Development of Mid-Century Anthropogenic Emissions Inventory in Support of Regional Air Quality Modeling under Influence of Climate Change

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ABSTRACT

A future-year (here, mid-21st century) emissions inventory (EI) for North America has been developed in support of a modeling study of regional ozone and fine particle matter concentration levels in the continental U.S under the influence of global climate change. Since the time span of such a long projection is beyond that of regular EI's used in typical regional air quality modeling, it is necessary to identify an alternative and practical approach that allows the future-year projection to account for potential emission controls and climatic and socio-economic changes. However, a technical challenge arises because doing so requires considering and combining various different types of information (with which emissions from human activities are associated) in an integrated way. Often, information given or generated for global-scale studies has less detail and uses coarser spatial-temporal resolution. We have extensively researched and reviewed a number of existing regional- and global-scale emissions projection efforts and then set up a methodology, which, we believe, is a good candidate for the current application, based on data availability and accessibility, spatial-temporal coverage and resolution, and future-scenario consistency (i.e. IPCC SRES A1B). The method consists mainly of two steps: 1) Near-future EI projection (to the year 2020) and 2) Distant-future EI projection (to mid-century). The former is based closely on both the US EPA CAIR EI and the Environment Canada EI while the latter follows approaches proposed by the RIVM IMAGE EI. In this work, we describe the methodology of the above-mentioned development and present its results.

INTRODUCTION

The future of regional air quality under the long-term, interactive change of climate and emissions is considered as an important and challenging question. Several research projects under the support of the U.S. Environmental Protection Agency (EPA) have been conducted to evaluate this through various approaches. Most of them, if not all, try to evaluate future air quality by creating future climate and emissions then simulate within regional air quality models (http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/recipients.display/rfa_id/362). A future-year (here, mid-21st century) emissions inventory (EI) for North America has been developed in support of our modeling study of regional ozone and fine particle matter concentration levels in the continental U.S under influence of global climate change. Since the time span of such a long projection is beyond that of regular State Implementation Plan (SIP) EI's used in typical regional air quality modeling (about 10~20years), it is necessary to identify a practical approach that allows the future-year projection to account for possible emission controls and climatic and socio-economic changes. However, a technical challenge arises because doing so requires considering and combining various different types of information (with which emissions from human activities are associated) in an integrated way. Often, information given or generated for global-scale studies has less detail and uses coarser spatial-temporal resolution. We have extensively researched and reviewed a number of existing regional- and global-scale emissions projection efforts and then set up a methodology, which, we believe, is a good candidate for the current application, based on data availability and accessibility, spatial-temporal coverage and resolution, and future-scenario consistency (i.e. IPCC SRES A1B, the driving future emissions scenario adopted). Methods used and results from the study are discussed below, focusing primarily on future emissions development. An outline of on-going research is also given.

APPROACH

USA

We make an effort to make our future emissions as consistent as possible to the Inter governmental Panel on Climate Change (IPCC) SRES A1B scenario that is used to develop our future climate (IPCC, http://www.grida.no/climate/ipcc/emission/). The SRES A1B describes a future world of rapid economic growth and global population that peaks in mid-century and declines thereafter, rapid introduction of more efficient technologies, and balanced usage between fossil fuels and other energy sources. We, however, try not to restrict ourselves to the A1B if there is better information available. As a base year inventory, we choose the 2001 Clean Air Interstate Rule (CAIR) rulemaking emissions inventory prepared by the EPA after considering data availability, spatial-temporal extent and resolution, and modeling consistency (US EPA, 2005).

Our method of growing 2050 emissions from the 2001 base year consists of two steps: 1) get the projected EI for near-future which already incorporates all of "visible" growth and control (up to year 2020) and 2) perform a distant-future EI projection (up to mid-century) using more coarse-but-integrated modeling approach. The former is based on the US EPA CAIR 2020 EI while the latter follows approaches given by the Netherlands's National Institute for Public Health and the Environment (RIVM)'s Integrated Model to Assess the Global Environment (IMAGE) model (RIVM, http://www.mnp.nl/image/). We selected year 2020 CAIR EI as our near-future emissions because it: 1) is readily available, 2) is "official" data that is used for rule making, 3) uses the most recent national database for base year 2001 when we conducted our research, 4) uses the most updated growth and control assumptions, and 5) has the content and format which is the most consistent with our needs. The base-year and year 2020 inventories were developed in a "SMOKE-ready" format and includes the following pollutants: carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), sulfur dioxide (SO_2), ammonia (NH_3), particulate matter less than or equal to 10 microns (PM_{10}), and particulate matter less than or equal to 2.5 microns ($PM_{2.5}$). As noted above, RIVM's Integrated Model to Assess the Global Environment (IMAGE) was selected to project emissions from year 2020 to year 2050 (http://www.mnp.nl/image/). We selected this model because it: 1) is the model that covers the time horizon up to the year 2050(year 2100 maximum) and is readily available, 2) was used for a US EPA's inter-continental scale transport modeling project (Streets and Fernandes, 2002), 3) has other sub-models which can incorporate interactions among components (i.e. integrated model), and 4) uses widely used scenarios (i.e. IPCC SRES) which are consistent with the scenario that our climate/meteorological model is based on (A1B). For particulate species, we incorporate work of Street et al. (2004), research that also uses IPCC A1B as the reference scenario.

On-road mobile emissions inventory for EPA CAIR was developed using National Mobile Inventory Model (NMIM, http://www.epa.gov/otaq/nmim.htm) which pre-calculates MOBILE6. The inventory, therefore, comes with county/SCC based emissions data, rather than activity data. Since one of the purposes of this research is the assessment of impact of climate change in the future, we develop MOBILE6 input data that can be combined with future meteorological variables to calculate emissions. The Regional Planning Organization (RPO) year-2018 emissions merged by VISTAS (VISTAS BaseF, hereafter) that combines up-to-date State Implementation Plan (SIP) inventories was used for onroad mobile sources (http://www.rpodata.org/vistas/vistas.html). The VISTAS BaseF emissions inventory is updated as of late 2005 and represents typical-condition calendar year 2018 forecasts. Annual VMT, speed and other Mobile6 related control/regulation data are the data components. The BELD3 land use database (US EPA, http://www.epa.gov/ttn/chief/emch/biogenic/) was used in estimating biogenic emissions, and it was held constant for both base year and future year due to the lack of a clear scientific basis for forecasting distant-future land use changes.

