Environment and Natural Resources Trust Fund
Research Addendum for Peer Review

Project Manager Name: Julian Marshall
Project Manager Email Address: julian@umn.edu
Project Title: Addressing Ozone Pollution in Minnesota: Equity and Efficiency
Project Number: 138-F1+2+5

ABSTRACT

The state of Minnesota is in attainment with EPA's current ozone standard but is in danger of not meeting stricter standards proposed by EPA. This project combines satellite measurements, monitoring data, and air quality modeling to study ozone pollution and exposure in Minnesota, and examines the effectiveness and environmental equity of potential control options. Our work will develop a better understanding of the chemistry impacting ozone concentrations in Minnesota, thereby informing the design of effective control strategies.

1. INTRODUCTION

Ozone exposure increases susceptibility to respiratory infections, medication use by asthmatics, and hospital admissions for individuals with respiratory disease [*Halonene et al*., 2010]. Ozone may contribute to premature death, especially in people with heart and lung disease [*Jerrett et al.,* 2009; *Bell et al.*, 2006]. Ozone also reduces crop yields and harms sensitive ecosystems [*VanDingenen et al.,* 2009]. Ground-level ozone is one of the six criteria pollutants defined in the federal Clean Air Act. For all criteria pollutants, the Environmental Protection Agency establishes health-based concentration standards, known as National Ambient Air Quality Standards (NAAQS). States must measure ambient (outdoor) concentrations to ensure compliance with those standards.

Minnesota is in attainment with the current ozone standard (75 ppb, 8-hour average) but could well violate stricter standards (60-70 ppb) currently being proposed by the Environmental Protection Agency [*EPA*, 2010]. Figure 1 shows policy-relevant ozone concentrations (fourth highest 8-hour average in 2009) for several monitoring sites maintained by the Minnesota

Pollution Control Agency (MPCA). Several monitors reported concentrations in the range proposed by EPA for the future NAAQS (60-70 ppb).

