Fresh air in the 21st century?

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[1] Ozone is an air quality problem today for much of the world's population. Regions can exceed the ozone air quality standards (AQS) through a combination of local emissions, meteorology favoring pollution episodes, and the clean-air baseline levels of ozone upon which pollution builds. The IPCC 2001 assessment studied a range of global emission scenarios and found that all but one projects increases in global tropospheric ozone during the 21st century. By 2030, near-surface increases over much of the northern hemisphere are estimated to be about 5 ppb (+2 to +7 ppb over the range of scenarios). By 2100 the two more extreme scenarios project baseline ozone increases of >20 ppb, while the other four scenarios give changes of −4 to +10 ppb. Even modest increases in the background abundance of tropospheric ozone might defeat current AQS strategies. The larger increases, however, would gravely threaten both urban and rural air quality over most of the northern hemisphere. *INDEX TERMS:* 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Prather, M., et al., Fresh air in the 21st century?, *Geophys. Res. Lett.*, *30*(2), 1100, doi:10.1029/2002GL016285, 2003.

1. Introduction

[2] The air we breathe can contain noxious substances in the form of trace gases and aerosols. Ozone (O_3) is identified as one of the more serious of these air pollutants, and the large abundances of O_3 observed within and downwind of metropolitan regions are clearly identified with emissions of ozone precursors, specifically, oxides of nitrogen (NOx), carbon monoxide (CO) and volatile organic compounds (VOC), by the industrial and transportation sectors [*Haagen-Smit*, 1951]. Breathing ozone, even at relatively low abundances, is correlated with pulmonary damage and asthma attacks [e.g., *Peden*, 2001; *Desqueyroux et al.*, 2002; *Mortimer et al.*, 2002]. Ground-level O_3 damages agricultural crops and natural ecosystems [e.g., *Mauzerall and Wang*, 2001; *Oksanen and Holopainen*, 2001] and reacts with environmental compounds to produce other toxic substances [e.g., *Morrison and Nazaroff*, 2002].

[3] Ozone is an air quality problem today for much of the world's population. For example, in the U.S. the 8-hour ozone standard of 80 ppb (all abundances are mole fraction, ppb = 10^{-9}) was exceeded over the last decade by an average 28 days per year for New England, where "serious" to "severe" non-attainment areas cover the populous regions [U.S. Environmental Protection Agency, Region 1: New England, http://www.epa.gov/region01/eco/ozone/]. In Europe, more than half the urban population is exposed to ozone above the 8-hour standard of 55 ppb for more than 30 days per year [*EEA*, 2002]. Some developing countries like India have air quality standards (AQS) for SO_2, NO_2, aerosols, but not O_3. The impacts of O_3 pollution on vegetation and in developing countries is only recently being assessed [e.g., *Emberson et al.*, 2001; *Taylor*, 2001]. The global damages caused by increasing O_3 levels have not been fully evaluated.

[4] Strategies to abate urban O_3 originally focused on local or regional solutions such as the State of California's Air Quality Management Districts (http://www.aqmd.gov/). The 1979 Geneva Convention on Long-Range Transboundary Air Pollution (http://www.unece.org/env/lrtap/) now has Protocols that consider continental-scale transport of O_3 and its precursors. Recent studies have shown that transoceanic, intercontinental transport of O_3 and related pollutants couples the major continents of the northern midlatitudes [*Tarrason and Iversen*, 1998; *Wild and Akimoto*, 2001; *Li et al.*, 2002] and hint that the O_3 AQS may be a global problem. Still, the typical scientific study to aid policy decisions on future O_3 AQS [e.g., *Jensen et al.*, 2001] does not consider global-scale changes in tropospheric O_3 that are anticipated during the 21st century.

[5] More than a dozen research groups analyzed the changes in atmospheric chemistry projected for the 21st century as part of the OxComp workshop of the Third Assessment Report of the Intergovernmental Panel on

