



Project Summary

Climate Change and Its Interactions with Air Chemistry: Perspectives and Research Needs

J. E. Penner, P. S. Connell, D. J. Wuebbles, and C. C. Covey

The full report outlines and estimates where possible the interactions between climate change and atmospheric chemistry that need investigation on both local and/or regional and global scales. This problem is enormously complex and is not simply one of estimating temperature change and running chemical models already in use. The changing climate influences many different factors such as precipitation, atmospheric transport, changes in budgets of species with biological sources, changes in UV light because of stratospheric ozone depletion, changes in deposition rates, etc. The single most significant finding in this study is that very little is known about the interactions of the above cited effects with either climate or air pollution. There is however significant evidence to indicate that atmospheric emissions and concentrations of radiatively and chemically important trace gases such as CO_2 , CH_4 , N_2O , CF_2Cl_2 , CFCl_3 , and CO are increasing. These increases are largely derived from human related activities. Current analyses suggest that it is improbable that present trends towards increasing concentrations will be arrested or reversed in the near future.

This Project Summary was developed by EPA's Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, NC, to announce key findings of the

research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The record of CO_2 increase, established by a continuous record of observations at Manna Loa, Hawaii, since 1958, together with the more recent identification of increasing trends in CH_4 , N_2O , and the chlorofluorocarbons, establishes beyond a doubt the influence that man can have on the global atmospheric composition. Furthermore, the most sophisticated models that we now possess all agree that the continuance of these trends will lead to a significant change in climate (see for example, Ramanathan et al., 1987). This change in climate must feed back to alter the composition of the atmosphere, because many of the sources important for determining the composition are sensitive to a change in climate. Furthermore, chemical rates and interactions themselves are sensitive to climate change.

The full report attempts to outline and estimate where possible the interactions between climate change and atmospheric chemistry that need investigation on both local and/or regional and global scales. The problem is enormously complex and is not simply one of estimating temperature change and running chemical models we already possess to get an answer. The ways that a changing climate influences atmospheric chemistry include not only temperature and

precipitation changes, but changes to atmospheric transport processes, changes to the budgets of species with biological sources (which respond to temperature and moisture changes), changes to light levels due to stratospheric ozone depletion which would alter photolysis rates, changes to vegetative cover which would alter deposition rates, changes in the rate of export of pollutants from the urban/regional environment to the global one, etc. Furthermore, changes in atmospheric chemical composition will lead to climate change.

Figure 1 gives an overview of the climate/chemistry system and the interactions that it will be necessary to understand in order to predict the future state of our planet. The responses of the various subsystems shown there are coupled to each other and to the realized climate change itself. For example, climate change has the potential to alter water vapor concentrations. Changes in the concentration of water vapor would profoundly alter many species concentrations by impacting atmospheric OH concentrations. Because OH acts as a scavenger for many of the pollutants released by man, changes in this species

will alter concentrations of many other trace species. Changes to H₂O will also alter tropospheric O₃ concentrations. Because O₃ absorbs infrared radiation, these changes will feedback to alter the climate. As another example, climate change also has the potential to alter the biological sources and sinks of certain gases. Because biological processes supply many of the species of radiative importance in the troposphere, changes in these sources will feed back to alter the climate response.

Changes in global chemistry will be intimately tied to changes in regional chemistry and changes on one scale will affect changes on others. Just as the globally averaged temperature response to a given change in composition will be manifested by different changes in various different regions, the "average" composition change will be different in different regions. Determination of how this all ties together to feed back on the climate change is a formidable problem indeed. The full report begins with the step: a discussion of possible compositional changes on both regional and global scales from the variety of changes that are expected to be introduced by climate change, and

potential climatic changes resulting from known and suspected compositional change.

Trends in Global Atmospheric Composition and Climate

Earth's climate is the result of the interaction of solar and longwave radiation with the surface of the planet and the gaseous constituents in its atmosphere. It happens that both the surface properties that determine the amount of reflected radiation and the constituents of the atmosphere that absorb and interact with radiation are subject to change by man. In order of importance, the atmospheric species that are most significant for radiative transfer are H₂O, CO₂, O₃, CH₄, N₂O and potentially CFC-11 and CFC-12 (Ramanathan et al., 1987). Of these, all but H₂O and O₃ have established abundance trends thought to be directly traceable to emissions of human industrial and agricultural activity (Wuebbles and Edmonds, 1988). H₂O and O₃ may also be increasing, but trend detection is made difficult because of inadequate monitoring and/or spatial and temporal heterogeneity of distributions. Table 1 summarizes current knowledge

