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*Supplement of*

# Average versus high surface ozone levels over the continental USA: model bias, background influences, and interannual variability

**Jean J. Guo et al.**

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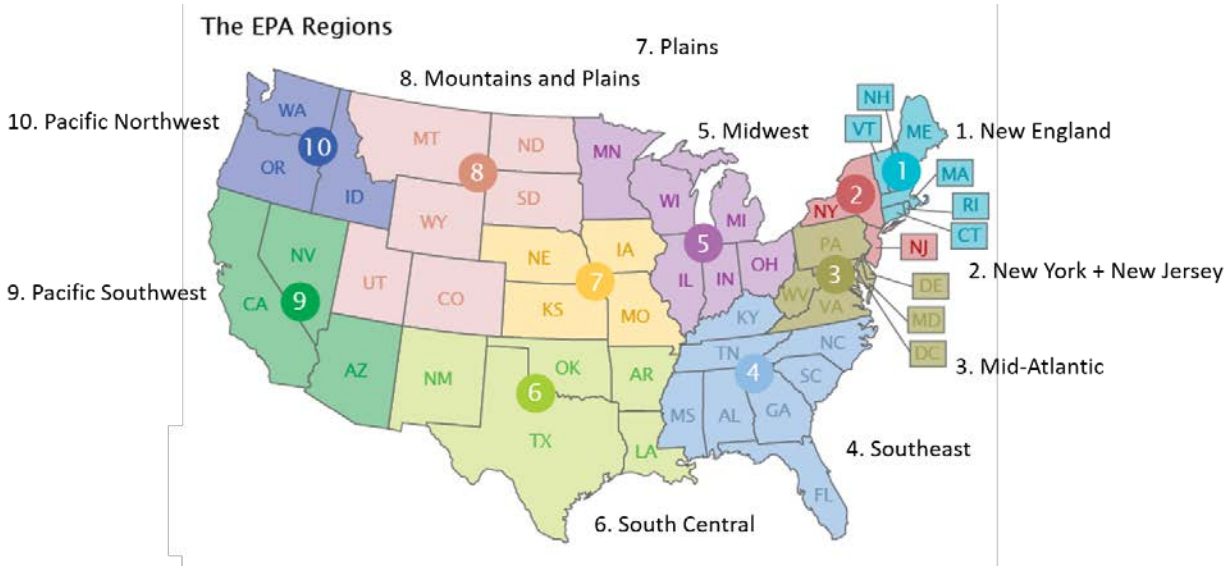
## Supplemental Figures

**Supplemental Table 1: The number of observational sites that fall within each EPA region for EPA AQS and CASTNet. (*) We include data from the Mount Bachelor Observatory in the Pacific Northwest region.**

| Region | EPA AQS | CASTNet | *Total* |
|---|---|---|---|
| 1. New England | 82 | 7 | *89* |
| 2. New York + New Jersey (NY+NJ) | 61 | 7 | *68* |
| 3. Mid-Atlantic | 138 | 14 | *152* |
| 4. Southeast | 309 | 24 | *333* |
| 5. Midwest | 255 | 18 | *273* |
| 6. South Central | 202 | 5 | *207* |
| 7. Plains | 71 | 2 | *73* |
| 8. Mountains and Plains | 153 | 12 | *165* |
| 9. Pacific Southwest | 325 | 14 | *339* |
| 10. Pacific Northwest | 48 | 6* | *54* |
| ***Total*** | ***1644*** | ***109*** | ***1753*** |



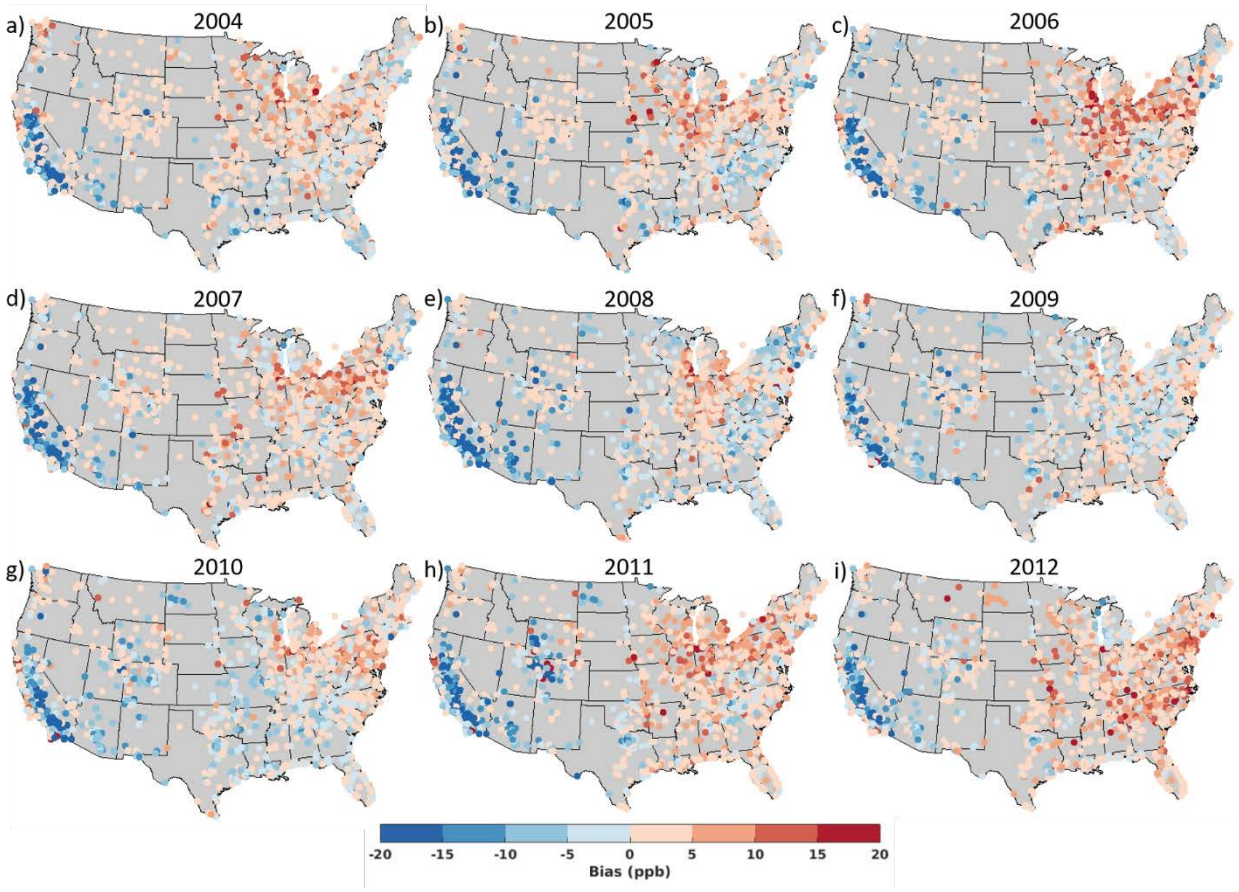

**Supplemental Figure 1: Map of the states falling within each EPA region in the continental United States (adapted from U.S. Environmental Protection Agency, 2012).**

**Supplemental Table 2: Number of EPA AQS sites collecting MDA8 $O_3$ data during each year from 2004-2012.**

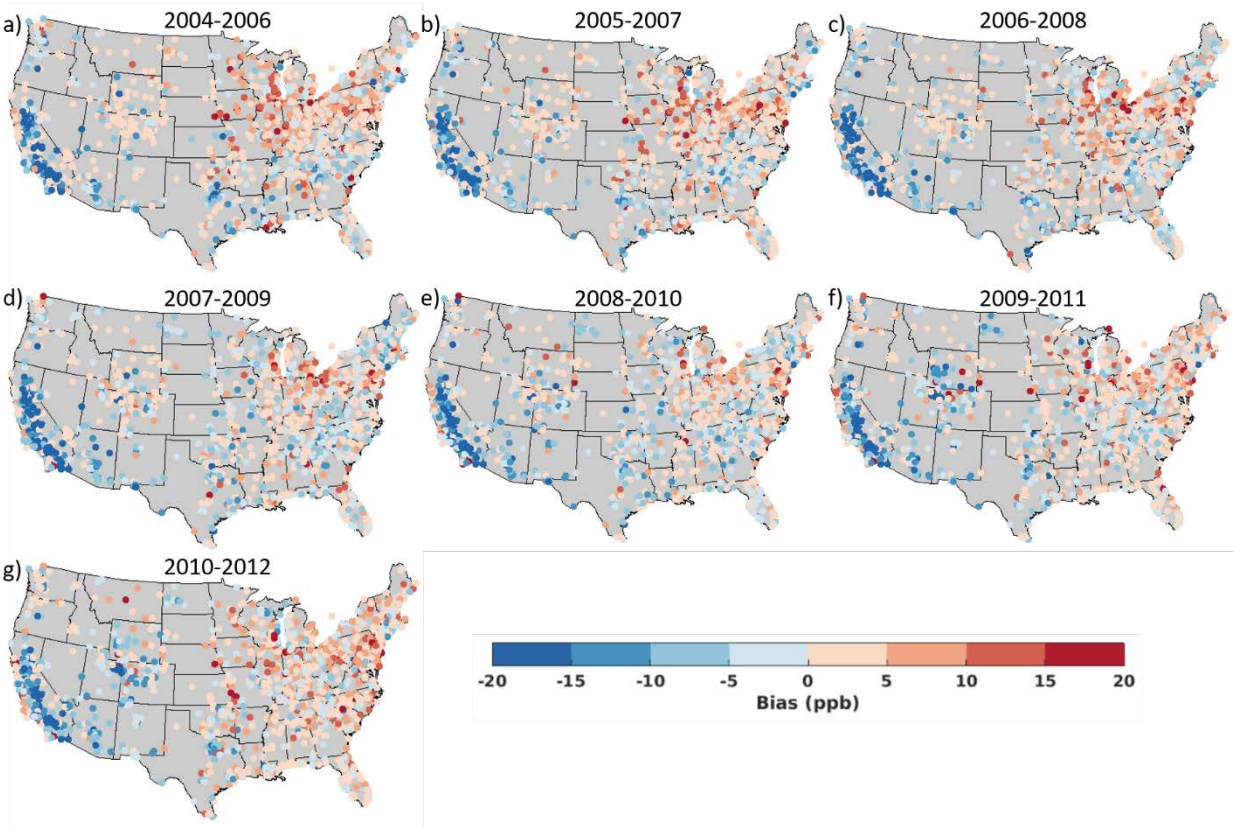
| Number of EPA AQS Sites | |
|---|---|
| **2004** | 1219 |
| **2005** | 1207 |
| **2006** | 1211 |
| **2007** | 1237 |
| **2008** | 1241 |
| **2009** | 1251 |
| **2010** | 1280 |
| **2011** | 1333 |
| **2012** | 1315 |