Combining two future emissions inventories was conducted as follows: 1) EPA CAIR inventories for year-2001 and year-2020 were processed with SMOKE programs (SMKINVEN and SMKREPORT) to ensure consistency in data formatting and generate an emissions summary by each SCCs, 2) Emissions and surrogates (agricultural production and black/organic carbon for missing NH_3 and PM, respectively) from IMAGE and Streets et. al. (2004) were estimated for USA/Canada/Mexico and for Y2001/Y2020/Y2050 to get growth factors for these periods, 3) The cross-references from US Source Classification Code (SCC) to IMAGE sector/fuel combination were developed, 4) The growth factors were applied to the year inventories, using cross references described above to estimate year 2050 inventory for North America, 5) For on-road mobile sources in the US, we first used the RPO 2018 VMT projection and Mobile6 input scenarios files and "grow" 2018 VMT using IMAGE transportation sector growth factor to represent post-2018 change. Finally, emissions were calculated using SMOKE/Mobile6 with future meteorological (MM5) data.

Canada and Mexico

In our initial work (Manomaiphiboon et al., 2005a and Manomaiphiboon et al., 2005b) and EPA CAIR EI, Canada and Mexico were held constant for base and future year. This approach may be good enough for near future (i.e. year 2020) but is insufficient for distant future because the air quality impact would be affected by this "constant emissions assumption." We therefore decided to apply a very simple growth approach for Canada and Mexico even though their emissions information is limited and emissions amounts are relatively small compared to the US at present. Our projection approach for these countries is: 1) use the most updated available emissions inventory, and 2) apply simple growth factor using IMAGE model. For Canada, we update the present emissions inventory from US EPA's 1996 Canadian inventory to the combination of Environmental Canada (EC)'s emissions (year 2000 for point sources and year 2020 for area, nonroad, on-road mobile, available at http://www.epa.gov/ttn/chief/net/canada.html) and New York State's Department of Environmental Conservation (NYS DEC)'s point source inventory. Since EC's point source inventory is available only as CMAQ-ready format, we used NYSDEC's year 2002 SMOKE-ready format point source data which is based on EC's National Pollutant Release Inventory (NPRI) data(http://www.ec.gc.ca/pdb/npri/npri_home_e.cfm). Then we scale NYSDEC's EI using EC's province subtotal to avoid inconsistency between the datasets. After getting the "scaled" point source inventory, we apply year 2050/2002 (point source) and 2050/2020 (area, nonroad, and on-road mobile) growth factors to the base datasets. Some source sub-sectors, say, volcano, fugitive dust, fertilizer application, and fire, were not "grown" so that we can maintain consistency with US data. For Mexico, we update present the emissions inventory from US EPA's 1999 BRAVO inventory to the combination of BRAVO EI and Mexico NEI (http://www.epa.gov/ttn/chief/net/mexico.html). Since Mexico NEI only covers 6 states, we merged it with BRAVO EI to cover our entire modeling domain. Since Mexico NEI does not have fugitive dust in it, we use BRAVO EI's value instead for the six-border states. After getting a merged inventory, we apply year 2050/1999 growth factors to the datasets. The same source sub-sectors to Canada's case, however, were not "grown" to maintain consistency with US data.

RESULTS AND DISCUSSION

Present and future years emissions from IMAGE model (Y2001 – Y2020 – Y2050)

Figure 1 shows the IMAGE emissions (A1B) by fuels (left) and by source sectors (right) for three IPCC regions (USA/Canada/Mexico) and three years (Y2001/Y2020/Y2050). For SO_2, the dominant fuel is coal (CL) for US and Canada and heavy oil (HO) for Mexico (Mexico is part of Central America region in IMAGE). In the U.S., and Canada, SO_2 emissions are forecast to decline substantially between 2001 and 2020 (~70%) but the rate of decline is lower between 2020 and 2050 (~15%). For Mexico, emissions are forecast to increase between 2001 and 2020 (~100%) but decline after 2020 (70% of 2020). Power generation (POWGEN) is dominant sector for SO_2 emissions for all three countries (60~80% in US). For NO_x, the dominant fuels are light oil (LO) and coal for US and Canada (70~80% overall) but light oil and heavy oil are the important contributors in Mexico (75%). In the U.S., and Canada, NO_x emissions are forecast to decline throughout all future years. Mexico shows an opposite trend as emissions increase. Transportation (TR) is dominant sector for Y2001 for all three countries but power generation (POWGEN) sector becomes more important as total emissions decrease in the future. In the U.S. and Canada, NO_x emissions decline because of the implementation of emission controls on vehicles and major stationary sources, while power generation seems to drive the NO_x emissions increase in Mexico. For NMVOC, the country-by-country emissions trend shows similar patterns to SO_2 and the dominant fuel is light oil (more than half of emissions from fuel in US, 2001). The transportation, industrial process (INDPRO) and fugitive emissions (LOSS) are the dominant sectors for NMVOC (more than 95% overall). This trend is consistent with high growth rates in such things as industrial solvents, paints, glues, and chemicals production. Such industrial commodities are typically associated with economic development. Emissions of NMVOC from such activities are also typically high and not easy to control. Only recently have the developed countries instituted measures to capture organic compounds and re-use them. Hydrocarbon emissions from growing transportation fleets of Mexico would add to NMVOC emissions. Since NH_3 emissions are not calculated in the IMAGE model, we decided to use agricultural activities as surrogates. Only livestock production from the IMAGE model was used to “grow” NH_3 emissions because NH_3 emissions from fertilizer application are set as a constant through years in CAIR emissions. PM species from Streets et al., (2004) show similar pattern to NO_x.

Present and Future emissions from our approach

USA

In this section, we present year-2050 emissions inventory developed using year 2020 CAIR emissions inventory and growth factors from the IMAGE model and the work of Streets et al. (2004). Since the purpose of this section is to describe projected emissions, we do not include sectors which remain constant over years, for example, fire and fugitive dust. Figure 2 shows SO2 emissions by states and by source types (point, area, nonroad, and on-road mobile) for year 2001, 2020, and 2050. Based on the CAIR emission inventory, point source is a dominant source type due to high emissions of the power generation sector. As for regional distribution, the Midwest region shows higher SO2 emissions due to its coal-fired power generation capability. Area source contribution is relatively high in the Northeast compared to other regions due to its higher residential oil combustion. Due to control and fuel change, the year 2050 SO2 emissions decrease by more than 50% compared to its 2001 level. Note that we use CAIR control case for year 2020 that has more control on IPM sector than CAIR base case. Figure 3 shows NOx emissions with the same format as SO2 case above (i.e. Figure 2). For NOx, mobile sources (nonroad and on-road) contribute more than half of the total emissions and the point sources’ portion is about 40%. Emissions decrease throughout future years for mobile and for point sources. On-road mobile emissions show a distinct decrease until year 2020 due to control programs (e.g., federal Tier 2). Note that on-road mobile source emissions amount is not from SMOKE/Mobile6 but from NMIM in CAIR EI. So, we applied IMAGE growth factors to the CAIR on-road mobile emissions beyond 2020. We are testing our methodology using SMOKE/M6 with present/future MM5 data. As for regional distribution, California, Texas and Midwest regions show higher NOx emissions in Y2001 but have less significance in the future years. Figure 4 shows NMVOC emissions and area source category is an important source type (about

