TVA NOx Emissions Correlated with Reductions in Ozone in Great Smoky Mountains National Park



Open-top Chamber Facility (Active from 1988 – 1992)

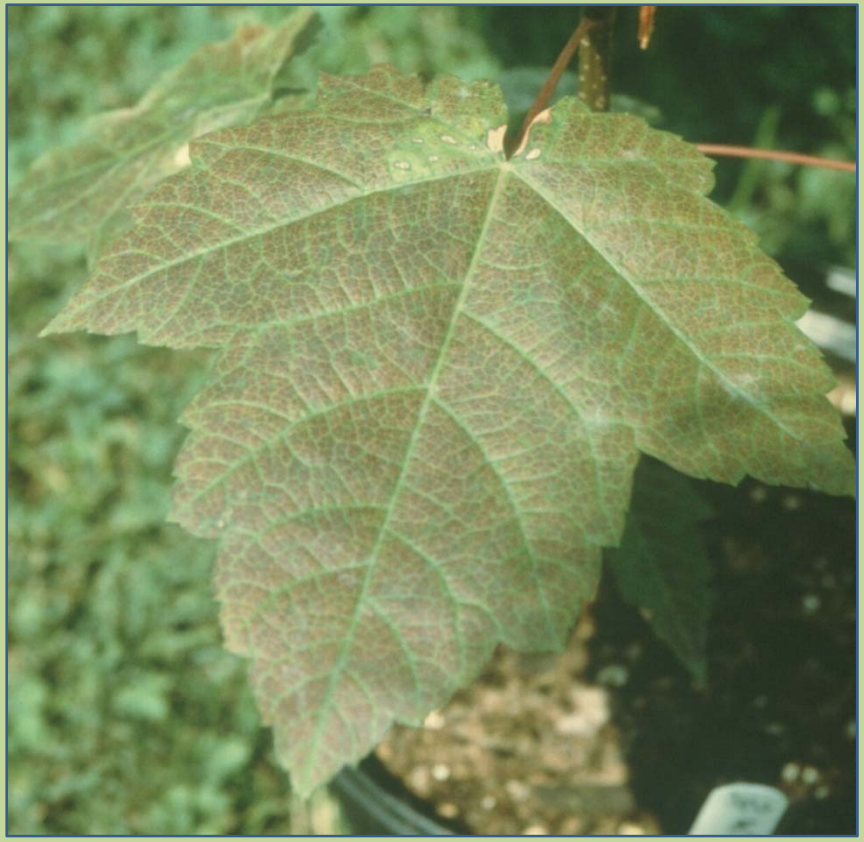
Twin Creeks, Great Smoky Mountains National Park, near Gatlinburg, TN

Ozone Injury on Black Cherry (*Prunus serotina*)

Seedlings after exposure to various ozone treatments (percents of ambient)