**Supplemental Table 3: Global and US emissions totals for 2004-2012.**

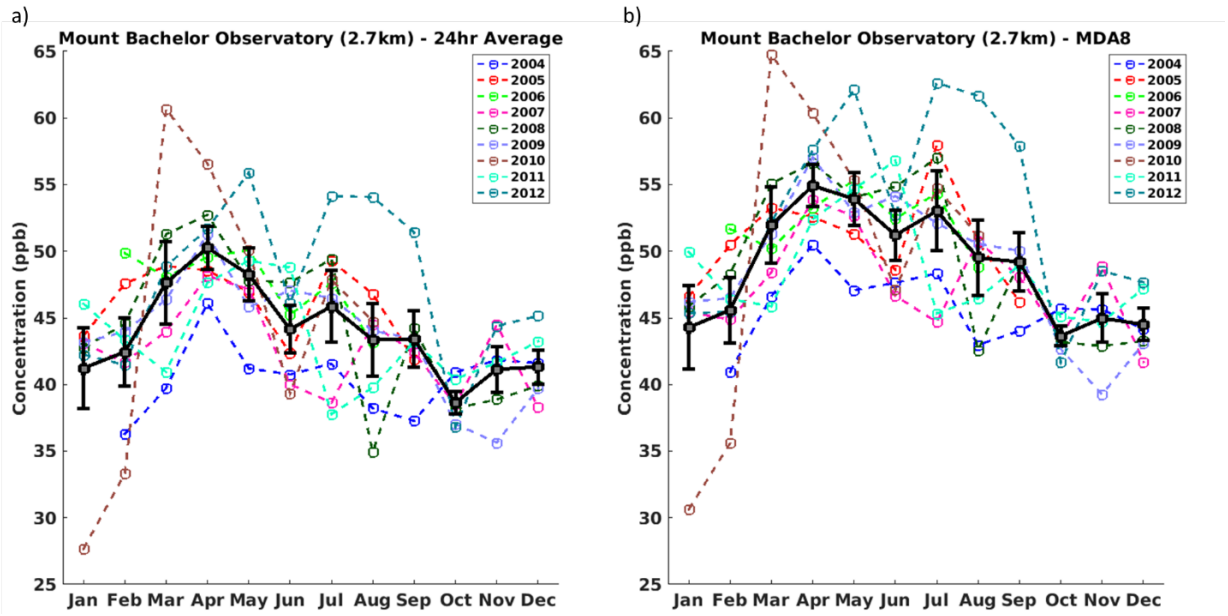
| | Emissions | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Global** | *Anthropogenic NO with biofuels (Tg N)* | 30.3 | 30.2 | 30.1 | 29.9 | 29.5 | 29.0 | 28.8 | 28.8 | 28.8 |
| | *Biomass burning (Tg N)* | 4.5 | 4.7 | 4.6 | 4.6 | 3.9 | 3.5 | 5.0 | 3.7 | 3.7 |
| | *Soil (Tg N)* | 9.0 | 9.1 | 8.8 | 8.5 | 8.4 | 8.6 | 8.4 | 8.6 | 9.2 |
| | *Lightning (Tg N)* | 5.5 | 6.1 | 6.2 | 6.4 | 6.9 | 7.3 | 7.2 | 7.1 | 7.2 |
| | *Isoprene (Tg C)* | 493.0 | 499.3 | 471.5 | 453.6 | 435.3 | 455.4 | 466.0 | 453.3 | 467.3 |
| **US** | *Anthropogenic NO with biofuels (Tg N)* | 6.32 | 6.04 | 5.75 | 5.44 | 5.13 | 4.63 | 4.36 | 4.36 | 4.36 |
| | *Biomass burning (Tg N)* | 0.02 | 0.06 | 0.06 | 0.07 | 0.04 | 0.04 | 0.05 | 0.12 | 0.12 |
| | *Soil (Tg N)* | 0.78 | 0.86 | 1.02 | 0.92 | 0.82 | 0.79 | 0.77 | 0.95 | 1.10 |
| | *Lightning (Tg N)* | 0.86 | 0.86 | 0.77 | 0.75 | 1.10 | 1.13 | 1.13 | 1.28 | 1.31 |
| | *Isoprene (Tg C)* | 18.1 | 21.5 | 21.9 | 22.0 | 19.3 | 18.3 | 20.2 | 22.0 | 22.4 |



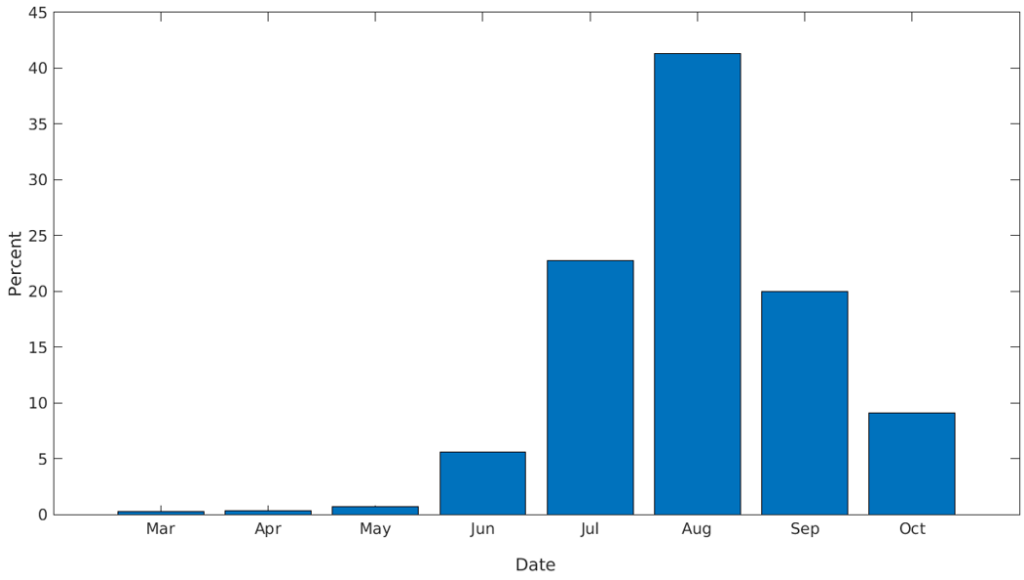

**Supplemental Figure 2: Average model bias (model – observed) on the $O_3$_top10obs days during (a) 2004, (b) 2005, (c) 2006, (d) 2007, (e) 2008, (f) 2009, (g) 2010, (h) 2011, and (i) 2012.**




**Supplemental Figure 3: Model bias (model – observed) on the 4th highest MDA8 $O_3$ day at each observational site averaged for each three-year span. (a) 2004-2006, (b) 2005-2007, (c) 2006-2008, (d) 2007-2009, (e) 2008-2010, (f) 2009-2011, and (g) 2010-2012.**



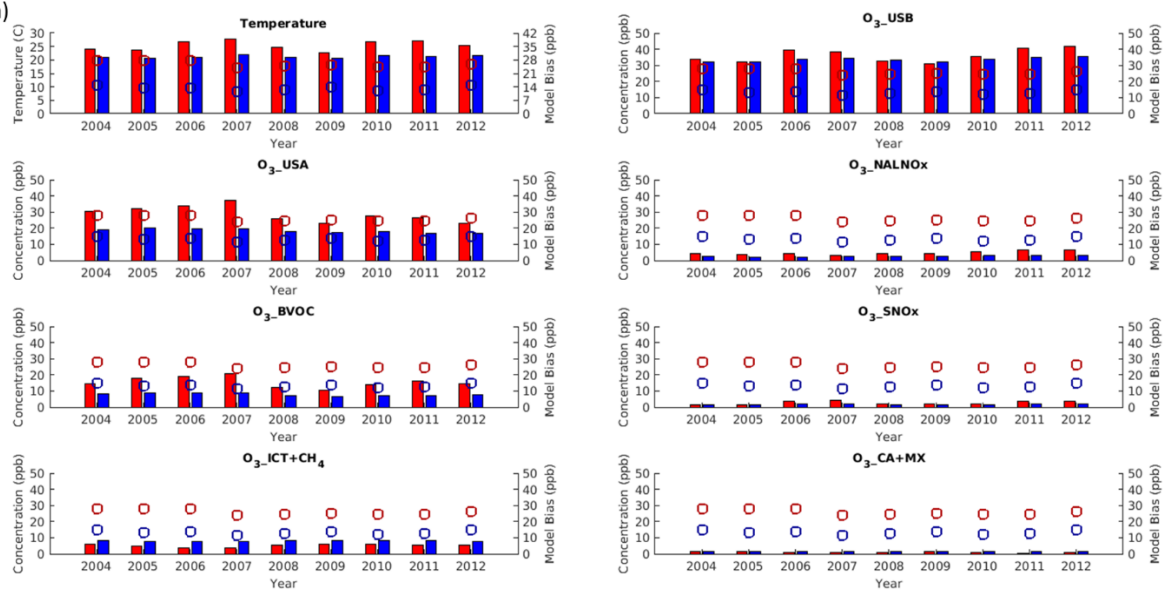

**Supplemental Figure 4: Monthly average of observed (a) daily 24-hour and (b) MDA8 $O_3$ concentrations averaged across 2004-2012 at Mount Bachelor Observatory. Black line shows the average of each month from 2004-2012. Error bars show the standard deviation in the interannual variability in each month. Dashed lines show the concentrations for each individual year.**

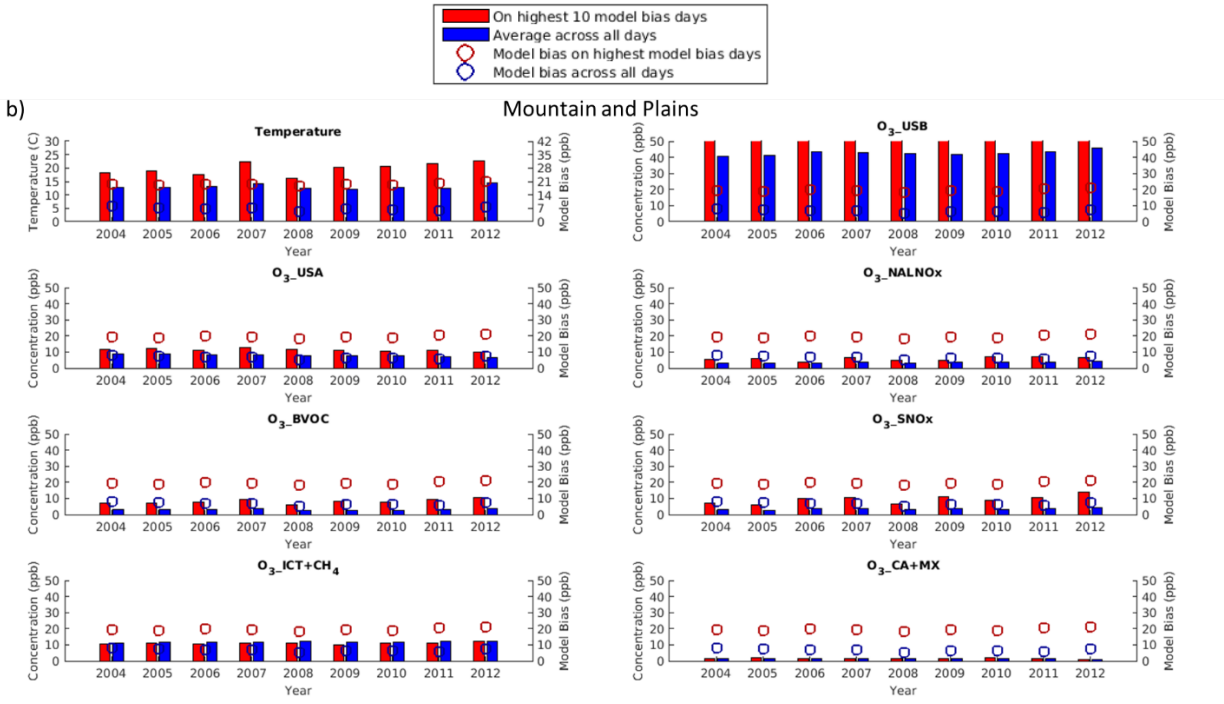



**Supplemental Figure 5: Percent of total top 10 most biased days from Jan-Dec (9 years x 10 days x 10 regions) that fell within each month in the United States. All the most biased days fell between Mar-Oct.**

