

Chapter 2

A Modeling Study of the Influence of Hemispheric Transport on Trends in O₃ Distributions Over North America

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Abstract Changing emission patterns across the globe are resulting in heterogeneous changes in tropospheric chemical composition and likely altering the long-range transport of air pollutants and their impact at receptor regions. In this study, we combine results from multi-decadal simulations with the WRF-CMAQ model with source-region sensitivity information derived with the Decoupled Direct Method (DDM) to examine trends in long-range transport contributions to background O₃ concentrations at receptor regions.

2.1 Introduction

Strategies for reduction in pollution levels of surface air over a region are complicated not only by the interplay of local emission sources and complex physical, chemical, dynamical processes in the atmosphere, but also by the hemispheric background levels of pollutants. Contrasting changes in emission patterns across the globe (e.g. declining emissions in North America and Western Europe in response to implementation of control measures and increasing emissions across Asia, Central America, and Eastern Europe due to economic and population growth) are resulting in heterogeneous changes in the tropospheric chemical composition which are likely altering long-range transport impacts and, consequently, background pollution levels at receptor regions. To investigate these issues, the coupled Weather Research and Forecasting—Community Multiscale Air Quality (WRF-CMAQ) model is expanded to hemispheric scales and multi-decadal model

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simulations were recently performed for the period spanning 1990–2010 to examine changes in air pollution across the Northern hemisphere resulting from changes in emissions over this period (Xing et al. 2015).

2.2 Model Setup

The coupled WRF-CMAQ modeling system (Wong et al. 2012) was exercised for a 21-year period spanning 1990–2010 to simulate changes in tropospheric ozone (O_3) resulting from changes in anthropogenic emissions during this period. Model simulations were performed over a domain encompassing the entire Northern Hemisphere (Fig. 2.1), set on a polar stereographic projection and discretized with a horizontal grid spacing of 108 km (cf. Mathur et al. 2012, 2014). Year specific emissions for the Northern Hemispheric domain were derived from the EDGARv4.2 global emission inventory (Xing et al. 2015). The CB05 chemical mechanism was used to represent gas-phase photochemistry. In addition, O_3 mixing ratios in the top most model layer (~ 50 hPa) were modulated based on scaling of the spatially and temporally varying potential vorticity fields to represent possible effects associated with stratosphere-troposphere exchange (Mathur et al. 2008).

The entire Northern Hemisphere modeling domain was divided into seven source regions (see Fig. 2.1) nominally representing: (1) North America (NAM), (2) Europe and Russia (EUR+RUS), (3) East and Southeast Asia (EAS+SEA), (4) South Asia (SAS; the Indian subcontinent), (5) Northern Africa and the Middle East (NAF+MDE), (6) Central America (CAM), and (7) Other (the rest of the

Fig. 2.1 The Northern Hemisphere modeling domain and source region definition



geographic domain). The CMAQ model configured with the decoupled direct method (DDM; Napelenok et al. 2008) was then exercised over an annual cycle for the base year 2006 to estimate the sensitivity (S_j) of O_3 to nitrogen oxides (NO_x) and volatile organic compound (VOC) emissions from each source region, j . The estimated long-range transport of O_3 to a receptor region, m , can then be estimated as $\sum S_j$ for $j \neq m$. Further, if ΔE_j^N is the change in emission for year N relative to the base year and C^N is the simulated concentration for year N , then the receptor region concentration due to long-range transport may be approximated by the Taylor series expansion combining the DDM-based sensitivity estimates and the concentration predictions for each year in the 21-year period as:

$$C_{LRT,m}^N = \left(\sum_{j \neq m} S_j \Delta E_j^N \right) \left(C^N / \sum S_j \Delta E_j^N \right).$$

In the equation above, the first term is the first-order Taylor series approximation, while the second term represents a renormalizing factor acknowledging the challenges in reconstructing a non-linearly evolving field with first-order approximations.

2.3 Results and Discussion

Figure 2.2 presents examples of simulated source-region fractional contributions to boundary layer and seasonal-average O_3 levels for two source regions: North America and East and Southeast Asia. The impact of long-range inter-continental transport of O_3 across the Pacific and Atlantic Oceans are evident from this

