Science, engineering, and technology in the policy process for natural systems

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Abstract

Natural systems and society share a symbiotic relationship with each affecting the health and welfare of the other. More importantly, society's impacts on natural systems can lead to negative side effects on society such as increased respiratory illness from air pollution, contaminated drinking water from industrial runoff, and increased skin cancer risk from stratospheric ozone depletion. Mitigating the risks of these side effects often requires the development and implementation of public policy. But policy makers may have a limited understanding of complex natural and societal systems and their interactions. Scientists and engineers can help policy makers by offering their knowledge of these systems as well as technological solutions to mitigate the impacts of societal behavior. However, the expertise of scientists and engineers may not be fully utilized by policy makers for many reasons including scientists and engineers inability to provide the appropriate knowledge, scientists and engineers inability to effectively communicate with policy makers, or policy makers inability to incorporate scientific and engineering knowledge into policy development. The current work develops improved understanding of the interaction of scientists, engineers, and policy makers in the policy process for natural systems. This understanding is developed by constructing, testing, and analyzing a system dynamics model of stratospheric ozone depletion.

Keywords: public policy, technology, stratospheric ozone depletion, statistical screening, system dynamics

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Introduction

Societies and natural systems share a symbiotic relationship in which the well being of one can be impacted by the behavior or conditions of the other. Societal systems include communities, governments, industry, and agriculture. Societies impact natural systems with their behavior, often degrading the condition and robustness of the natural system. For example, the release of ozone depleting substances (ODS) during the 20th century thinned the stratospheric ozone layer. In large, complex societies, public policy makers play an important role in the relationship between social conditions and social behaviors by developing public policies. The development of public policy in response to social conditions caused by natural systems involves synthesizing a great deal of information about a natural system and its impact on society. As the size and sophistication of society increases, the interaction between societal and natural systems grows more complex. This can lead to the development of inefficient, ineffective, or potentially harmful public policies. Expert domain knowledge offers policy makers a better understanding of the interaction of societal and natural systems. As used here, domain knowledge is the collective knowledge of society concerning a natural system, a societal system, or the interaction between a natural and societal system. Domain knowledge includes both scientific knowledge about natural systems (e.g. atmospheric science) and engineering knowledge about technologies that can be used to manipulate a system (e.g. CFC alternatives). Developing expert domain knowledge can be used to develop and improve public policies.

An example of the interaction of natural and societal systems in which domain expertise was used to develop and implement public policy is stratospheric ozone depletion. In the 1970's, scientists studying the stratospheric ozone layer discovered that human behavior could impact the ozone layer (Molina and Rowland 1974). Scientists found that man-made substances, most notably chlorofluorocarbons (CFCs), could deplete stratospheric ozone. A depleted stratospheric ozone layer would allow more ultra-violet (UV) radiation to reach the Earth's surface. Medical science had long understood that increased exposure to UV radiation increases skin cancer risks (NAS 1975; Morrisette 1989; Andersen and Sarma 2002; Parson 2003; Dimitrov 2006; Fahey 2006). As scientists and medical experts began to publicize the risks associated with stratospheric ozone depletion the general public and policy makers (first in the United States and then throughout other parts of the world) increasingly accepted the scientific evidence and looked for solutions to the problem. Beginning in the late 1970s the United States began to implement policies that limited the production and use of CFC's in non-essential applications (e.g. aerosol cans) (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). Eventually a global effort was undertaken to drastically reduce all uses of CFC's and other ozone depleting substances (ODS), culminating in the 1987 Montreal Protocol which established production and use limits on ozone depleting emissions for over 190 nations (Fahey 2006). A key element in the ability of nations participating in the Montreal Protocol to reduce stratospheric ozone depleting emissions was the development of ODS replacement technologies. CFC producers in the 1970s began to develop substitute products that allowed production of ODSs to be phased out (Parson 2003).

Stratospheric ozone depletion is an example of domain experts using their understanding of the natural system not only to alert policy makers to a problem (stratospheric ozone depletion) but also to develop potential solutions to the problem (ODS replacement technologies). However, domain expertise has not always been fully utilized in the development of public policy in relation to natural systems. Examples of the ineffective or underutilization of domain expertise in natural system public policy are numerous. Lead was known to cause brain damage as early as 1923 but regulations for its removal from everyday life in the U.S. were not implemented until the 1970's (Bocking 2004). Siting a low level nuclear waste facility in the U.S. is seemingly impossible even with the support of domain experts for the peaceful use of nuclear material and assurances of the facility's safety (Weingart 2001). Failure of domain experts to communicate the impacts of societal behavior on natural systems to decision makers limits societal welfare and may waste a portion of the major investments in science and technology (Pielke 2007).

Understanding the interactions among natural systems, societies, and expert knowledge is critical for effective policy development. However, developing this understanding is difficult, largely due to the dynamic behaviors inherent in these complex systems. The first step to improved understanding of these coupled systems is to explicitly identify feedback within the natural-societal system interaction. To identify and better understand this feedback, the current work will answer the question ***how can domain experts most effectively influence public policy for natural systems?*** The first step to improved understanding of these closed-loop structures is to explicitly identify feedback within the natural/societal system interaction. We next develop a conceptual feedback model of the interaction of natural and societal systems using the stratospheric ozone depletion case. A simulation model of stratospheric ozone depletion is formulated to test the conceptual model. The model is analyzed to determine the drivers and constraints on system feedback structures in the stratospheric ozone case. The model is then used to test system behavior under different scenarios. Finally, conclusions are drawn and directions for future research are identified.

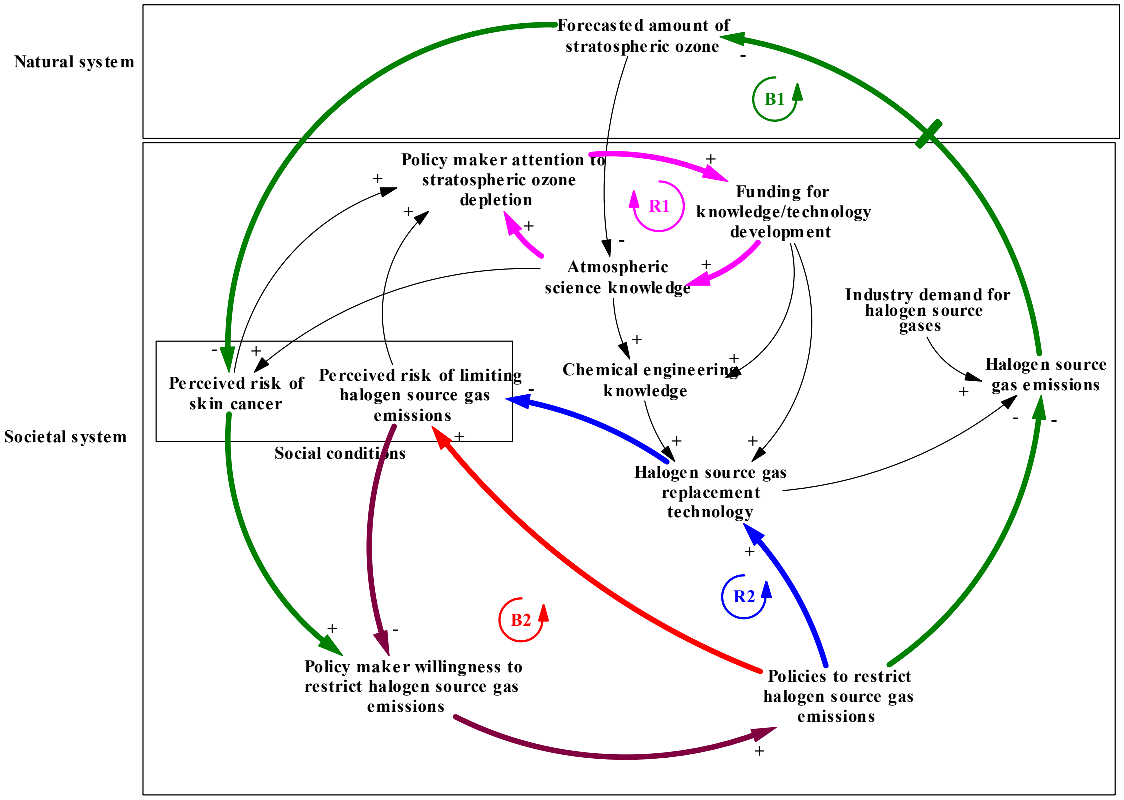
A Feedback Perspective of Stratospheric Ozone Depletion

Stratospheric ozone depletion offers an excellent case to study the dynamic interaction of natural and societal systems, science, technology and public policy. The policy response to stratospheric ozone depletion is widely viewed as a success with Morrisette (1989) noting that the United States' response was "both significant and remarkable. It had taken less than five years to move from the scientific discovery of a potentially serious environmental problem to the implementation of a major new regulation designed to solve that problem." To date, scientific evidence shows a reduction in the amount of ozone-depleting substances in the atmosphere as well as preliminary indications of stratospheric ozone recovery (UNEP 2007). Several researchers have noted the importance of scientific knowledge (Andersen et al. 2000; Andersen and Sarma 2002;

Parson 2003; Dimitrov 2006; UNEP 2007) and the development of ODS replacement technology (Morrisette 1989; Andersen and Sarma 2002) in the policy process. From a modeling perspective, data on stratospheric ozone depletion is plentiful and readily available (e.g. UNEP 2005). As a provision of the Montreal Protocol, the United Nations Environmental Programme publishes a scientific assessment of stratospheric ozone depletion every four years that provides physical system data (e.g. UNEP 2007). From a policy perspective, stratospheric ozone depletion has been extensively used in policy research (e.g. Rowlands 1995; Buck 1998; Bocking 2004; Degarmo 2005; Dimitrov 2006) and several researchers have compiled a "history" of stratospheric ozone depletion (e.g. Andersen and Sarma 2002; Parson 2003). The availability and detail of this data provide a solid foundation upon which a formal simulation model (shown later) of the interaction of science, technology, public policy, based on the stratospheric ozone depletion case can be developed.