Southeast

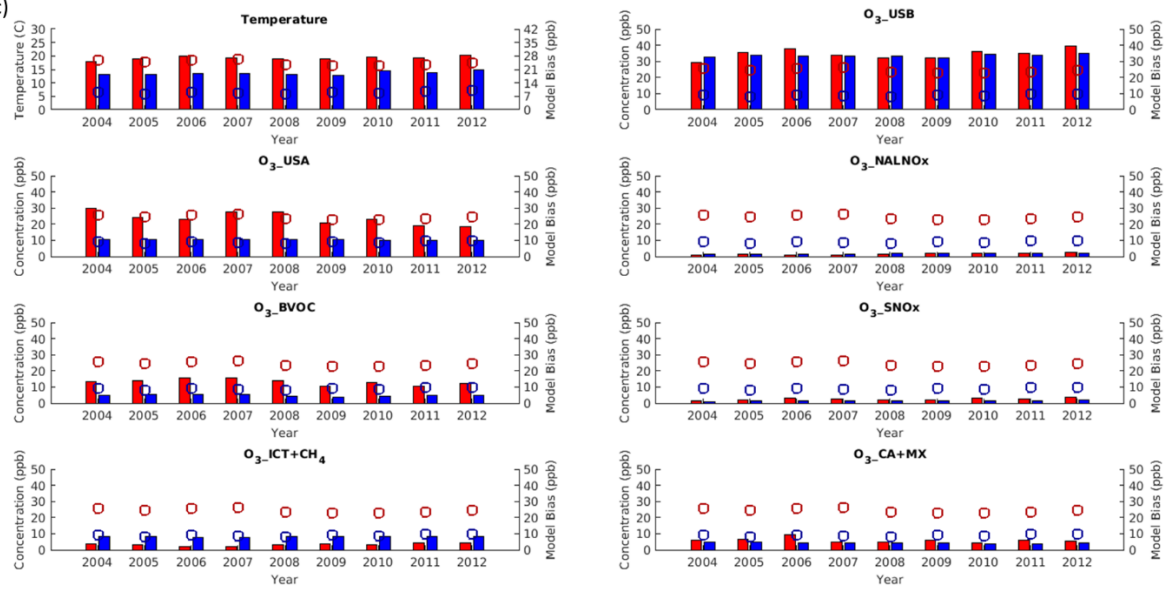
a)

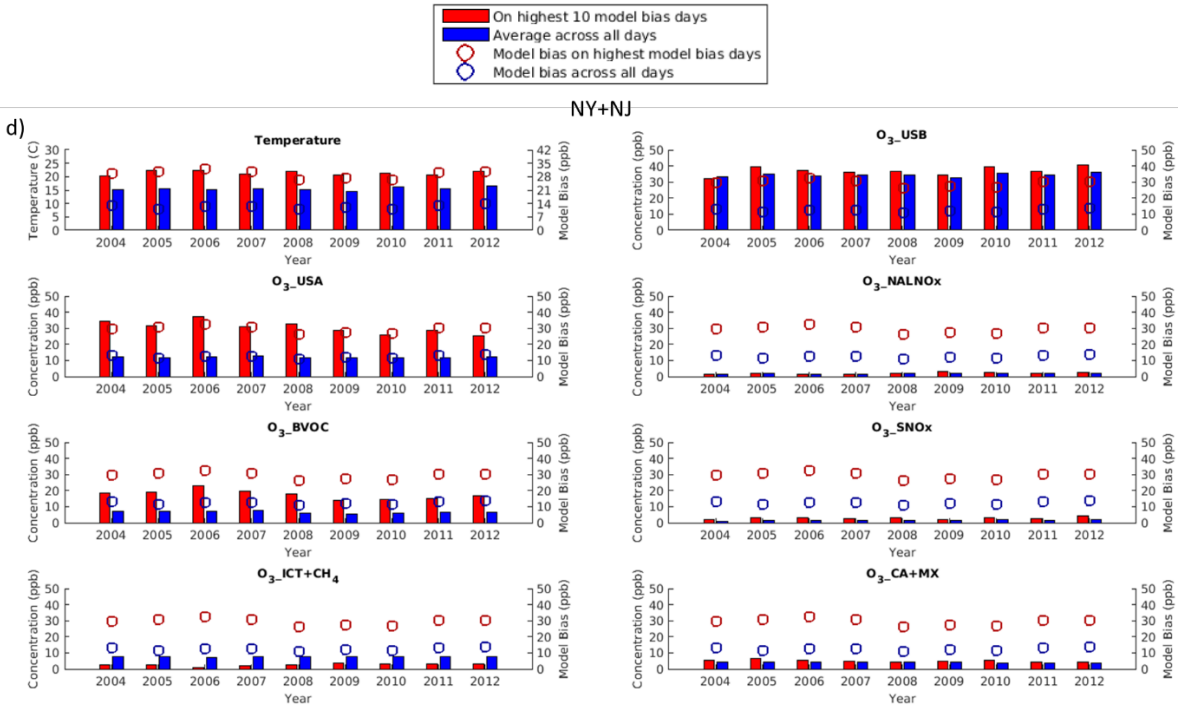

Temperature
Temperature (C)
Model Bias (ppb)
O3_USB
Concentration (ppb)
O3_USA
O3_NALNOx
O3_BVOC
O3_SNOx
O3_ICT+CH4
O3_CA+MX
Year
2004 2005 2006 2007 2008 2009 2010 2011 2012


On highest 10 model bias days
Average across all days
Model bias on highest model bias days
Model bias across all days
b)
Mountain and Plains
Temperature
Temperature (C)
Model Bias (ppb)
Year
O3_USB
O3_USA
O3_NALNOx
O3_BVOC
O3_SNOx
O3_ICT+CH4
O3_CA+MX
Concentration (ppb)

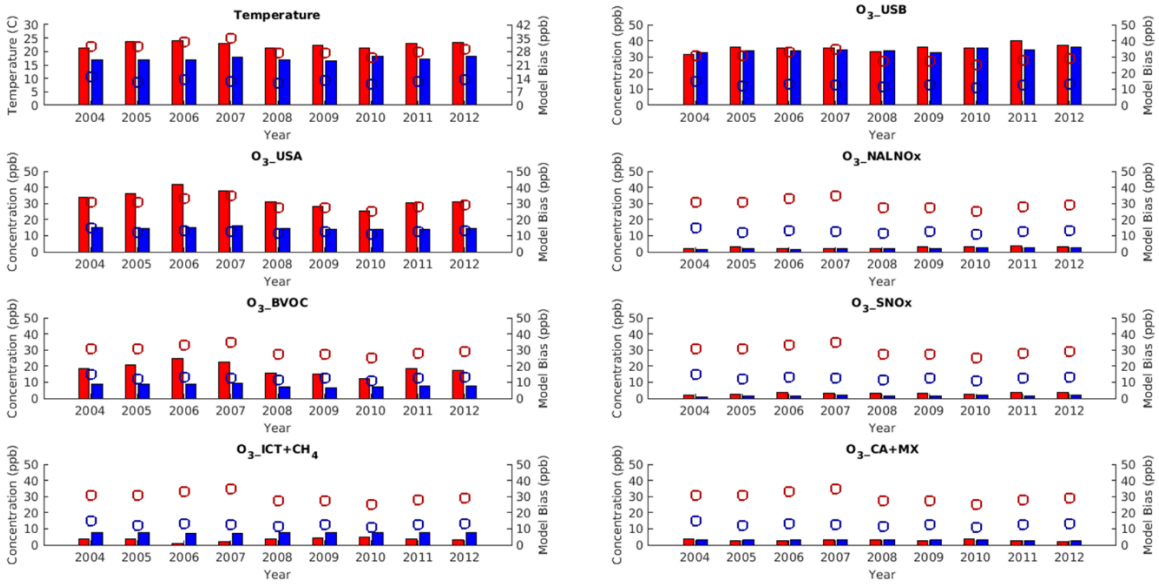
New England

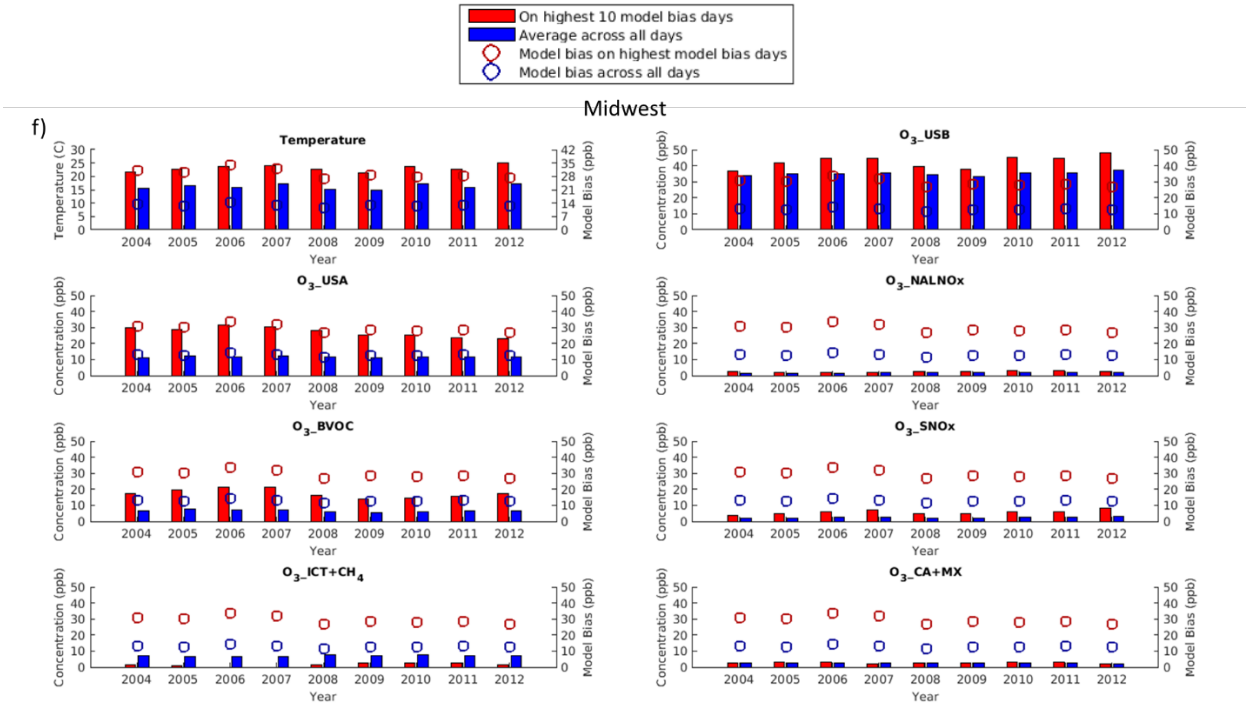
c)