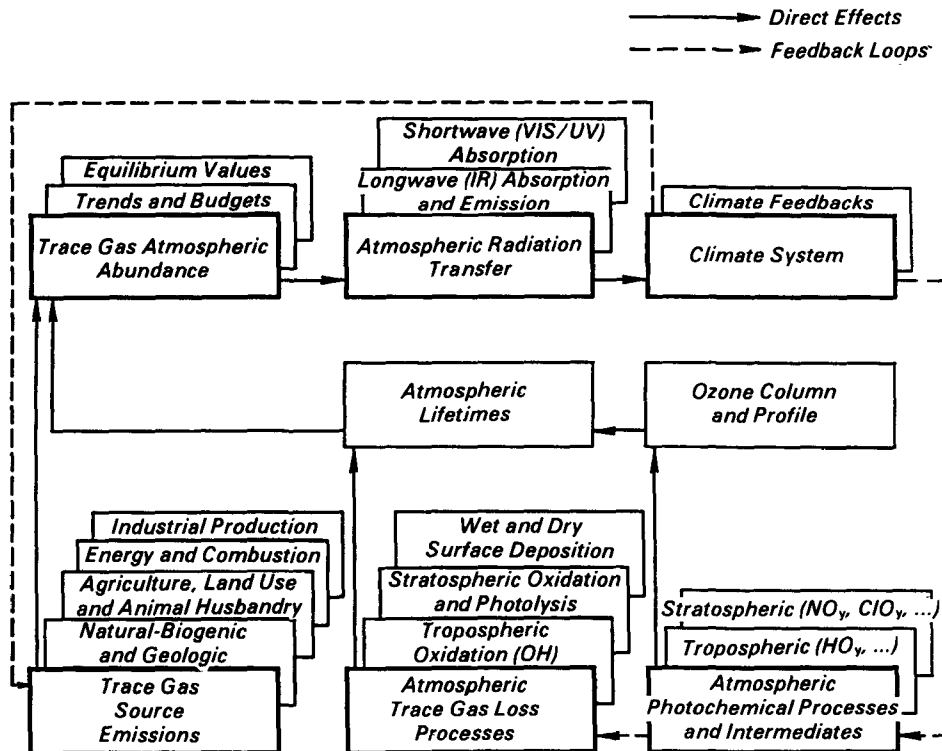


Figure 1. Climate/chemistry system.

of global-scale observed abundance trends and the importance of these trends for chemistry/climate interactions. The full report discusses the evidence for these trends and some of the uncertainties associated with prediction of future trends.

In addition to the established trends in CO₂, CH₄, N₂O, and the chlorocarbons

listed in Table 1, a suite of other species have also been suspected of change. Trends in these species are much more difficult to establish, because their lifetimes are generally short (1 day to several months), leading to spatial and temporal variations that have precluded, so far, the global characterization of their abundances. These species include the

nitrogen oxides, carbon monoxide, non-methane hydrocarbons, and tropospheric aerosols. Of these, nitrogen oxides, carbon monoxide, and non-methane hydrocarbons have significant fossil fuel derived sources while tropospheric aerosols have a known graphitic component that is also related to combustion processes. Thus, trends can

Table 1. Established and Suspected Trace Species Trends

<i>Trace Constituent</i>	<i>Estimated Annual Increase</i>	<i>Importance for Climate</i>
CO ₂	0.4%	Absorbs infrared radiation; affects stratospheric O ₃
CH ₄	1.1%	Absorbs infrared radiation; affects tropospheric O ₃ and OH; affects stratospheric H ₂ O and O ₃
N ₂ O	0.2%	Absorbs infrared radiation; affects stratospheric O ₃
CFCI ₃	5.0%	Absorbs infrared radiation; affects stratospheric O ₃
CF ₂ Cl ₂	5.0%	Absorbs infrared radiation; affects stratospheric O ₃
CH ₃ Cl ₃	5.0%	Absorbs infrared radiation; affects stratospheric O ₃
CH ₃ F ₂ Cl	12.0%	Absorbs infrared radiation; affects stratospheric O ₃
CFCI ₂ CF ₂ Cl	10.0%	Absorbs infrared radiation; affects stratospheric O ₃
Tropospheric O ₃	0.8%*	Absorbs uv and infrared radiation
Stratospheric O ₃	-0.3% ^u	Absorbs uv and infrared radiation
CO	-1%	Involved in tropospheric O ₃ and OH cycles
NO _x	?	Involved in O ₃ and OH cycles and precursor of acidic nitrates
NMHC	?	Involved in tropospheric O ₃ and OH cycles
(CH ₃) ₂ S	?	Produces CCN which can alter cloud albedo; forms SO ₂
OCS	?	Forms aerosol in stratosphere which alters albedo
CS ₂	?	May be major source of OCS in the troposphere
SO _x	?	Major precursor of acid rain
H ₂ S	?	Major natural source of SO ₂
Tropospheric OH	-?	Scavenger for many atmospheric pollutants, including CH ₄ , CH ₃ CCl ₃ , CH ₃ F ₂ Cl

*In lower troposphere.

