The goal of this assessment is to review the state of the science on background O\textsubscript{3} for the continental U.S., with an emphasis on work published since 2011. We intend to publish this assessment as a peer-reviewed journal article. The authors have been working for about two months, so we do not have a full draft report yet, but we want to provide an opportunity for the community and stake-holders to provide input. To that end, this document presents our primary goals, some of the figures we may include in the final document, a bibliography and some thoughts on recommendations. This draft is being released now as a way to help focus some of the discussion at our workshop, to be held in Denver on March 28-29, 2017.

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The views, opinions and findings contained in this report are those of the authors and should not be construed as official National Oceanic and Atmospheric Administration or Environmental Protection Agency or U.S. Government position, policy or decision.
Definitions

The term “background O$_3$” has been used in many different ways. For the purposes of this assessment, we define the following terms:

U.S. background O$_3$ (USBO): O$_3$ formed from all natural sources plus anthropogenic sources in countries outside the U.S. We included impacts from CH$_4$ emissions, both domestic and international, as part of USBO.

North American Background (NAB) is defined as O$_3$ formed from all natural sources plus anthropogenic sources in countries outside North America. We included impacts from CH$_4$ emissions, both domestic and international, as part of NAB.

Baseline O$_3$: O$_3$ measured at relatively remote sites that have little or no recent influence from US domestic emissions.

Non-Controllable O$_3$ sources (NCOS): These are sources of O$_3$, or its precursors, that could not reasonably be controlled by U.S. domestic legislation. Examples of NCOS are intrusions of stratospheric air or emissions from wildfires.

All of the terms above can be expressed as seasonal, monthly or daily means, maximum daily 8-hour averages (MDA8) or using other statistical metrics.

Goal for this assessment

1. Summarize key spatial and temporal patterns of baseline O$_3$.
2. Review published work on USBO for the continental U.S. and summarize consistent and robust patterns.
3. Identify discrepancies between estimates of USBO and, if possible, the causes for these discrepancies.
4. Examine different approaches used to get USBO and evaluate strengths/weaknesses of these approaches.
5. Examine evidence for NCOS and their role in daily and seasonal O$_3$ concentrations.
6. Review methods to quantify NCOS and evaluate strengths/weaknesses of each approach.
7. Develop a set of recommendations for future research in this area.

Our review focuses mainly on work done since 2011 and builds on earlier studies (NRC 2009; McDonald-Buller 2011).
Feedback requested

The committee requests your input on this assessment. Your input will be most useful to the extent that it:

1. Relates to the goals of this assessment;
2. Provides a specific reference or publication that supports your input;

Our final report will include recommendations on:

1. Additional routine observations needed;
2. Model improvements needed;
3. Necessary model evaluations;
4. Need for targeted measurement-model campaigns;
5. Other recommendations.
A lot of good work has been published on background O$_3$. To this end, the tables and figures below are being considered by the committee.

**Table 1. Model estimates for background ozone (multiple definitions) and its individual sources, adapted and updated from Fiore et al. 2014.**

