Introduction

Reduced Complexity Models (RCMs) fit within the class of what are commonly known as integrated assessment models (IAMs). These tools connect emissions of local air pollution to ambient concentrations, exposures, physical health and environmental effects, and monetary damage. What distinguishes the RCMs from other IAMs is the approach to air quality modeling. The RCMs do not employ conventional chemical transport models (CTMs), which are considered state-of-the-art but are complex and computationally demanding; rather, the tools employ more simplified representations of the complex physical and chemical mechanisms that link emissions to concentrations. The goal is to capture the essential elements of these processes while economizing on time and expense needed for model execution.

The RCMs are intended to complement CTMs rather than to serve as a direct substitute. In particular, RCMs are not appropriate for analyses focusing on daily or hourly pollution episodes, given RCMs relatively coarse temporal resolution. In addition, the RCMs are less robust for analyses of large changes in emissions; RCMs are intended, first and foremost, to explore marginal changes in emissions.

The three RCMs available through the CACES website are EASIUR (Heo et al., 2015), InMAP (Tessum et al., 2017), and AP3 (Muller, 2019). Each adopts a different approach to connecting emissions to concentrations. EASIUR employs a regression-based approximation to CTM output. InMAP employs a CTM-like framework but with annual-average temporal resolution, and AP3 (and its predecessors—APEEP and AP2) employs Gaussian modeling augmented with reduced-form chemistry modules. A more thorough discussion of the models and their performance can be found here (Gilmore et al., 2019).

Model Performance

When comparing the marginal damages produced by the models, Gilmore (et al., 2019) found that national emission-weighted average per-tonne damages for ground-level emissions vary among models by roughly 20%, 30%, 30% and 10% for primary $PM_{2.5}$, SO_2, NO_x and NH_3 emissions, respectively. The variation among models is somewhat higher for elevated sources; emission-weighted damages vary by roughly 40%, 30%, 40% and 20% for inert primary $PM_{2.5}$, SO_2, NO_x and NH_3 emissions, respectively.

Gilmore et al., (2019) also conducted an evaluation of the predicted ambient concentrations of total $PM_{2.5}$ and by species for the RCMs against ambient monitoring data. The performance of the RCMs was compared to that of WRF-Chem, a CTM. For total $PM_{2.5}$ INMAP and AP2 produced total $PM_{2.5}$ surfaces correlated at 0.56 and 0.59 with the monitor data, whereas the WRF-Chem surface was correlated at 0.74. Generally, model performance was strongest for sulfate (correlations greater than 0.7) and weaker for nitrate and ammonium (correlations between 0.4 and 0.7). This performance difference by species mirrors performance by CTM models, which also tend to perform better for sulfate than nitrate and ammonium.

Output

Each of the three models calculates the marginal social cost, or marginal damage, from emissions of precursors of fine particulate matter ($PM_{2.5}$) or from direct $PM_{2.5}$ emissions. $PM_{2.5}$ exposure is associated with a risk of premature mortality (see Health Impact Functions below), which is evaluated in monetary terms (see Valuation of Mortality Risk below). The marginal social costs presented here include only the mortality damages from $PM_{2.5}$ exposure. Morbidity damages, ecosystem damages, and damages due to other pollutants (e.g., ozone, NO_x, and SO_2) are not included. However, previous analyses have demonstrated that $PM_{2.5}$ mortality damages typically represent the vast majority of total monetized damages from these emissions (USEPA, 1999).

Marginal social costs are expressed here in ($ per U.S. metric ton). AP3 and InMAP calculate marginal social cost for sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), primary (directly emitted) $PM_{2.5}$, and volatile organic compounds (VOCs). EASIUR currently covers the same pollutants less VOCs. Ambient concentration estimates produced by AP3 are annual averages (expressed in micrograms per cubic meter) resolved at the county level. InMAP employs a variable grid resolution, with the smallest size cell being 1 km × 1 km. EASIUR is based on marginal social costs directly computed from a CTM (CAMx, run at 36 km resolution) for selected locations and then a statistical regression that is used to infer marginal social costs across the United States.

AP3 and InMAP produce annual-average concentration estimates; EASIUR produces annual and seasonal averages. Each of the models produces distinct marginal social cost estimates by release height to capture differences in dispersion according to whether an emission occurs at ground level or from an elevated point source.

The marginal social costs on this website are available at county resolution. The core calculations behind EASIUR and InMAP take place on a Cartesian grid, and we have re-mapped their results to a county geography. AP3's calculations are estimated and reported at the county level.

The marginal social costs reported here are "source-oriented". That is, they represent the total damages resulting from a metric ton of emissions in a given source county. These damages include damages experienced in the source county itself as well as all surrounding and downwind counties. It is important to recognize that these effects are felt widely. Much of the $PM_{2.5}$ formation and health damages often occur hundreds of kilometers downwind.