^uIn upper stratosphere

be expected, as have been observed for the fossil fuel derived trend in N_2O . The magnitude of the trend expected for each specie will depend on its lifetime, of course. Data to support good estimates, however, do not exist, due to the high variability of both sources and sinks in space and time.

The importance of nitrogen oxides, carbon monoxide and non-methane hydrocarbons derive from their ability to alter the global tropospheric chemistry of OH and O_3 . Ozone directly affects climate through its solar and infrared absorption, while OH moderates the concentrations of CH_4 , CH_3CCl_3 , and other hydrogen-containing halocarbons that are infrared absorbers. OH also directly affects the photochemical cycling or removal of the nitrogen oxides, CO, and the non-methane hydrocarbons. Changes in O_3 and OH will enhance the predicted climate change over and above that expected from the species that have established abundance trends.

As a consequence of the uncertainties in budget, scenario, and climate response aspects, climate change predictions are more appropriately made in terms of broad likely ranges rather than specific values. (Similarly, the impacts on the regional topics discussed in the full report can be construed as sensitivities over a range of possible input and boundary condition values.) As an example of studies of climate-chemical interactions projecting climate change into the next century, Ramanathan et al. (1987) consider three scenarios generally

characterized by liberal, conservative and intermediate views of the extension of currently observed abundance trends. The range of global equilibrium temperature change for the 50-year period ending in 2030 is 0.8 to 4.1K, incorporating uncertainties in both scenario and climate sensitivity. The range of realized temperature change over this period is about 0.5 to 1.2K, including uncertainty in the rate of ocean thermal diffusivity. These are substantial fractions of the 11K glacial-interglacial temperature contrast deduced from antarctic ice core data (Barnola et al., 1987; Genthon et al., 1987). In order to narrow the range of uncertainty in the predicted climate change, we need to better understand the global chemical changes that are occurring as well as how regional chemistry and regional emissions impact "global" chemistry. The next two sections show how the expected climate changes will affect many aspects of both global and regional chemistry, making a full assessment of all the feedbacks a challenging problem for the future.

Urban/Regional Chemistry and Climate Change

The temperature increases associated with the trends in trace species discussed above are global average temperature changes. Not all regional, however, will experience the same temperature increase; furthermore, changes other than just a temperature increase can be expected. These

changes could include, for example, changes in cloud types and amounts, changes in meteorological conditions in a given region, and changes in background free tropospheric concentrations of a variety of species. This variety of changes will alter the chemical processes that take place on urban and regional scales and that lead to oxidant formation and acid deposition. It is important to try to understand the effects of these changes on regional chemistry, because we have already implemented emission control policies that may not be appropriate for a climatically different future. New policies that are implemented should account for the possibility that climate change will alter the formation of oxidant and acid deposition.

Determining how climate change would alter regional chemical processes is a difficult problem, because many types of change need to be accounted for. Here, we can only list potential climate changes and sketch the resulting changes to oxidant formation and acid deposition. Actual regional weather, of course, occurs in an episodic fashion and regional models are run consistent with episodic events. Climate change, on the other hand, is generally construed to be a statistical average change. It is not yet possible to know how the changes we discuss here in terms of a local or regional response might integrate over time to delineate a more "statistical" and useful answer.

Table 2 gives a list of climate and global chemistry associated changes that

Table 2. Climate Change Parameters Important for Regional Chemistry

1. A change in the average maximum or minimum temperature and/or changes in their spatial distribution and duration leading to a change in reaction rate coefficients and the solubility of gases in cloud water solution.
2. A change in stratospheric O_3 leading to a change in photolysis rate coefficients.
3. A change in the frequency and daily pattern of cloud cover and types of cloud formed leading to a change in photolysis rate coefficients and heterogeneous rates of conversion of SO_2 .
4. A change in the frequency and intensity of stagnation episodes or a change in the depth of the planetary boundary layer and its diurnal cycle leading to more or less mixing of polluted air with background air.
5. A change in background boundary layer and/or free tropospheric concentrations of water vapor, hydrocarbons, NO_x , and O_3 (due to changes in mixing processes or sources such as lightning for NO_x) leading to more or less dilution of polluted air in the boundary layer with background air and altering the chemical transformation rates in both the boundary layer and the free troposphere.
6. A change in the vegetative and/or soil emissions of hydrocarbons and NO_x which are sensitive to temperature and/or light levels leading to changes in their concentrations.
7. A change in deposition rates to vegetative surfaces whose stomatal resistance is a function of temperature, light intensity and other factors leading to changes in concentrations.
8. A change in energy usage or technology leading to a change in energy-related emissions and their concentrations.
9. A change in secondary aerosol formation leading to changes in photolysis rates, the planetary albedo, and heterogeneous reaction rates.
10. A change in circulation and/or precipitation patterns leading to a change in the abundance of pollutants deposited locally versus exported off the continent.