On highest 10 model bias days
Average across all days
Model bias on highest model bias days
Model bias across all days
NY+NJ
d)
Temperature
Temperature (C)
Model Bias (ppb)
Year
O3_USB
O3_USA
O3_NALNOx
O3_BVOC
O3_SNOx
O3_ICT+CH4
O3_CA+MX
Concentration (ppb)
2004
2005
2006
2007
2008
2009
2010
2011
2012

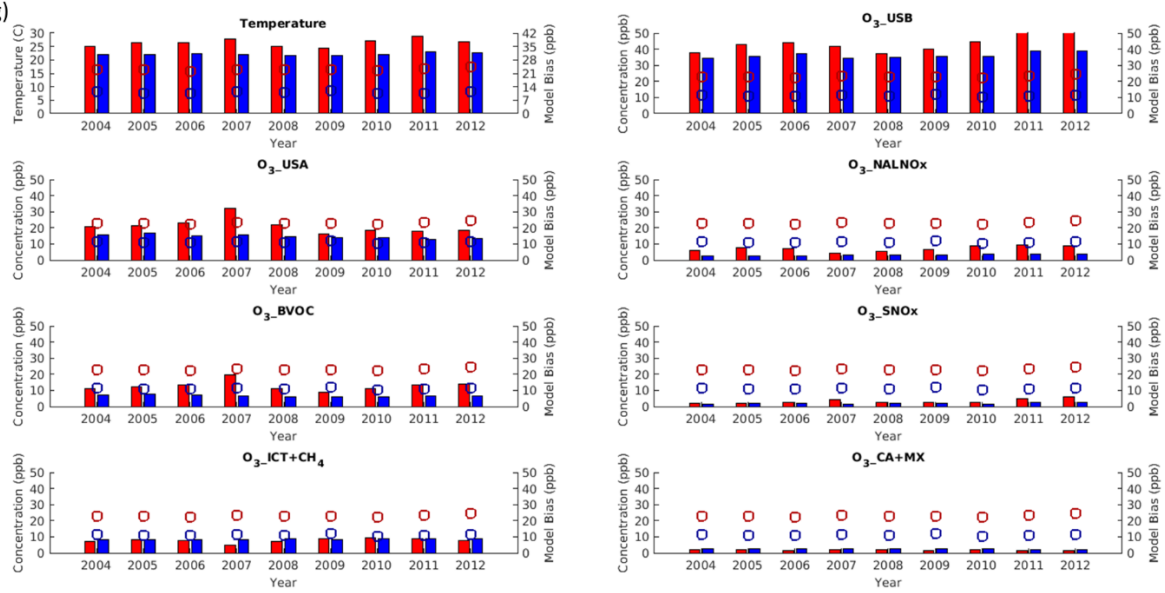
e) Mid-Atlantic

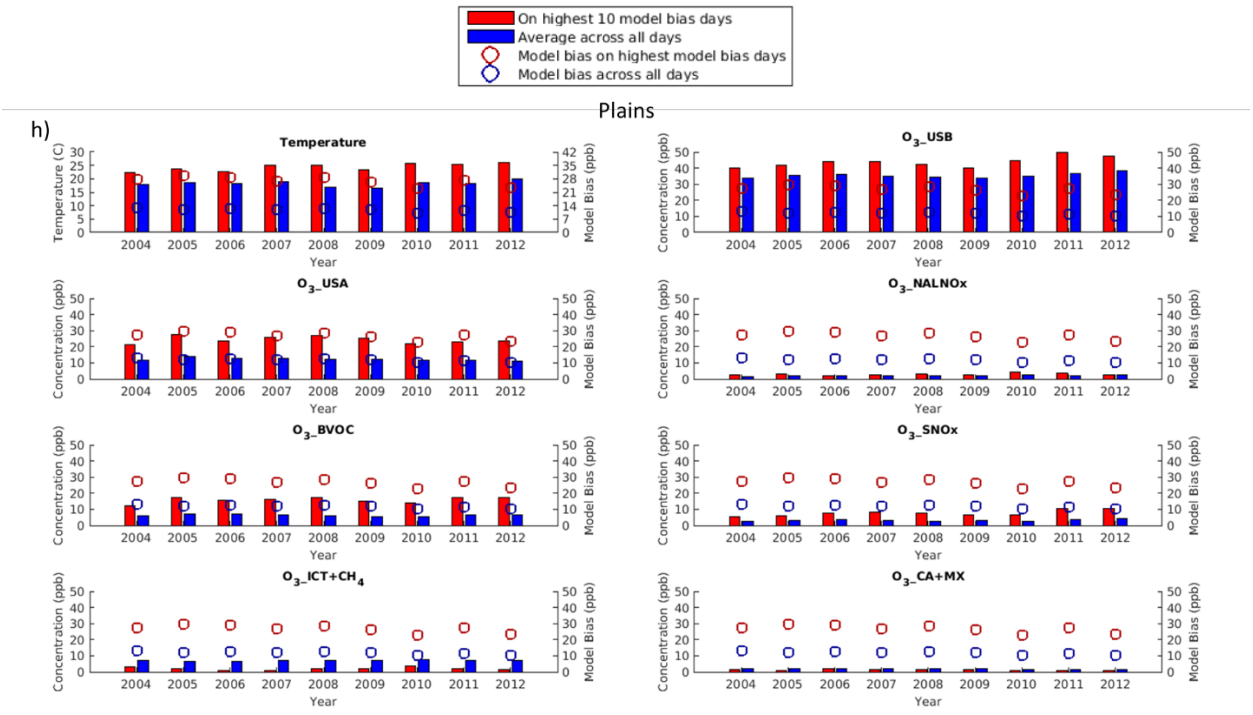



On highest 10 model bias days
Average across all days
Model bias on highest model bias days
Model bias across all days
f)
Midwest
Temperature
O3_USB
O3_USA
O3_NALNOx
O3_BVOC
O3_SNOx
O3_ICT+CH4
O3_CA+MX
Temperature (C)
Concentration (ppb)
Model Bias (ppb)
Year
2004
2005
2006
2007
2008
2009
2010
2011
2012

South Central

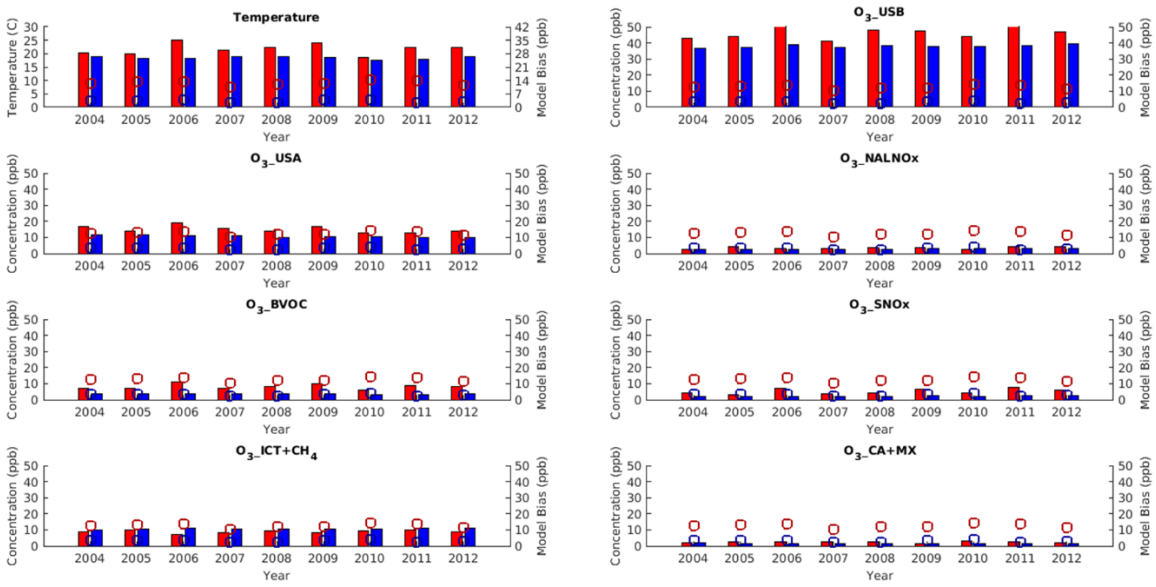
g)

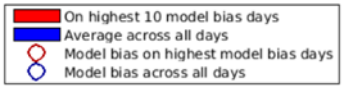


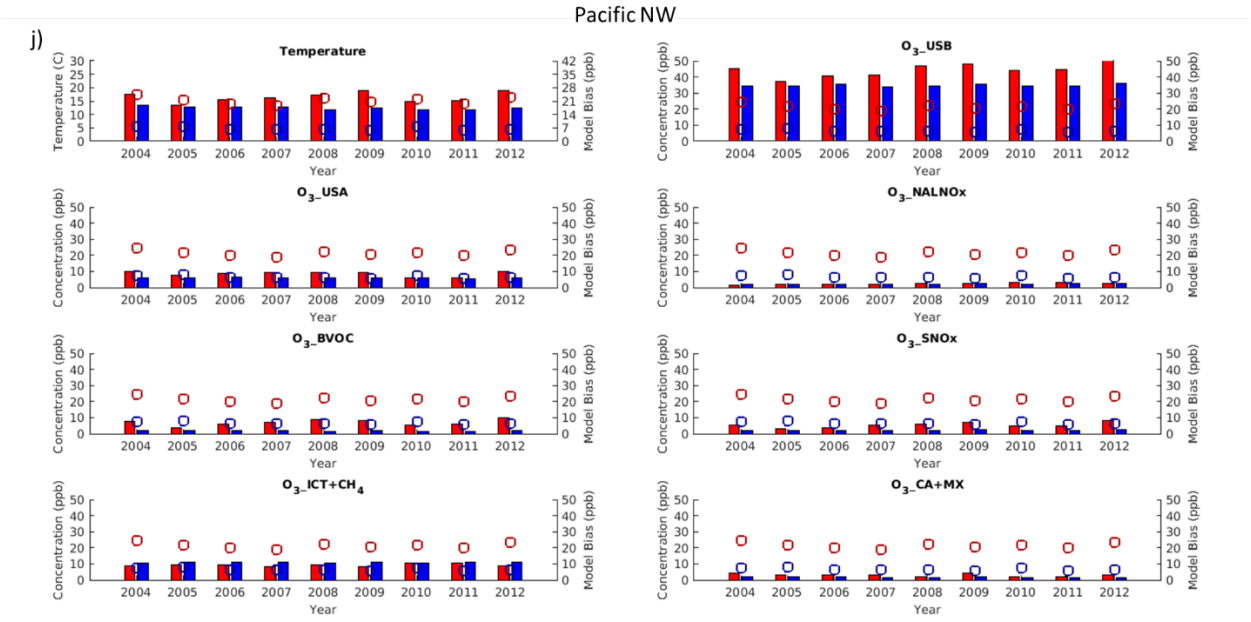

On highest 10 model bias days
Average across all days
Model bias on highest model bias days
Model bias across all days
Plains
h)
Temperature
O3_USB
O3_USA
O3_NALNOx
O3_BVOC
O3_SNOx
O3_ICT+CH4
O3_CA+MX
Temperature (C)
Concentration (ppb)
Model Bias (ppb)
Year
2004
2005
2006
2007
2008
2009
2010
2011
2012

