

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

Invited Paper

On the use of data from commercial NO_x analyzers for air pollution studies

By Russell R. Dickerson
Daniel C. Anderson
Xinrong Ren

Abstract

Reactive oxidized nitrogen species play a central role in environmental pollution, and long term monitoring is widespread. But conventional NO_x (defined as NO + NO₂) analyzers employing heated converters respond to many species in addition to the compounds NO and NO₂. The response of these instruments to nitric acid, peroxyacetyl nitrate, alkyl nitrates and other oxidized nitrogen species (the sum of these plus NO_x is defined as NO_y) is well established, but the ratio of NO_x to NO_y varies widely in time and space making the accuracy of commercial NO_x monitors uncertain. Care must be taken when comparing spectroscopic measurements of NO₂ or numerical models to output from commercial NO_x monitors. Correction factors can be developed for specific conditions, and long term trends can be meaningful. Recent studies comparing modeled NO_x to measurements with large interferences can involve errors of a factor of two or more and produce misleading guidance on science and policy; the need for rigorous model evaluation adds urgency to the deployment of “true NO_x” monitors.

Introduction

Excess reactive oxidized nitrogen, concentrations above the natural atmospheric background in the atmosphere, lead to a variety of environmental problems, especially ground level ozone, a recalcitrant air quality problem that poses a threat to human health and climate. Ozone production rates respond nonlinearly to NO_x concentrations [*Chameides et al.*, 1992; *Crutzen*, 1973; *Sillman et al.*, 1990] making it vitally important to measure NO_x (NO+NO₂) specifically and to represent NO_x concentrations accurately in chemical transport models e.g., [*Lelieveld et al.*, 2015]. If the modeled concentration of NO_x is wrong, simulations can give misleading guidance on pollution control policy. Because ozone production rates fall off at higher NO_x levels, model overestimates in NO_x concentrations can contribute to underestimates in the benefit to ozone from a given cut in NO_x emissions e.g., [*Gilliland et al.*, 2008].

Oxides of nitrogen are most frequently monitored via a chemiluminescent reaction with ozone [*Fontijn et al.*, 1970] with NO measured directly and higher oxides following reduction to NO [*Fehsenfeld et al.*, 1987; *Winer et al.*, 1974]. Because NO₂ is designated one of the criteria pollutants by the United States Environmental Protection Agency (USEPA), States are required to demonstrate attainment of the standard, and chemiluminescence NO_x analyzers are in common use. Most monitors reporting to the EPA’s Air Quality System, AQS, (<https://www.epa.gov/aqs>) employ commercial NO_x analyzers with hot molybdenum NO₂ converters – one purpose of this paper is to alert users these do not measure true NO_x, because they suffer substantial interferences from other reactive nitrogen species. These interfering species include nitrous acid (HONO), nitric acid (HNO₃), nitric acid anhydride (N₂O₅), organic nitrogen peroxides, alkyl nitrates (RONO₂), nitryl chloride (ClNO₂) and other important air

47 pollutants. These instruments more nearly measure NO_y than NO_x; in the US, a good
48 approximation is NO_y = NO_x + HONO + HNO₃ + 2XN₂O₅ + PANs + RONO₂, where PANs
49 represents the family of peroxyacetyl nitrates and RONO₂ represents the family of alkyl nitrates.
50 When nitrate aerosol passes through the inlet it can likewise be detected as NO_x, and some
51 species such as NH₄NO₃ thermally decompose to NH₃ and HNO₃ that can cause interferences.
52 Although NH₃ oxidation on heated molybdenum is usually small at ambient humidity, under
53 certain circumstances ammonia and amines can also cause substantial interferences [Saylor *et al.*,
54 2010; Suzuki *et al.*, 2011]. The difference between NO_y and NO_x is sometimes referred to as
55 NO_z, and gives an indication of the aging of the air parcel e.g., [Gaudel *et al.*, 2018; Kleinman *et*
56 *al.*, 2002]. Commercial “NO_x” instruments are in common use because the interferences do not
57 cause a problem when such monitors are deployed to demonstrate attainment with NO₂ standards
58 – they provide an upper bound on NO₂ and NO_x concentrations. So while these monitors can be
59 useful, they generate numbers with variable, and often severe, high bias.