Figure 1 applies a generic conceptual model of the feedback structures underlying natural and societal system interaction to the stratospheric ozone depletion case. In 1928 the first commercial application of CFCs was developed (Andersen and Sarma 2002). CFC's were viewed as a replacement for more hazardous materials in commercial applications such as refrigeration. By the 1960's the use of CFC's and other ozone depleting substances had expanded and there was a large industry demand for these halogen source gases[5] (Parson 2003) ("industry demand for halogen source gases" in Figure 1). The industrial demand for halogen source gases led to the emission and accumulation of halogen source gases in the stratosphere ("halogen source gas emissions" in Figure 1). Over time this accumulation led to the depletion of the stratospheric ozone layer (Morrisette 1989; Andersen and Sarma 2002; Parson 2003; Farley 2006; UNEP 2007) ("forecasted amount of stratospheric ozone" in Figure 1). Once the depletion of stratospheric ozone was discovered in the 1970's the public became aware of the expected risks from stratospheric ozone depletion, most notably an increased risk of skin cancer (Morrisette 1989) ("perceived risk of skin cancer" in Figure 1). Because of these risks the public pressured policy makers to address the problem of stratospheric ozone depletion (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). This pressure increased the policy maker willingness to address stratospheric ozone depletion and eventually led to restrictions on the production of halogen source gases in "non-essential" applications (Morrisette 1989; Andersen and Sarma 2002; Parson 2003) ("policy maker willingness to restrict halogen source gas emissions" and "policies to restrict halogen source gas emissions" and associated causal links in Figure 1). These restrictions eventually caused a decrease in the rate of halogen source gas emissions (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). Limiting halogen source gas emissions is described by Loop B1 in Figure 1.

[5] The term "halogen source gas" is a term commonly used in the discussion of stratospheric ozone depletion. It refers to all ozone depleting substances that are emitted from commercial applications (Fahey 2006).



Partial Feedback Loop Legend:

B1 – Stratospheric ozone control loop
R1 – Knowledge generation loop
B2 – Risk of regulation loop
R2 – Replacement technology development loop

Figure 1: Stratospheric ozone depletion described using the dynamic hypothesis

Scientists had been studying stratospheric ozone since the mid 1800's (Andersen and Sarma 2002). However, when scientists began to notice a change in the amount of stratospheric ozone the pace of stratospheric ozone research increased, rapidly increasing the amount of scientific knowledge on the subject (Dimitrov 2006) ("atmospheric science knowledge" in Figure 1). This increase in scientific knowledge provided additional information to policy makers on the problem and the nature of this information (i.e. the severity of the problem) increased the attention of policy makers to the problem (Andersen and Sarma 2002; Parson 2003; Dimitrov 2006) ("policy maker attention to stratospheric ozone depletion" in Figure 1). The attention of policy makers to the problem led to additional funding for stratospheric ozone depletion research (Dimitrov 2006) ("funding for knowledge/technology development" in Figure 1). Additional knowledge creation is described by Loop R1 in Figure 1[6].

In 1978 public pressure on policy makers in the United States resulted in restrictions on "non-essential" aerosol propellants (Morrisette 1989; Rowlands 1995). This resulted in a decrease in the rate of halogen source gas emissions. But some scientists and policy makers argued that further restrictions on halogen source gas production and use were required to fully address the problem of stratospheric ozone depletion (Morrisette 1989; Andersen and Sarma 2002; Parson 2003). However, industry was concerned that a further increase in halogen source gas restrictions would harm the nation's economy (Rowlands 1995) ("perceived economic risk of limiting halogen source gas emissions" in Figure 1). These perceived economic risks reduced the willingness of policy makers to restrict halogen source gas emissions (Andersen and Sarma 2002; Parson 2003). Limiting the economic risks of halogen source gas emission restrictions is described by Loop B2 in Figure 1.

One means to overcome the economic risk of limiting halogen source gas emissions was the development of replacement technology for halogen source gases. This technology was developed in response to policies to restrict halogen source gas emissions, engineering knowledge development, and funding (Andersen and Sarma 2002; Parson 2003; Dimitrov 2006) ("halogen source gas replacement technology" and associated causal links in Figure 1). Replacement technology reduced the expected economic risk of halogen source gas emission restrictions and reduced halogen source gas emissions (Morrisette 1989; Rowlands 1995). Developing replacement technology is partially described by Loop R2 in Figure 1.

The four feedback loops identified in Figure 1 describe an explanation for system behavior in the stratospheric ozone depletion case. Commercial use of halogen source gases eventually led to the depletion of the stratospheric ozone layer. The risk of increased skin cancer associated with stratospheric ozone depletion led to pressure on policy makers to restrict "non-essential" halogen source gas use (Loop B1). However, economic risks restricted the ability of policy makers to impose further restrictions (Loop B2). The strength of Loop B2 limited the strength of Loop B1. This policy resistance was partially overcome by the development of replacement technologies (Loop R2) whose development was enabled by the development of additional atmospheric science and chemical engineering knowledge (Loop R1). This weakened the strength of Loop B2

[6] It is important to note that this policy maker attention driven knowledge creation loop is not the only driver of knowledge and technology development rather it is a driver of knowledge and technology development. Fore example, the link between "forecasted amount of stratospheric ozone depletion" and "atmospheric science knowledge" in Figure 1 describes the increase in knowledge due to scientists' interest in understanding a change in the natural system. However, policy maker attention to the problem was an important element of driving the development of knowledge and technology after the initial discovery of stratospheric ozone depletion (Andresen and Sarma 2002; Dimitrov 2006). This is true in other cases such as increased funding in recent years for climate change, cancer, and AIDS research.

while increasing the strength of Loop B1. This feedback description of stratospheric ozone depletion is next tested using a formal system dynamics model.

A Formal Model of Stratospheric Ozone Depletion

Formalizing the conceptual feedback model of stratospheric ozone depletion (Figure 1) requires a model that captures the richness of elements from physical science, knowledge development, public risk perception, and public policy while maintaining a level of complexity that facilities understanding of the system. This challenge is described by Meadows and Robinson (1985/2007) who, in an evaluation of nine different models of different natural-societal system interactions, noted that "...all of these models are detail-rich where the forest is almost totally obscured by the trees. The modelers themselves cannot comprehend all the interactions that must have led to a certain result..." (p. 366). Claussen et al. (2002) offer a modeling philosophy to overcome this challenge. They note the use of models of intermediate complexity to fill the gap between conceptual models of a large system and detailed comprehensive models of sub-systems to improve understanding of climate systems. The model in the current work follows this intermediate modeling philosophy by making simplifying assumptions in the detail of each sub-system modeled while focusing on the interactions between sub-systems.

The simulation model used to investigate the dynamics of stratospheric ozone depletion is comprised of 5 sectors (Figure 2). The model structure within each sector is based on existing models or theories. The "atmospheric sector" is based on the physical relationships that govern the anthropogenic destruction of stratospheric ozone. The "society risk perception sector" is based on Kasperson et al's (2005) risk amplification framework. The knowledge development sector is based on Sterman's (1985) modeling of Kuhn's (1962/1970) description of the evolution of science. The "public policy sector" is based on Kingdon's (2003) agenda setting framework. The "ODS emission sector" is based on historical emission trends for various ODSs. Text near the links between sectors describes the flow of tangible and intangible information, conditions, and assets between sectors. The interaction between sectors is based on the dynamic hypothesis shown in Figure 1. The model (including equation descriptions) and calibration files are available from the author. A more detailed description of each model sector is available in Appendix A.

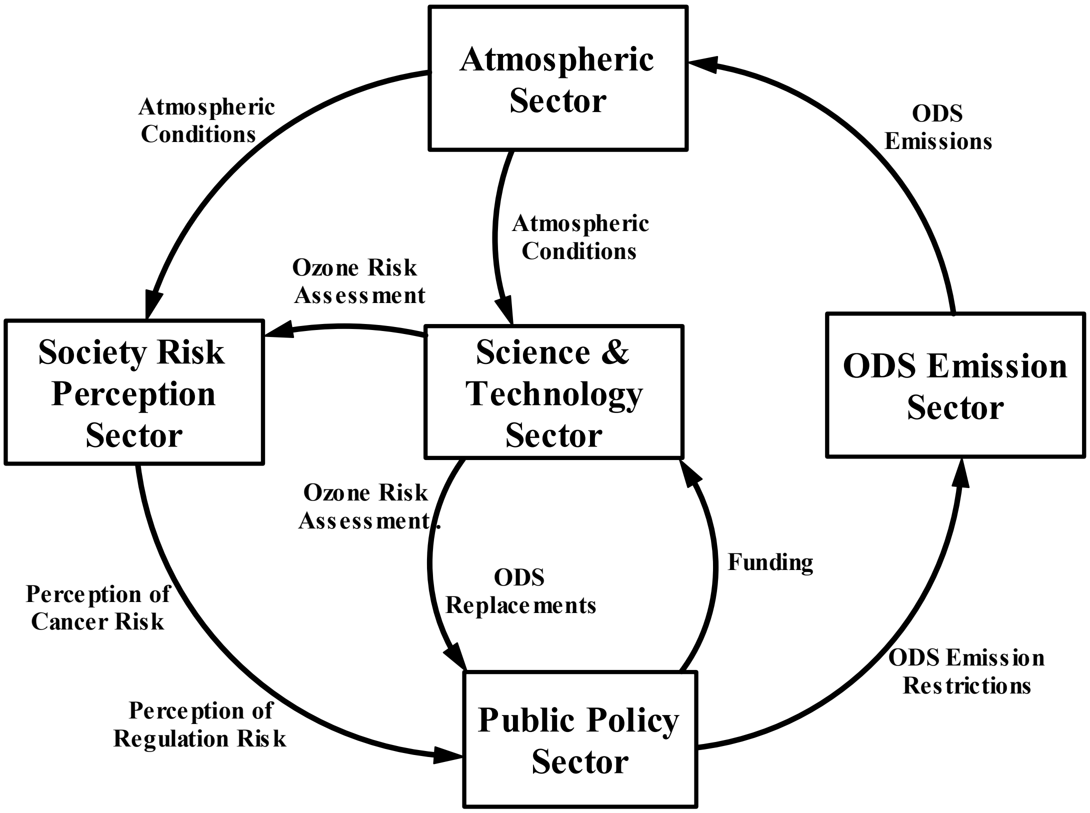


Figure 2: Sector diagram of stratospheric ozone depletion model

Model Testing

The model was tested using standard test methods for system dynamics models (Sterman 2000). Basing model sectors on established theory improves the model's structural similarity to processes within the real system. Model unit consistency tests further strengthen the model's representation of relationships within the real system. Extreme conditions tests were performed by setting model inputs, such as scientific funding or ODS ozone depletion potential, to zero or other extreme values and simulating system behavior. Model behavior remained reasonable.