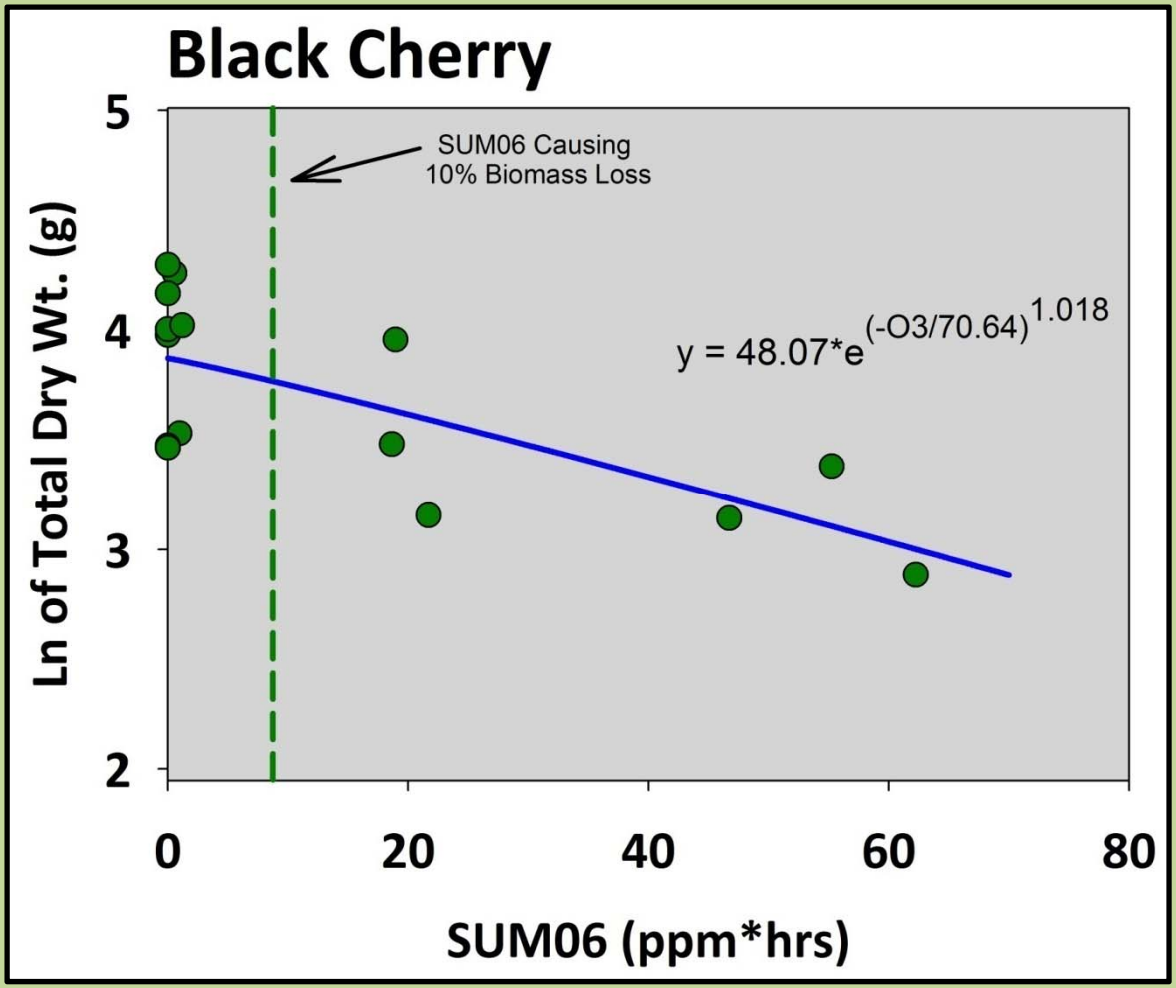
Ozone Injury on Red Maple (*Acer rubrum*)

Leaf from CF treatment



Leaf from 2X ambient treatment

Ozone Exposure Response Function for Seedlings exposed in Open Top Chambers