60
61 The high efficiency of hot molybdenum converters for NO_y has been known for some time
62 [Fehsenfeld *et al.*, 1987; McClenny *et al.*, 2002] and many investigations have documented or
63 quantified substantial interferences in commercial instruments deployed in Europe, Asia, South
64 America, as well as North America [Dunlea *et al.*, 2007; Geddes and Murphy, 2014; Hassler *et*
65 *al.*, 2016; Lamsal *et al.*, 2008; Leston and Ollison, 2017; Luke *et al.*, 1998; Ordonez *et al.*, 2006;
66 Piters *et al.*, 2012; Poulida *et al.*, 1994; Reed *et al.*, 2016; Steinbacher *et al.*, 2007; Suzuki *et al.*,
67 2011; Villena *et al.*, 2012; Wild *et al.*, 2014; Xu *et al.*, 2013]. In this invited paper we will
68 discuss the appropriate comparison of remotely sensed NO₂ to surface-based measurements as
69 well as models and measurements of reactive nitrogen, and show how uncertain high bias or
70 assumptions of equivalence between NO_x and NO_y can lead to misleading results.

71 72 **State of the Science**

73 A review of the literature demonstrates that the fraction of atmospheric NO_y composed of NO_x
74 usually fall off quickly with distance from sources. Near emitters, NO_x can dominate NO_y in
75 the winter in daytime [Allen *et al.*, 2018; Salmon *et al.*, 2018], but in the summer, when
76 photochemical smog production is at a maximum, NO_x is usually a small fraction of the total
77 NO_y even close to cities. For example, in DISCOVER-AQ using research grade instruments
78 over the Baltimore/Washington area, true NO_x accounted on average for less than half the total
79 NO_y [Anderson *et al.*, 2014; Hembeck *et al.*, 2019; Lee *et al.*, 2018]. Similar results were
80 observed in Michigan [Thornberry *et al.*, 2001], Texas ([https://www-
81 air.larc.nasa.gov/missions/discover-aq/P3B-Profiles.tx2013.html](https://www-air.larc.nasa.gov/missions/discover-aq/P3B-Profiles.tx2013.html)), New York State [Ninneman *et*
82 *al.*, 2019; Schwab *et al.*, 2009] and Switzerland [Ordonez *et al.*, 2006]. At roadside in heavy
83 traffic most of the NO_y can be NO_x [Hassler *et al.*, 2016], but farther downwind (within hours)
84 other species dominate [Dunlea *et al.*, 2007; Ninneman *et al.*, 2019; Schwab *et al.*, 2009].
85 Although nitric acid vapor and partially oxidized alkyl nitrates may stick to inlets, the loss may
86 be reversible and other species such as PAN and simple alkyl nitrates pass through sample lines
87 like NO₂. Nighttime chemistry can also be important for air and water quality – ozone reacts
88 with NO₂ to yield NO₃, N₂O₅, and related species thus NO_y can greatly exceed NO_x even in
89 winter [Brown and Stutz, 2012; Brown *et al.*, 2012]. Most AQS-reported NO_x is therefore more
90 accurately considered NO_y, with NO_y – HNO₃ as a lower limit. Evaluating model NO_x
91 concentrations with output from monitors with heated converters will lead to erroneous
92 conclusions for winter chemistry as well. Because of the variety of interfering species, the

93 correction to measurements from commercial NO_x instruments with hot molybdenum varies
94 with the hydrocarbon mix as well as photochemical environment, and thus with time of day and
95 season. The overestimate in NO_x has led the EPA to call for “true NO_x” in the Enhanced
96 Monitoring Plans (80 FR 65292; October 26, 2015).