could impact urban and regional oxidant formation and acid deposition along with some notes about the chemical and physical processes that these changes could alter. In the full report the effect of some of these changes on the maximum ozone concentration generated in a simple box model of urban smog is estimated (see Table 3). The calculations demonstrate that several of the expected effects might individually increase maximum ozone concentrations by as much as 20%. For the other changes listed in Table 2, it was not possible to estimate their effects, because there was no adequate knowledge of the forcing function from climate simulations, and because regional models need to be applied. Very few calculations for any of these effects were available from previous analyses. The importance of this finding is difficult to judge because the overall contribution of gas phase conversion rates as compared to heterogeneous conversion rates of SO₂ to SO₄⁼ in a relative statistical sense is not yet established for the episode they modeled.

For acid deposition, even fewer quantitative estimates of the effect of any of these climate-related changes is available. At a workshop held in February 1988, Walcek and Chang (1988) estimated that increases in temperature could significantly increase the gas phase conversion rates of SO₂ to SO₄⁼ in their model. The importance of this finding is difficult to judge because the

overall contribution of gas phase conversion rates as compared to heterogeneous conversion rates of SO₂ to SO₄⁼ in a statistical sense is not yet established. For the episode they modeled, the heterogeneous rates of conversion were far more important. Hales (1988) considered the effect of a temperature increase at constant relative humidity on the SO₂ conversion rates in a cloud/chemistry model of a cyclonic storm. The deposition rate of SO₄⁼ was increased significantly, because precipitation amounts increased. In addition, the pH of cloud water increased, increasing the role of O₃ at the expense of H₂O₂ in converting SO₂ to SO₄⁼. Thus, in an altered climate, local acid precipitation may increase and the chemistry of O₃ formation may become far more important to acid formation. Both these sets of researchers felt that the effects of climate change could be very significant.

Very little else is known about how acid deposition might change as a result of climate change. However, because over 30% of sulfur that is now emitted over land areas in North America is exported off the coast (Galloway et al., 1984), we infer that regional deposition patterns could change significantly, if circulation patterns change.

Global Chemistry and Climate Interactions

The above discussion has shown that climate change has the potential to alter

regional chemistry. In addition, climate-driven changes can also alter global chemistry. Some of these changes feed back to alter the climate as well. Two important ones are considered in this section: climate-driven changes to tropospheric OH concentrations and climate-driven changes to tropospheric O₃. Tropospheric OH is important to climate because it acts as the primary chemical scavenger of a variety of gases (some of which are infrared absorbers and helping to create the climate change). Tropospheric ozone is important because it is, itself a strong absorber of infrared radiation.

A variety of species interact with OH and the odd hydrogen family of species to determine its abundance. Many of the species on whose concentration OH depends on will be altered by climate change; for example, H₂O concentration will probably increase in general, if relative humidity tends to remain fixed as temperatures rise. Similarly, O₃ may increase in response to direct as well as climate-driven increases in NO_x, NMHCs, and CH₄ emissions. Also changes in the emissions of NO_x, NMHCs and CH₄ will directly affect OH concentrations. Changes to stratospheric O₃ could also alter tropospheric OH by increasing tropospheric photolysis rates. Finally, temperature increases will alter temperature-dependent photochemical reaction rates that are important in the OH budget. Table 4 summarizes the estimated response of OH to changes in

Table 3. Estimated Change in Urban Ozone

<i>Climate-Driven Perturbation</i>	<i>Estimated O₃ Change*</i>	<i>Notes</i>
<i>Temperature increase from 25° to 30°C</i>	<i>+ 20%</i>	
<i>Increase biogenic emissions of NMHC consistent with a 5°C temperature increase</i>	<i>3 - 10%</i>	<i>Could be larger in regions where biogenic emissions are more important</i>
<i>25% decrease in column O₃ abundance</i>	<i>+ 10%</i>	<i>This work and Liu and Trainer (1987)</i>
	<i>-7% to +47%</i>	<i>Gery et al. (1987)</i>
<i>Increase cloudiness leading to a 10% decrease in photolysis rates</i>	<i>- 10%</i>	
<i>Increase boundary layer depth by 2</i>	<i>- 50%</i>	

* Estimated using a simple box model of urban photochemistry with initial HC/NO_x = 7. See Atherton and Penner (1988) for details