Pacific SW

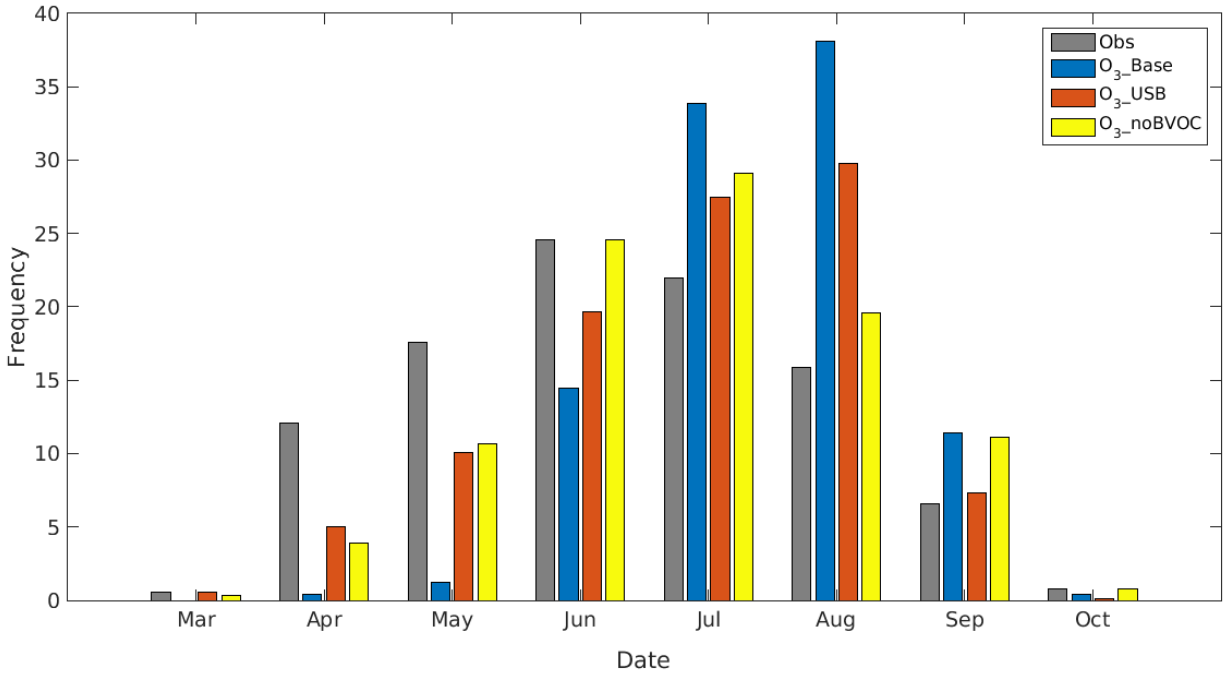
i)


Temperature
Temperature (C)
Model Bias (ppb)
Year
O3_USB
Concentration (ppb)
O3_USA
O3_NALNOx
O3_BVOC
O3_SNOx
O3_ICT+CH4
O3_CA+MX
2004
2005
2006
2007
2008
2009
2010
2011
2012

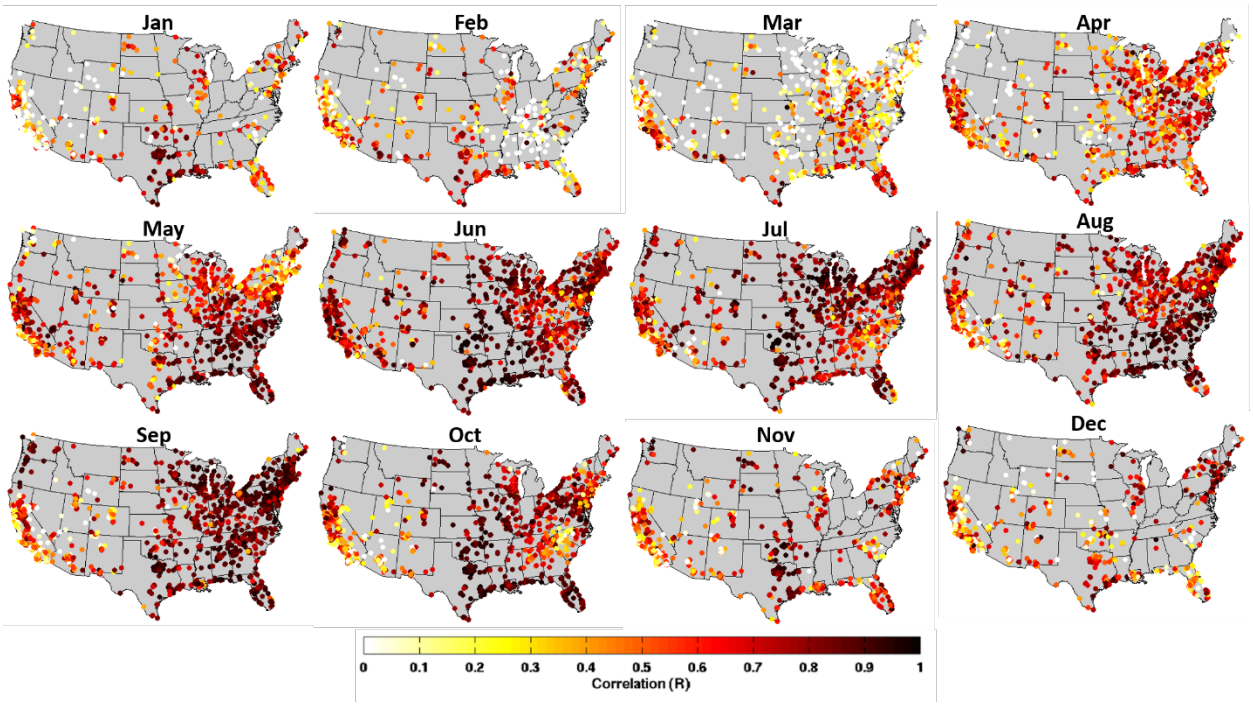

On highest 10 model bias days
Average across all days
Model bias on highest model bias days
Model bias across all days



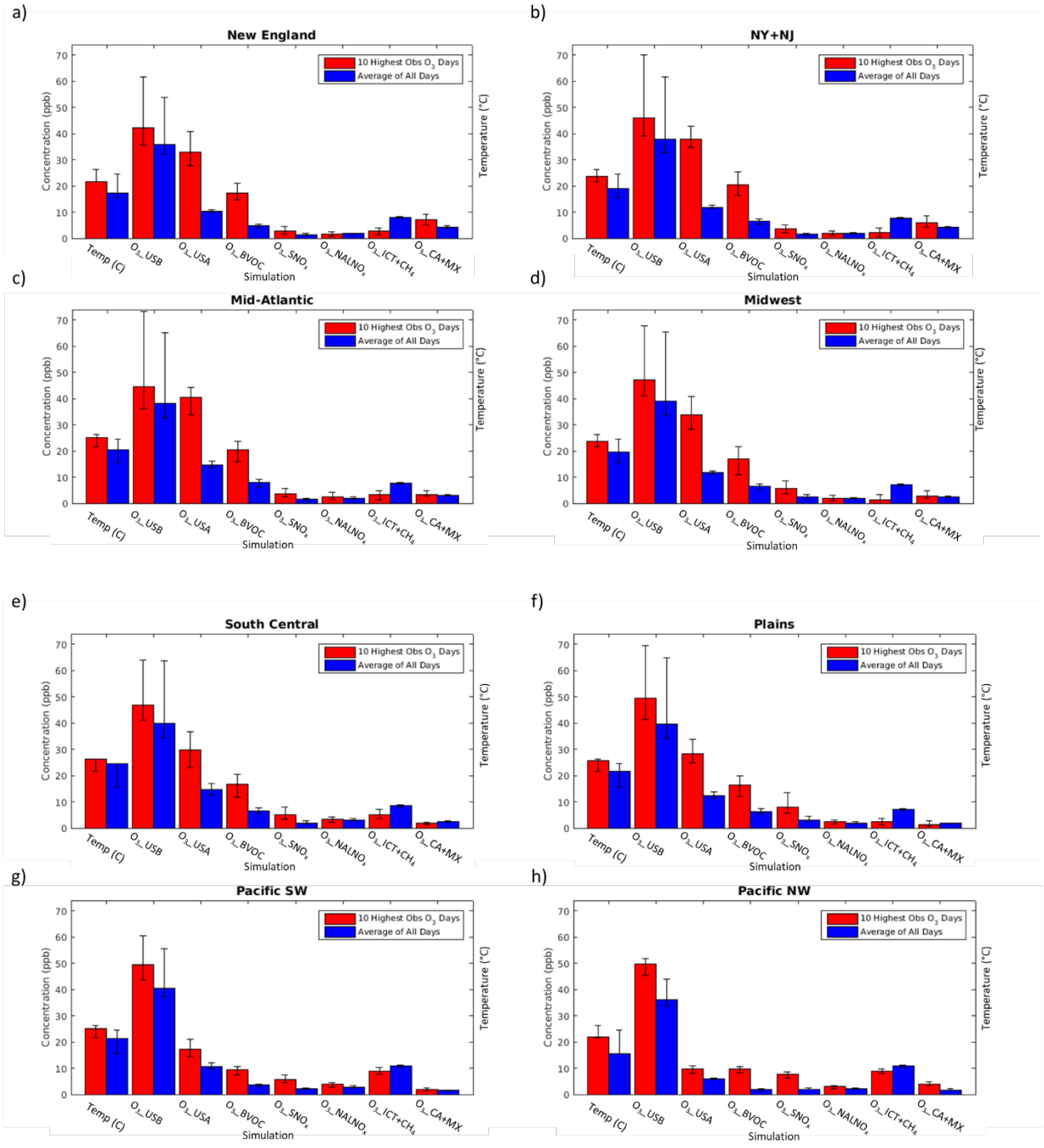

**Supplemental Figure 6: Average influence of each sensitivity simulation on MDA8 $O_3$ in each region on the 10 most biased days from Mar-Oct (red) versus averaged across all days (blue). Red circles show the average model bias ($O_3$_Base – observations) on the top 10 model bias days. Blue circles show the model bias averaged across all days. The circles do not vary between subplots.**