40% in Y2001). Emissions decrease throughout future years but not as significantly as SO_2 and NO_x because the control programs for NMVOC for area and point sources are less stringent. Major emissions controls are being applied in on-road and nonroad mobile sources. The spatial distribution of NMVOC shows similar pattern to NO_x, as California, Texas and Midwest regions show higher emissions. Figure 5 shows $PM_{2.5}$ emissions and point source category is an important source type (about 45%). Emissions decrease throughout future years but point source emissions increase from 2001 to 2020. Note that fugitive dust and fire emissions which comprise about 50% of total $PM_{2.5}$ are not included in this analysis since they remain constant through years. $PM_{2.5}$ emissions are high in California, Texas, Midwest regions, and Southern US region. The area source contribution is high in west coast, mid-Atlantic and northeast states whereas the point source contribution is high in Texas, Midwest and southern states.

Canada and Mexico

Figure 6 shows 2001 and 2050 Canadian emissions for all seven species. Most emissions except PM species will drop more than 30%. Figure 7 shows 1999 and 2050 Mexico emissions for all seven species. As discussed previously, NO_x emissions increase more than twice due to growth of the power generation industrial sector. SO_2, however, increases at much lower rate compared to NO_x due to point source controls. CO and PM emissions show decreases and agricultural activities seem to drive NH_3 emissions increase in Mexico.

Test of future on-road mobile emission

Even though we have not run SMOKE/Mobile6 with future MM5 data yet, for 12 Northeast and mid-Atlantic states, we tested the impact of VMT vs. controls without considering meteorological variable changes in the future for 2018, which is a future year for regional haze SIP. We also put the year 2018 VMT to year 2050 (our target modeling year) and ran Mobile 6 to test what happens if year 2018 VMT is unchanged and we keep "on-the-table" regulations and controls. As seen in the figure 8, VMT increases 10~30% compared to the base year (i.e. year 2002). In spite of VMT increase, CO emissions decrease dramatically because of controls in the future years. Emissions decrease much slower after 2018 given fewer anticipated controls during post-2018 years. From this experiment, we confirm that the present regulations are not very effective in controlling emissions in post-2018 era. As observed from EPA's research, NMVOC emissions will increase post 2018 due to VMT increase and this trend will continue if new regulations or new technologies are not introduced (US EPA, http://www.epa.gov/tier2/finalrule.htm#regs).

ON-GOING WORK

We are currently running SMOKE to generate emissions for GCM-MM5/CMAQ to test several cases of air quality impact in present and future cases including: 1) base-year emissions with base-year climate data, 2) base-year emissions with future-year climate data (accelerated climate change case – only point/mobile/biogenic emissions are affected), and 3) future-year emissions with future-year climate data. For each future case, we are performing 18 months of simulation (i.e. one full year plus 3 summer months of the previous and following years). In addition, since there exist large uncertainties in predicting future climate conditions, it is of further interest to examine how such uncertainties could impact our estimation of future regional air quality and implications related to the control strategies to reduce Ozone and FPM precursors. To do so, we will use the uncertainty ranges of meteorological variables of interest, which are suggested and quantified by recent simulations (Webster et al., 2002 and 2003) using the Integrated Global System Model (IGSM) (Prinn et al., 1999), and then perturb future meteorological fields by some representative uncertainty values from those ranges through and within the MM5 model.