To test the ability of the model to replicate real system behavior, the model was calibrated to the stratospheric ozone depletion case. When available, data from the real system (e.g. the total amount of global stratospheric ozone) were used to set model parameters. When data were not available reasonable values were assumed and the model's behavior was tested for sensitivity (described later). Simulated system behavior was compared to actual system behavior. Figure 3 compares the simulated percent change in total global stratospheric ozone to the scientifically measured percent change. The variance between the simulation line and measured data line in Figure 3 is due to the raw nature of the measured data and the use of simplifying assumptions in the model formulation. Measured ozone destruction data includes variations in stratospheric ozone caused by solar cycles, volcanic activity, and other sources of natural variation in stratospheric ozone levels. The model ignores these natural variations and focuses only on stratospheric ozone depletion due to anthropogenic sources[7]. Figure 4 compares the simulated emission of CFC-113 to actual emissions as well as the emission restrictions established by the Montreal Protocol and subsequent amendments. A total of 25 additional comparisons (not shown here for brevity) compared model behavior to emissions of other ODSs, the transport of ODS through the atmosphere, and the concentration of total stratospheric chlorine.

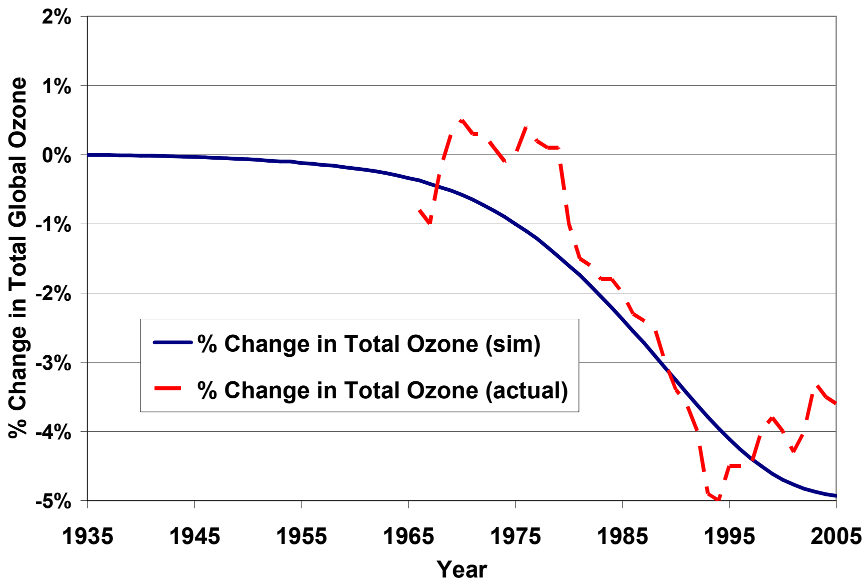


Figure 3: Percent change in total global stratospheric ozone

[7] This assumption is supported by Figure 3-1 in UNEP (2007) which quantifies various ozone destruction impact factors and their overall impact on stratospheric ozone destruction. This figure shows that the decline in stratospheric ozone is attributed to anthropogenic sources. In the model, stratospheric ozone destruction begins to slow and the ozone layer begins to recover after 2005. This is consistent with ozone recovery projections in Fahey (2006). This assumption is in-line with accepted system dynamics modeling practice as described by Forrester (1961) who notes, "system models should predict and reproduce the behavior character of a system, not specific events or particular, unique sections of actual system time history" (p. 128).

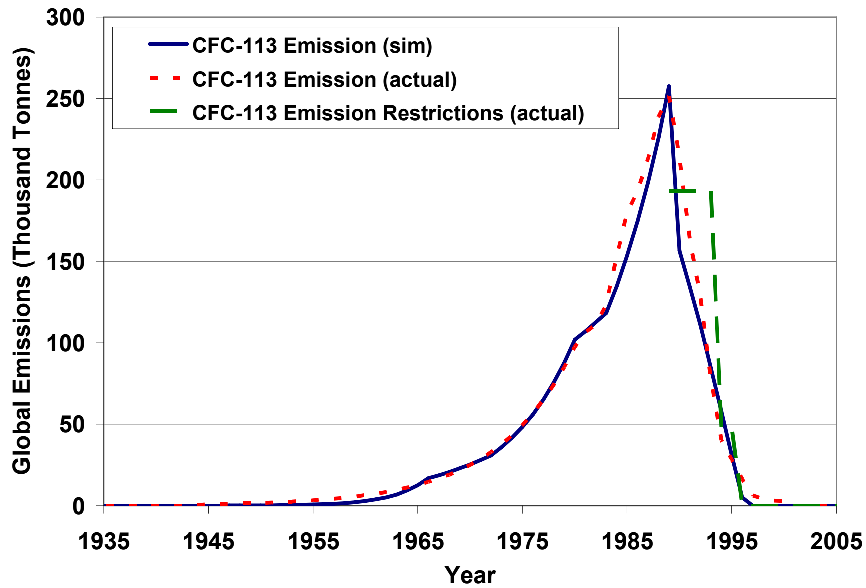


Figure 4: Global emissions of CFC-113 and emission limits established by the Montreal Protocol and subsequent amendments.

In addition to physical system data, model behavior was also compared to qualitative policy and knowledge development data. For example, model simulations show that atmospheric science knowledge begins to gradually increase in the 1950's and 1960's followed by a rapid increase in knowledge during the 1970's and 1980's. This is consistent with descriptions of the growth in scientific knowledge concerning stratospheric ozone (e.g. Dimitrov 2006). Model simulations also show that policy makers largely ignored stratospheric ozone depletion prior to the 1970's. However, simulations reveal that during the 1970's and 1980's policy makers paid increasing levels of attention to stratospheric ozone depletion. This is consistent with descriptions of the stratospheric ozone policy process (e.g. Andersen and Sarma 2002). Based on these tests the model was assessed useful for investigating the feedback dynamics of public policy, expert domain knowledge, and technology development in the interaction of natural and societal systems. Complete model testing files and results are available from the author.

Model Analysis

The model was analyzed to better understand how system structure drives system behavior using univariate sensitivity analysis and statistical screening (Ford and Flynn 2005; Taylor et al. 2007). Since the current work focuses on the influence of domain expertise on the public policy process, both analyses focus on system structures that describe the interaction between domain experts and policy makers in addressing stratospheric ozone depletion. Analysis of all exogenous model parameters is not included here for brevity.

Sensitivity analysis was performed by varying exogenous model parameters from their values in the calibrated ozone simulation (Figure 3). The maximum percent decrease in stratospheric ozone was selected as the performance measure for this analysis. The maximum percent decrease in stratospheric ozone reflects the greatest loss in stratospheric ozone realized over the course of a simulation. The exogenous parameters tested in the analysis, their ozone case calibrated value, their respective units, and a brief definition of the parameter are shown in Appendix B. Sensitivity results for selected parameters are shown in Figures 5 and 6. The vertical axis of Figures 5 and 6 displays the maximum percent decrease in stratospheric ozone (reported as a negative percentage). The horizontal axis of Figures 5 and 6 displays the percent change in parameter values from their calibrated case values. Sensitivity results for additional parameters are shown in Appendix C.