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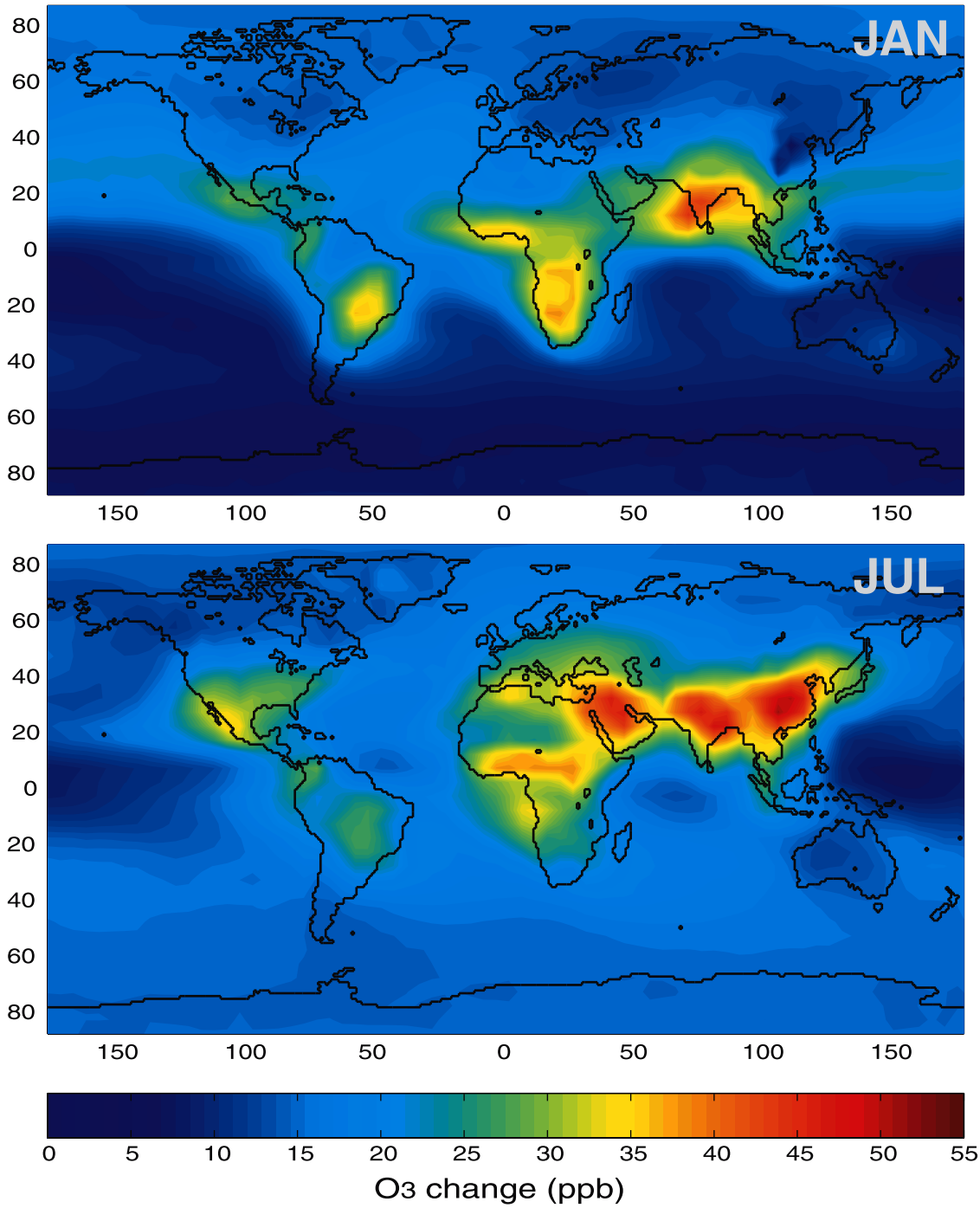

Figure 1. Monthly mean surface O_3 increase (ppb) for Jan and Jul from Y2000 to Y2100 following scenario A2x. Results are the average of 10 models [*Prather and Ehhalt*, 2001]: HGIS, IASB, KNMI, MOZ1, MOZ2, UCAM, UCI, UIO1, UKMO, ULAQ.

Climate Change (IPCC/TAR) [*Prather and Ehhalt*, 2001]. Three-dimensional global models were used to project the changes in greenhouse gases resulting from changing anthropogenic emissions based on the Special Report on Emissions Scenarios (SRES) [*Nakićenović et al.*, 2000]. The IPCC/TAR reported tropospheric O_3 column as a climate forcing and only noted briefly that surface O_3 increases by 2100 might be "threatening attainment of air quality standards over most metropolitan and even rural regions..." Surface maps and seasonality of these projected O_3 changes are presented and discussed here for the first time.