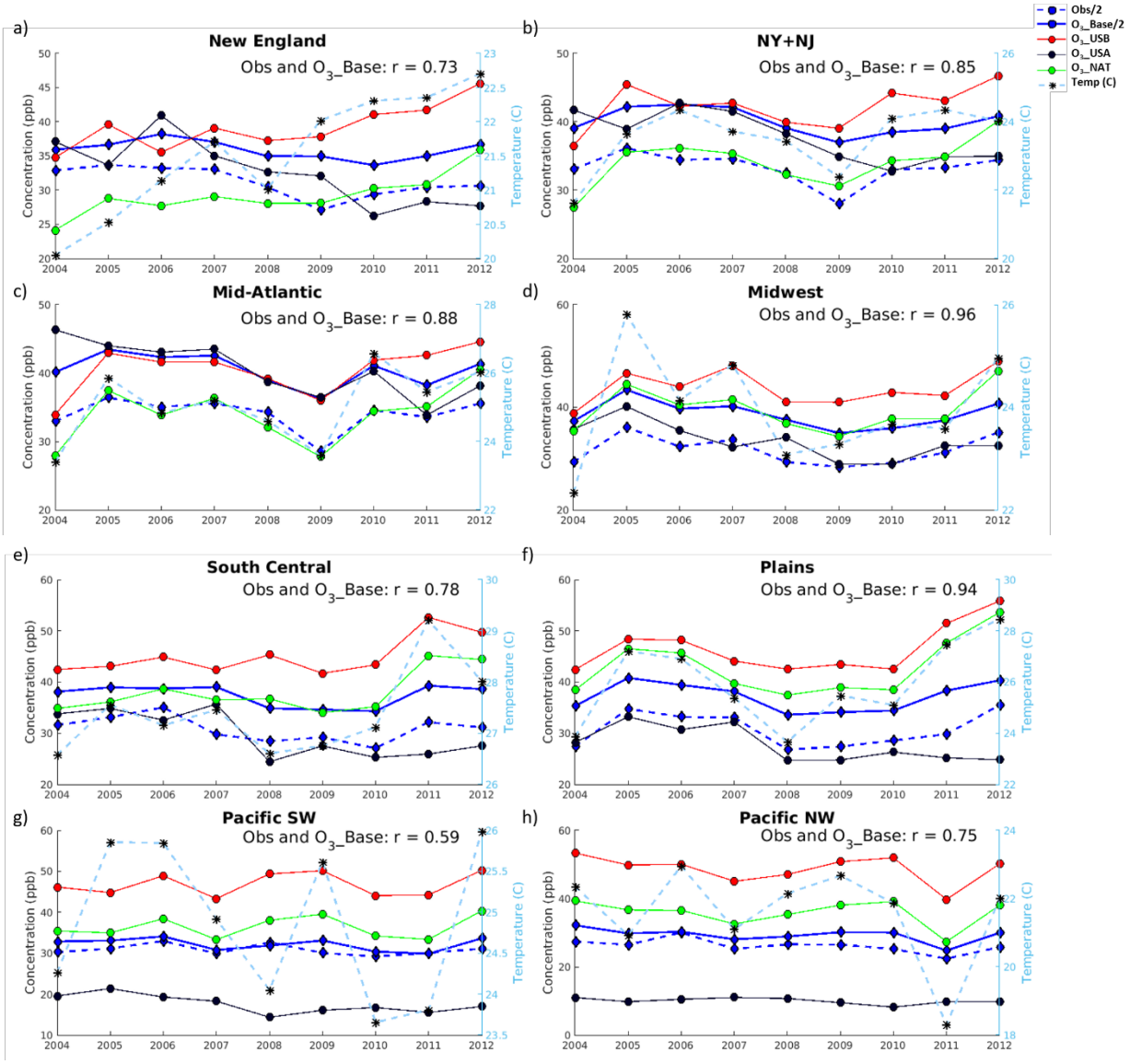

**Supplemental Figure 7: Percent of total top ten days (9 years x 10 days x 10 regions) from Jan-Dec (365 or 366 days) in the observations, $O_3$_Base, $O_3$_USB, and $O_3$_noBVOC that fell within each month for all sites across the U.S.A. All the top ten days for each simulation fell between Mar-Oct.**




**Supplemental Figure 8: Correlation between 2004-2012 year-to-year monthly averages for MDA8 $O_3$ in the observation and in the model ($O_3$_Base) for each individual month.**




**Supplemental Figure 9: Average 2004-2012 influence of each sensitivity simulation to $O_3$_Base in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW on the MDA8 $O_3$_top10obs_JJA days (red) versus averaged across all days (blue). Error bars show the average concentration on the lowest versus highest year for each sensitivity simulation in each region.**



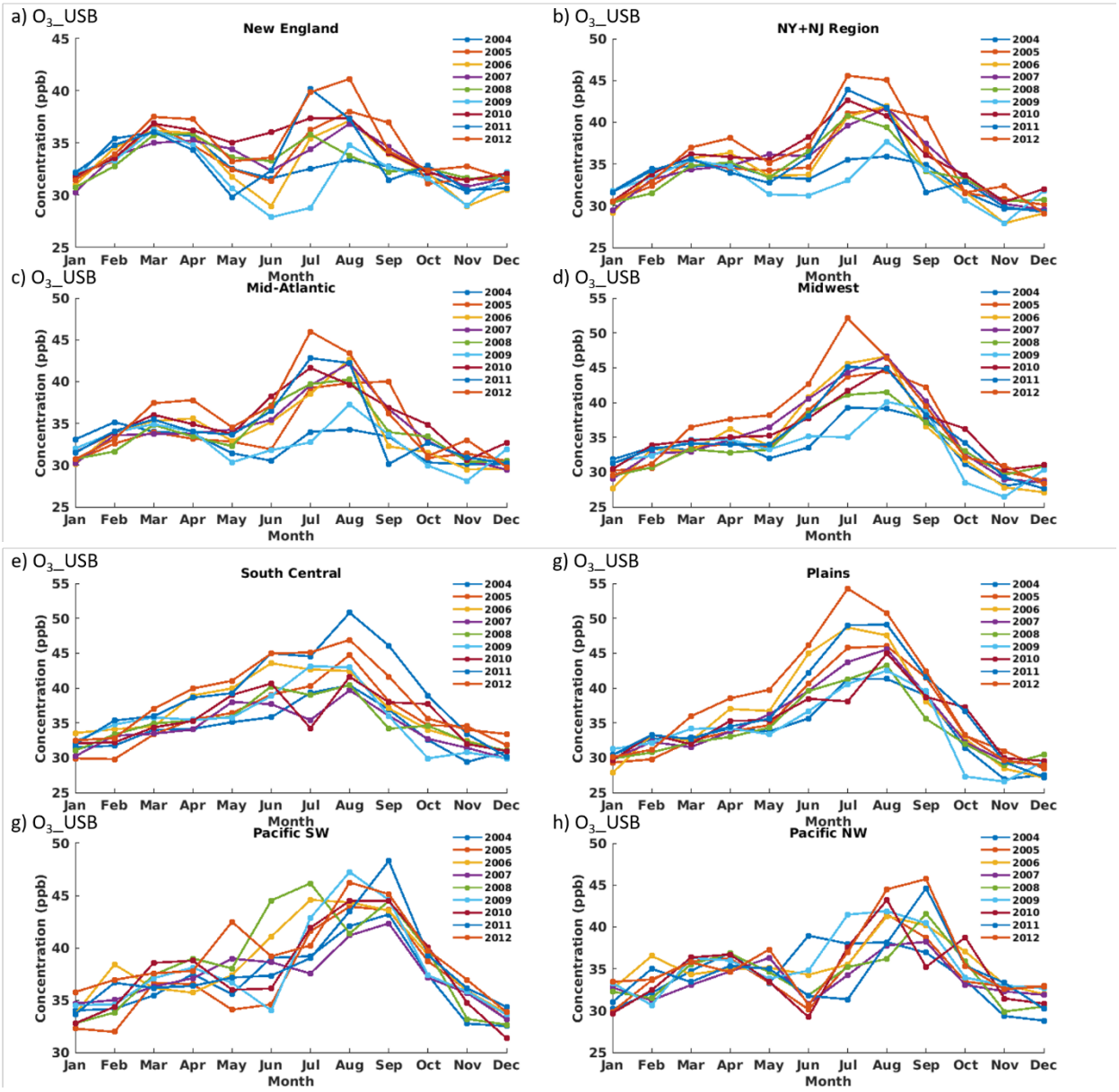

**Supplemental Figure 10: Average yearly MDA8 $O_3$_top10obs_JJA concentrations for observations (divided by 2 to fit on the same axes; blue dashed line), $O_3$_Base (divided by 2; blue solid line), $O_3$_USB (red), $O_3$_USA (black), $O_3$_NAT (green) MDA8, and temperature (in degrees C; light blue) sampled on the $O_3$_top10obs days in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW.**

**Supplemental Table 4: Monthly average temperature across all days in each season (average of 2004-2012) in (1) GEOS-Chem, in (2) the Global Historical Climatology Network (GHCN) and the Climate Anomaly Monitoring System (CAMS) (in degrees C), and (3) the difference between these values.**