ACKNOWLEDGEMENTS

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KEY WORDS

Future Emissions
IPCC SRES
IMAGE
CAIR
SMOKE
Climate Change

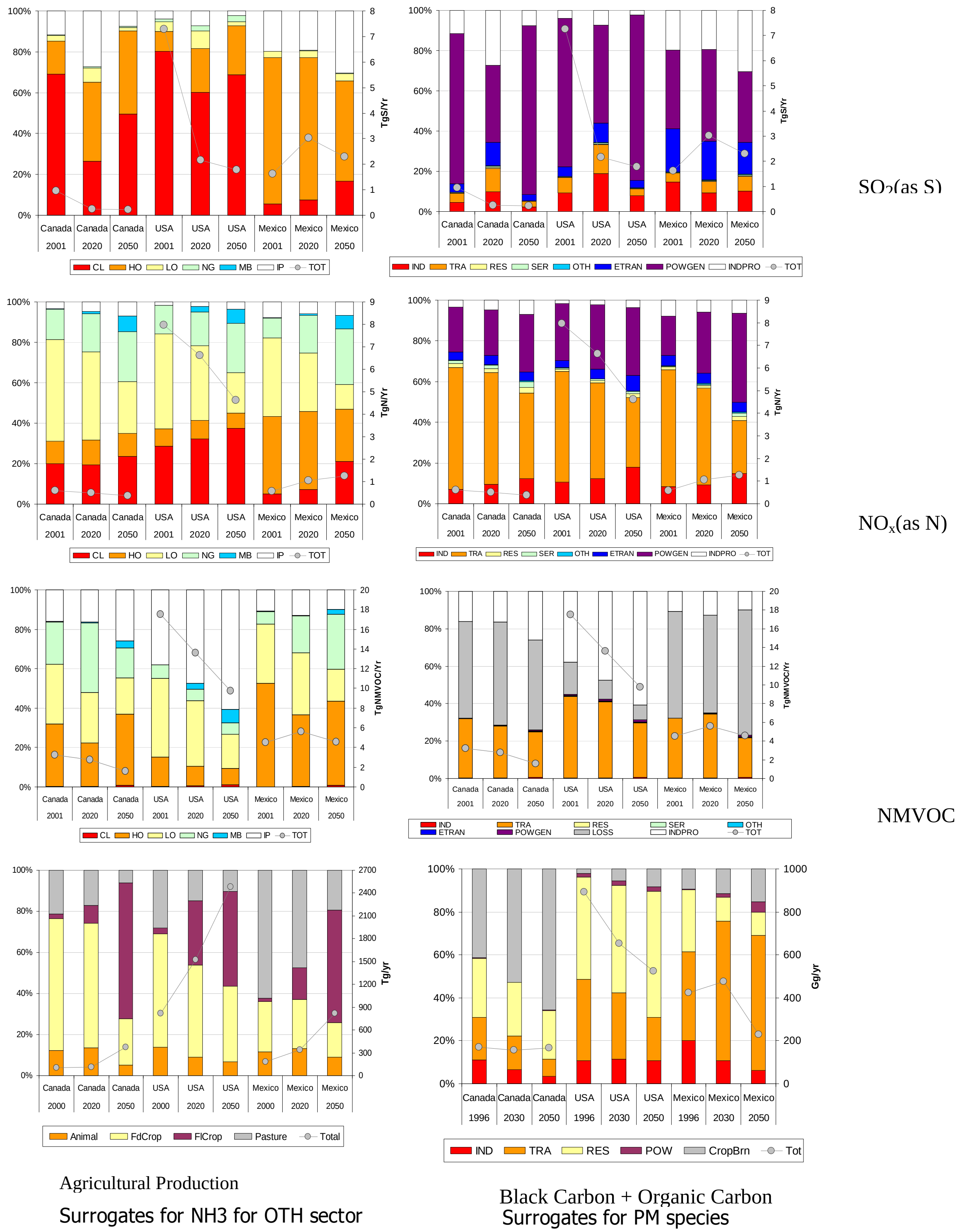


Figure 1. IMAGE emissions (A1B) by fuels (left) and by source sectors (right) for three IPCC regions (USA/Canada/Mexico) and three years (Y2001/Y2020/Y2050)
CL: Coal, HO: Heavy Oil, LO: Light Oil, NG: Natural Gas