97
98 Using NO_x monitor data for research-grade studies is challenging, and methods vary widely. An
99 interference correction algorithm for monitor results presented in the AQS has been developed
100 for comparison of remotely sensed NO₂ to surface sites. *Ordonez et al.* (2006) compared
101 measurements from the Global Ozone Monitoring Experiment (GOME) spectrometer to ground based
102 *in situ* measurements. They reported much better agreement with vertical column NO₂ when
103 interferences were taken into account. The ratio of true NO₂ to that measured with conventional
104 commercial analyzers ranged from 0.858 in January to 0.485 in June [*Ordonez et al.*, 2006]. To
105 infer ground level NO₂ concentrations from the Ozone Monitoring Instrument (OMI) a
106 correction algorithm was developed to estimate the conversion factor, CF:

$$CF = \frac{NO_2}{NO_2 + \Sigma N + 0.95P N) + 0.35HNO_3}$$

109
110 [*Lamsal et al.*, 2008]. This has sometimes been applied when comparing measurements and
111 models [*Souri et al.*, 2017; *Souri et al.*, 2018]; although it is strictly only valid for the satellite
112 overpass time and generally clear skies, the method appears to give reasonable results when
113 appropriate uncertainty is considered. These corrections may not be applicable in winter or at
114 night when N₂O₅ chemistry can be active and important. Determining trends in NO_x can rely on
115 consistent measurements even if interferences are substantial. For example, Kang et al. (2013)
116 used NO_x from AQS to investigate trends, but limited results to only 6-9am locally when the
117 boundary layer is shallow and vehicular emissions are fresh, although the ratio of NO_x to NO_y
118 falls with distance from major sources, and could cause a bias. The authors describe the NO_x
119 analysis as a qualitative measure, and they appear to successfully distinguish changes in
120 emissions vs. meteorology and conclude that emissions as model input are inconsistent with
121 observed changes. In an study of trends over the US, investigators tried to minimize the
122 interferences by focusing on early morning measurements when the model indicated NO_y is
123 composed mostly of NO_x [*Tong et al.*, 2015]; these methods appear to be adequate to distinguish
124 trends in emissions during the global recession.

125
126 Other studies appear to compare modeled NO_x directly to measurements with a heated converter.
127 In Beijing, the role of regional transport in an ozone episode was recently determined with the
128 Community Multiscale Air Quality (CMAQ) [*Liu et al.*, 2019]. Commercial NO_x analyzers with
129 sensitivity to NO_z species
130 (<http://www.mee.gov.cn/gkml/sthjbgw/stbgth/201809/W020180905375349444950.pdf>) were
131 employed to evaluate modeled NO_x. Although NO₂ concentrations were generally high, often
132 above 100 μg/m³ (~50 ppb), interfering species could contribute substantially to measurements
133 in more rural locations such as Shanxi Province.

134
135 In a five-city study [*Friberg et al.*, 2017] CMAQ simulations of air pollution were compared to
136 measurements of a variety of species including NO_x. Data from the State and Local Air
137 Monitoring Stations (SLAMS) network were used. As reported by the USEPA

138 (<https://www3.epa.gov/ttn/amtic/files/nearroad/NearRoadTAD.pdf>) these instruments are almost
139 exclusively commercial NO_x analyzers with heated converters. It is inappropriate to compared
140 modeled NO_x to output from monitors with known interferences. The interfering species could
141 contribute to the low spatiotemporal correlations observed for NO_x relative to high values seen
142 for secondary species such as ozone. Comparison of modeled NO_y to monitor output or use of a
143 CF would be more appropriate and might lead to better agreement.

144
145 To obtain air pollution data at fine resolution, a model fusion approach was applied and
146 evaluated with observations from monitors in the Central Speciation Network (CSN) and
147 Southeast Aerosol Research and Characterization network (SEARCH) network as well as
148 monitors operated by the Georgia Environmental Protection Department [Bates *et al.*, 2018].
149 While the SEARCH monitors employ photolytic conversion of NO₂ to NO [Hansen *et al.*, 2003]
150 and are thus more nearly specific to NO_x, many monitors employed for this study were
151 commercial instruments with interferences
152 (<https://airgeorgia.org/informationaboutno2.html#NO3>). Modeled NO_x should not be compared
153 to these measurements. This inherent sensitivity to additional species in commercial NO_x
154 analyzers could generate small errors for near-road monitors and major bias in monitors farther
155 from sources; these errors could compromise epidemiological studies.

