New Directions: Understanding Interactions of Air Quality and Climate Change at Regional Scales

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The estimates of the short-lived climate forcers' (SLCFs) impacts and mitigation effects on the radiation balance have large uncertainty because the current global model set-ups and simulations contain simplified parameterizations and do not completely cover the full range of air quality-climate interactions (AQCI). Most AQCI studies to date used coarse grid models that cannot adequately resolve the highest SLCFs concentrations in the densest source regions and mesoscale circulations/processes (Anderson et al., 2003). Therefore, the radiative and vertical transport impacts and associated air quality issues in coarse grid models are likely to be under-represented at the regional and local scales. Since AQCI can be locally predominant due to the heterogeneity in emissions loading and process interactions, regional models capable of capturing AQCI are critically needed so that the cumulative effects on larger scale radiative forcing of the earth-atmosphere can be accurately assessed. Regional models include detailed physical, dynamical, and chemical formulations. However, the credibility of these models in properly simulating AQCI has not been critically assessed so the models could be used more confidently for developing effective regulatory policies.

Global modeling studies have offered important insights into the AQCI processes and the associated uncertainties. The use of diverse formulations and assumptions among models in AEROCOM led to a large spread in the simulated SLCFs impacts on climate which has shaped the formation of AEROCOM Phase II (Schultz et al., 2009). In the absence of a roadmap, any new effort with the regional-scale coupled models may also lead to enhanced spread in the simulated AQCI among these models. Many studies highlight that some SLCFs emissions have large uncertainty (e.g., Koch et al., 2011).

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Carbonaceous aerosol emission source strength is one of the highly uncertain sources of SLCFs as differences among modeled global biomass burning emissions can be as large as ~25% (Koch et al., 2011). There is also a large uncertainty in ammonia emissions (Makar et al., 2009), which, in turn, affects the composition and hygroscopicity of airborne aerosols, thereby affecting the resulting radiative forcing estimation. A systematic analysis of the variability in the emission source strengths in models is needed to facilitate an improved understanding of AQCI in a particular model as well as in model inter-comparisons. Thus, a clear strategy is needed for identifying the causes for the diversity seen in the model simulations and potential methodologies to quantify and reduce uncertainties so that emission scenarios can be determined in the policy context with increased confidence.

Application of a regional modeling system requires specification of lateral boundary conditions, not only for meteorological variables but also for gaseous pollutants and particulate matter species. Global model outputs could be used to prescribe lateral boundary concentrations, but the descriptions of these variables differ between global and regional-scale models. Also, the number of species and the processes included in the regional and global models differ. Even if both modeling systems happen to use identical chemistry and aerosol codes, the results of regional-scale models would still depend to some degree on the results of their driving global models. Thus, it is important to quantify the extent to which the results of regional models will be influenced by the global models and how this impacts pollutant levels and their radiative effects.

Traditional and remotely sensed (surface-based, satellite-based, or aircraft) measurements for many meteorological and air quality variables are available now and several four-dimensional observational datasets will be available for many locations across the globe in the near future. Since large uncertainties can exist in surface and satellite-based retrievals, simulators (that convert modeled parameters to those parameters that are directly observed -- such as modeled precipitation to radar reflectivity or modeled aerosol optical property to lidar backscattering) are becoming popular since they are proving to be better tools for model performance evaluation. A comprehensive observational database and a clear model evaluation strategy guiding the regional modeling community is needed while taking advantage of the pathways followed by the communities such as AQMEII, HTAP and AEROCOM. There is extensive experience in inter-comparison of model predictions and surface observations that are highly resolved in time, space and chemical speciation (e.g., Solazzo et al., 2011) that may be drawn upon for regional climate modeling studies.

Some of the familiar metrics used in global studies (e.g., global warming potential; global change in radiative forcing at the top of the atmosphere) may not be suitable for regional AQCI studies and, thus, there may be a need for new methodologies or new metrics to facilitate regional model inter-comparisons. Also, changes or improvements in physics and chemistry that led to models' agreement for one particular parameter for site-dependent measurement data for a region can lead to biased simulations with respect to other parameters. These issues illustrate that new metrics for a process-based model evaluation inclusive of several such process-related parameters (including meteorology and chemistry) are needed to facilitate model inter-comparison in a comprehensive manner (see Dennis et al., 2010).