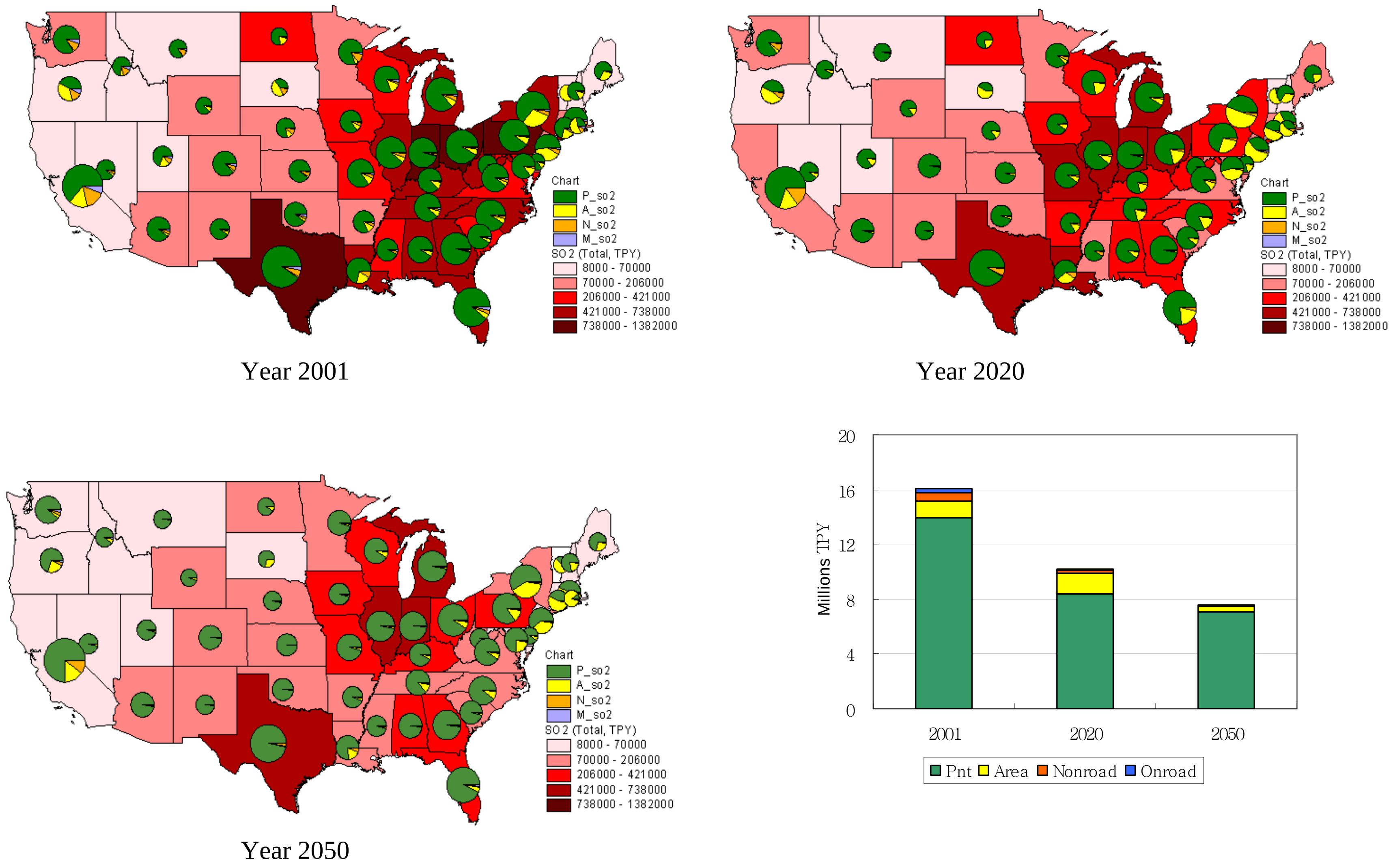


Figure 2. Present and future years SO_2 emissions by state and by source types

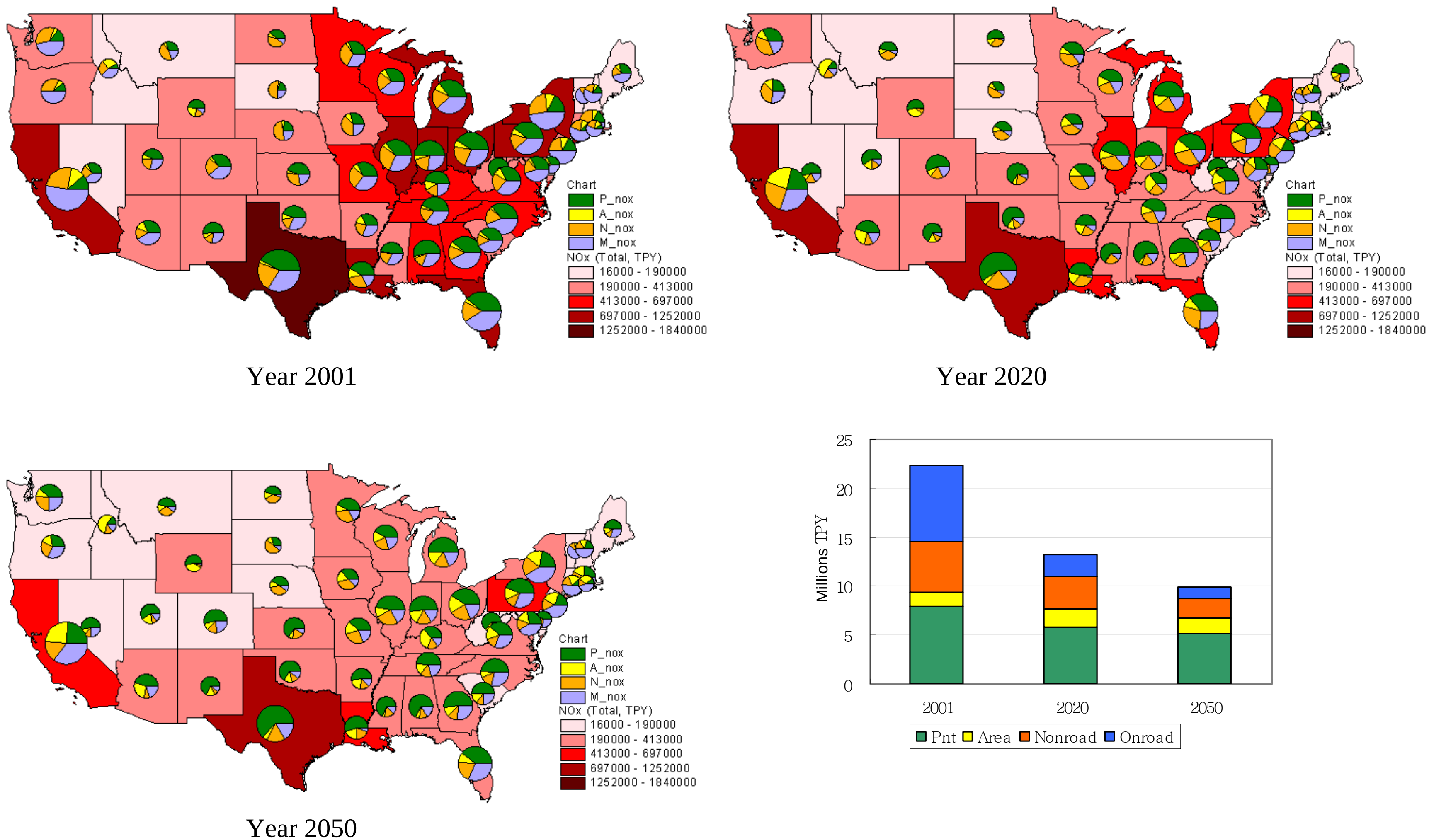


Figure 3. Present and future years NO_x emissions by state and by source types

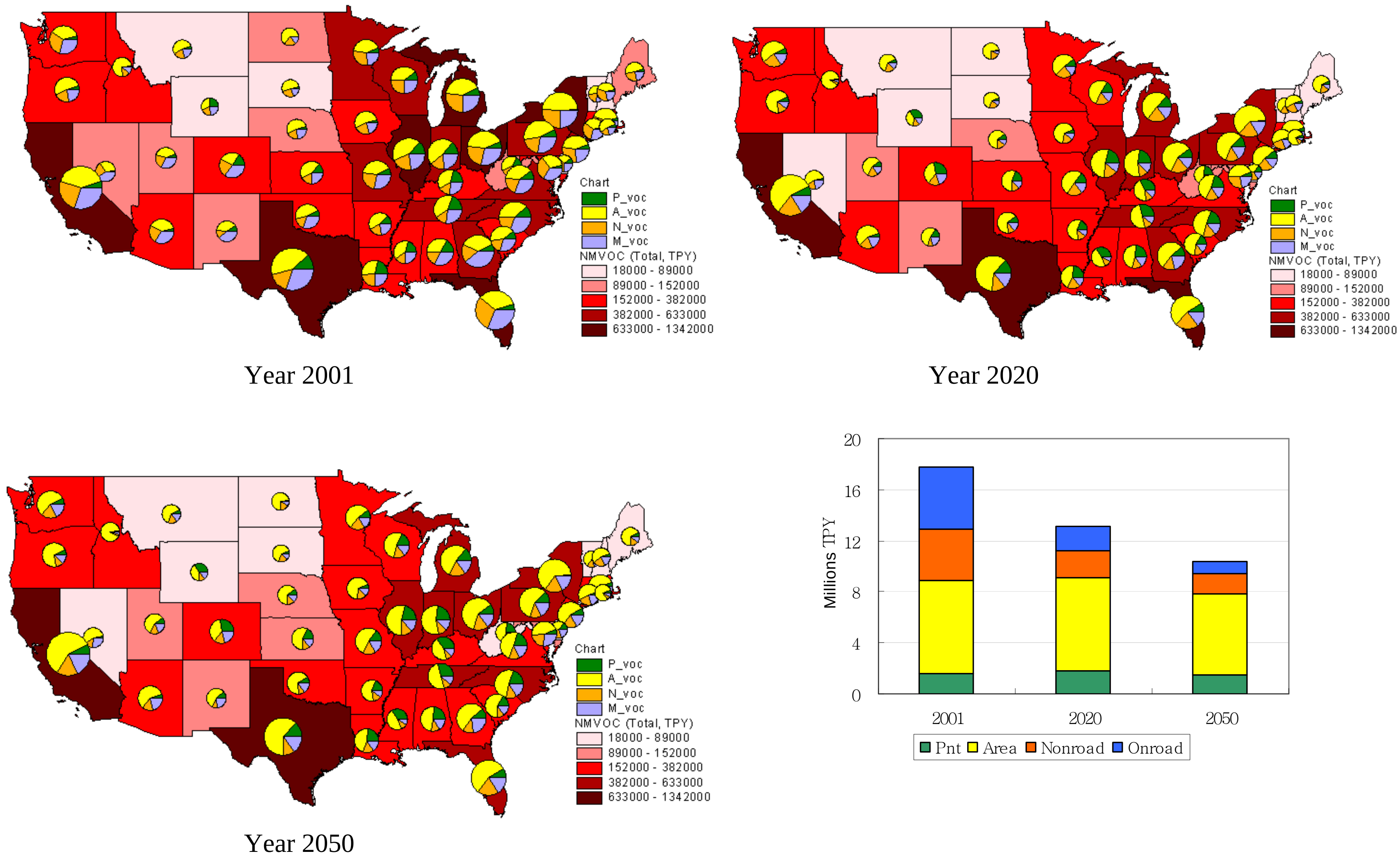