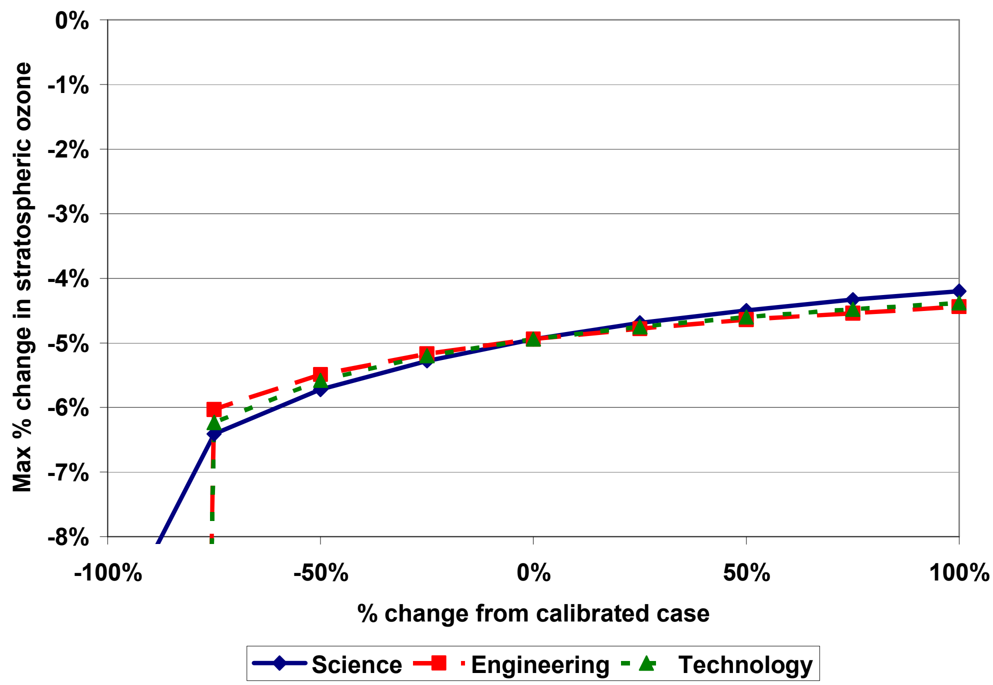


Figure 5: Sensitivity of stratospheric ozone to unit funding for science and technology

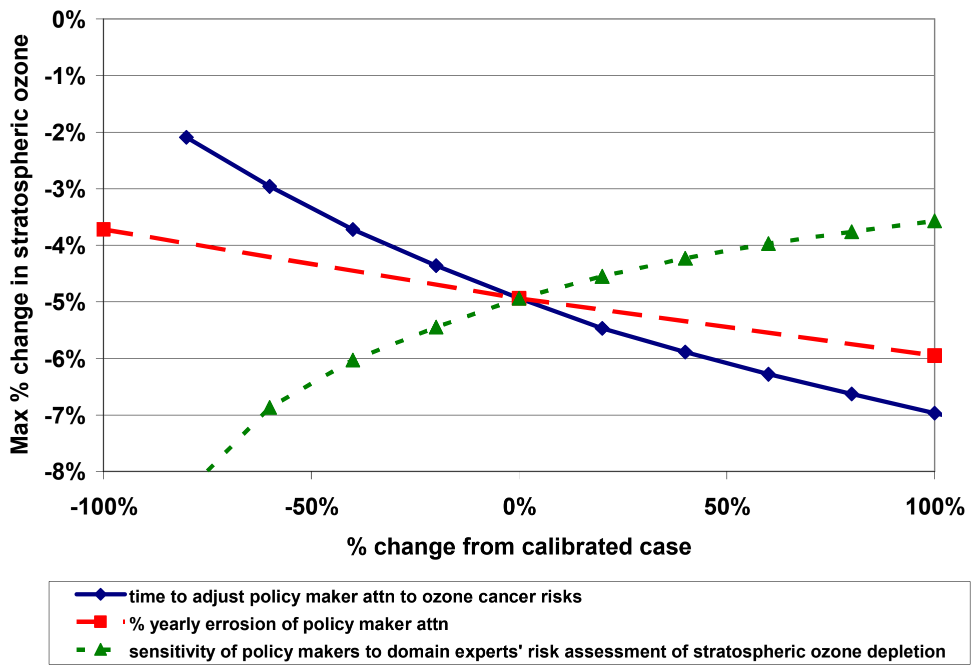


Figure 6: Sensitivity of stratospheric ozone to policy maker -domain expert interaction parameters

Figures 5 and 6 reveal several insights into the effects of the interaction of domain experts and policy makers on stratospheric ozone depletion. Figure 5 shows that unit funding for science, engineering, and technology development displays threshold values, below which the system behaves drastically different than the calibrated case. Similar results for other parameters that describe the development of science, engineering, and technology are shown in Appendix C. These threshold values indicate that there is a minimum knowledge development capability required to address stratospheric ozone depletion. However, above these threshold values, continuing to increase knowledge development parameters produces only marginal improvement in the amount of stratospheric ozone depleted (e.g. the flattening slopes displayed in Figures 5 as the unit funding is increased from the calibrated case conditions).

Figures 6 reveal that the amount of stratospheric ozone depletion is more sensitive to parameters that describe the interaction of policy makers and domain experts than to parameters that describe knowledge development. For example stratospheric ozone depletion is relatively sensitive to the time required to increase policy maker attention to ozone related cancer concerns. The amount of stratospheric ozone depletion is also relatively sensitive to the sensitivity of policy makers to domain experts’ risk assessment of stratospheric ozone depletion. This is due to the feedback mechanisms described in Figure 1. The parameters *time to adjust policy maker attention to ozone related cancer risks* and *sensitivity of policy maker attention to domain experts' stratospheric ozone depletion risk assessment* impact the gain around the knowledge creation loops (Loop

R1). By more rapidly increasing the strength of the knowledge creation loops, both policy makers and the general public more rapidly become aware of the health threat posed by stratospheric ozone depletion. This strengthens the stratospheric ozone control loop (Loop B1) which seeks to restrict ODS emissions. Knowledge creation also drives the development of ODS replacement technology which increases the strength of the replacement technology development loop (Loop R2) which weakens the strength of the risk of regulation loop (Loop B2). This feedback explanation of the behavior of the system is further supported by statistical screening analysis.

Statistical screening of system dynamics models analyzes exogenous parameter influence on system performance throughout a simulation (Ford and Flynn 2005; Taylor et al. 2007). Exogenous parameter influence on system performance is measured using correlation coefficients. The higher the correlation coefficient magnitude, the more influence the exogenous parameter (and the surrounding model structure) on the depletion of stratospheric ozone. For a more detailed description of statistical screening analysis see Taylor et al. (2007) and Ford and Flynn (2005). The evolution of correlation coefficients for high influence exogenous parameters that describe the interaction of domain experts and policy makers are shown in Figure 7.

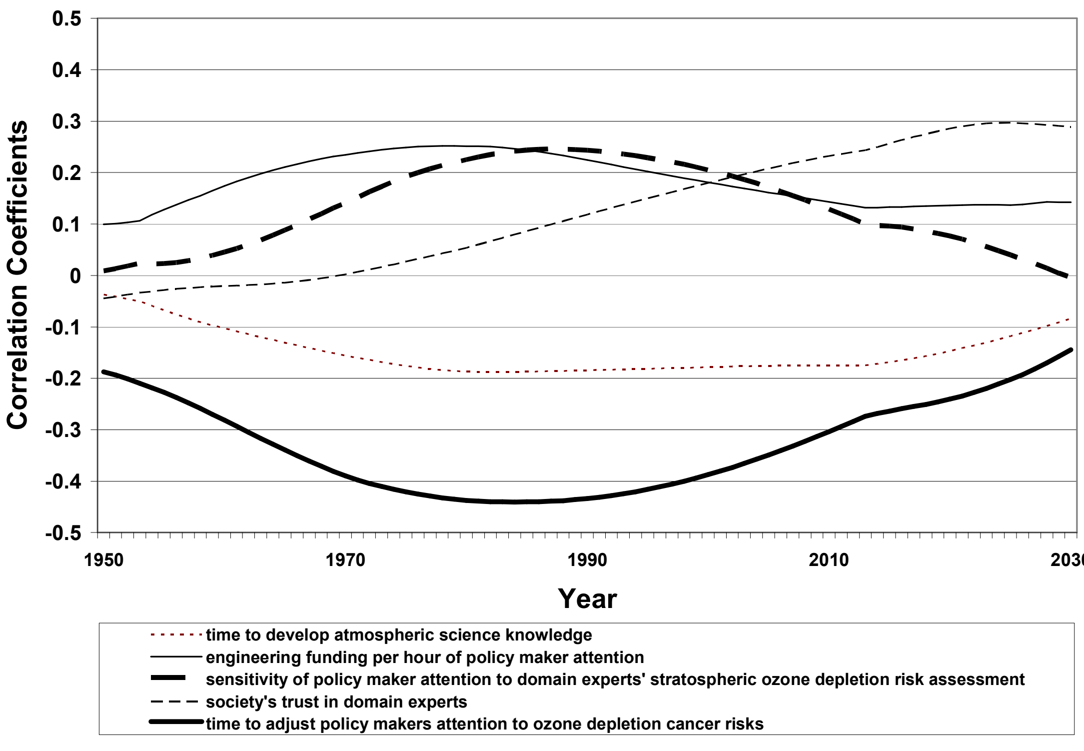


Figure 7: Correlation coefficients for selected exogenous model parameters

Figure 7 reveals that during the course of the simulation, of the parameters that describe the interaction of policy makers and domain experts, the *time to adjust policy maker* *attention to ozone depletion cancer risks* has the highest magnitude correlation coefficient during the course of the simulation. This suggests that the *time to adjust policy maker attention to ozone depletion cancer risks* and the surrounding model structure have a large influence on the ability of system to respond to stratospheric ozone depletion. This is consistent with the results of the sensitivity analysis discussed earlier.

Discussion

Model analysis results reveal an interesting insight into the interaction of domain experts and policy makers in addressing stratospheric ozone depletion. As previously discussed, based on the current work, the high leverage of the *time required to increase policy maker attention to ozone related cancer risks* and *policy maker sensitivity to domain experts' stratospheric ozone depletion risk assessment* indicate that the strength of the knowledge generation feedback loops (Loop R2) plays a critical role in implementing regulations to implement ODS emission restrictions. However, the results also reveal that the strength of the knowledge generation loops is more sensitive to policy maker attention to the problem of stratospheric ozone depletion rather than the application of additional resources to knowledge development.

This insight can be demonstrated by considering the stratospheric ozone depletion case. Stratospheric ozone depletion is widely considered a "success story" in the response of society to a natural system concern (Morrissett 1989; Dimitrov 2006). What changes in system parameters could have resulted in stratospheric ozone depletion being a less successful case? Consider two scenarios. The first scenario assumes that unit funding allocated to knowledge of stratospheric ozone development is reduced by 50% from the calibrated case. The second scenario assumes that policy maker reaction time to stratospheric ozone depletion is increased by 50% from the calibrated case (i.e. policy makers are slower to pay attention to stratospheric ozone depletion). These scenarios can be simulated using the stratospheric ozone depletion model. The percent change of total global stratospheric ozone for each of these scenarios and the calibrated stratospheric ozone depletion case are shown in Figure 8.