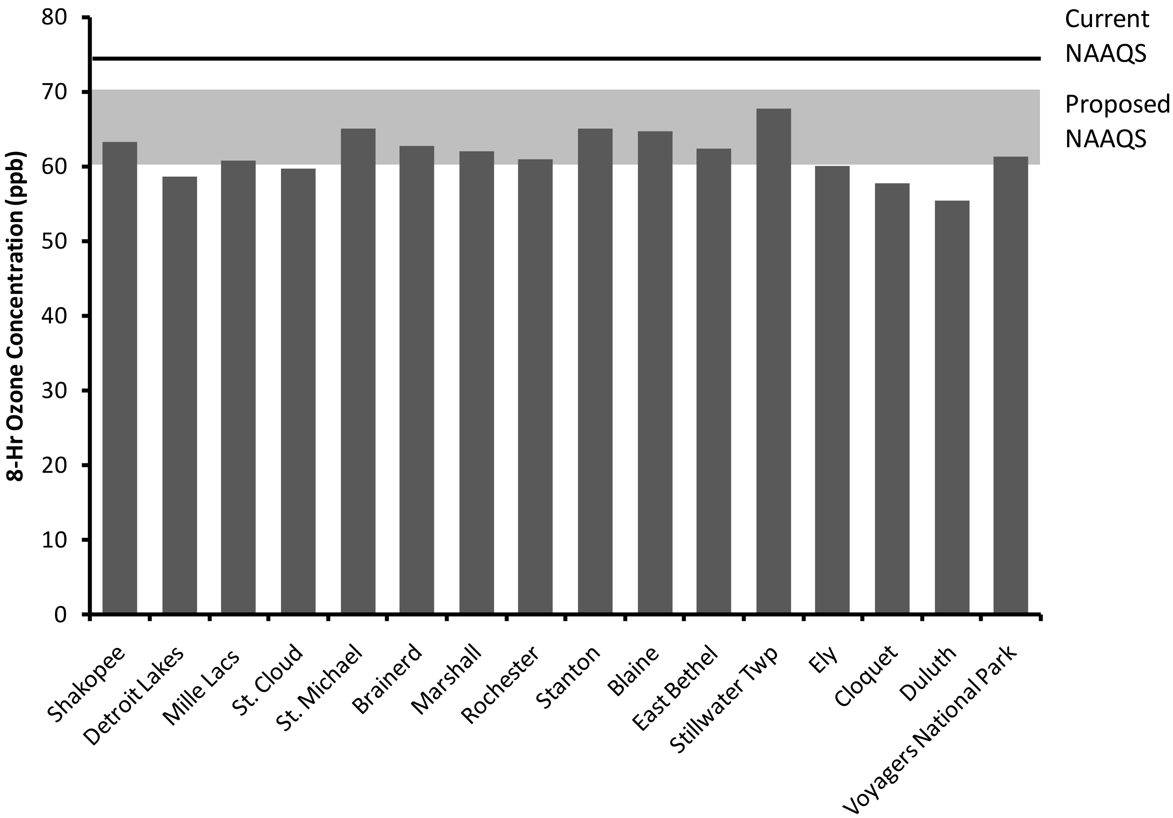

Figure 1 - The 4th highest 8-hour ozone concentrations for MPCA monitors throughout Minnesota in 2009. Data are publically available from MPCA's Environmental Data Access system (www.pca.state.mn.us).

Reducing ambient ozone concentrations is a complicated process for several reasons. Ground-level ozone is not emitted directly, but instead is formed in the atmosphere via a series of chemical reactions involving precursor nitrogen oxides (NO_x) and volatile organic compounds (VOCs). The chemical reactions that generate ozone are complex and interdependent; lowering emissions of a precursor will not necessarily yield an improvement in ozone concentrations. The ozone impacts of a given control strategy depend strongly on the relative abundance of the two precursors (NO_x; VOCs), as well as local conditions (e.g., temperature, meteorology, spatial and temporal distribution of emissions). In some cases, poorly-chosen emission reductions can actually worsen ozone pollution.

Existing research shows that in areas with an abundance of VOCs ("NO_x-limited regimes"), reducing NO_x improves ozone but reducing VOCs has little impact. In areas with an abundance of NO_x ("VOC-limited regimes"), reducing VOCs improves ozone but reducing NO_x can actually increase ozone concentrations, including the peak ozone concentrations regulated by the EPA. This non-linearity is the result of competing reactions at higher NO_x concentrations which can result in decreased ozone concentrations as NO_x increases [*Seinfeld and Pandis*, 2006]. "VOC-limited" regimes can exist in urban and suburban areas while "NO_x-limited" regimes typically exist in more rural areas. Developing a robust understanding of which of these regimes are present in Minnesota, and where, will improve our understanding of how ozone concentrations will respond to various policy-driven changes in precursor emissions.

Designing and testing effective control strategies for Minnesota will require a strong understanding of

1) the current state of regional ozone chemistry,
2) relative importance of anthropogenic (man-made) and biogenic (plant-based) precursor emissions in the state and region,
3) the extent to which that pollution from neighboring states affects air quality in Minnesota, and
4) the populations that are impacted by the ozone concentrations.

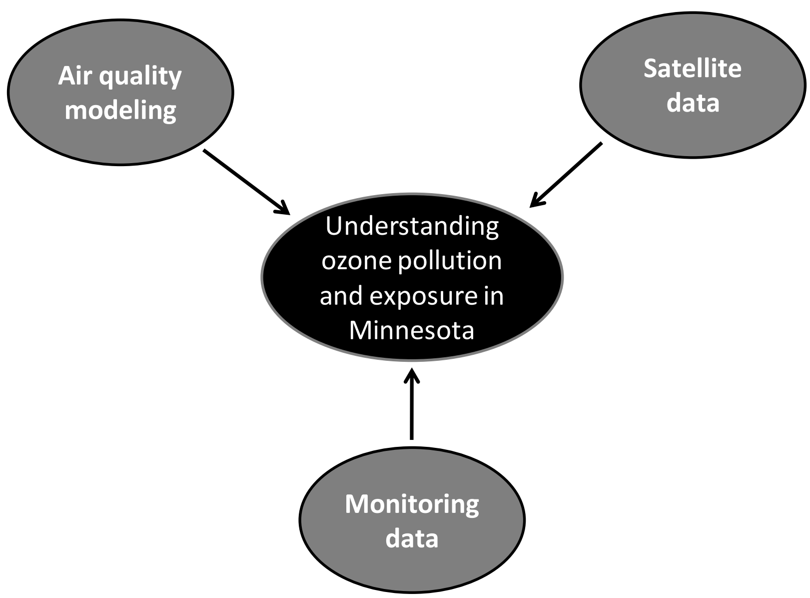

Figure 2 – Information employed in this study.