Figure 4. Present and future years NMVOC emissions by state and by source types

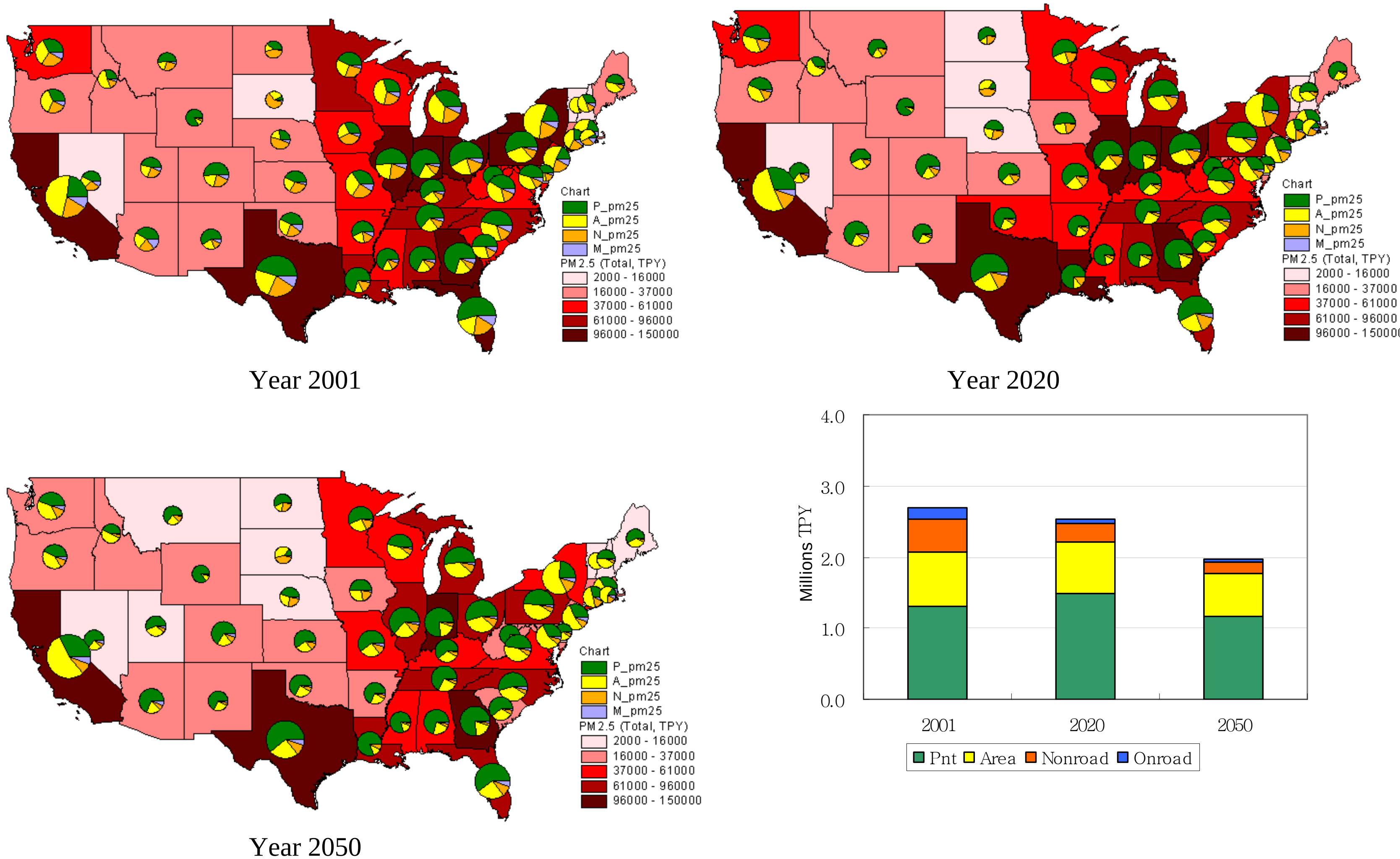
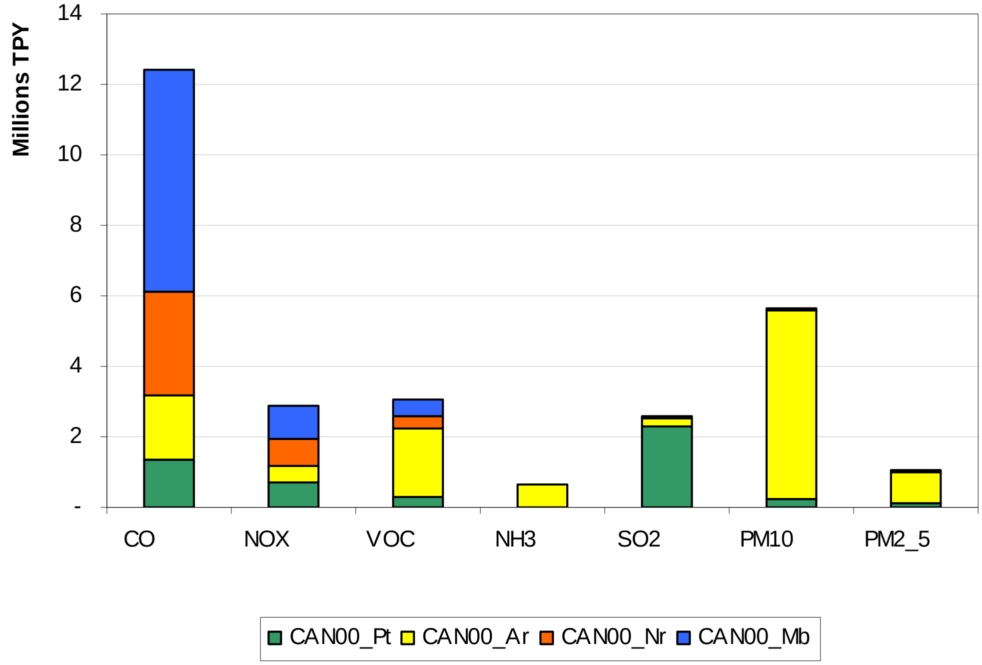


Figure 5. Present and future years $PM_{2.5}$ emissions by state and by source types