2. Results

[6] The increases in near-surface O_3 projected from year 2000 to year 2100 for one of the extreme SRES scenarios are shown in Figure 1 as January and July monthly averages. The largest increases typically occur in the tropics

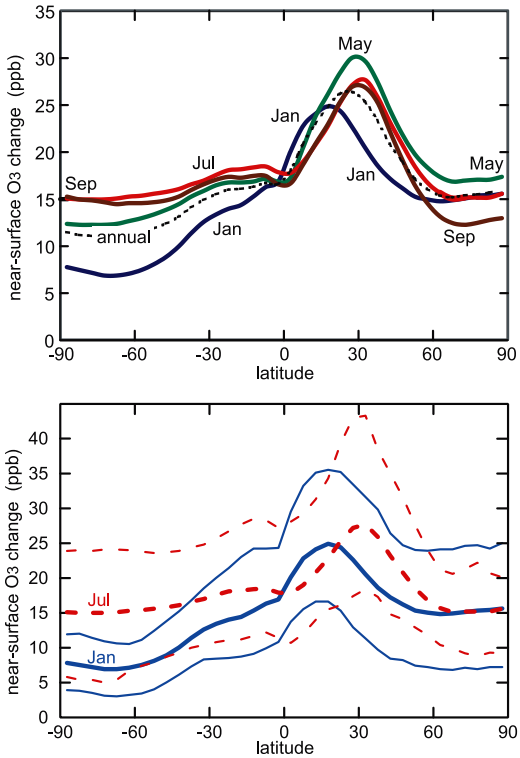

Figure 2. (top) Zonal-mean surface O_3 increase (ppb) from Y2000 to Y2100 as a function of latitude following scenario A2x. See Figure 1. The 4 months shown (Jan(blue), May(green), Jul(red), Sep(brown)) bound all other months and are labeled at their extrema. The annual average (dashed) is also shown. (bottom) The Jan zonal average (blue, thick solid) and Jul zonal average (red, thick dashed) are shown again with their minima and maxima (thin lines). These min/max are the zonal averages of the extreme model result for each 5° × 5° grid box.

where high sunlight conditions prevail, but the rise in O_3 affects most of the globe, including what are currently thought of as clean-air remote regions. These values are taken from global tropospheric chemistry model simulations for the IPCC/TAR scenario A2x, which was the only scenario analyzed with the full chemistry models [*Prather and Ehhalt*, 2001]. This projection of anthropogenic emissions is based on the preliminary SRES A2 scenario and a preliminary estimate of the methane (CH_4) abundance. Prior to the completion of the TAR the SRES scenarios were revised and the CH_4 abundances were recalculated to include the emissions of NOx, CO, and VOC.

[7] In all, fourteen independent models contributed results to the IPCC/TAR calculation of tropospheric O_3 change using the SRES emission scenarios. The meteorology and spatial resolution of these models range widely, they include both assimilated and climate-model winds, and most resolve the meteorology at 6 hours or better. Of these, ten (HGIS, IASB, KNMI, MOZ1, MOZ2, UCAM, UCI, UIO1, UKMO, ULAQ) gave complete calculations and diagnostics for scenario A2x, and their average is analyzed here. Results for the contemporary atmosphere (year 2000) were quite realistic in simulating observations of O_3 and CO at remote sites. While results vary from model to model, the basic pattern and magnitude of tropospheric O_3 changes in these ten models is similar (see figures 4.12–13 of *Prather and Ehhalt* [2001]), and thus the average is a robust estimate for these emissions. The differing treatment and resolution of chemistry in the boundary layer of these models prevented a meaningful comparison of ground-level O_3. Instead, we reported the average over 0 to 2 km in altitude and expect this abundance to be representative of the time-mean ground-level O_3 except over intense emission regions. These averages, at 5° latitude by 5° longitude resolution, are available along with the minimum and maximum range of the ten models.

[8] The tropical hot spots in Figure 1 can be explained by the shifting pattern of emissions of NOx and CO in the SRES emission patterns for scenario A2x. Anthropogenic NOx emissions increase 3.4-fold from year 2000 to year 2100. Relative increases in Europe (2.0) and North America (1.8) are less than the average, with relative increases in India (5.9), Southeast Asia (5.7), Africa (7.7), and South America (8.7) driving the total. Anthropogenic CO emissions increase 2.4-fold from year 2000 to year 2100. Relative increases in Europe (2.0) and North America (1.6) are likewise below the average; but relative increases in India (4.4), Southeast Asia (4.6), Africa (6.0), and South America (6.5) are much greater. These scenarios project an overall shift in precursors to lower latitudes with consequent impact on O_3 as noted previously [*Gupta et al.*, 1998].