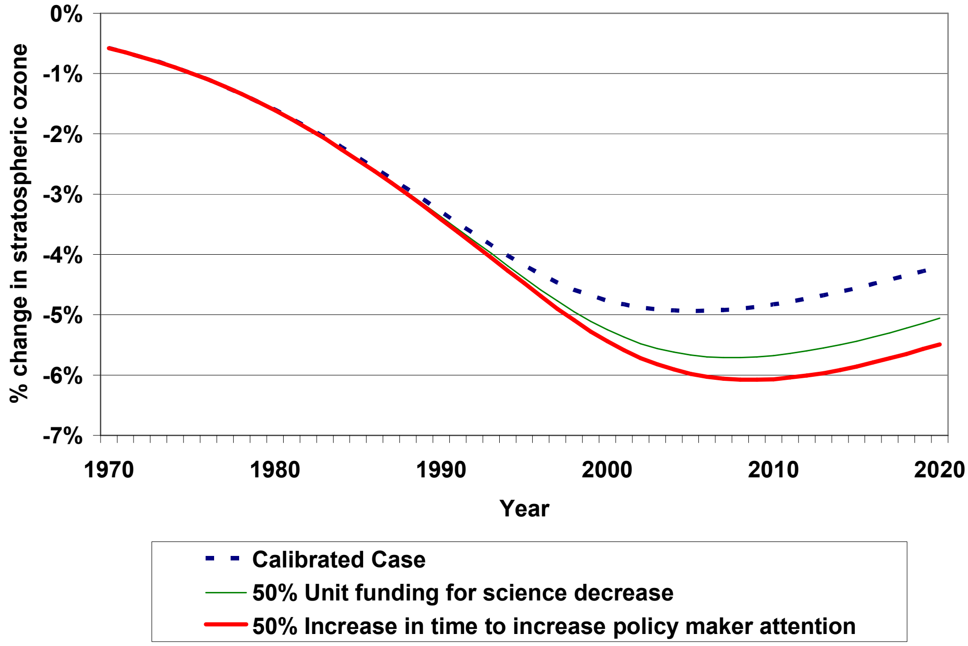


Figure 8: Stratospheric ozone depletion scenarios

Figure 8 demonstrates that a 50% increase in the time required to increase policy maker attention to stratospheric ozone depletion (resulting in a 23% change from the calibrated case) is more detrimental to addressing stratospheric ozone depletion (i.e. results in a larger depletion of stratospheric ozone) than a 50% reduction in science funding (resulting in a 16% change from the calibrated case). This is due to the difference in the gain of the two parameters investigated on the knowledge creation loops (Loop R1). The slower reaction of policy makers to stratospheric ozone depletion results in a slower increase in the strength of the knowledge creation loop relative to the science funding decrease scenario. This delays the development of ODS replacement technology, which delays the implementation of ODS emission restrictions which delays the reduction in ODS emissions in the atmosphere. This delay results in greater levels of stratospheric ozone depletion due to the increased levels of ODS in the stratosphere. From a feedback perspective (Figure 3) this delays the shift in dominance from the risk of regulation loop (Loop B2) to the stratospheric ozone control loop (Loop B1). This delay in feedback dominance shift increases the overall health risk of society from stratospheric ozone depletion.

Conclusions

The current work uses a system dynamics model to investigate the influence of domain experts in the public policy process for natural systems. A conceptual feedback model of natural-societal system interaction is used to develop a highly integrated formal model of stratospheric ozone depletion. Model analysis reveals that the system is most sensitive to delays in increases of policy maker attention to stratospheric ozone depletion and policy maker sensitivity to domain experts' stratospheric ozone depletion risk assessments.

The current work offers a few key implications for domain experts wanting to increase their influence in the public policy process for natural systems. Feedback mechanisms for knowledge development are more sensitive to policy maker attention to a problem or issue rather than a general increase in knowledge development funding. This result *does not* indicate that funding for knowledge development is not critical to address problems concerning natural societal system interaction. It does indicate that knowledge development is required, but is not sufficient alone, to resolve natural system problems. This is consistent with the findings of Pielke (2007) and Sterman (2008). In his investigation of public confusion regarding climate change Sterman (2008) concludes, "Of course, we need more research and technical innovation – money and genius are always in short supply. But there is no purely technical solution for climate change. For public policy to be grounded in the hard-won results of climate science, we must now turn our attention to the dynamics of social and political change" (p. 533).

This work also indicates that knowledge development (and ultimately domain expert influence in the policy process) is increased by increasing policy maker attention to a specific problem rather then a general push for increased knowledge development funding in general. By increasing policy maker attention to a specific problem, the knowledge generation loop is strengthened more rapidly, enabling both policy makers and domain experts to shift dominance between feedback loops that resist policy action (e.g. Loop B2 in the stratospheric ozone case) to feedback loops that address problems in interactions between society and natural systems (e.g. Loop B1 in the stratospheric ozone case). Policy maker attention is not the only driver of knowledge and technology development but this work (and others e.g. Dimitrov 2006; Kindgon 2003) demonstrate that it can be an important contributor.

Future research can address limitations of the current work. Model analysis revealed that the time to increase policy maker attention to a problem is a high leverage parameter in addressing problems involving the interaction of society and natural systems. An expanded model of natural-societal system interaction could "endogenize" this exogenous parameter to develop additional understanding of system performance drivers. The model could also be improved by incorporating more detail into the modeling of specific sectors (e.g. risk perception, public policy). The current model also assumes scientific consensus regarding a particular problem. This assumption allows for a simplified model structure but may not be an accurate reflection of reality for other problems involving societal-natural system interaction. Future work can investigate the impact of incomplete or "conflicting" domain expertise concerning the cause, extent, and solutions to a specific problem involving societal-natural system interaction.

Future work can also improve the generalizability of the conclusions by applying the conceptual model to other cases describing the interaction of natural and societal system interaction. The conceptual model has been applied to the U.S. civilian nuclear power case which revealed that societal concerns with the health risks associated with nuclear plant operation strengthened the radiation control loop (similar to Loop B1 in Figure 1). Model testing revealed that nuclear knowledge and technology development were unable to overcome the strength of Loop B1 due to society's high level of nuclear power risk perception. See Taylor (2009) for a more detailed description of the application of the conceptual model to the U.S. civilian nuclear power case.

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Appendix A: Description of formal simulation model

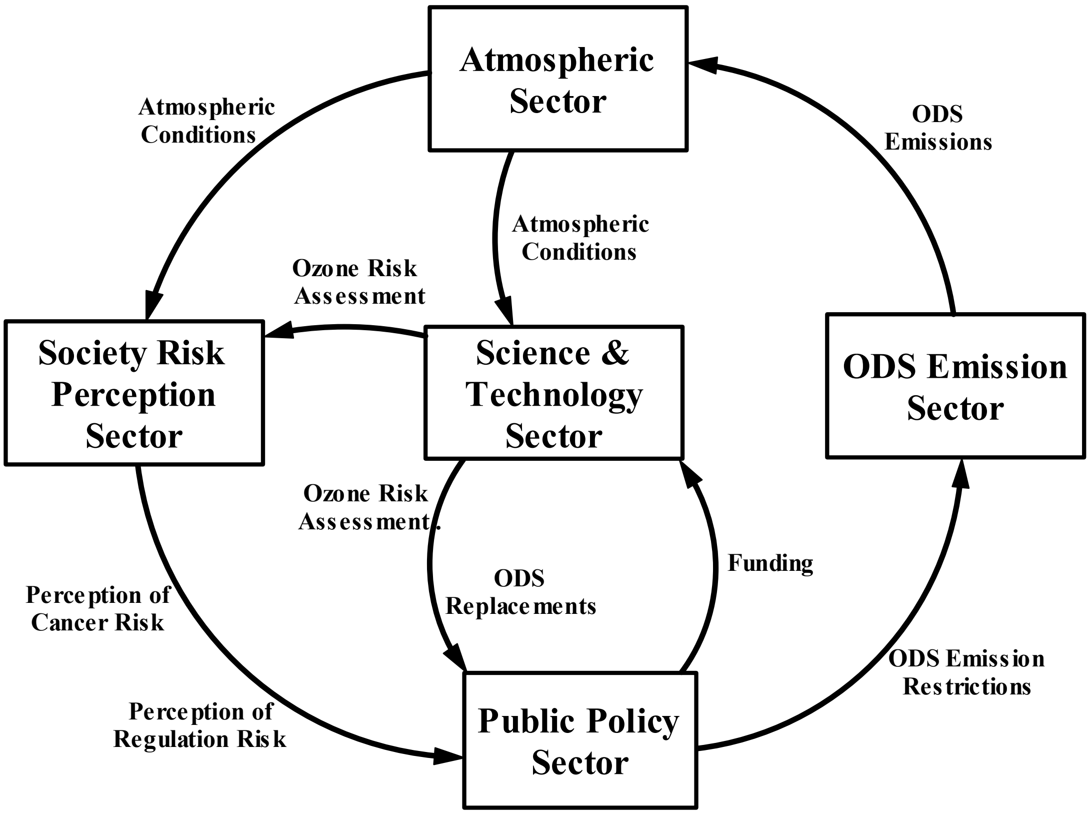

Figure A.1: Sector diagram of stratospheric ozone depletion model

Atmospheric Sector Description

The atmospheric sector is comprised of structures that describe stratospheric ozone and structures that describe the transmission of ODS from the troposphere to the stratosphere. Stratospheric ozone is described using a single stock with a single inflow and outflow (Figure A.2). The inflow to the stock represents the natural creation of stratospheric ozone and is assumed constant based on the average production of stratospheric ozone (Dessler 2000). The outflow from the stock describes the destruction of stratospheric ozone and is the sum of natural and anthropogenic ozone destruction. Natural ozone destruction is modeled using a first order linear negative feedback structure whose decay rate is calibrated so that in equilibrium ozone production is equal to ozone destruction. This formulation allows the natural ozone destruction rate to decrease as ozone is destroyed because there is less ozone available for natural destruction. This formulation is a simplifying assumption that is consistent with detailed understanding of the stratospheric ozone destruction process (Dressler 2000) including such processes as solar cycles, volcanic effects, quasi-biennial oscillation, and annual cycles (UNEP 2007). The anthropogenic ozone destruction rate is the product of the amount of reactive gases in the atmosphere (described next) and the amount of ozone that can be destroyed by a given quantity of reactive gas.