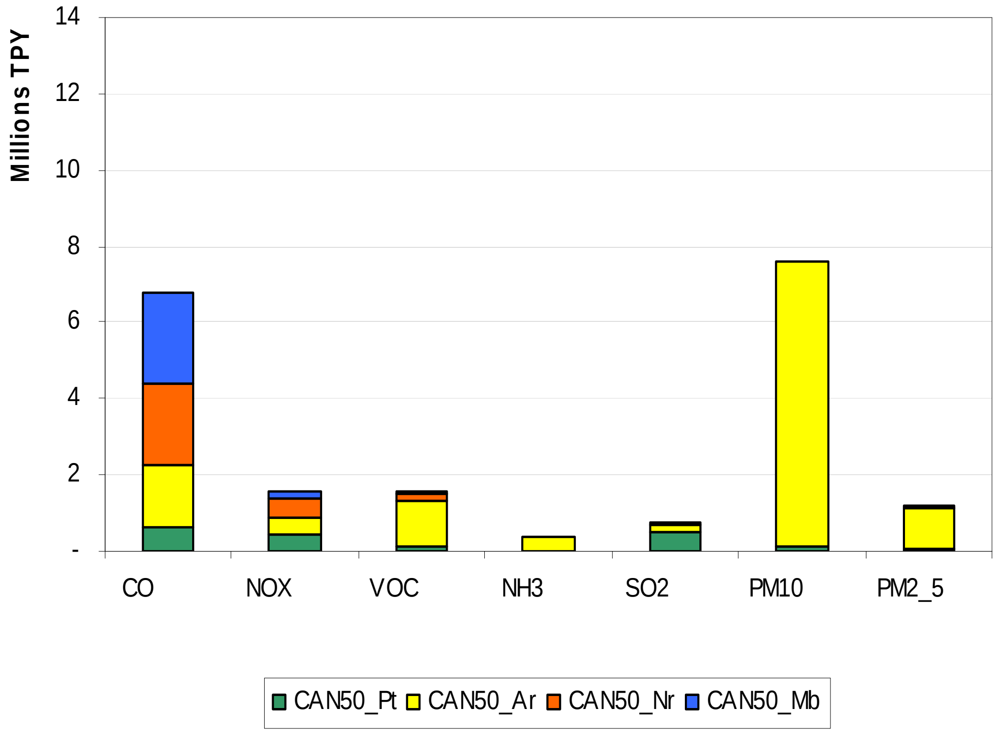
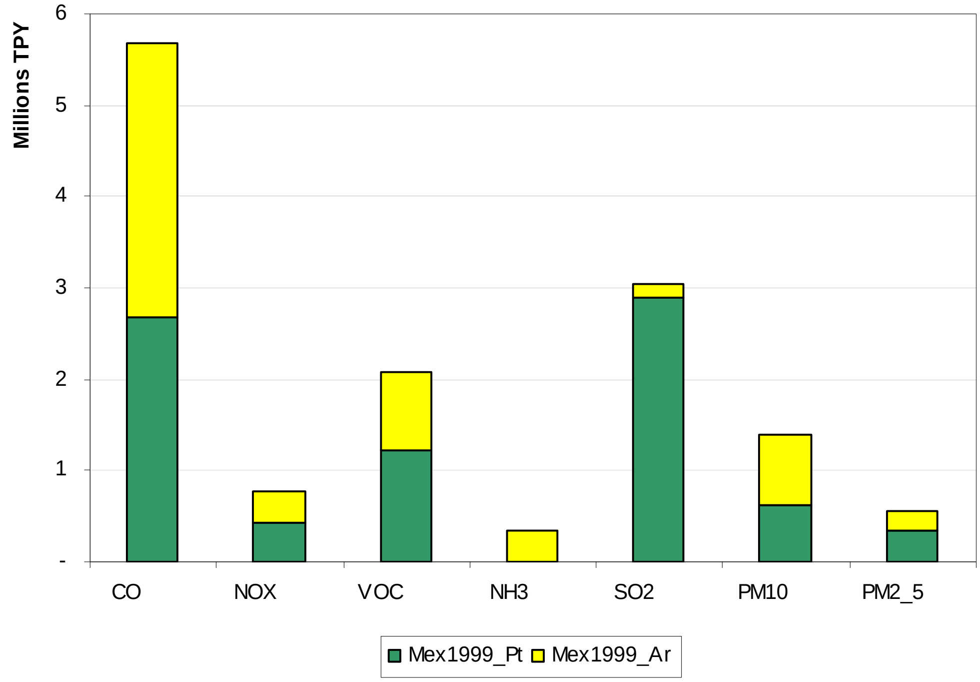


Figure 6. Year 2001 and Year 2050 Canada point, area, nonroad, and on-road mobile source emissions