Table 4. Estimated Change in Global OH

<i>Climate-Driven Perturbation</i>	<i>Change in OH</i>	<i>Reference</i>
+5°C	few percent	LLNL 1-D model
10-30% increase in H ₂ O	few percent	Thompson et al. (1988)
2 x O ₃ in troposphere	~10% over ocean >10% over continents	Thompson et al. (1988)
Increase biogenic NMHC emissions	Current emissions decrease OH by a factor of 2 near surface; no estimate for effect of increased emissions	Trainer et al. (1987)
10% increase in NO _x	+5%	Thompson et al. (1988)
Simultaneous increase in CO, CH ₄ , NMHC	Decrease in OH	Isaksen and Hov (1987)
Simultaneous increase in CO, CH ₄ , NO _x , NMHC	Increase in OH	Isaksen and Hov (1987)

tropospheric species concentrations, temperatures, and photolysis rate constants. However, prediction of future changes in global-average tropospheric OH abundances depends on accounting for the simultaneous action of the many coupled OH_x-controlling processes. Projected increases in CO, CH₄ and NMHCs are likely to lead to continued decrease in total tropospheric OH abundance, as is shown by Isaksen and Hov (1987) in a two-dimensional model of coupled perturbations to the troposphere. This average conclusion includes, however, significant regional diversity, in which some areas of the troposphere may be characterized by OH increase. For example, Isaksen and Hov (1987) find that OH is increased slightly in their model when increases in the emissions of NO_x were added to those of CO, CH₄, and the NMHCs.

Global tropospheric ozone abundance is a balance between transport of roughly 5×10^{10} molecules cm⁻² s⁻¹ from the stratosphere (Levy et al., 1985), surface deposition to land and vegetation estimated to be of similar magnitude (e.g., Fabian and Pruchniewicz (1977)), and photochemical sources and sinks whose magnitudes are estimated to be comparable to or larger than the stratospheric source (NRC, 1984). Because tropospheric ozone abundances can be controlled by global scale transport, regional scale transport, and photochemistry, the distribution and lifetime of tropospheric ozone is significantly heterogeneous in time and space. It is clear that in some regions of

the troposphere, with urban smog the extreme example, photochemical processes dominate the ozone budget and produce a net source of ozone. In the upper troposphere, transport from the stratosphere dominates. In still other areas, where NO_x abundances are very low, photochemical processes lead to a net destruction of ozone.

The photochemical production of ozone occurs primarily when peroxy radicals generated in the OH-initiated oxidation of CO, CH₄, and higher hydrocarbons (NMHC) oxidize NO to NO₂, which leads to ozone formation after NO₂ photolysis. Destruction occurs if the region is NO-poor and the peroxy radical reacts with ozone instead. Ozone loss also occurs when O(¹D), which is generated by O₃ photolysis, reacts with H₂O. This is also the primary source of tropospheric OH. The OH and O₃ chemistry cycles are thereby thoroughly intertwined, implying that the same mechanisms of climate change that could alter tropospheric OH will also create changes in the ozone budget and cycle both directly, by altering photochemistry of O₃, and indirectly, by altering OH and peroxy radical concentrations that are involved in O₃ photochemistry. In addition, of course, the amount of O₃ transported into the troposphere from the stratosphere could change as a result of stratospheric O₃ depletion or due to changes in circulation between the two atmospheric regions. A number of calculations indicate that tropospheric ozone can be expected to increase via, basically, the same

mechanisms that are responsible for the formation of photochemical smog. For example, in the two-dimensional model of Isaksen and Hov (1987), when CH₄ concentrations were increased by 1.5% yr⁻¹, O₃ concentrations increased by .45% yr⁻¹. Larger O₃ increases were predicted for simultaneous increases in CH₄, CO, NO_x, and NMHCs. No estimate, however, has accounted for the heterogeneity of photochemical sources and sinks expected in different regions.

Modeling Capabilities and Limitations

In order to fully and meaningfully address the issues involved in the interaction of air chemistry and climate, it will be necessary to somehow link climate models, global chemistry models and urban/regional models. Figure 2 shows, in a general fashion, the processes that need to be represented and that will require the linking of the three types of models. Full lines indicate changes and effects that can, at least in some fashion, be estimated with today's models. Dashed lines indicate processes that interconnect global models of climate, global models of chemistry, and regional chemical models, but about which very little is known. To create a fully interconnected system would require models we do not now possess. The spatial scales and time scales represented in these three types of models are totally different, and it is not at all clear how to join them together (see Figure 3).