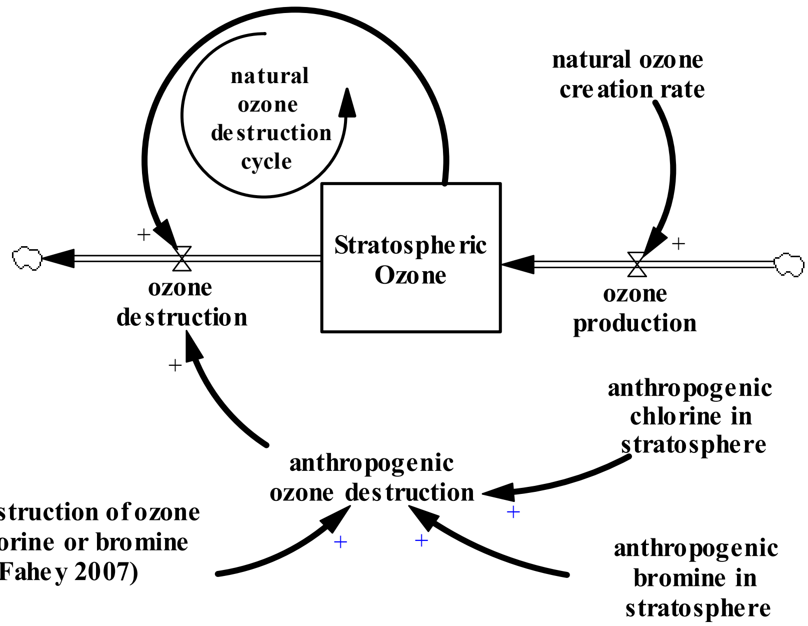

Figure A.2: Atmospheric model sector

ODS transport is modeled using a set of three stock systems (Figure A.3) to describe the movement of ODS from their emission source into the stratosphere. The specific ODS modeled are CFC-11, CFC-12, CFC-113, CCl_4, CH_3CCl_3, Halon-1301, Halon-1211, anthropogenic methyl bromide, and HCFC-22. The transport of ODS from the troposphere (near earth) to the stratosphere is modeled using a two stock aging chain with rate constants determined from stratospheric chemistry (UNEP 2007). Upon reaching the stratosphere, ODS are broken down into reactive chlorine or bromine (depending upon their chemical composition) atoms which flow into a stock of reactive chlorine or bromine. The sum quantity of chlorine and bromine stocks for all nine ODS determines how much ozone is destroyed due to anthropogenic sources. An exogenous parameter describes how many molecules of ozone can be destroyed by a single atom of chlorine or bromine. The value of this parameter is used to calibrate model behavior but the final value is within the accepted range described in the literature (Fahey et al. 2006).

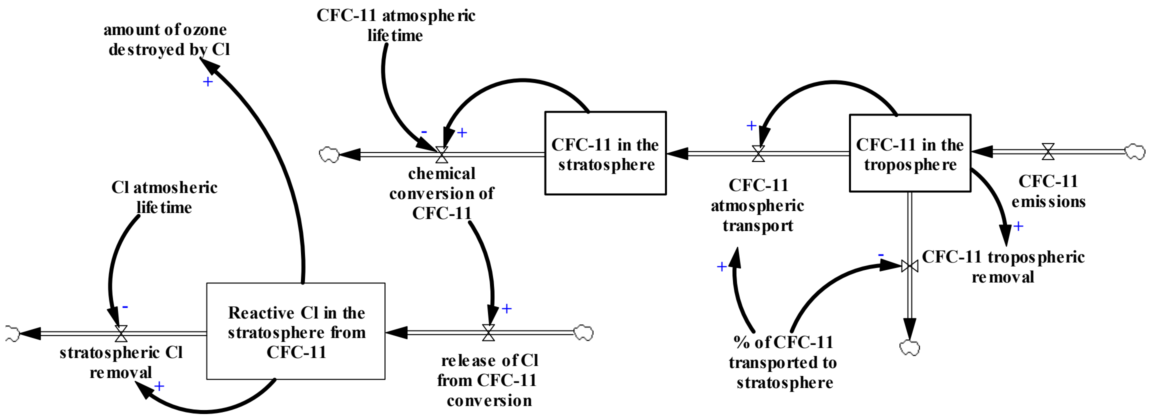

Figure A.3: Atmospheric transport model structure (CFC-11)[8]

ODS Emission Sector Description

The ODS emission sector describes the emission of ODS at the Earth's surface. As with the atmospheric sector there are parallel, similar model structures that describe the emission of the nine ODS explicitly modeled. These structures are similar in that all nine ODS are modeled using a single stock with a single inflow and outflow and all nine structures assume that annual ODS production is equal to ODS emission. This assumption is supported by examination of historical UN production and consumption data (UNEP 2005). These structures differ in that the unregulated production of six of the ODS (CFC-11, CFC-12, CFC-113, CCl_4, Halon-1301, and Halon-1211) are modeled using a first order exponential delay (Sterman 2000) while the three remaining ODS (CH_3CCl_3, anthropogenic methyl bromide, and HCFC-22) are modeled using a constant inflow. This modeling decision is based on an examination of historical data in which six of the ODS displayed exponential growth while the three remaining ODS displayed linear growth during the unregulated period. The annual increase in ODS production is described using an exogenous parameter based on historical production and emission data.

[8] The transport of an ODS from the troposphere to the stratosphere is modeled based on the natural destruction of ODS in the troposphere and the convection of ODS to the stratosphere. This is described through the "% of ODS transported to the stratosphere" (shown in Figure A.3 and based on atmospheric column concentration) and the "average time required to transport ODS to the stratosphere" (not shown in Figure A.3 and based on a chlorine concentration lag of 3-5 years as described in Dressler 2000). The model formulation assumes that the time element of this formulation is equal for stratospheric transport and tropospheric destruction. This assumption was necessary due to the inability to locate accurate time delay data for the ODS modeled. This assumption is only valid when the time delays for atmospheric transport and tropospheric destruction are equal. The future availability of detailed transport time delay data would allow for an improved model formulation.

The regulation of ODS substances mimics the dynamics of regulations implemented through the Montreal Protocol and subsequent amendments. ODS restrictions in the Montreal Protocol where phased in depending upon the specific substance, its phase out schedule, and the baseline value used to determine the phase out. A baseline value is set as the benchmark for future emission reductions which are implemented as step percent decreases in this baseline value at future dates. For example, in developed countries, the baseline value used to determine reductions in CFCs emissions was based on the 1989 production of CFCs. In 1989 the permitted production of all CFCs was frozen at the current annual production rate. In 1994 this permitted rate was reduced by 75% with a 100% reduction (i.e. complete production phase out) in 1996.

In the model, when policy makers decide to regulate a specific ODS emission (described later) the model freezes the current annual production rate of the ODS. The rate at which ODS emissions are reduced is determined by a continuous emission reduction percentage from the frozen rate. This continuous emission reduction percentage is determined by the availability of replacement technology (described later) and the willingness of policy makers to regulate (described later). As the policy maker willingness to regulate and the availability of replacement technology increase, the percentage of annual ODS emission baseline emissions is reduced at a faster rate (and vice versa). This formulation captures the underlying principles of the regulation of ODS through the Montreal Protocol while still maintaining an endogenous regulatory decision and implementation process.

Public Policy Model Sector Description

The public policy model sector is based on Kingdon's (2003) agenda setting framework. The framework views agenda setting in the U.S. as the joining of three concurrent elements or streams that describe problems, solutions, and the political environment. The problem stream contains all issues that certain people or groups define as a problem. The solutions stream contains potential solutions (in the form of policies, technology, or ideas) to problems. The political stream describes the current political climate (e.g. regulation vs. de-regulation, strength of lobbyists, liberal vs. conservative, etc.). An issue is placed on the agenda (and eventually acted upon) when these three streams "join." For example, in the case of stratospheric ozone depletion the problem stream consisted of the depleted ozone (Rowlands 1995; UNEP 2007), the solution stream consisted of emission restrictions enabled by replacement technology (Andersen and Sarma 2002; Parson 2003; Dimitrov 2006), and the political stream consisted of a political willingness to act (Morrisette 1989). These streams were joined and the resulting agenda item resulted in the Montreal Protocol and the subsequent amendments.

The problem stream is modeled using a two stock structure that represents the attention of policy makers to the problem of stratospheric ozone depletion (Figure A.4). Kingdon (2003) notes that policy makers' view of problem severity is directly proportional to the amount of attention given to a problem. One stock represents policy makers' attention to skin cancer risks posed by stratospheric ozone depletion. This stock is increased by both the public's concern of increased skin cancer risks and scientists assessment of ozone risks and decreased by the "natural" erosion of policy maker attention to the problem. The second stock represents policy makers' attention to the economic risks of regulation ODS in response to stratospheric ozone depletion. This stock is increased through the increase in policy maker attention to skin cancer risks from stratospheric ozone depletion, the sensitivity of policy makers to economic risks, and the availability of replacement technology and decreased through the "natural" erosion of policy maker attention to the problem. The fraction of attention paid to the cancer risks associated with stratospheric ozone depletion relative to the attention paid to the economic risks associated with regulation ODS emissions determines the rate at which ODS emissions will be reduced.