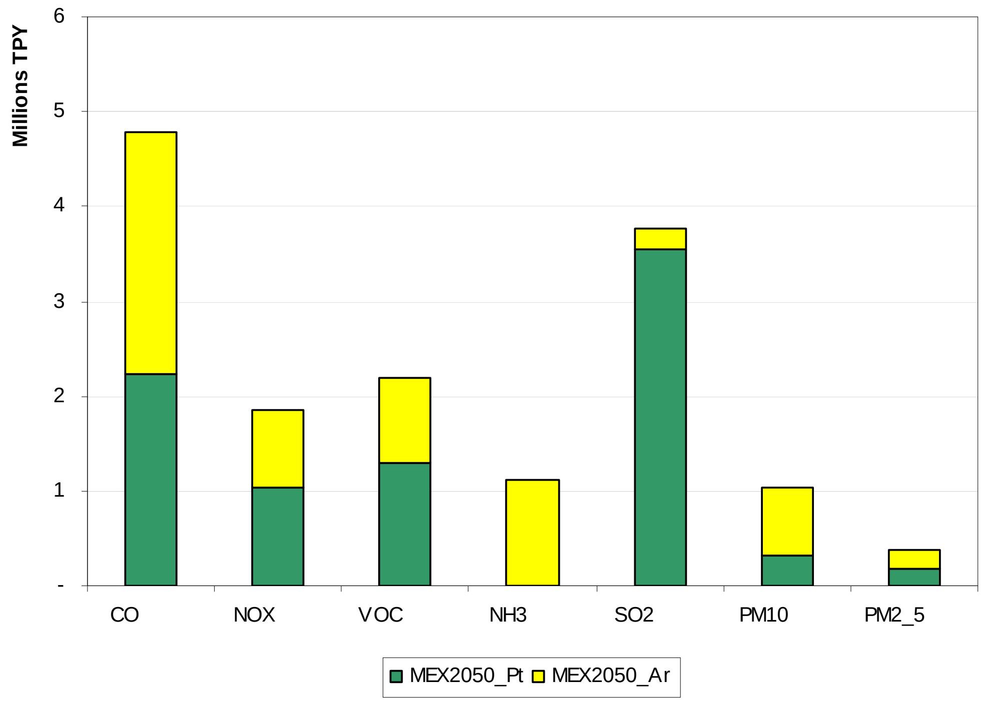
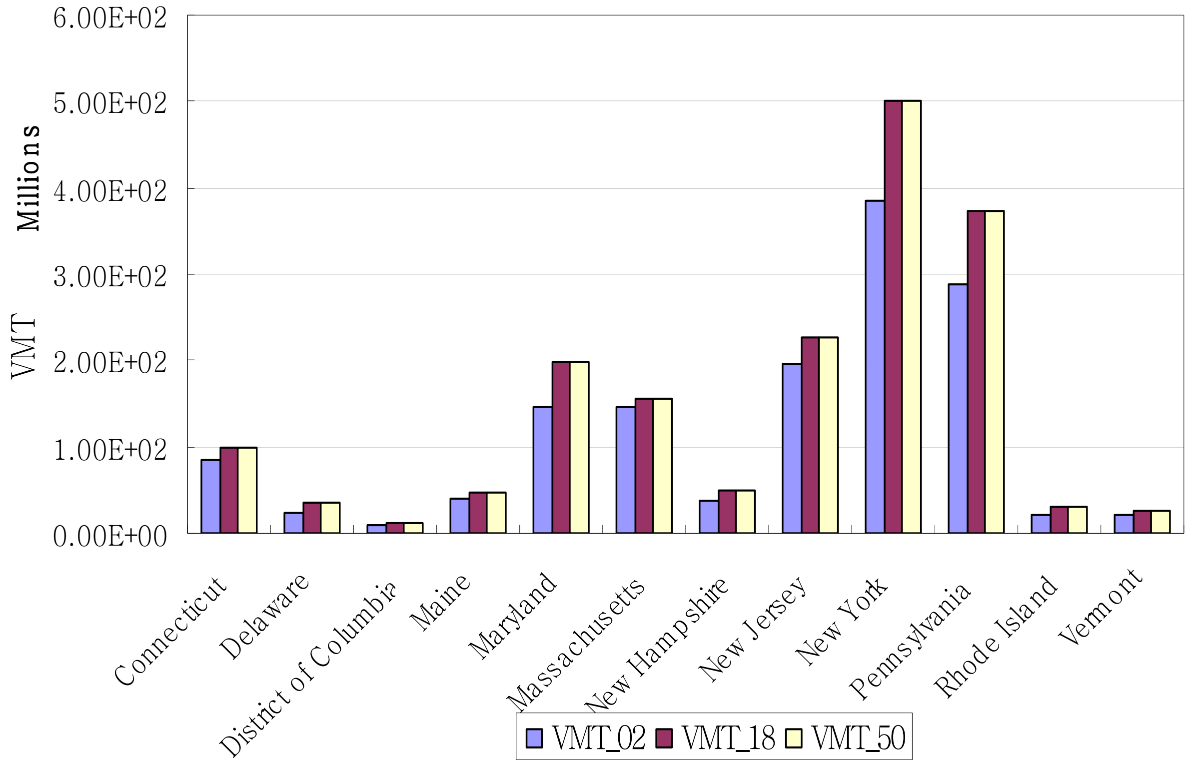


Figure 7. Year 1999 and Year 2050 Mexico point and area (stationary area, nonroad, on-road mobile) source emissions



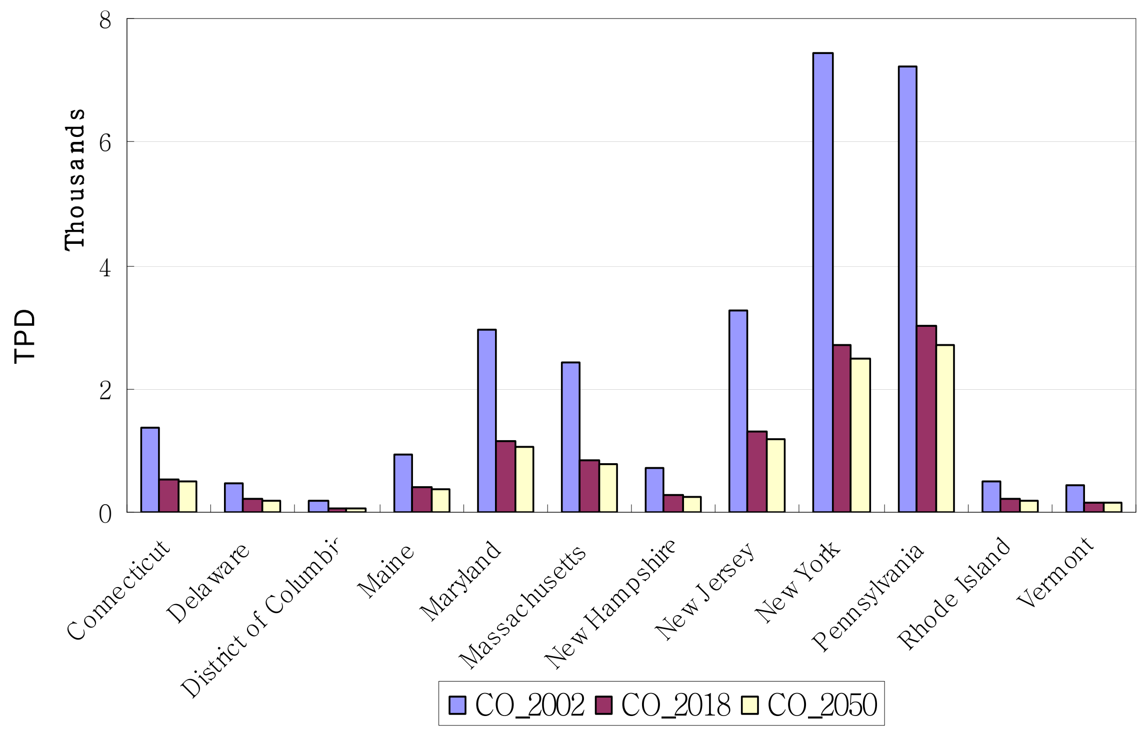


Figure 8. VMT and CO from three one-day SMOKE/M6 runs(2002/2018/2050) for MANE-VU states