156
157 A recent paper [Qin *et al.*, 2019] investigates the sensitivity of ozone in CMAQ to input
158 variables including emissions. The authors compared modeled NO_x to AQS-reported
159 measurements in the Great Lakes area (interferences are not discussed) and concluded that
160 “using CB6 combined with a 30% reduction of on-road mobile NO_x emissions and MEGAN led
161 to the best performance.” They indicate that this result is superior to runs with a 50% NO_x
162 emissions reduction. But commercial monitors do not allow for such precision; modeled NO_x
163 was apparently compared to instruments that more nearly measured NO_y. The model domain
164 includes much of the eastern United States where on average NO_y greatly exceeds NO_x (see
165 above); emissions overestimates are likely substantially larger than those reported.

166
167 Quantitative assessment of ozone formation and effective policy require not just reasonable
168 simulation of ozone and relative reduction factors, but also good estimates of ozone precursors
169 especially NO_x and NO_y. To be reliable, models must get ozone right for the right reasons.
170 Several modeling studies found substantially better agreement [Canty *et al.*, 2015; Mao *et al.*,
171 2018] when a 50% or greater reduction was applied to vehicular NO_x emissions. Errors in NO
172 concentration impact the fate of HO₂ and RO₂ and cascade throughout the entire simulation. We
173 suggest that model results provide quantitative guidance only when emissions are evaluated
174 against reliable measurements; these results add urgency to the deployment of true NO₂ and true
175 NO_y monitors. Until such data are available, modeled NO_y (minus some fraction of HNO₃) is
176 more comparable to measurements with heated converters.

177
178 Comparing model NO_x with measurements from commercial monitors can lead to fundamental
179 errors – NO_x concentrations impact radicals and alter the relative role of NO_x vs. VOCs in the
180 rate of ozone production. More realistic comparison of simulations to measurements may well
181 indicate substantially greater model high bias for reactive nitrogen and better simulate the
182 response of the ozone in the atmosphere to controls on NO_x emissions. This would also bring
183 model results into better agreement with research indicating a historical overestimate of NO_x

184 emissions in the National Emissions Inventory (NEI), for example [Anderson *et al.*, 2014;
185 Brioude *et al.*, 2013; Castellanos *et al.*, 2011; McDonald *et al.*, 2018; Travis *et al.*, 2016].
186 Policy relevant science requires careful evaluation of observations and appropriate comparison to
187 simulations.

188

189 **Acknowledgments**

190 Support for measurements including DISCOVER-AQ was provided by MDE, NASA, NIST, and
191 NSF.

192

193 **References**

194

195 Allen, C., et al. (2018), NO_x instrument intercomparison for laboratory biomass burning source
196 studies and urban ambient measurements in Albuquerque, New Mexico, *Journal of the*
197 *Air & Waste Management Association*, 68(11), 1175-1189.

198 Anderson, D. C., et al. (2014), Measured and modeled CO and NO_y in DISCOVER-AQ: An
199 evaluation of emissions and chemistry over the eastern US, *Atmospheric Environment*,
200 96, 78-87.

201 Bates, J. T., et al. (2018), Application and evaluation of two model fusion approaches to obtain
202 ambient air pollutant concentrations at a fine spatial resolution (250m) in Atlanta,
203 *Environmental Modelling & Software*, 109, 182-190.

204 Brioude, J., et al. (2013), Top-down estimate of surface flux in the Los Angeles Basin using a
205 mesoscale inverse modeling technique: assessing anthropogenic emissions of CO, NO_x
206 and CO₂ and their impacts, *Atmospheric Chemistry and Physics*, 13(7), 3661-3677.