<table>
<thead>
<tr>
<th>Study, Model</th>
<th>Study period; Metric</th>
<th>Background</th>
<th>Non-Controllable Ozone Sources (NCOS) that contribute to Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDonald-Bueller et al., 2011$^b$, based on Zhang et al. (2011) GEOS-Chem (GC) ($\frac{1}{2}^\circ$x$\frac{1}{3}^\circ$)</td>
<td>Mar-Aug 2006-2008; MDA8</td>
<td>NAB$^a$: 39-44 (spring); 35-45 (summer); low-alt 27±8; high-alt 40±7; 51-59 (4$^\text{th}$ highest)</td>
<td><em>Natural</em>: 18±6 (low-alt); 27±6 (high-alt); 34-45 (4$^\text{th}$ highest). <em>CH4+ICT</em>: 13-16 (spring) 11-13 (summer); 13 (high alt); 9 (low alt)</td>
</tr>
<tr>
<td>Emery et al. (2012) CAMx (12 km$^2$); GC boundary conditions</td>
<td>Mar-Aug 2006; MDA8</td>
<td>NAB$^a$: 25-50 ppb (20-45 in GC); 35-100 (4$^\text{th}$ highest; 65 max without fires; 55 max in GC)</td>
<td><em>Fires</em>: 10-50 ppb (events)</td>
</tr>
<tr>
<td>Lin et al. (2012a) GFDL AM3 (~50km$^2$)</td>
<td>Apr-Jun 2010; MDA8</td>
<td>NAB$^a$: 15 WUS high-alt sites: 50±11 (mean); 55±11 (days when obs exceed 60 ppb)</td>
<td><em>Strat</em>: 15 WUS high-alt sites: 22±12 (mean); 15-25 for obs O$_3$ @ 60-70; 17-40 for obs O$_3$ @ 70-85. <em>Median, bias-corrected</em>: 10-22 (W); 8-13(NE); 3-8 (SE) <em>Max, bias-corrected</em>: 35-55 (W); 30-45 (EUS)</td>
</tr>
<tr>
<td>Mueller and Mallard (2011); CMAQ, GC boundary conditions (36 km$^2$)</td>
<td>2002; MDA8</td>
<td></td>
<td><em>Fires</em>: 30-50 (WUS, events) <em>Lightning</em>: 10-30 (Southern US, events)</td>
</tr>
<tr>
<td>Zhang et al. (2014); GC ($\frac{1}{2}^\circ$x$\frac{1}{3}^\circ$)</td>
<td>Mar-Aug 2006; MDA8</td>
<td></td>
<td><em>Lightning</em>: 6-10 ppbv (summer); <em>Fires</em>: ~20 (local events), 1-3 (WUS summer mean); <em>Strat</em>: 8-10 (WUS spring mean), up to 15 (events)</td>
</tr>
<tr>
<td>Lin et al. (2012b); GFDL AM3 (~50km$^2$)</td>
<td>May-Jun 2010; MDA8</td>
<td></td>
<td><em>Asian</em>: 8-15 (Intermountain west, when obs exceed 60 ppb, June 20-22), 5-8 (southern CA, when obs exceed 75 ppb, June 22)</td>
</tr>
<tr>
<td>Reference</td>
<td>Model</td>
<td>Source Apportionment</td>
<td>Time Period</td>
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<tr>
<td>Dolwick et al. (2014); CMAQ: CAMx (12km²)</td>
<td>CMAQ (MDA8) CAMx source apportionment</td>
<td>Apr-Oct 2007</td>
<td>USB and USB: Intermountain WUS: 40-45 (bias-corrected, seasonal mean), Pacific Coast: 25-35 Highest 10% of days in a season: &gt;70-80% (WUS rural sites), &gt;40-60% (WUS urban sites)</td>
</tr>
<tr>
<td>Fiore et al. (2014); GC (1/2°x2/3°), GFDL AM3 (2°x2°)</td>
<td>Mar-Aug 2006; MDA8</td>
<td>NAB: WUS high-alt sites: ~40-50 (spring), ~25-40 (summer) AM3: 40-70 (median), 50-60 (75th percentile), &lt;60 (summertime max), &lt;50 (summertime 75th percentile)</td>
<td></td>
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<tr>
<td>Lin et al. 2015</td>
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<tr>
<td>Lin et al. 2017</td>
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<tr>
<td>Huang et al. (2011); Huang et al., 2017</td>
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<td>Lefohn et al., 2014</td>
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<td>Brown-Steiner</td>
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<td>Pfister et al. 2013 (NOx tagging)</td>
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<tr>
<td>Emmons et al. 2012 (NOx tagging)</td>
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<td>Figure 10 for Asia → NAmerica (regional average)</td>
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<tr>
<td>Huang et al. 2013 (adjoint)</td>
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<td>Figure 3 for sources → US (need to read from map)</td>
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<tr>
<td>CAMx OSAT studies?</td>
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<tr>
<td>CMAQ APCA/ISAT studies?</td>
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<tr>
<td>Kwok et al.</td>
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</tbody>
</table>
Cohan & Napelenok (2011)
Collet et al. 2012
Stock et al. 2013
Kwok et al. 2015
Henderson et al. 2014

|---|---|---|---|
| WAQS CAMx and CMAQ<sup>e</sup> 12-km for western U.S.; 4-km for intermountain states | 2011 CAMx source apportionment<sup>d</sup> | ESTIMATES FROM VARIOUS MODEL SETUPS? | ESTIMATES FOR INTERNATIONAL, WILDFIRES, BIIGINIC

<sup>a</sup>North American Background (NAB) or U.S. Background (USB), defined as the ozone concentrations sampled from the lowest (surface) model layer in a simulation with North American or U.S., respectively, anthropogenic (includes fossil fuel and biofuel combustion; fertilizer NO<sub>x</sub>; aircraft and shipping (check true for all studies) emissions within the domain set to zero (could include how this domain is defined in the different studies).

<sup>b</sup>References within this work include a comparison of Zhang et al. 2011 to earlier work.

<sup>c</sup>GIVE MORE DETAIL + REFS ON HOW SOURCE APPORTIONMENT WORKS IN CAMx

<sup>d</sup>To estimate background contribution from international transport and biogenic U.S. emissions, including wildfires.

<sup>e</sup>QUESTION: HOW DID INTERNATIONAL TRANSPORT GET DONE IF IT WASN”T PASSED THROUGH BCs???

<sup>f</sup>Boundary conditions (BCs) of total simulated ozone from the MOZART model, GEOS-Chem and AM3 models.

<sup>g</sup>All of the global model simulations included U.S. anthropogenic emissions, thus the BC include O<sub>3</sub> from U.S. emissions that circle the globe and are not directly comparable other estimates of USB, so we define this here as “Regional Background Ozone” (RBO). In addition to the CAMx source apportionment simulations, the WAQS performed U.S. anthropogenic zero-out sensitivity simulations to estimate background O<sub>3</sub> levels.