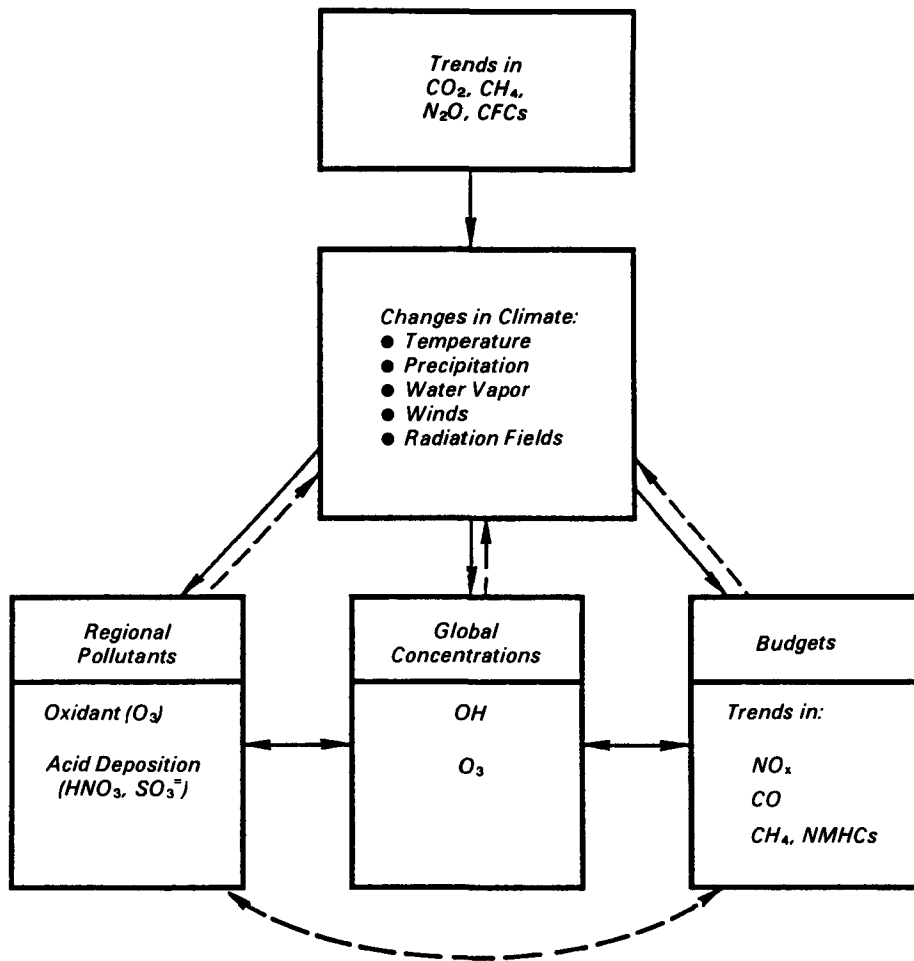


Figure 2. Processes that interconnect climate, global chemistry, and regional chemistry.

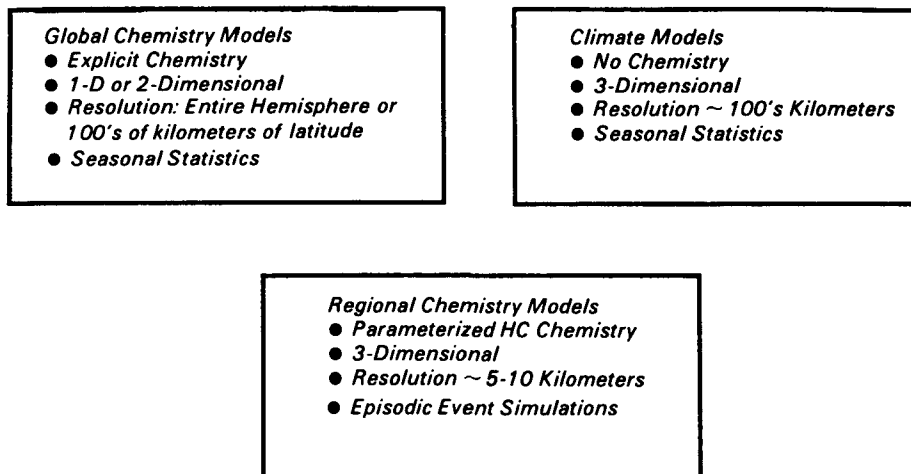


Figure 3. Characteristics of current models.

Climate change is typically studied with general circulation models. These predict precipitation patterns, wind patterns, global cloudiness, and temperature change statistics with a resolution of about several hundred kilometers. Because many important processes take place on smaller scales, these must be parameterized in the models, leading to inconsistent results on the scales important to regional chemistry.