Knowing which socioeconomic populations are most impacted by exposure to ozone, and how those distributions would shift under specific emission reduction options, is a critical aspect of pollution control strategy. This project will combine regional air quality modeling, satellite measurements, and MPCA monitoring data to study the current state of ozone pollution and precursor emissions in Minnesota, and examine the effectiveness and environmental equality of a range of potential emissions reductions.

Our research complements MPCA's work in this area. Specifically, if Minnesota violates the stricter ozone standard, MPCA would be required to model potential control strategies; our project extends beyond MPCA's purview by evaluating satellite data to understand the chemistry of ozone formation in Minnesota, and investigating equity and environmental justice aspects of current ozone exposure and of potential control scenarios.

2. HYPOTHESIS AND GOALS

We will apply satellite measurements, ground-based observations, and an air quality model to answer the following questions related to ozone in Minnesota:

- Where are the high ozone concentrations ("hot spots") in Minnesota?
- Where are the NO_x-limited and VOC-limited regimes throughout the state?
- How do ozone concentrations change under different control strategies?
- What impact do emissions from outside Minnesota have on ozone concentrations in Minnesota?
- What specific populations are most severely impacted by high ozone concentrations?

3. METHODOLOGY

3.1 Description of Model and Data Sources

3.1.1 Air Quality Model

For this study, we will use a state-of-the-science three-dimensional regional chemical transport model, CAMx [*ENVIRON*, 2010]. CAMx is approved by EPA for use in policy development and is commonly used for ozone modeling. We will employ a coarse (12 km) grid for the Midwest, and a fine (4-km) nested grid for Minnesota. We will model April–October (for 2005) as this "ozone season" is the relevant time period for high ozone concentration days. We will model chemical reaction rates using a standard approach, the Carbon Bond Mechanism Version 5 which is based on the original Carbon Bond mechanism developed by *Gery et al.* [1989]. This approach represents the chemistry of ozone formation by grouping organic species according to functional groups.

CAMx requires a variety of inputs related to meteorology and emissions. Meteorological inputs include temperature, pressure, wind speeds, and cloud information, and these will be developed using the Weather Research and Forecasting (WRF) model [*NCAR*, 2010] using data assimilation to ensure that the WRF output is consistent with meteorological observations for 2005. A number of studies have carried out detailed evaluations of WRF in the context of air quality modeling [e.g. *Borge et al*., 2008; *Matsui et al*., 2009].

The emissions inputs will be developed using the Sparse Matrix Operator Kernel Emissions (SMOKE) System [*UNC*, 2009]. SMOKE uses EPA's National Emission Inventory (NEI) in combination with meteorological data to compute emissions for a specific timeframe as inputs for CAMx. For this study we will use the NEI 2005 and a Canadian emission inventory (generated by Environment Canada) which is also available from the EPA. Our team had experience with CAMx, WRF, SMOKE and NEI 2005, all of which we are currently using for a separate research project.

This work will also apply the Decoupled Direct Method (DDM) in CAMx in order to evaluate the sensitivities of ozone concentrations to different source categories and regions. The DDM tool tracks sensitivities through the different modeled processes [*Dunker et al*., 2002], and will provide key information for determining the impact on Minnesota ozone from emissions transported across state and national boundaries.

3.1.2 Ground-Based Data

We will obtain ozone concentrations measured by MPCA at their monitoring sites, which are located throughout the state (based on direct contact with MPCA and through MPCA's Environmental Access Database, www.pca.state.mn.us). The MPCA sites record hourly ozone information from late spring until early fall, and span urban, suburban and rural areas. Our investigation will use the MPCA monitoring data to evaluate CAMx model results and to quantify model accuracy.

3.1.3 Satellite Data

We will use satellite data to analyze NO_x and VOC concentrations across the state, and to further evaluate the CAMx output. The MPCA data provide good temporal coverage, but only in locations with monitors. The satellite measurements will be a critical addition by providing uniform data coverage across the state (though with less temporal information). We will use formaldehyde (HCHO) and nitrogen dioxide (NO_2) as indices for VOCs and NO_x, respectively, in terms of testing the CAMx model and its emission inventories.