$W126_{24hr}$ that causes 2% Seedling Biomass Loss

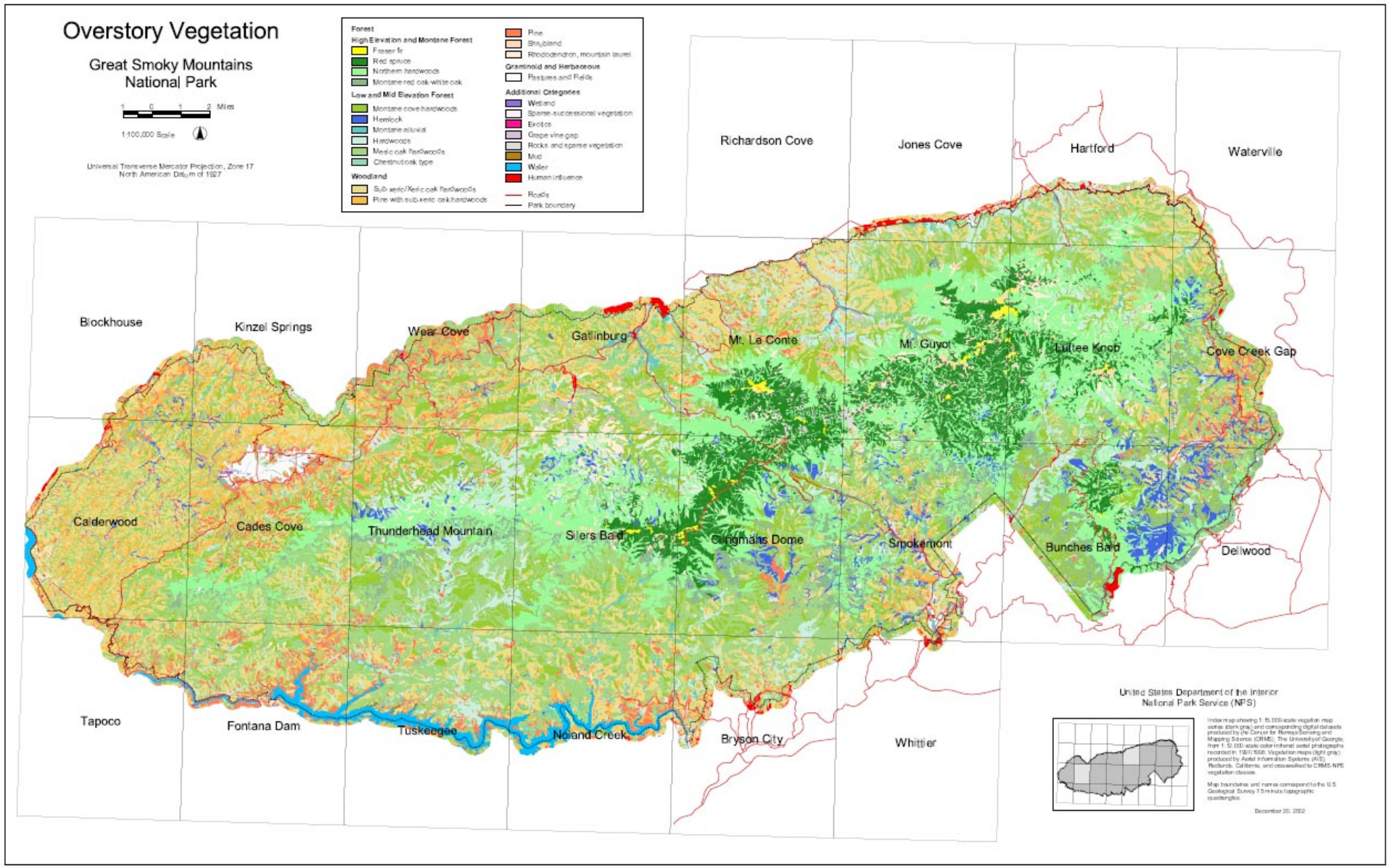
Species	W126 (ppm*hrs)
Black Cherry	1
White Pine	6
Tulip Poplar	8
Red and Sugar Maples	19