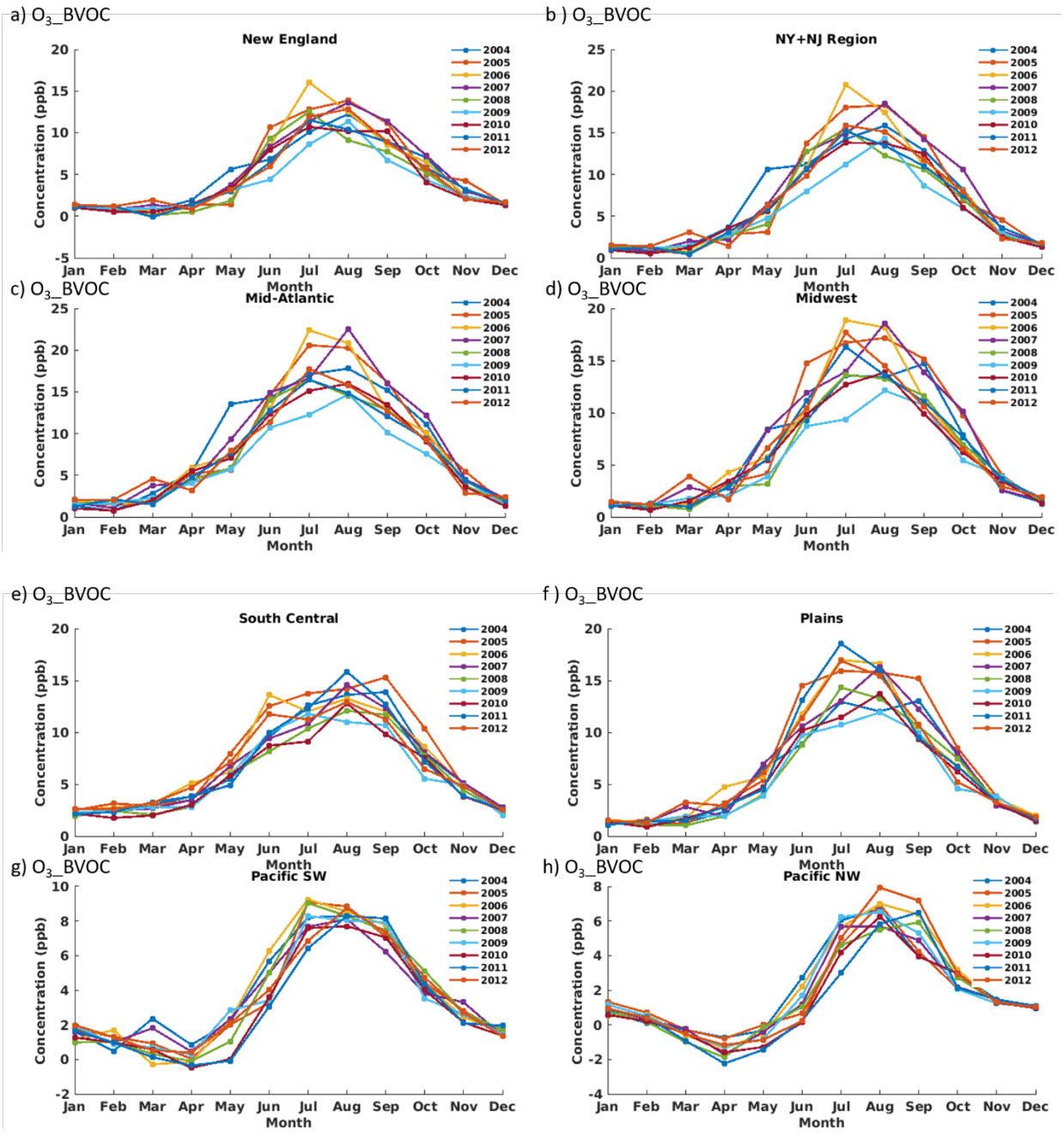
| | Model Temperature (C) | | | GHCN+CAMS Temperature (C) | | | Model Temp. Bias | | |
|---|---|---|---|---|---|---|---|---|---|
| *Region* | *MAM* | *JJA* | *SON* | *MAM* | *JJA* | *SON* | *MAM* | *JJA* | *SON* |
| New England | 7 | 19 | 11 | 8 | 20 | 11 | 0 | -1 | 1 |
| NY+NJ | 9 | 21 | 12 | 9 | 21 | 12 | 0 | 0 | 1 |
| Mid-Atlantic | 12 | 23 | 14 | 12 | 23 | 14 | 0 | 0 | 0 |
| Southeast | 17 | 26 | 18 | 17 | 26 | 18 | 0 | 0 | 0 |
| Midwest | 10 | 22 | 12 | 10 | 22 | 12 | 0 | 0 | 0 |
| South Central | 18 | 27 | 19 | 19 | 28 | 20 | -1 | -1 | -1 |
| Plains | 13 | 25 | 13 | 13 | 25 | 13 | 0 | 0 | 0 |
| Mountains + Plains | 7 | 20 | 9 | 7 | 19 | 8 | 0 | 1 | 1 |
| Pacific SW | 14 | 23 | 17 | 14 | 22 | 17 | -1 | 0 | 0 |
| Pacific NW | 8 | 17 | 10 | 8 | 17 | 9 | 0 | 0 | 1 |

**Supplemental Table 5: Correlation between (1) $O_3$_Base and $O_3$_USB and (2) $O_3$_Base and $O_3$_USA on the average of $O_3$_top10obs_JJA days from 2004-2012 in each region.**

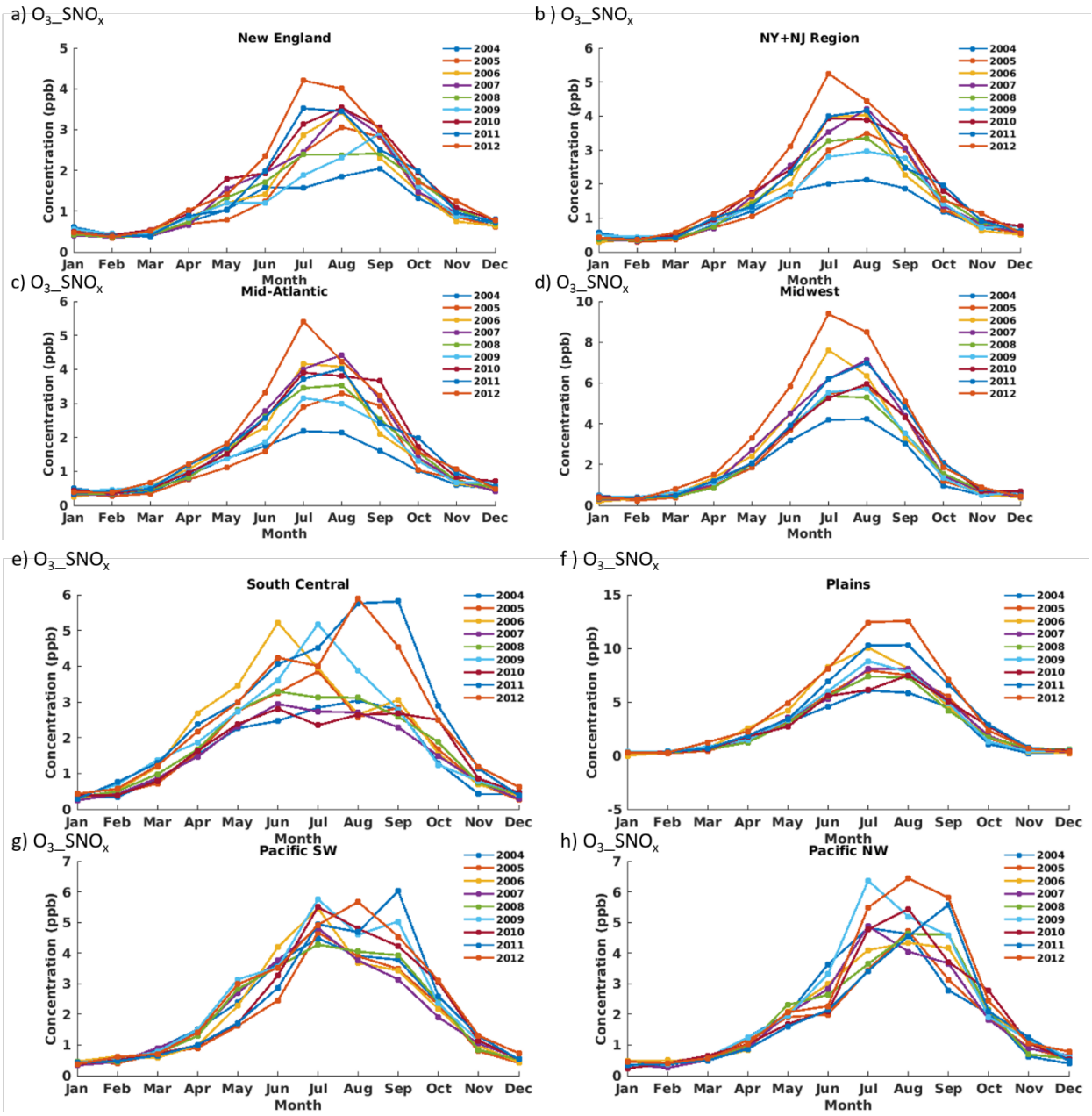
| | *Correlation* | |
|---|---|---|
| *Region* | $O_3$_Base and $O_3$_USB | $O_3$_Base and $O_3$_USA |
| New England | 0.28 | 0.64 |
| NY+NJ | 0.50 | 0.58 |
| Mid-Atlantic | 0.54 | 0.70 |
| Southeast | 0.66 | 0.59 |
| Midwest | 0.75 | 0.76 |
| South Central | 0.71 | 0.72 |
| Plains | 0.80 | 0.75 |
| Mountains + Plains | 0.95 | 0.64 |
| Pacific SW | 0.72 | 0.28 |
| Pacific NW | 0.98 | 0.05 |