For this work, we will employ measurements of HCHO and NO_2 columns from the Ozone Monitoring Instrument (OMI) [*Millet et al.,* 2008; *Duncan et al.,* 2009]. Of the available satellite sensors, OMI's high spatial resolution (13×24 km^2 at nadir) and daily global coverage offer substantial advantages for resolving spatial variability and reducing measurement uncertainty through improved sampling statistics. The small footprint also reduces data contamination by clouds, which is the primary source of error in the retrievals [*Millet et al.,* 2006].

3.2 Specific Tasks

3.2.1 Characterization of Current Ozone Levels

We will evaluate model performance against ground level measurements from MPCA and satellite observations, using standard metrics to assess model accuracy based on recommendations from the *EPA* [1991]. Candidate evaluation metrics include error and bias for the predicted peak maximum, hourly concentrations and 8-hour and 24-hour mean concentrations.

If we find clear evidence of an emissions bias, we will explore the possibility of scaling certain emissions and/or investigate alternative emissions datasets (e.g. those available from LADCO). We also plan to consult with MPCA as local experts on emissions in the region.

Using model predictions, as informed by the ground- and satellite-based observations, we will evaluate areas throughout the state based on the degree to which regional ozone production is NO_x- versus VOC-limited. We will apply a sensitivity analysis in CAMx (perturbing NO_x slightly and examining the resulting incremental change in ozone production) to do this classification. As mentioned earlier, this regime identification is critical for developing potential control strategies. We will also use this information to determine areas of particular concern (ozone "hot spots") across the state. This will allow us to focus the development of potential strategies with those areas in mind.

This analysis represents fundamental information for effective ozone control, since controlling the wrong precursor pollutant can be ineffective in reducing ozone, and may even make things worse in some areas. This task will provide valuable information for designing and testing ozone pollution control strategies most likely to be effective in Minnesota.

3.2.2 Evaluation of Potential Control Strategies

We will evaluate categories of potential emission reduction strategies to determine the effectiveness of each in reducing ozone pollution. For example, we will start by studying the effectiveness of statewide reduction in emissions from certain sectors (on-road mobile, off-road mobile, point sources, area sources). We will carry out this portion of the investigation using sensitivity analysis: by decreasing the emissions from these sectors in the emissions inventory in CAMx, and then observing the resulting change in modeled concentrations. We will then test region-specific emission reductions (e.g. urban vs. rural) to account for differing ozone chemistry regimes in different regions of the state. We can then compare the predicted ozone concentrations, ozone metrics, sensitivities and potential ozone exceedances for each of the scenarios, including the base case (no emission reduction). From these results we can determine which sectors provide the most promising options for decreasing ozone concentrations throughout the state.

As a next step, we will identify the impact of emissions from outside the state of Minnesota on air quality in the state of Minnesota. We will do this by studying the sensitivity of the ozone concentrations using the DDM tool in CAMx (described above). Since ozone production is non-linear, studying these sensitivities will help to quantify the level of improvement in ozone pollution that is achievable by Minnesota action alone, while also allowing us to study the potential impacts of Minnesota emissions on other areas in the Upper Midwest.

The exposure impacts of a potential emissions control strategy may vary among demographic groups. The investigations outlined above will evaluate not only ground-level ozone concentrations but also ozone exposures to specific socioeconomic groups. Specifically, for each potential emissions reduction strategy we will explore the extent to which ozone exposures would increase or decrease for specific socioeconomic or demographic groups. Air quality legislation aims not only to safeguard public health but also to do so equitably across the population; our results will help inform how to accomplish this.

The work proposed here represents a state-of-the-science investigation of ozone chemistry. The modeling effort is computationally intensive. We will use computing resources at the Minnesota Supercomputing Institute at the University of Minnesota which will allow us to run the air quality model in parallel over hundreds of processors. Employing MSI resources will be necessary for us to test several emissions reduction strategies and accomplish the overall goals of the project.

4. RESULTS, DELIVERABLES AND THE TIMETABLE

Two-year project, 8/1/2011 – 7/31/2013.