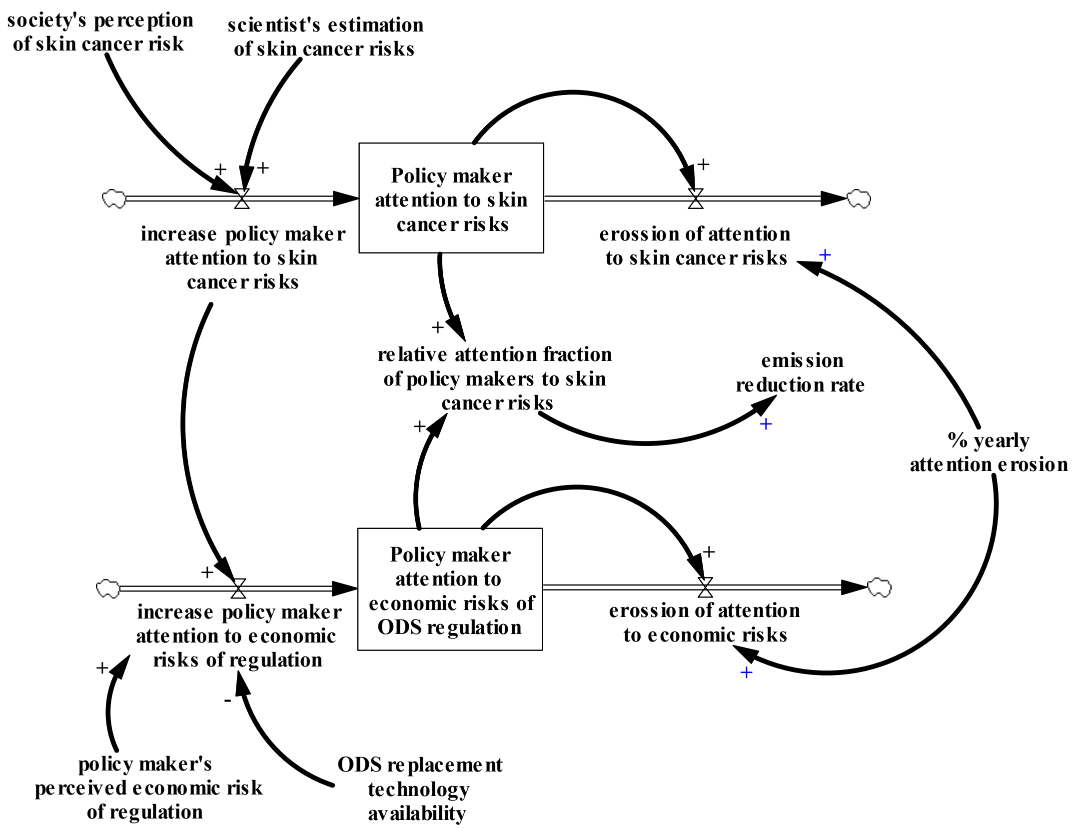

Figure A.4: Problem stream model structure based on Kingdon (2003)

While the problem stream determines the *rate* at which ODS emissions are reduced, the political stream determines *if* ODS emissions will be reduced. The political stream is modeled using a first-order negative feedback with explicit goal system. The stock in this system describes the political willingness to regulate ODS. Political willingness describes a policy maker's perception of the political risks (e.g. electability, ability to campaign, affect on bargaining power) associated with regulating (or not regulating) ODS emissions. A value of zero indicates no political willingness to regulate ODS emissions and a value greater then zero indicates an increased willingness to regulate emissions. The goal for this system is determined by the availability and political sensitivity to replacement technology, society's perceived cancer risk and the political sensitivity to this risk, and the strength of influence of interest groups on the political process. Policy makers regulate specific ODS when their political willingness exceeds the minimum political willingness to regulate a specific ODS.

The solutions stream describes the availability of ODS replacement technologies to minimize the economic risks of ODS emission restrictions. ODS replacement technologies are developed in the science and technology sector (described later). As described above, these technologies impact the willingness of policy makers to restrict ODS emissions and the rate at which ODS emissions are reduced.

Science and Technology Model Sector Description

The science and technology sector is based on Sterman's (1985) model of Kuhn's (1962/1970) theory of scientific revolutions (Figure A.5). This theory argues that knowledge is created by solving "puzzles" related to a particular phenomenon. Sterman (1985) models this process as an application of resources (science practitioners) to puzzle solving. The current work uses a similar structure but uses financial resources as opposed to practitioners to drive the creation of knowledge and technology creation. The current work does not include the concept of paradigm shift in scientific knowledge from Kuhn's theory. This assumption was made in order to simplify the model structure. This assumption is supported by the relatively short simulation time (< 100 years) and by the notion that, despite initial doubts, knowledge of stratospheric ozone depletion and replacement technology was considered sound during the period under investigation, i.e. there was no paradigm shift in the scientific domain during the simulation period. As policy maker attention to stratospheric ozone depletion increases, more funding (both public and private) is applied to creating stratospheric ozone depletion knowledge and ODS replacement technologies.

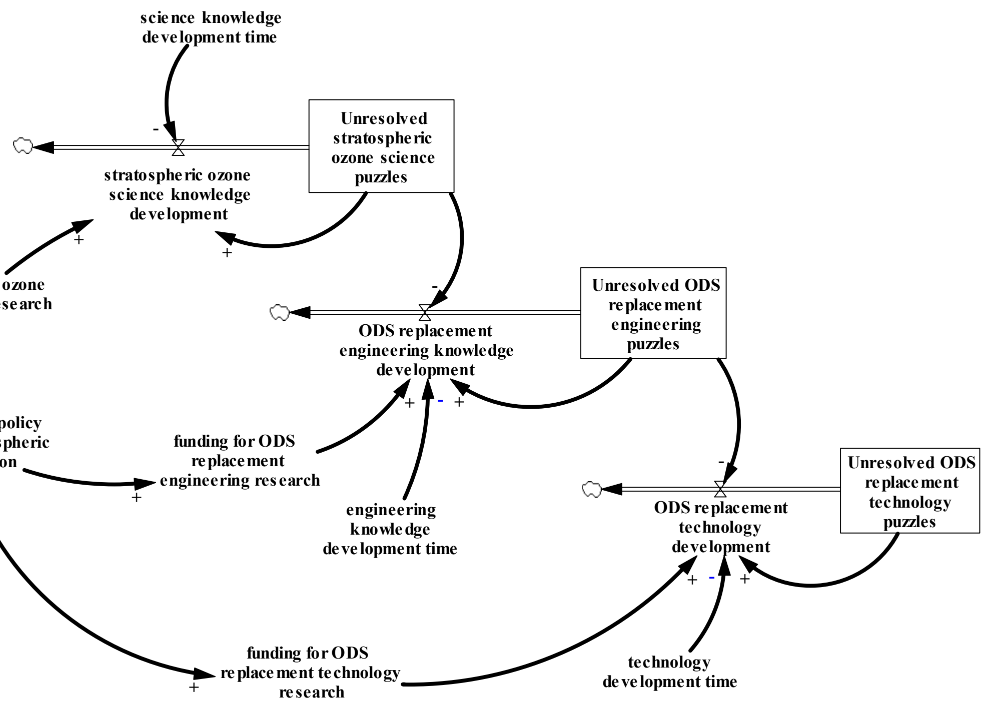

Figure A.5: Science, engineering, and technology development sector (based on Sterman (1985))

Knowledge and technology creation is modeled using a set of three interconnected first-order linear negative feedback structures. Atmospheric science knowledge, ODS replacement engineering knowledge, and ODS replacement technology are each described using one of the three first-order linear structures. Funding is applied to each structure in direct proportion to the amount of policy maker attention being applied to both the health and economic risks of stratospheric ozone depletion. The rate of development of atmospheric science knowledge is increased by increased funding and an increase in the amount of stratospheric ozone destroyed. The rate of development of ODS replacement engineering knowledge is increased by the increased funding and an increase in the amount of atmospheric science knowledge. The rate of development of ODS replacement technology is increased by increased funding and an increase in the amount of ODS replacement engineering technology. The interconnected nature of the model structure of scientific, engineering, and technology development reflect improved efficiencies gained through additional knowledge. For example, engineers could develop replacement technology without the availability of atmospheric science knowledge but this could lead to ineffective or inefficient replacement technologies. These dependences are displayed in the stratospheric ozone case in the use of HCFCs to replace CFCs. Atmospheric scientists understood that HCFC are more reactive in the troposphere so less of what is emitted gets through to the stratosphere depleting less stratospheric ozone than a similar CFC (Andersen and Sarma 2002). This knowledge allowed engineers to utilize

HCFCs as initial replacements for CFC until a completely inert replacement can be developed.

Society's Risk Perception Sector Model Description

Society's view of risks associated with stratospheric ozone depletion is modeled based on Kasperson et al's (2005) risk amplification/attenuation framework. This framework argues that individuals in society learn of risks through different communication channels and events. As individuals interact with one another and with other institutions (media, government, political groups), they can either amplify the risks as compared to the scientifically defined risk (e.g. nuclear power, mad cow disease, Ebola virus) or attenuate the risk (e.g. automobile accidents, smoking, high fat diets). The result of society's risk perception can include societal behavioral changes and regulatory actions.

This risk perception framework is modeled using a single-stock, goal seeking negative feedback structure. Society receives a scientific assessment of the skin cancer risk associated with stratospheric ozone depletion. Their acceptance of this risk depends on the amount of scientific knowledge available and society's confidence in this knowledge. An amplification/attenuation factor is then applied to this risk to reflect society's perception of this risk. This amplified risk perception is the goal that the single-stock negative feedback structure seeks. The rate at which society as a whole adjusts to this goal is determined by an exogenous parameter that describes the effectiveness of scientists in communicating this information to society.