Regional and urban chemistry and deposition models need meteorological and climate change information on much smaller scales. Typically, an urban oxidant model would occupy much less than one grid square of a general circulation model. Regional models require a detailed description of the meteorology appropriate to at most several GCM grid points. A challenge for the future is to design a means for bridging across these spatial scales (assuming the GCM predictions for climate change on a regional basis become more robust (Grotch, 1988)). Some initial work in this direction has begun (Giorgi, 1988) but these initial efforts will require significant ongoing support to understand the level of confidence that might be placed in their predictions. A further challenge is to try to bridge across the evident differences in time scales. GCM calculations attempt to predict statistics of the predicted climate averaged over a reasonably long period - i.e., one week or more. Regional and urban models have only been applied to particular episodes - with at most a several day time period. A method for interpreting the results of the episodic predictions, within the context of the climate change statistics must be devised.

The connections between global chemistry models and regional and urban models are even more tenuous. Three-dimensional chemistry models capable of treating the horizontally inhomogeneous gas concentrations evident in the global troposphere are only now beginning to be developed. Sub-grid scale parameterizations that currently plague the GCM simulations will likely have impacts for the chemistry models as well. Further, sub-grid scale parameterizations of chemistry are likely to be important in these models because chemical processes that alter concentration distributions on urban and regional scales would need to be treated in some realistic fashion. A case in point is the transformation of nitrogen oxides within the urban domain to less chemically

active organic nitrate forms (Atherton and Penner, 1988). It will likely be important to develop schemes to make the chemistry on these larger scales consistent with the chemical transformations that we know take place on smaller scales.

Finally, regardless of our ability (or lack thereof) to physically link these modeling systems, our basic knowledge of the global tropospheric chemical system needs refinement and tuning. Our knowledge of biogeochemical cycles is crude at best. Therefore, our ability to confidently predict trace gas trends is crude, and certainly our ability to predict the impact of climate change on biologically emitted source gases is nearly non-existent. Hence, substantial effort is called for to truly understand the interactions of our planet's chemistry and climate systems.

Conclusions and Research Needs

Some major findings of the analyses reviewed or developed in the full report are:

1. There is clear evidence that atmospheric emissions and concentrations of radiatively and chemically important trace gases, such as CO₂, CH₄, N₂O, CF₂Cl₂, CFC₃, and CO are increasing, and have been increasing for a long time. These increases derive largely from human related activities. Current analyses suggest that it is improbable that present trends towards increasing concentrations will be arrested or reversed in the near future. Predictions of future scenarios for their growth are limited by uncertainties in trace gas budgets and in forecasting economic growth, energy use and other factors.
2. The direct effects from the radiative forcing from these gases on climate are not in question. However, there are many uncertainties associated with the climate feedback processes that will determine the eventual change in temperature and other climatic variables. Climate models indicate that global surface temperatures for a doubling of CO₂, the radiative equivalence of which could occur by mid-21st century, is in the range of 1.5 to 4.5K, with general circulation models giving results in the upper end of this range.
3. General circulation models are in general agreement regarding the

effects of climate change on a global basis, but are in substantial disagreement on the effects over specific regions. Representations of clouds, the planetary boundary layer and surface processes all contribute to the uncertainties in determining the derived climate change. Currently, the results from GCMs should not be regarded as reliable indicators of regional effects from climate change.

4. The effects of climate change on urban and regional scale chemistry could be quite significant but very little information currently exists on the sensitivity of air quality models to climatic parameters. The few studies available suggest that oxidant formation may be sensitive to changes in temperature, in stratospheric ozone in cloud cover, in boundary layer depth, in background concentrations and in induced emissions responses. No information exists on whether the frequency of stagnation episodes would be affected by climate change.
5. Likewise, little is known about how acid deposition would be affected by climate change. Types of climate change that could affect the conversion rate of SO₂ to sulfate and the acid deposition include changes in temperature, stratospheric ozone background concentrations, circulation patterns, frequency and types of clouds formed, and precipitation patterns.
6. The interactions we discussed between climate change and global tropospheric chemistry primarily centered around perturbations to the distributions of ozone and the hydroxyl radical. Changes in ozone, driven by increasing concentrations of CO and NO_x for example, can have a direct impact on climate. At the same time climate change can influence ozone concentrations. Hydroxyl radical is the primary chemical scavenger of such radiatively and chemically important gases as CH₄, NMHC, and CO therefore, changes in OH concentrations, whether due to direct emissions of CH₄ or CO, or due to climate induced changes in temperature of H₂O, can have a significant impact on the lifetimes and transport of radiatively active gases.
7. Studies of global tropospheric chemistry are currently limited due to unavailability of three-dimensional global scale models that can adequately

quately account for the spatial variations in trace gas emissions and photochemistry.

8. Urban and regional emissions, particularly of NO_x and NMHC, may affect global scale tropospheric chemistry and thus affect climate. However, the chemical forms of these species by the time they reach the global scale are not well known, nor represented adequately in current global models.
9. In general, the current modeling tools available, both in terms of climate models and air quality models, are insufficient to delineate meaningful diagnostic or prognostic analyses of all of the changes in climate parameters of interest.