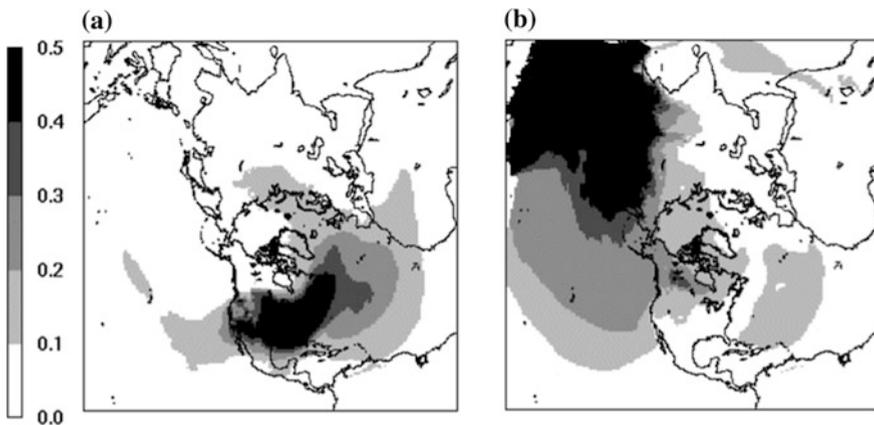


Fig. 2.2 Source region fractional contributions to boundary-layer and seasonal average (Spring) O_3 mixing ratios for **a** North America (NAM), and **b** East and Southeast Asia (EAS+SEA)

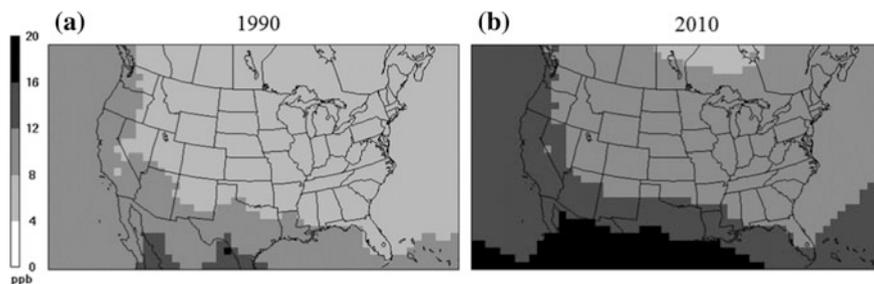


Fig. 2.3 Estimated boundary-layer average O_3 during Spring (March–April–May) from long-range transport during **a** 1990 and **b** 2010

illustration, with emissions from a continent contributing up to several percent to the O_3 mixing ratios in the boundary layer over other continents.

Figure 2.3 presents estimated O_3 over the U.S. attributable to long-range transport using the methodology summarized in Eq. 1 for the years 1990 and 2010. The difference in O_3 mixing ratios between these years is representative of the increasing contributions, over the past two decades, of long-range transport to O_3 within the U.S. boundary layer.

These results emphasize the impact of contrasting changes in emission patterns across the globe on altering long-range transport impacts and consequently background O_3 levels at receptor regions. The expansion of CMAQ to hemispheric scales provides a consistent framework to assess such changes. Additionally, the combination of DDM sensitivity estimates with multi-decadal model calculations enables the examination of both seasonal changes and source region contributions to background pollution levels at receptor regions.

Disclaimer: Although this work has been reviewed and approved for publication by the U.S. Environmental Protection Agency, it does not necessarily reflect the views and policies of the agency.

Questions and Answers

Questioner: S. Aksoyoglu

Question: Was there any change in vegetation and then biogenic emissions between 1990 and 2010 represented in the model?

Answer: The land-use was kept constant during this period as there exists no dataset to consistently represent changes across all the land-use categories used in the model over the multi-decadal period examined here. Thus possible impacts of changes in vegetation were not reflected in the biogenic emission estimates. Biogenic emissions however did change due to changes in temperature and radiation during this period and seasonally to the land cover.

Questioner: S. Galmarini

Question: Can you briefly illustrate the advantages of scaling up the modeling efforts from a more detailed experience (e.g., from regional to global)? What are the advantages?

Answer: Our past attempts at linking regional and global scales models has met with mixed success, in that biases from the larger model often propagate to the regional scale and confound interpretation of results. The primary motivation for scaling up was to have consistency in process representations across all scales. Thus, one now has a consistent modeling framework (in terms of process biases/errors) to enable examination of the effects of long-range transport on regional pollution. Scaling up however did necessitate the inclusion of additional processes to accurately represent longer term processes (e.g., organic nitrate chemistry), new environments (marine emissions), and careful examination of 3-D transport.

Questioner: Kaj Mantzius Hansen

Question: The stratospheric contributions to surface O₃ concentrations appear to be significant. Have you investigated the trends in this contribution over the simulated period?

Answer: Stratospheric contributions to surface and boundary layer O₃ are not limited only to episodic and local deep intrusion events. Our results support the notion that some fraction of the O₃ in the mid-lower troposphere originated in the stratosphere, and is gradually transported downwards through synoptic features and deep clouds and eventually entrained to the boundary layer. Thus O₃ in air masses entering North America likely have both an inter-continental anthropogenic components and a stratospheric contribution. We use a potential-vorticity scaling to specify O₃ at our model top (50 mb)—thus the modeled stratospheric contribution responds to changing dynamics over the two decade period but not say to any plausible effects associated with the recovery of the ozone hole. Trends in the stratospheric contribution is intriguing and should be investigated—unfortunately the current simulations do not allow for a detailed investigation of this nature.

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