Overview of a Typical RCM Analysis

Typical RCM users will have an emissions scenario in mind; that is, they must have specified how the emissions of various pollutants (primary $PM_{2.5}$ and its precursors) will increase or decrease in each county of the United States in metric tons per year. From this website, they will download marginal social costs for each pollutant and county of interest.

For each county and pollutant, the resulting damages (or benefits) from the emissions changes can be computed as:

$$Damages\ \left(\frac{\$}{year}\right) = Emissions\left(\frac{tons}{year}\right) x\ Marginal\ Social\ Cost\ \left(\frac{\$}{ton}\right)$$

Total damages can be found by summing the result of this calculation for all pollutants and counties. If emissions increases (decreases) are expressed as positive (negative) values, then positive values represent health damages and negative values represent health benefits.

Best practices are to use results from all three RCMs available here to test the robustness of the conclusions of your analysis. Additionally, users should consider whether different health impact functions and different valuations for mortality risk change the conclusions of their analysis (see below).

Calibration Year

There are versions of AP3 available for each of the National Emissions Inventory years (1999, 2002, 2005, 2008, 2011, and 2014). The InMAP and EASIUR models are based on the 2005 NEI. In addition, population and mortality rate data used by each model is matched to the NEI year. Because of nonlinearities in $PM_{2.5}$ formation (Ansari and Pandis, 1998), marginal social costs are somewhat sensitive to calibration year that determines the baseline levels of $PM_{2.5}$ in the atmosphere. There is some relevant literature that quantifies the changing sensitivity of $PM_{2.5}$ levels with the baseline calibration year (Pinder et al., 2008; Holt et al., 2015), and this is a topic of current inquiry.

Health Impact Functions

All three RCMs primarily focus on premature mortality risk associated with exposure to annual-average $PM_{2.5}$. To estimate these effects, the models typically provide users with the option of whether to use the American Cancer Society (ACS) study (Pope et al., 2002; Krewski et al., 2009) or the Harvard Six Cities study (H6C), (Dockery et al., 1993; Lepeule et al., 2012). The concentration-response estimates reported in each of these studies have been widely used by academic researchers and in policy analyses (USEPA, 1999; 2011). Users can also select a third, more recent, concentration-response function, reported by Pope et al. (2019). The mortality risks for a exposure to a given level of $PM_{2.5}$ are about 2.5 times higher in the H6C study compared to ACS, providing a measure of the underlying uncertainty in the epidemiological results. These two studies have been reviewed and discussed in more detail. The Pope et al. (2019) value is intermediate between ACS and H6C and is recommended here as a default, "best guess" value. Users, however, are urged to consider whether using ACS or H6C concentration-response functions alters the conclusions of their analyses. Estimates for health impacts are disaggregated by age category, throughout the U.S. population.

Valuation of Mortality Risk

The standard measure of the value of premature mortality risk is often referred to as the Value of a Statistical Life (VSL). This parameter reflects the marginal rate of substitution between money and mortality risk (Viscusi, Aldy, 2003). It should be understood as the willingness of a typical person to pay to avoid some very small risk to their life and not as a normative evaluation of the value of an individual's life per se. This parameter, and by extension the RCMs, do not apply monetary values to specific lives saved or lost. Rather, since the concentration response relationships convey changes in mortality *risk* in a given year, location, and age group, the application of the VSL monetizes that change in risk. The VSL is applied uniformly across populations regardless of age, race, or income.

The RCMs are able to employ user-defined VSLs. The default is the USEPA's VSL of $7.4 million (expressed in $2006). VSL values, as with any dollar value, need to be adjusted for inflation. They are also generally adjusted to reflect increases in per-capita income as individuals with more disposable income are more willing to pay for decreased mortality risks. Our online tool allows the user to select a VSL based on the year of interest. Alternatively, users may input their own VSL value. This should be input in millions of dollars, e.g. $8.5M would be input as "8.5" not as "8,500,000".

A USEPA-sponsored review of the literature found a range of VSL values (in $2006) between $0.9 million and $21 million (USEPA, 2016). Again, users are urged to consider whether the use of alternative VSL values alters the conclusions of their analyses.

Other Ways to Use RCMs

The marginal social costs reported here are the key outputs of the three RCMs and are sufficient to enable the analyses of interest to most users. More advanced uses of RCMs examine changes in $PM_{2.5}$ concentrations in downwind locations, the distribution of damages downwind, and environmental justice implications. These more advanced analyses require source-receptor versions of the RCMs or direct use of the RCM models themselves. These are available by request from the RCM developers themselves, and work is underway to make them available in a more user-friendly format.

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