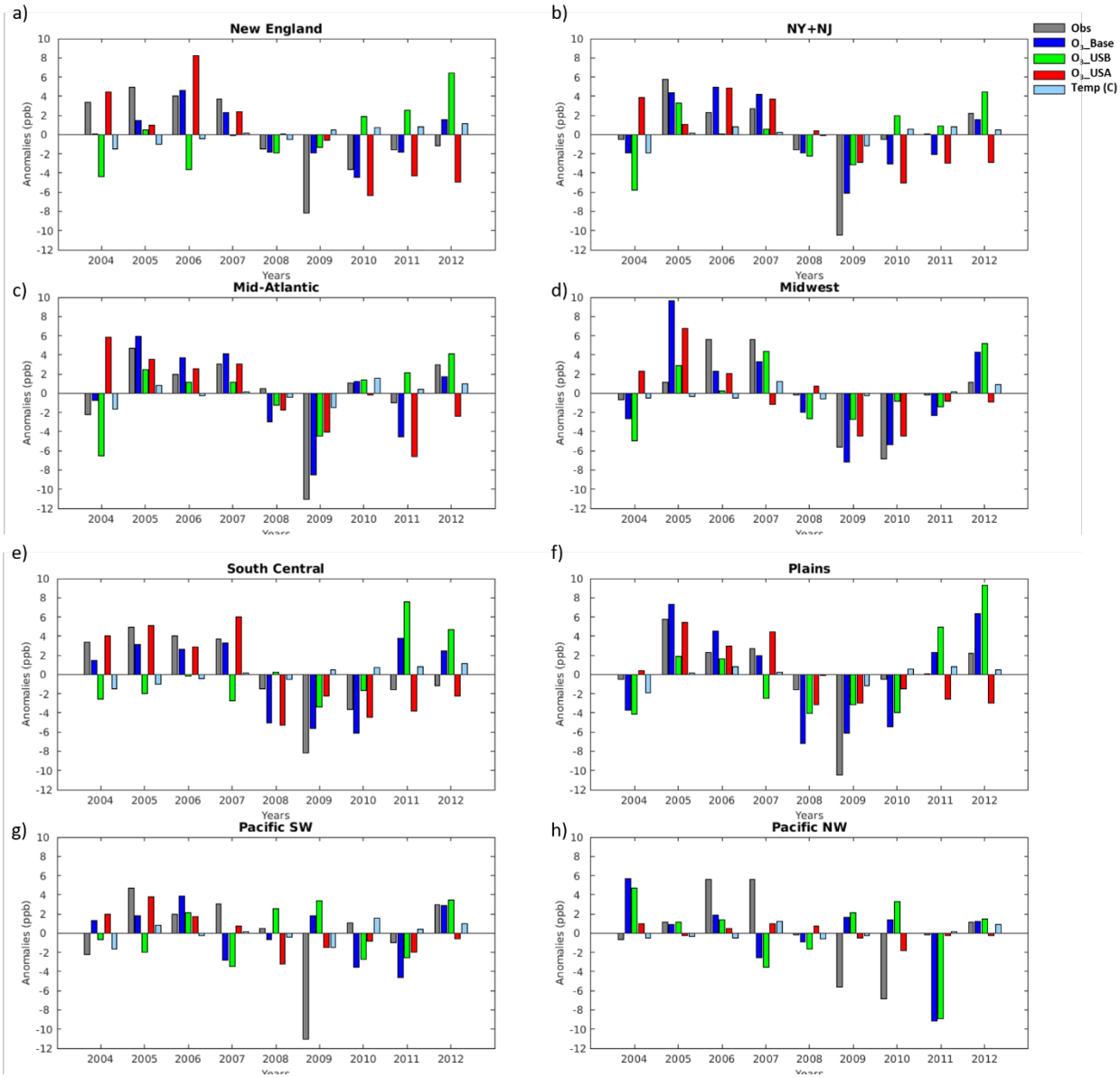

80 **Supplemental Figure 11: Monthly average MDA8 $O_3$_USB concentrations in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW.**



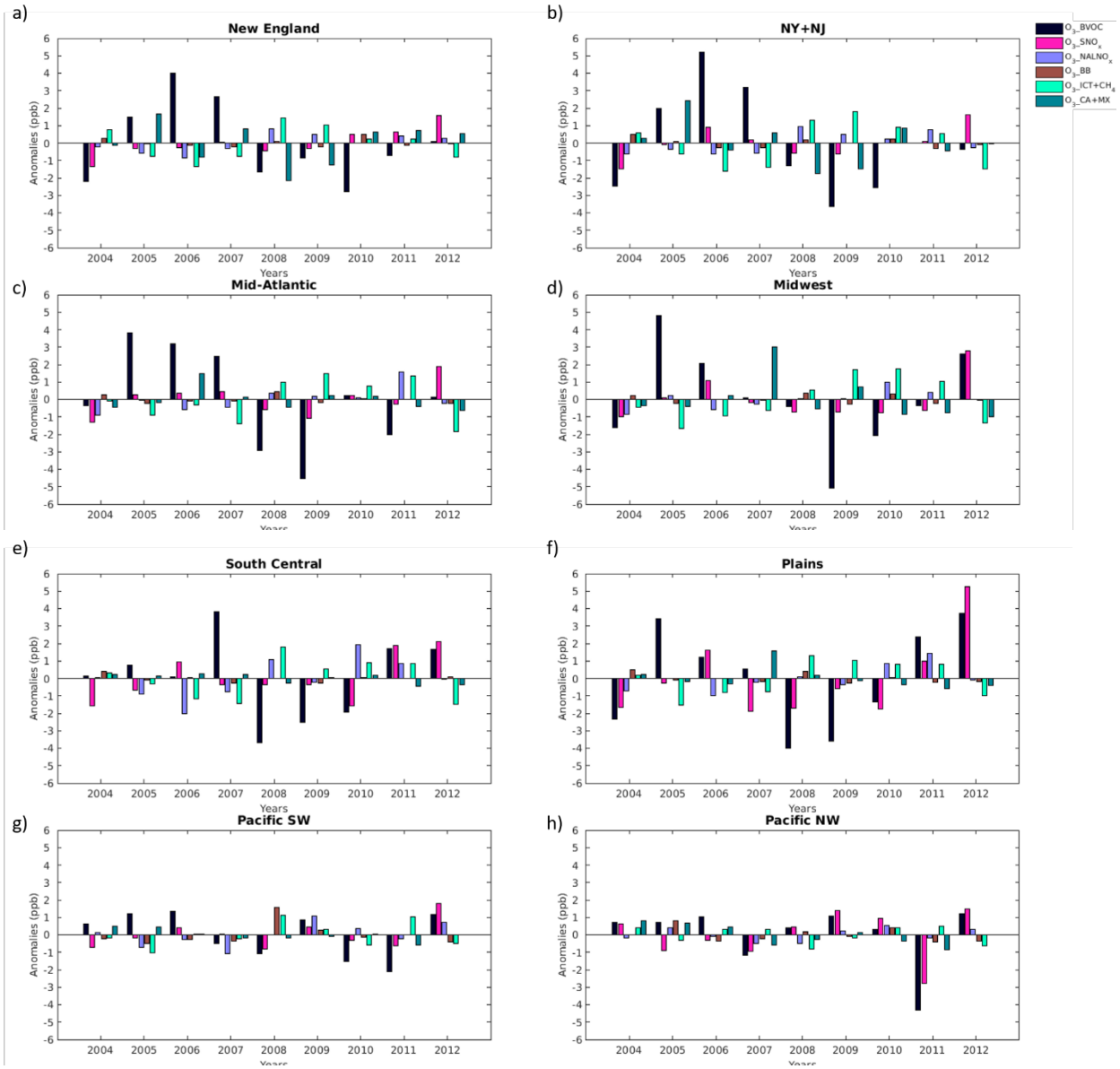

**Supplemental Figure 12: Monthly average MDA8 $O_3$_BVOC concentrations in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW.**



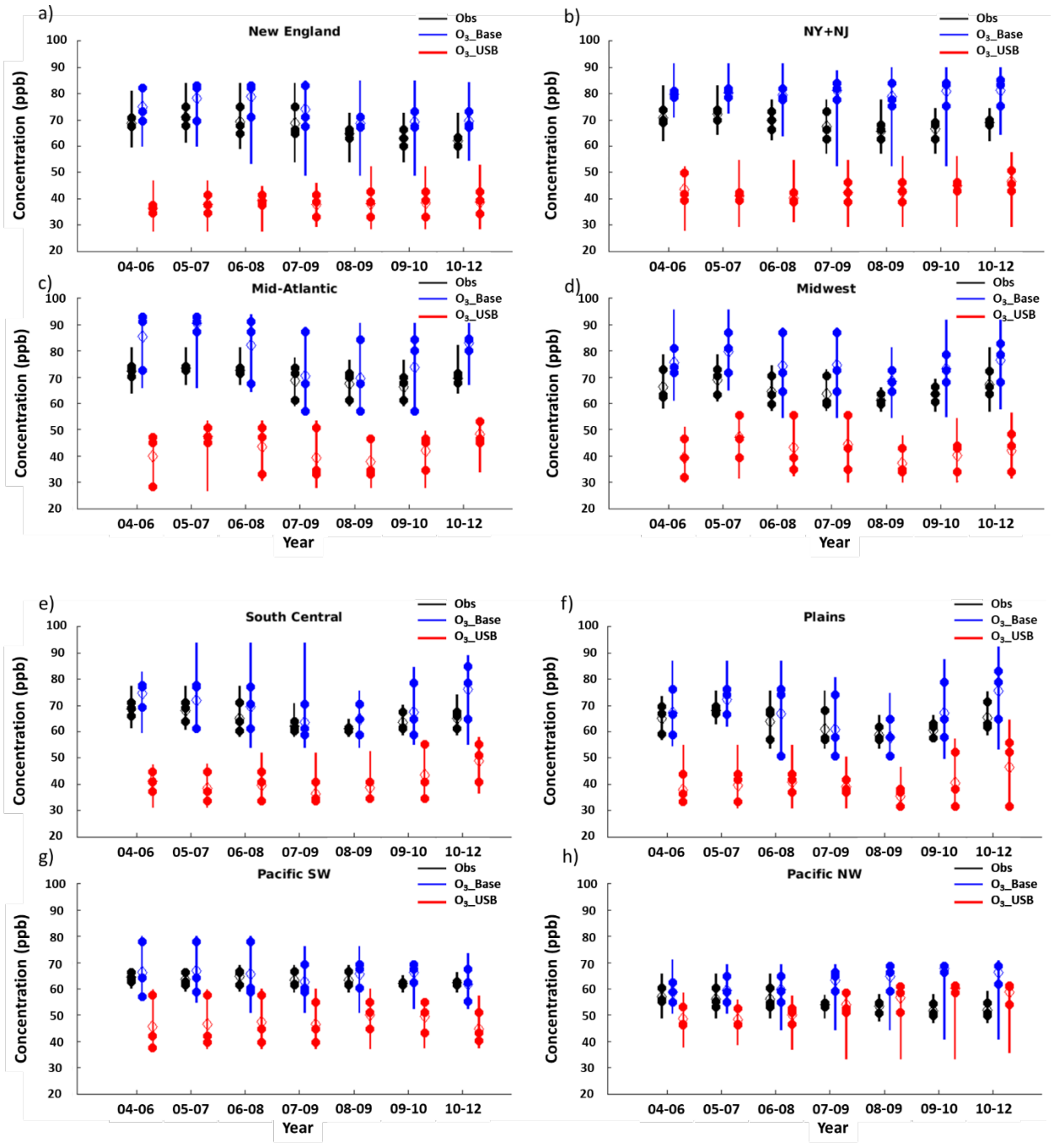

**Supplemental Figure 13: Monthly average MDA8 $O_3$_$SNO_x$ concentrations in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW.**




**Supplemental Figure 14: Anomaly on the MDA8 $O_3$_top10obs_JJA days of each sensitivity simulation relative to the 2004-2012 average in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW. Each panel shows the anomaly from observations, $O_3$_Base, $O_3$_USB, $O_3$_USA, and temperature (in degrees C).**




**Supplemental Figure 15: Anomaly on the $O_3$_top10obs_JJA days for each sensitivity simulation relative to the 2004-2012 average in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW. Each panel shows the anomaly from $O_3$_BVOC, $O_3$_$SNO_x$, $O_3$_$NALNO_x$, $O_3$_BB, $O_3$_ICT+$CH_4$, and $O_3$_CA+MX.**




**Supplemental Figure 16: Summary information for each region showing the three 4$^{th}$ highest days in each year (solid dots) that went into the calculation of the three-year average of the 4$^{th}$ highest MDA8 $O_3$ day (hollow diamond). Error bars show the range between the highest and lowest $O_3$_top10obs days across each 3-year span (i.e, across 30 total points) occurring between March and October in (a) New England, (b) NY+NJ, (c) Mid-Atlantic, (d) Midwest, (e) South Central, (f) Plains, (g) Pacific SW, and (h) Pacific NW. Observations are shown in black, $O_3$_Base is in blue, and $O_3$_USB is in red.**