<sup>h</sup>At sites where AM3 over-estimates the observed MDAt 03 level and the estimated stratospheric contribution exceeds the model bias, this bias is assumed to be caused.

<sup>i</sup>Bias-correction was calculated by taking the daily model calculated USB/Base MDAt ozone fractions and multiplying it by the daily MDAt bias at each monitoring location. This product is then subtracted from the original USB<sup>a</sup> (zero-out) or USB<sup>c</sup> (source apportionment) estimate.
Table 2. Ten highest modeled O$_3$ days for the Chatfield monitor, south of Denver, in 2011 and the ten highest observed days in 2011. See also Figures 7, 8 and 9. From The Colorado State Implementation Plan (Colorado Air Quality Control Commission, 2016)

<table>
<thead>
<tr>
<th>Highest 10 modeled O$_3$ days</th>
<th>Highest 10 observed O$_3$ days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2011 Observed</td>
</tr>
<tr>
<td>7/5/2011</td>
<td>69</td>
</tr>
<tr>
<td>7/12/2011</td>
<td>71</td>
</tr>
<tr>
<td>8/26/2011</td>
<td>71</td>
</tr>
<tr>
<td>7/4/2011</td>
<td>63</td>
</tr>
<tr>
<td>8/3/2011</td>
<td>67</td>
</tr>
<tr>
<td>7/6/2011</td>
<td>71</td>
</tr>
<tr>
<td>8/27/2011</td>
<td><strong>81</strong></td>
</tr>
<tr>
<td>7/23/2011</td>
<td>73</td>
</tr>
<tr>
<td>7/29/2011</td>
<td>66</td>
</tr>
<tr>
<td>8/22/2011</td>
<td>75</td>
</tr>
</tbody>
</table>
Fig 1a. Conceptual diagram showing sources contributing to MDA8 O₃ for a hypothetical receptor location on 5 different days.

Fig 1b. Conceptual diagram showing sources contributing to daily O₃ for a hypothetical receptor location. Adapted from a presentation by Terry Keating, US EPA.
Fig 2. The three year averaged MDA8 vs DOY for 8 sites around the US. The data have been smoothed using a 10-day running average.
Fig 3a. 2013-2015 Design Value measured at 1203 AQS sites around the country vs elevation. Also shown is the DV from the Mt. Bachelor Observatory in central Oregon (black square).

Fig 3b. As above, but with points colored by longitude.
Figure 4. Trends in the 95th percentile for daytime surface O$_3$ at 53 monitoring sites for spring (top) and summer (bottom). From Cooper et al 2012.
Figure 5. Comparison of seasonal MDA8 North American background O$_3$ from two global chemical transport models. In spring, the largest differences appear over much of the western US and eastern seaboard and in summer, the largest appear over the SW US (from Fiore et al 2014).

Figure 6. Comparison of fourth highest daily NAB O$_3$ from two global chemical transport models (from Fiore et al 2014).
Figure 7. Modeled and observed hourly $O_3$ for the Denver region on June 7, 2011 at 1700 GMT (10 am local time). Observed values are shown as diamonds superimposed on the modeled results. The color scale is the same for both values. From “Final Report “Denver Metro/North Front Range 2017 8-Hour Ozone State Implementation Plan: 2011 Base Case Modeling and Model Performance Evaluation”.
Figure 8. As above for July 5, 2011 at 2000 GMT (1 pm local time). Observed values are shown as diamonds superimposed on the modeled results. The color scale is the same for both values. From same reference as Figure 7.
Figure 9. As above for July 18, 2011 at 2300 GMT (4 pm local time). Observed values are shown as diamonds superimposed on the modeled results. The color scale is the same for both values. From same reference as Figure 7.
Figure 10. Difference ($\Delta O_3$) between modeled and measured annual mean $O_3$ concentration (year=2000) from North American, Asian and European datasets. From Parrish ea 2014.
Figure 1. CMAQ 2007 mean USBO for April-October estimated by a zero out approach (US EPA 2014).

Figure 12. Stratospheric contribution at a surface site in Las Vegas, as modeled using Flexpart and AM3 during the LVOS experiment (Langford 2017).
Figure 13. Comparison of trends in 4\textsuperscript{th} highest annual MDA8 at one site in Los Angeles (Crestline) and multiple monitors in Denver. From Lin et al 2017.

Figure 14. Estimated wildfire contribution to MDA8 O\textsubscript{3} in Salt Lake City for 104 days in 2008-2015 with elevated PM and overhead smoke (HMS). From Gong et al 2017.
Figure 15. Observed 1988-2014 trends in spring (left) and summertime (right) daily maximum 8-h ozone for the 95th (top) and 50th percentiles (bottom) at 70 U.S. rural sites. Larger circles indicate sites with statistically significant trends (p<0.05). Figure from Lin et al. 2017.
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