Mean $W126_{24hr}$ (ppm*hrs) in recent years (2012-2016)

Low Elevation: 2.421

High Elevation: 10.655

Overstory Vegetation in GRSM



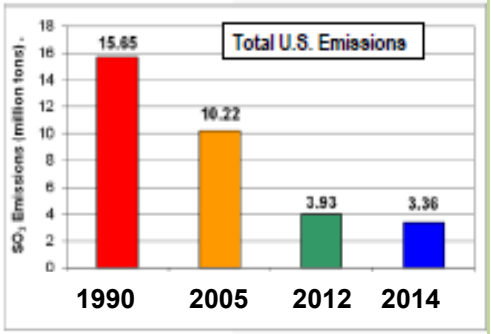
Annual SO_2 Power Plant Emissions 1990-2014 *

75% Reduction

Progress Energy Asheville Plant

GSMNP

Scale: Largest bar equals 2.2 million tons of SO_2 emissions in Ohio, 1990
Source: EPA, 2011



- 1990
- 2005
- 2012 Cross-State Air Pollution Rule
- 2014 Cross-State Air Pollution Rule
- States controlled for fine particles (annual SO2 and NOx) (23 States)
- States not covered for fine particles

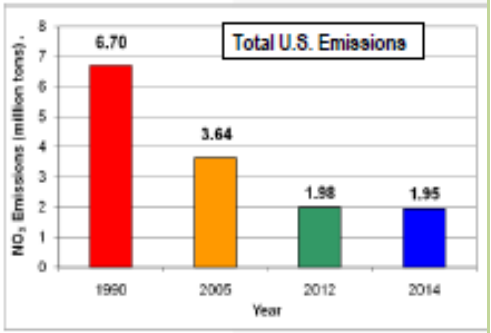
Courtesy of Jim Renfro, NPS

Annual NO_X Power Plant Emissions 1990-2014 *

71% Reduction

TVA
Bull Run Plant

GSMNP



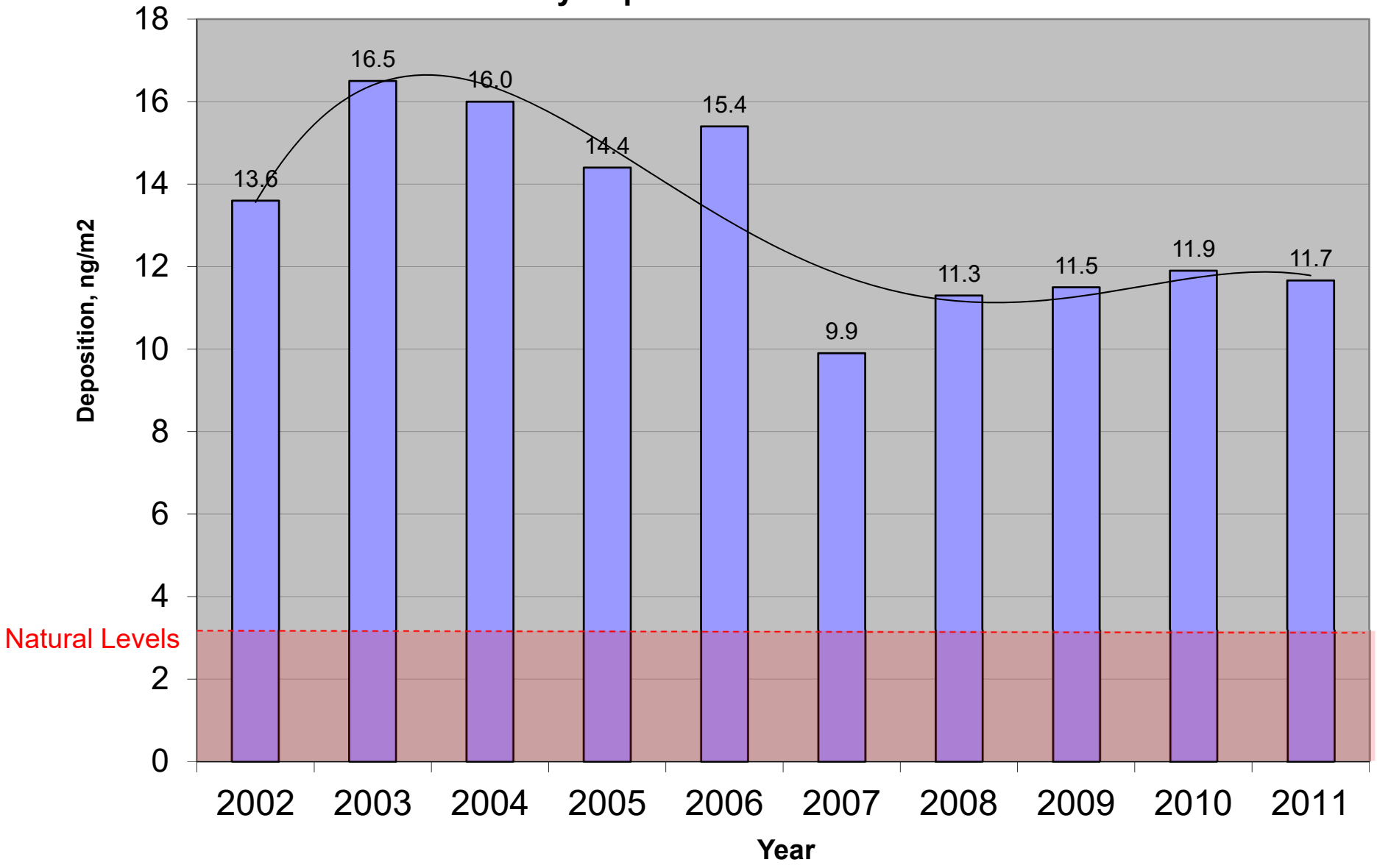
Scale: Largest bar equals 534 thousand tons of NO_X emissions in Ohio, 1990
Source: EPA, 2011

1990
2005
2012 Cross-State Air Pollution Rule
2014 Cross-State Air Pollution Rule
States controlled for fine particles (annual SO2 and NOx) (23 States)
States not covered for fine particles

Courtesy of Jim Renfro, NPS

Annual Total Wet Mercury Deposition

Great Smoky Mountains National Park
Mercury Deposition Network - Site TN11 -



Improvement in Haze at Great Smoky Mountains National Park

Conclusions

1. For elevations below 600 m, ozone is low in the morning and peaks in late afternoon
2. Above 600 m, diurnal profiles are relatively flat, with a noticeable decrease around noon
3. The TN side of GRSM appears to have higher exposures than the NC side at equivalent elevations
4. Since 2003, ozone concentrations above 60 ppb have declined significantly in frequency, especially at higher elevations in GRSM
5. Loss of high ozone concentrations, and more respite periods between episodes, greatly reduces risk to plants

Ozone Reductions Due to Lower NOx Emissions as Mandated by Clean Air Act and Clean Smokestacks Act


Questions?