207 Brown, S. S., and J. Stutz (2012), Nighttime radical observations and chemistry, *Chemical Society*
208 *Reviews*, 41(19), 6405-6447.

209 Brown, S. S., et al. (2012), Effects of NO_x control and plume mixing on nighttime chemical
210 processing of plumes from coal-fired power plants, *Journal of Geophysical Research-*
211 *Atmospheres*, 117.

212 Canty, T. P., et al. (2015), Ozone and NO_x chemistry in the eastern US: evaluation of
213 CMAQ/CB05 with satellite (OMI) data, *Atmospheric Chemistry and Physics*, 15(19),
214 10965-10982.

215 Castellanos, P., et al. (2011), Ozone, oxides of nitrogen, and carbon monoxide during pollution
216 events over the eastern United States: An evaluation of emissions and vertical mixing,
217 *Journal of Geophysical Research-Atmospheres*, 116.

218 Chameides, W. L., et al. (1992), OZONE PRECURSOR RELATIONSHIPS IN THE AMBIENT
219 ATMOSPHERE, *Journal of Geophysical Research-Atmospheres*, 97(D5), 6037-6055.

220 Crutzen, P. J. (1973), A discussion of the chemistry of some minor constituents in the
221 stratosphere and troposphere, *Pure Appl. Geophys.*, 106, 1385-1399.

222 Dunlea, E. J., et al. (2007), Evaluation of nitrogen dioxide chemiluminescence monitors in a
223 polluted urban environment, *Atmospheric Chemistry and Physics*, 7(10), 2691-2704.

224 Fehsenfeld, F. C., et al. (1987), A ground-based intercomparison of NO, NO_x, NO_y measurement
225 techniques, *J. Geophys. Res.*, 92(12), 14710-14722.

226 Fontijn, A., A. J. Sabadell, and R. J. Ronco (1970), HOMOGENEOUS CHEMILUMINESCENT
227 MEASUREMENT OF NITRIC OXIDE WITH OZONE - IMPLICATIONS FOR CONTINUOUS

228 SELECTIVE MONITORING OF GASEOUS AIR POLLUTANTS, *Analytical Chemistry*, 42(6),
229 575-&.

230 Friberg, M. D., et al. (2017), Daily ambient air pollution metrics for five cities: Evaluation of
231 data-fusion-based estimates and uncertainties, *Atmospheric Environment*, 158, 36-50.

232 Gaudel, A., et al. (2018), Tropospheric Ozone Assessment Report: Present-day distribution and
233 trends of tropospheric ozone relevant to climate and global atmospheric chemistry
234 model evaluation, *Elementa-Science of the Anthropocene*, 6.

235 Geddes, J. A., and J. G. Murphy (2014), Observations of reactive nitrogen oxide fluxes by eddy
236 covariance above two midlatitude North American mixed hardwood forests,
237 *Atmospheric Chemistry and Physics*, 14(6), 2939-2957.

238 Gilliland, A. B., C. Hogrefe, R. W. Pinder, J. M. Godowitch, K. L. Foley, and S. T. Rao (2008),
239 Dynamic evaluation of regional air quality models: Assessing changes in O₃ stemming
240 from changes in emissions and meteorology, *Atmospheric Environment*, 42(20), 5110-
241 5123.

242 Hansen, D. A., et al. (2003), The southeastern aerosol research and characterization study: Part
243 1-overview, *Journal of the Air & Waste Management Association*, 53(12), 1460-1471.

244 Hassler, B., et al. (2016), Analysis of long-term observations of NO_x and CO in megacities and
245 application to constraining emissions inventories, *Geophysical Research Letters*, 43(18),
246 9920-9930.

247 Hembeck, L., et al. (2019), Measured and Modelled Ozone Photochemical Production in the
248 Baltimore-Washington Airshed, *Atmospheric Environment*.

249 Kleinman, L. I., et al. (2002), Ozone production efficiency in an urban area, *Journal of*
250 *Geophysical Research-Atmospheres*, 107(D23).