Results	Deliverable	Completion Dates
1a. Model ozone concentrations using CAMx. Evaluate CAMx output by comparing against MPCA measurements and against satellite observations of nitrogen dioxide and formaldehyde.	Hourly, spatially resolved ozone, nitrogen dioxide and VOC concentrations from CAMx that have been compared to ground- and satellite-based observations.	4/30/2012
1b. Identify hotspot locations for ozone pollution and the specific populations that are impacted.	Map of ozone hot spots in Minnesota.	4/30/2012
1c. Use satellite measurements and model results to diagnose the sensitivity of ozone pollution in Minnesota to NO_x versus VOC emission control strategies.	Map showing NO_x and VOC-sensitivity for ozone production across Minnesota.	6/30/2012
2a. Compare the effectiveness of statewide reductions in emissions on concentrations.	Comparison of predicted ozone exceedances and concentrations associated with each emissions reduction scenario.	9/30/2012
2b. Determine the effectiveness of region-specific emissions reductions.	Comparison of predicted ozone exceedances and concentrations associated with each emissions reductions scenario.	11/30/2012
2c. Evaluate the impact of out-of-state emissions on ozone in Minnesota.	Sensitivities of ozone in Minnesota to emissions from outside Minnesota.	2/28/2013
2d. Compare the inequity of ozone exposure under each emissions reduction strategy.	Exposures for different groups currently and under each emissions reduction scenario.	5/30/2013

5. DISSEMINATION AND USE

The findings from this research will be shared with the Minnesota Pollution Control Agency and the Environmental Protection Agency to aid in their planning. They will also be shared with the scientific community through publication in highly ranked peer-reviewed journals.

6. BUDGET

Total Trust Fund Request Budget (*2 years*)

Budget Item	**Amount**
Personnel:	
Professor Julian Marshall, PI *(0.9 month summer salary per year for two years, $35,140 salary, $11,702 fringe, 33.3% fringe rate)*	$ 46,842
Professor Dylan Millet, Co-PI (0.9 month summer salary per year for two years, $16,879 salary, $5,621 fringe, 33.3% fringe rate)	$ 22,500
Dr. Kristina Wagstrom, Co-PI (full support for two years, $88,000 salary, $17,494 fringe, 19.9% fringe rate)	$ 105,494
Graduate Research Assistant, Master's Student (full support for two years, $43,410 salary, $31,754 fringe - includes health care and tuition)	$ 75,164
TOTAL ENVIRONMENT & NATURAL RESOURCES TRUST FUND $ REQUEST	$ 250,000

Other Funds

Source of Other Funds	**Amount**
Other Non-State $ Being Applied to Project During Project Period:	
Computational expenses at the Minnesota Supercomputing Institute (MSI does not charge us for the use of the resources, this amount is the estimated value of the use of the resources)	$ 15,000

7. CREDENTIALS

Abbreviated C.V.'s are attached for each of the investigators listed below on the project.

Dr. Julian Marshall, Assistant Professor, Department of Civil Engineering, University of Minnesota

B.S., 1996, Chemical Engineering, *Princeton University*
M.S., 2002, Energy and Resources, *University of California - Berkeley*
Ph.D., 2005, Energy and Resources, *University of California - Berkeley*

Dr. Julian Marshall will be the overall coordinator of this project. His research focuses on exposure to air pollution, including pollution dispersion modeling and environmental justice aspects of air quality management.

Dr. Dylan Millet, Assistant Professor, Department of Soil, Water and Climate, University of Minnesota

B.S., 1998, Chemistry, *University of British Columbia*

Ph.D., 2003, Ecosystem Science, *University of California - Berkeley*

Dr. Dylan Millet's research applies measurements and models to understand the impacts of human activity and natural processes on the chemical composition of the atmosphere. His current research combines ground- and satellite-based measurements to better understand air quality and atmospheric composition.

Dr. Kristina Wagstrom, Postdoctoral Associate, Department of Civil Engineering, University of Minnesota

B.S., 2004, Chemical Engineering, *Illinois Institute of Technology*

Ph.D., 2009, Chemical Engineering, *Carnegie Mellon University*

Dr. Kristina Wagstrom's research applies regional air quality modeling (using CAMx) and source apportionment approaches to study the origins, transport, and fate of air pollutants.