The findings from this study lead naturally to the development of a list of important research needs. Some have been alluded to above. These are more fully delineated in Chapter 6 of the full report.

References

- Atherton, C. S. and J. E. Penner, "The transformation of nitrogen oxides in the polluted troposphere," *Tellus*, in press 1988.
- Barnola, J. M., D. Raynaud, Y. S. Korotkevich, and C. Lorius, "Vostok ice core provides 160,000-year record of atmospheric CO_2 ," *Nature*, 329, 408-414, 1987.
- Fabian, P. and P. G. Pruchniewicz, "Meridional distribution of ozone in the troposphere and its seasonal variations," *J. Geophys. Res.*, 82, 2063-2073, 1977.
- Galloway, J. N., D. M. Whelpdale, and G. T. Wolff, "The flux of S and N eastward from North America," *Atmos. Environ.*, 18, 2595-2607, 1984.
- Genthon, C., J. M. Barnola, D. Raynaud, C. Lorius, J. Jouzel, N. I. Barkov, Y. S. Korotkevich, and V. M. Kotlyakov, "Vostok ice core: climatic response to CO_2 and orbital forcing changes over the last climatic cycle," *Nature*, 329, 414-418, 1987.
- Gery, M. W., R. D. Edmond, and G. Z. Whitten, "Tropospheric ultraviolet radiation assessment of existing data and effect of ozone formation," SYSAPP-87-191. 1987.
- Giogi, F., private communication, 1988.
- Grotch, S. L., "Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data," U.S. Department of Energy, Carbon Dioxide Research Division, DOE/NBB-0084, 1988.
- Hales, J., paper presented at LLNL-EPA Workshop on Impacts of Climate Change, Chapel Hill, North Carolina, February, 1988 and Lawrence Livermore National Laboratory UCID-xxxx, 1988.
- Isaksen, I. S. A., and O. Hov, "Calculation of trends in the tropospheric concentration of O_3 , OH, CO, CH_4 and NO_x ," *Tellus*, 39B, 271-285, 1987.
- Levy, H., II, J. D. Mahlman, W. J. Moxim, and S. C. Liu, "Tropospheric ozone: The role of transport," *J. Geophys. Res.*, 90, 3753-3772, 1985.
- Liu, S. C. and M. Trainer, "Tropospheric ozone response to column ozone change," *J. Atmos. Chem.*, 1987.
- NRC, Global Tropospheric Chemistry: A Plan for Action, U.S. National Research Council, National Academy Press, Washington, DC, 1984.
- Ramanathan, V., L. Callis, R. Cess, J. Hansen, I. Isaksen, W. Kuhn, A. Lacis, F. Luther, J. Mahlman, R. Reck, and M. Schlesinger, "Climate-chemical interactions and effects of changing atmospheric trace gases," *Rev. Geophys.*, 25, 1441-1482, 1987.
- Thompson, A. M., R. W. Stewart, M. A. Owens, J. A. Herwehe, "Sensitivity of tropospheric oxidants to global chemical and climate change," submitted to *Atmos. Environ.*, 1988.
- Trainer, M. E., Y. Hsie, S. A. McKeen, R. Tallamraju, D. D. Parrish, F. C. Fehsenfeld, and S. C. Liu, "Impact of natural hydrocarbons on hydroxyl and peroxy radicals at a remote site," *K. Geophys. Res.*, 92, 11879-11894, 1987.
- Walcek, C. and J. Chang, paper presented at LLNL-EPA Workshop on Impacts of Climate Change, Chapel Hill, North Carolina, February, 1988 and Lawrence Livermore National Laboratory, UCID-xxxx, 1988.
- Wuebbles, D. J. and J. Edmonds, "A primer on greenhouse gases," U.S. Department of Energy, Carbon Dioxide Research Division, DOE/NBB-0083, 1988.

J. E. Penner, P. S. Connell, D. J. Wuebbles, and C. C. Covey are with
Livermore National Laboratory, Livermore, CA 94550.

J. Bufalini is the EPA Project Officer (see below).

The complete report, entitled, "Climate Change and Its Interactions with Air
Chemistry: Perspectives and Research Needs," (Order No. PB 89-126 601/AS;
Cost: \$15.95, subject to change) will be available only from:

National Technical Information Service

5285 Port Royal Road

Springfield, VA 22161

Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Atmospheric Research and Exposure Assessment Laboratory

U.S. Environmental Protection Agency

Research Triangle Park, NC 27711

OHIO
METER
6207100

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Official Business
Penalty for Private Use \$300

EPA/600/S3-88/046

0000329 PS

U S ENVIR PROTECTION AGENCY
REGION 5 LIBRARY
230 S DEARBORN STREET
CHICAGO IL 60604