251 Lamsal, L. N., et al. (2008), Ground-level nitrogen dioxide concentrations inferred from the
252 satellite-borne Ozone Monitoring Instrument, *Journal of Geophysical Research-*
253 *Atmospheres*, 113(D16), 15.

254 Lee, H. J., R. B. Chatfield, and M. L. Bell (2018), Spatial analysis of concentrations of multiple air
255 pollutants using NASA DISCOVER-AQ aircraft measurements: Implications for exposure
256 assessment, *Environmental Research*, 160, 487-498.

257 Lelieveld, J., J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer (2015), The contribution of
258 outdoor air pollution sources to premature mortality on a global scale, *Nature*,
259 525(7569), 367-+.

260 Leston, A. R., and W. M. Ollison (2017), Field evaluations of newly available "interference-free"
261 monitors for nitrogen dioxide and ozone at near-road and conventional National
262 Ambient Air Quality Standards compliance sites, *Journal of the Air & Waste*
263 *Management Association*, 67(11), 1240-1248.

264 Liu, H. L., M. G. Zhang, X. Han, J. L. Li, and L. Chen (2019), Episode analysis of regional
265 contributions to tropospheric ozone in Beijing using a regional air quality model,
266 *Atmospheric Environment*, 199, 299-312.

267 Luke, W. T., et al. (1998), A comparison of airborne and surface trace gas measurements during
268 the Southern Oxidants Study (SOS), *Journal of Geophysical Research-Atmospheres*,
269 103(D17), 22317-22337.

270 Mao, J. Q., et al. (2018), Southeast Atmosphere Studies: learning from model-observation
271 syntheses, *Atmospheric Chemistry and Physics*, 18(4), 2615-2651.

272 McClenny, W. A., E. J. Williams, R. C. Cohen, and J. Stutz (2002), Preparing to measure the
273 effects of the NO_x SIP call-methods for ambient air monitoring of NO, NO₂, NO_y, and
274 individual NO_z species, *Journal of the Air & Waste Management Association*, 52(5), 542-
275 562.

276 McDonald, B. C., et al. (2018), Modeling Ozone in the Eastern US using a Fuel-Based Mobile
277 Source Emissions Inventory, *Environmental Science & Technology*, 52(13), 7360-7370.

278 Ninneman, M., K. L. Demerjian, and J. J. Schwab (2019), Ozone Production Efficiencies at Rural
279 New York State Locations: Relationship to Oxides of Nitrogen Concentrations, *Journal of*
280 *Geophysical Research-Atmospheres*, 124(4), 2363-2376.

281 Ordonez, C., et al. (2006), Comparison of 7 years of satellite-borne and ground-based
282 tropospheric NO₂ measurements around Milan, Italy, *Journal of Geophysical Research-*
283 *Atmospheres*, 111(D5), 12.

284 Pitters, A. J. M., et al. (2012), The Cabauw Intercomparison campaign for Nitrogen Dioxide
285 measuring Instruments (CINDI): design, execution, and early results, *Atmospheric*
286 *Measurement Techniques*, 5(2), 457-485.

287 Poulida, O., K. L. Civerolo, and R. R. Dickerson (1994), OBSERVATIONS AND TROPOSPHERIC
288 PHOTOCHEMISTRY IN CENTRAL NORTH-CAROLINA, *Journal of Geophysical Research-*
289 *Atmospheres*, 99(D5), 10553-10563.

290 Qin, M., et al. (2019), Improving ozone simulations in the Great Lakes Region: The role of
291 emissions, chemistry, and dry deposition, *Atmospheric Environment*, 202, 167-179.

292 Reed, C., M. J. Evans, P. Di Carlo, J. D. Lee, and L. J. Carpenter (2016), Interferences in photolytic
293 NO₂ measurements: explanation for an apparent missing oxidant?, *Atmospheric*
294 *Chemistry and Physics*, 16(7), 4707-4724.