Appendix B: Exogenous parameters tested

Table 1: Parameters tested in univariate sensitivity analysis

Parameter Name	Calibrated Case Value	Units	Definition
Science, Engineering, and Technology Development Parameters			
% of atmospheric science puzzles solved per $million of funding	0.005	% per $1,000,000	The percent of unresolved science puzzles solved per million dollars of reseach funding.
% of chemical engineering puzzles solved per $million of funding	0.005	% per $1,000,000	The percent of unresolved engineering puzzles solved per million dollars of reseach funding.
% of ODS replacement technologies solved per $million of funding	0.005	% per $1,000,000	The percent of unresolved technology puzzles solved per million dollars of reseach funding.
time to develop atmospheric science knowledge	5	years	The average time required to develop atmospheric science knowledge
time to develop chemical engineering knowledge	5	years	The average time required to develop chemical engineering knowledge
time to develop ODS replacement technology	5	years	The average time required to develop chemical engineering knowledge
atmospheric science funding per hour of policy maker attention	100	$1,000,000 per hour per year	The annual amount of funding applied to resolving atmospheric science puzzles per hour of attention of policy makers to stratospheric ozone depletion. Inclues both public (e.g. NASA funding) and private (e.g. Dupont funding) research funding.
engineering funding per hour of policy maker attention	100	$1,000,000 per hour per year	The annual amount of funding applied to resolving atmospheric science puzzles per hour of attention of policy makers to stratospheric ozone depletion. Inclues both public (e.g. NASA funding) and private (e.g. Dupont funding) research funding.
ODS replacement technology funding per hour of policy maker attention	100	$1,000,000 per hour per year	The annual amount of funding applied to resolving atmospheric science puzzles per hour of attention of policy makers to stratospheric ozone depletion. Inclues both public (e.g. NASA funding) and private (e.g. Dupont funding) research funding.
Domain Expert, Policy Maker, and Societal Interaction Parameters			
time to adjust scientist's estimation of the decrease in stratospheric ozone	1	year	The adjustment period for scientist's estimation of the change in the total amount of stratospheric ozone.
time to adjust policy maker attention to ozone related cancer risks	5	years	The period over which policy makers adjust their attention to stratospheric ozone depletion.
% yearly errosion of policy maker attention	10	%	The annual errosion of policy maker attention to stratospheric ozone depletion
effectiveness of domain experts in communcating with society	50	% per year	Describes the ability of domain experts to communicate the risks associated with stratospheric ozone depletion to society. The percentage describes how quickly society accepts domain experts' risk assessment (higher numbers indicate more rapid assessment).
sensitivity of policy maker attention to domain experts' stratospheric ozone depletion risk assessment	500	hours per % increase in skin cancer risk per year	The degree in which policy makers increase their attention to stratospheric ozone depletion based on domain experts' risk assessment
society's trust in domain experts	70	%	Describes society's faith in domain experts in general. A value of 100% indicates complete trust. A value of 0% indicates complete mis-trust. Society's trust in domain experts has a direct affect on soceity's perception of the risks associated with stratospheric ozone depletion.
reference policy maker attention to the economic risks of ODS regulation	1	hour per hour	Describes the increase in policy maker attention to the economic risks of regulating ODS emissions in relation to the increase of policy maker attention to the health risks of stratospheric ozone depletion.

Appendix C: Sensitivity results

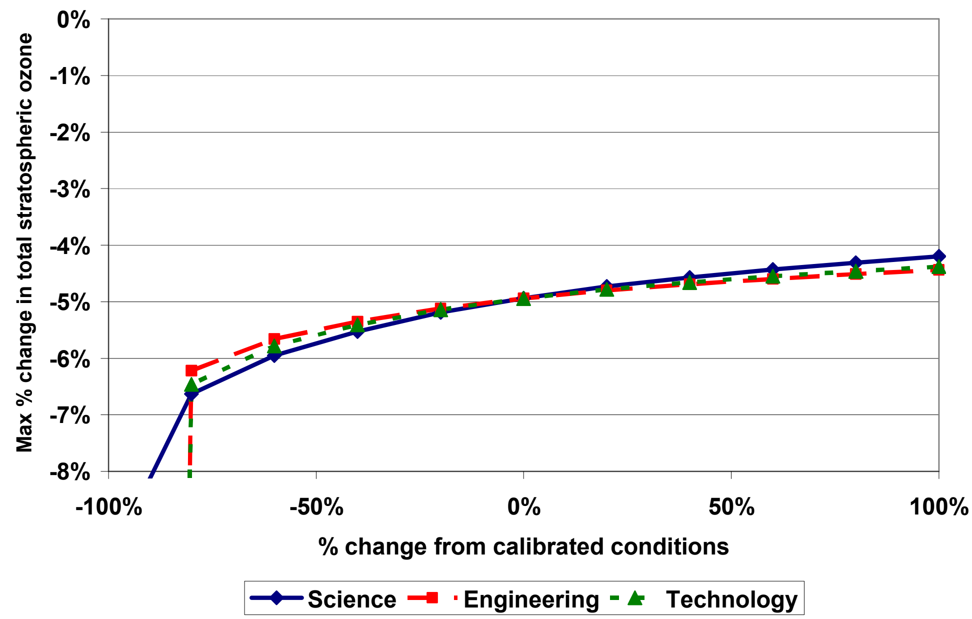

Figure 9: Sensitivity of stratospheric ozone to % of puzzles solved per dollar of funding

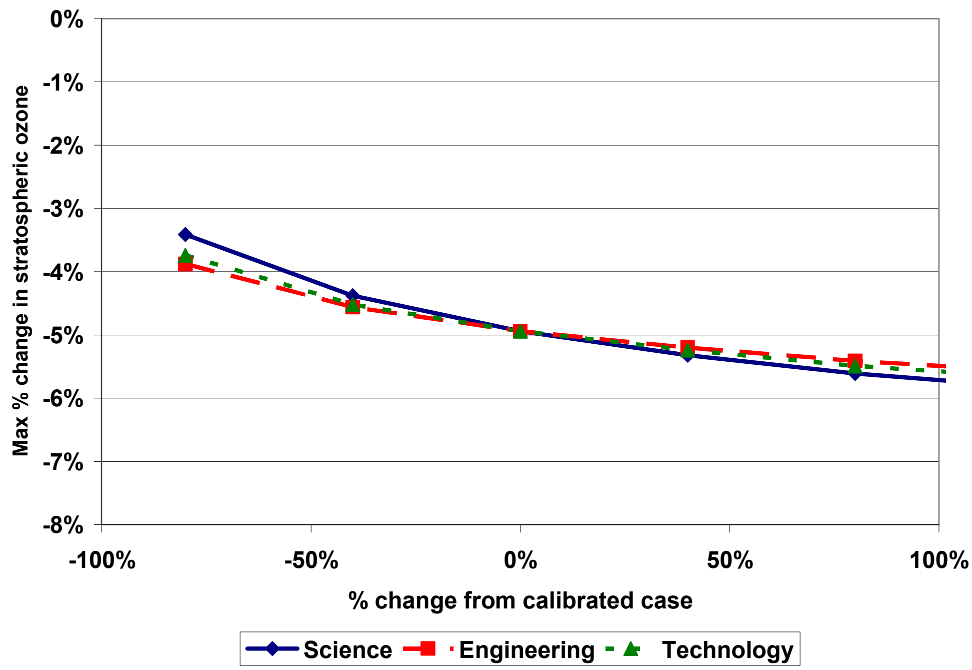

Figure 10: Sensitivity of stratospheric ozone to time required to develop knowledge

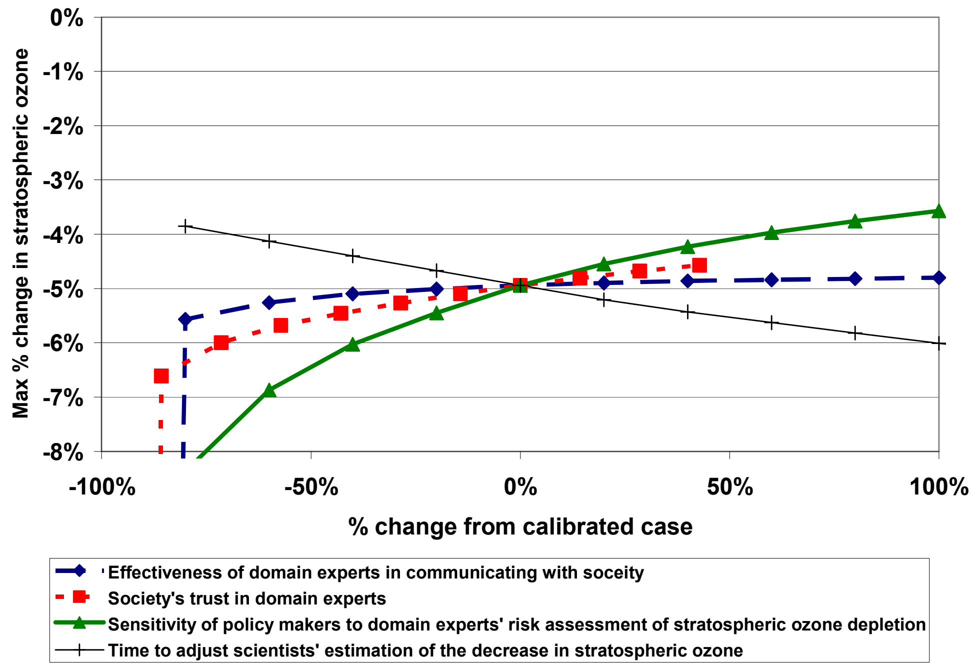

Figure 11: Sensitivity of stratospheric ozone to domain expert, society, and policy maker interaction