To build confidence in the AQCI studies, regional-scale integrated meteorology-atmospheric chemistry models (i.e., models with on-line chemistry) that include detailed treatment of aerosol life cycle (Mathur et al., 2010) and aerosol impacts on radiation (direct effects) and clouds (indirect effects) (Bangert et al., 2011) are needed (Zhang, 2008; Grell and Baklanov, 2011). For instance, such models can be used for the evaluation of co-benefits of emission policies onto health, agriculture and economy (Shindell et al., 2011). The overarching AQCI science questions that need more attention are: What is the extent of the spread in model projections arising from the differences in the treatment of *all processes* influencing AQCIs? What changes in the oxidizing capacity and assimilative capacity of the atmosphere can be expected in the future from envisioned climate change mitigation strategies? How does climate change affect the frequency, intensity and character of the extreme events (regional patterns of heat waves, droughts, wildfires, wintertime and summertime stagnations, and pollution levels in general) as well as biogenic emissions? What changes can be expected in the diurnal temperature range, and the temporal evolution of the planetary boundary layer, and, consequently, the levels of air pollution concentrations? Will climate change result in shifts in the large-scale weather circulation patterns which can affect air pollution hot spots on local and regional scales?

Before the regional air quality modeling community begins addressing the above questions, it is essential to examine the scientific credibility for the regional coupled (i.e., fully integrated meteorology-chemistry) models. Phase 1 activity of the Air Quality Model Evaluation International Initiative (AQMEII), which was launched in 2009 (see Rao et al., 2011), has focused on assessing regional-scale air quality models being used in North America and Europe. This large effort has successfully brought together 23 modeling groups from 15 countries across North America and Europe to assess the current state-of-science in off-line (uncoupled) air quality models (Galmarini and Rao 2011). In Phase 2, AQMEII will focus on helping build credibility for the coupled models and provide a better representation of feedback processes, namely, aerosol-cloud interactions and changes in emissions resulting from changing climate. In the past two decades, there has been a large reduction in the emissions of SO_2 and NO_x from both electric power and motor vehicle sectors have recently occurred in the United States and Europe. These changes in emissions have greatly reduced the scattering aerosols on both sides of the Atlantic Ocean, thereby reducing the cooling effect that would have been induced by sulfate aerosols, offsetting the warming effect induced by the LLCFs (Wild, 2009). Therefore, Phase 2 of AQMEII will examine coupled regional-scale models' ability to properly simulate the changes observed in surface radiation and temperature stemming from substantial emission reductions from regulatory programs implemented in North America and Europe over the past few decades.

At this juncture, in the context of the lessons learned from coordinated global studies and the phase I activity of AQMEII, the regional modeling community has an opportunity now to move to a coupled modeling paradigm and systematically evaluate the various physical and chemical processes incorporated in the coupled modeling systems. This can be accomplished by (1) Reviewing and validating assumptions, empirical formulations, and constants used in the models and reconciling differences among the models, (2) Identifying key algorithms and evaluating robustness of a set of AQCI process formulations (e.g., direct effects on radiation, indirect effects through clouds), (3) Applying standardized emission source inputs similar to those developed for the IPCC AR5 emission scenarios and documenting any deviations from a scenario by a particular modeling group to help study sensitivity of models to emission input variations, and providing uncertainty ranges for these emissions, (4) Prioritizing a set of observed and measured atmospheric variables relevant to each process evaluation that include meteorological and chemical variables, (5) Evaluating whether coupled regional models are capable of reproducing the observed changes in radiation and temperature brought about by the large reductions in SO_x and NO_x emissions over North America and Europe , (6) Developing an understanding of conditions during which coupled process become important for air quality applications, (7) Developing new metrics or identifying metrics relevant to model inter-comparison and evaluation of the statistical significance of metrics and climate response, and finally (8) Developing climate indices in terms of probabilities for persistent air pollution episodes.

It is time now to bring together the global climate and regional air quality modeling community to work collectively using a common modeling platform to facilitate in multi-model comparisons of current and future AQCI. One way to infuse interactions between these communities is to promote usage of similar physical and chemical formulations (Jacobson et al., 2007, 2010). For example, usage of common gas phase chemistry could lead to better specification of lateral boundary conditions. However, due to computational constraints associated with global models, detailed formulations that are used in regional models need to be modified to reduced forms. An activity of this nature would produce useful information on the capabilities of the current IPCC models at the regional-scale, cross-fertilization between regional and global modeling communities, and help strengthen the credibility for the modeled future scenarios.

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