295 Salmon, O. E., et al. (2018), Top-Down Estimates of NO_x and CO Emissions From Washington,
296 DC-Baltimore During the WINTER Campaign, *Journal of Geophysical Research-*
297 *Atmospheres*, 123(14), 7705-7724.

298 Saylor, R. D., E. S. Edgerton, B. E. Hartsell, K. Baumann, and D. A. Hansen (2010), Continuous
299 gaseous and total ammonia measurements from the southeastern aerosol research and
300 characterization (SEARCH) study, *Atmospheric Environment*, 44(38), 4994-5004.

301 Schwab, J. J., J. B. Spicer, and K. L. Demerjian (2009), Ozone, Trace Gas, and Particulate Matter
302 Measurements at a Rural Site in Southwestern New York State: 1995-2005, *Journal of*
303 *the Air & Waste Management Association*, 59(3), 293-309.

304 Sillman, S., J. A. Logan, and S. C. Wofsy (1990), THE SENSITIVITY OF OZONE TO NITROGEN-
305 OXIDES AND HYDROCARBONS IN REGIONAL OZONE EPISODES, *Journal of Geophysical*
306 *Research-Atmospheres*, 95(D2), 1837-1851.

307 Souri, A. H., Y. Choi, W. Jeon, J. H. Woo, Q. Zhang, and J. Kurokawa (2017), Remote sensing
308 evidence of decadal changes in major tropospheric ozone precursors over East Asia,
309 *Journal of Geophysical Research-Atmospheres*, 122(4), 2474-2492.

310 Souri, A. H., et al. (2018), First Top-Down Estimates of Anthropogenic NO_x Emissions Using
311 High-Resolution Airborne Remote Sensing Observations, *Journal of Geophysical*
312 *Research-Atmospheres*, 123(6), 3269-3284.

313 Steinbacher, M., et al. (2007), Nitrogen oxide measurements at rural sites in Switzerland: Bias of
314 conventional measurement techniques, *Journal of Geophysical Research-Atmospheres*,
315 112(D11).

316 Suzuki, H., et al. (2011), Comparison of laser-induced fluorescence and chemiluminescence
317 measurements of NO₂ at an urban site, *Atmospheric Environment*, 45(34), 6233-6240.
318 Thornberry, T., et al. (2001), Observations of reactive oxidized nitrogen and speciation of NO_y
319 during the PROPHET summer 1998 intensive, *Journal of Geophysical Research-*
320 *Atmospheres*, 106(D20), 24359-24386.
321 Tong, D. Q., et al. (2015), Long-term NO_x trends over large cities in the United States during the
322 great recession: Comparison of satellite retrievals, ground observations, and emission
323 inventories, *Atmospheric Environment*, 107, 70-84.
324 Travis, K. R., et al. (2016), Why do models overestimate surface ozone in the Southeast United
325 States?, *Atmospheric Chemistry and Physics*, 16(21), 13561-13577.
326 Villena, G., I. Bejan, R. Kurtenbach, P. Wiesen, and J. Kleffmann (2012), Interferences of
327 commercial NO₂ instruments in the urban atmosphere and in a smog chamber,
328 *Atmospheric Measurement Techniques*, 5(1), 149-159.
329 Wild, R. J., et al. (2014), A Measurement of Total Reactive Nitrogen, NO_y, together with NO₂,
330 NO, and O₃ via Cavity Ring-down Spectroscopy, *Environmental Science & Technology*,
331 48(16), 9609-9615.
332 Winer, A. M., J. W. Peters, J. P. Smith, and J. N. Pitts Jr. (1974), Response of commercial
333 chemiluminescent NO-NO₂ analyzers to other nitrogen-containing compounds, *Environ.*
334 *Sci. Technol.*, 8, 1118-1121.
335 Xu, Z., et al. (2013), Evaluating the uncertainties of thermal catalytic conversion in measuring
336 atmospheric nitrogen dioxide at four differently polluted sites in China, *Atmospheric*
337 *Environment*, 76, 221-226.
338