[9] The zonal mean increases in near-surface O_3 are shown in Figure 2 (top) for a selection of months that bound the annual range. For the summer months (May–Sep) from 25°N to 40°N the increase is larger than 25 ppb, with even greater increases in the vicinity of continents. Even in remote southern latitudes poleward of 50°S the increase ranges from 7 to 16 ppb. Figure 2 (bottom) shows the extreme ranges of all ten model results for Jan (dashed) and Jul (solid), selecting the extreme of all models for each 5° × 5° grid box to average zonally. Thus, based on the range of independent model results, the 2/3-likelihood confidence interval for the zonal mean increase in near-surface O_3 due to these emissions is judged to be less than ±5 ppb. As identified in the OxComp study, the increase in CH_4 abundance from 1750 ppb to 4300 ppb drives almost half of this O_3 increase, and it is primarily the increased emissions of NOx rather than CO or VOC that drive the other half.

3. Discussion

[10] What do projections of global tropospheric O_3 mean for AQS in the 21st century? Clearly, these increases are not intended as direct projections of urban O_3 change, but rather, they indicate an upward shift in the baseline levels of O_3 upon which regional pollution builds. The extreme, high-O_3 events as measured in the hourly AQS are driven by local emissions and less likely affected by baseline O_3 increases. Efforts to meet the new 8-hour standards, however, and particularly the European cumulative standards for crops and vegetation (AOT40), would be greatly impacted by baseline increases of 15 to 25 ppb. It is worrisome that the largest baseline increases occur in northern mid-latitudes around continents during summer when air quality is currently at its worst. There are already agricultural concerns about the summertime high O_3 in developing countries [*Mauzerall and Wang*, 2001]. In addition, the high O_3

regions coincide with increasing aerosol emissions [*Penner*, 2001], which further exacerbates human health impacts.

[11] How representative is this high-end scenario of future O_3 increases? Among the six final SRES illustrative scenarios, two (A2 and A1FI) have emissions of O_3 precursors as large as the A2x scenario shown here. If we scale the change in near-surface O_3 with that of the total tropospheric O_3 as reported in the TAR [*Prather and Ehhalt*, 2001], then these two scenarios would project changes like those illustrated here for the latter decades of the 21st century. On the other hand, the four less extreme SRES scenarios (A1B, A1T, B1, B2) project much lower fossil fuel use and smaller near-surface O_3 changes ranging from −4 to +10 ppb by 2100. More immediately, by 2030 all six scenarios would project near-surface O_3 increases that range from 9% to 34% (averaging 25%) of those shown here. Such near-term increases of about 5 (+2 to +7) ppb over the northern hemisphere would notably impede AQS attainment [*Fiore et al.*, 2002]. One critical element in these projections is the scenario for emissions of O_3 precursors, not just their amount, but their location. A known flaw with the SRES scenarios is that they did not explicitly consider the emergence of new ozone-related air quality regulations in developing countries. A revised and expanded SRES-like effort, one that focuses on the regional emissions of O_3 precursors and allows for emerging air quality regulations, is required for AQS planning over the next several decades.

[12] What is missing? These projections of 21st century changes in global tropospheric chemistry include only changes in anthropogenic emissions. As noted in the TAR, the response of the climate system to the overall anthropogenic forcing (including carbon dioxide) is expected to be larger than anything observed in the last millennium, and thus we expect natural ecosystems and their emissions of O_3 precursors to be altered. Unfortunately, we were unable to evaluate this feedback in the TAR due to a lack of research and publication on this topic. In addition, the physical climate change itself will alter the dynamics, temperature, and humidity of the troposphere, including possibly the occurrence of stagnation episodes that lead to AQS exceedences. One of the OxComp models (UKMO) has shown since the TAR that the 21st century physical climate change driven by the A2 scenario tends to reduce global tropospheric O_3 because of the higher humidity and temperature [*Johnson et al.*, 2001], a result consistent with earlier sensitivity studies [*Brasseur et al.*, 1998]. These missing feedbacks represent a major source of uncertainty in projecting near-surface baseline O_3 increases. They need to be evaluated within the research of the broader community before the next assessments.

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