8. REFERENCES

Bell ML, RD Peng, F Dominici, (2006), The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations, *Environmental Health Perspectives* 114(4), 532-536.

Borge, R., V. Alexandrov, J. Jose del Vas, J. Lumbreras, E. Rodriquez (2008), A comprehensive sensitivity analysis of the WRF model for air quality applications over the Iberian Peninsula, *Atmos. Environ*., 42, 8560-8574.

Duncan, B. N., Y. Yoshida, J. R. Olson, S. Sillman, R. V. Martin, L. Lamsal, Y. Hu, K. E. Pickering, C. Retscher, D. J. Allen, J. H. Crawford (2010), Application of OMI observations to a space-based indicator of NOX and VOC controls on surface ozone formation, *Atmos. Environ., 44*(18), 2213-2223.

Dunker, A.M., G. Yarwood, J.P. Ortmann, G.M. Wilson (2002), Comparison of Source Apportionment and Source Sensitivity of Ozone in a Three-Dimensional Air Quality Model, *Env. Sci. Technol*., *36*, 2953-2964.

EPA (2010) National ambient Air Quality Standards for Ozone, *Federal Register*, 75(11), 2938-3052.

ENVIRON International Corporation (2010), *CAMx User's Guide – Version 5.20*. Available from: www.camx.com.

Gery, M. W., G.Z. Whitten, J.P. Killus, M.C. Dodge (1989), A Photochemical Kinetics Mechanism for Urban and Regional Scale Computer Modeling, *Journal of Geophysical Research-Atmospheres,* 94(D10), 12925-12956.

Halonen, J.I., T. Lanki, P. Tiittanen, J.V. Niemi, M. Loh, J. Pekkanen (2010), Ozone and case-specific cardiorespiratory morbidity and mortality, *J. of Epidem. And Comm. Health*, 64(9), 814-820.

Jerrett, M., R.T. Burnett, C.A. Pope III, K. Ito, G. Thurston, D. Krewski, Y. Shi, E. Calle, M. Thun (2009), Long-Term Ozone Exposure and Mortality, *The New England Journal of Medicine*, 360(11), 1085-1095.

Hatsui, H., M. Koike, Y. Kondo, N. Takegawa, K. Kita, Y. Miyazaki, M. Hu, S.Y. Change, D.R. Blake, J.D. Fast, R.A. Zaveri, D.G. Streets, Q. Zhang, T. Zhu (2009), Spatial and temporal variation of aerosols around Beijing in summer 2006: Model evaluation and source apportionment, *Journal of Geophysical Research – Atmospheres*, 114.

Millet, D. B., D. J. Jacob, S. Turquety, R. C. Hudman, S. Wu, A. Fried, J. Walega, B. G. Heikes, D. R. Blake, H. B. Singh, B. E. Anderson, A. D. Clarke (2006), Formaldehyde distribution over North America: Implications for satellite retrievals of formaldehyde columns and isoprene emission, *J. Geophys. Res., 111*, D24S02.

Millet, D. B., D. J. Jacob, K. F. Boersma, T. Fu, T. P. Kurosu, K. V. Chance, C. L. Heald, A. Guenther (2008), Spatial distribution of isoprene emissions from North America derived from formaldehyde column measurements by the OMI satellite sensor, *J. Geophys. Res., 113*, D02307.

NCAR - National Center for Atmospheric Research (2010), *Weather Research and Forecasting Model ARW Version 3 Modeling System Users Guide*. Available from: www.wrf-model.org.

Seinfeld and Pandis (2006), *Atmospheric Chemistry and Physics*, 2nd Ed. Hoboken, NJ. Pg. 204-261.

UNC - Institute for the Environment at The University of North Carolina at Chapel Hill (2009), *SMOKE v2.6 User's Manual*. Available from: www.smoke-model.org.

US EPA (1991), *Guidelines for Regulatory Application of the Urban Airshed Model (UAM)*. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Van Dingenen, R., F.J. Dentener, F. Raes, M.C. Krol, L. Emberson, J. Cofala (2009), The global impact of ozone on agricultural crop yields under current and future air quality legislation, *Atmos. Env*., *43*(3), 604-618.