In follow-on to the research we have conducted during the past 5 years under NSF Grant ATM-9001310, Research on Greenhouse-Gas-Induced Climate Change, we herein propose 6 projects for the next 5 years.

**The Last Glacial-Interglacial Cycle.** The objective of this research is to simulate and understand the last Glacial-Interglacial Cycle. Following our success in simulating glacial onset from 115kya to 105kya, we will continue to use our 2-layer atmospheric general circulation/mixed-layer-ocean/ice-sheet/asthenosphere (AO/ISA) model, first to refine our onset-simulation temporally, and second to continue the simulation from 105kya to the present.

**Greenhouse-Gas-Induced Climate Change with Interactive Ozone Photochemistry.** The objectives of this research are to simulate and understand: (1) the influence of interactive ozone photochemistry on greenhouse-gas-induced climate change, and (2) the influence of greenhouse-gas-induced climate change on ozone, including the distribution of ultraviolet radiation at the earth’s surface. We will further develop our 24-layer stratospheric/tropospheric general circulation/photochemical (GC/PC) model, which presently contains 26 species and 90 reactions, to include heterogeneous chemistry, and couple it to our mixed-layer-ocean (MLO) model. To fulfill our objectives, we will use this model to perform a 1xCO₂ simulation and two 2xCO₂ simulations, one with interactive photochemistry and the other without interactive photochemistry.

**Greenhouse-Gas-Induced Climate Change with Interactive Tropospheric Methane Chemistry.** The objectives of this research are to determine: (1) the role of anthropogenic sources in the recent decline in the rate of tropospheric methane increase; (2) the role of wetlands in the changes of methane concentration and temperature during a glacial–interglacial transition; and (3) the role of 3 feedbacks contributing to changes of tropospheric methane and climate. We will further develop our 2-layer tropospheric GC/PC/MLO model, which presently contains 20 species and 36 reactions, and implement the photochemical algorithm into our 7-layer tropospheric GC/PC/MLO model. To fulfill objective (1), we will use our 7-layer tropospheric GC/PC/MLO model to perform three 10-year transient simulations, a control simulation with time-invariant regional anthropogenic methane sources, and two experiment simulations with time-varying methane sources, one with prescribed time-invariant total stratospheric ozone, and the other with prescribed time-varying total stratospheric ozone. To fulfill objective (2), we will use our 2-layer GC/PC/MLO model to perform for 150 kya and 130 kya, a control simulation with the feedbacks involving wetlands turned off, and an experiment simulation with these feedbacks turned on. To fulfill objective (3), we will perform 4 pairs of 1xCO₂ and 2xCO₂ simulations with our 7-layer GC/PC/MLO model.

**Estimation of the Climate Sensitivity, ΔT₂x.** The objective of this research is to obtain the best-possible estimate of the sensitivity of the climate system, ΔT₂x. We will do this by simulating the geographical distributions of aerosol concentrations, optical depths, radiative forcing and climate for two years following the Pinatubo eruption. We will incorporate into our 24-layer stratospheric/tropospheric GC/PC model the aerosol physics of our two-dimensional aerosol-layer model, and will couple this GC/PC-aerosol model with our 12-layer ocean GC model. We will perform 5 experiment simulations including the eruption, and 5 control simulations excluding it, the members of each simulation set differing only in their atmospheric initial conditions. In this way we will be able to estimate the contribution of natural internal variability to the post-Pinatubo temperature changes. We will compare the simulated and observed post-Pinatubo temperature changes to determine ΔT₂x.

**Anthropogenic Sulphate Aerosol Induced Climate Change for Integrated Assessments.** The objective of this research is to simulate the equilibrium climate change induced individually and collectively by the radiative forcing of 5 regional sources of anthropogenic sulphate aerosols for use by integrated assessment models. For this objective we will perform 6 equilibrium climate-change simulations with our 7-layer tropospheric GC/PC/MLO model.

**Potpourri.** Several projects in progress will be completed, including simulating the Last Glacial Maximum with our 11-layer atmospheric GC/MLO model and simulating future sea-level change with our AO/ISA model.
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1. Results from Prior NSF Support

The research performed under NSF Grant ATM-9001310, Research on Greenhouse-Gas-Induced Climate Change (4/15/90-9/30/95; $1,435,382), is summarized under 7 topics: (1) Model Development and Testing, (2) Climate Simulations and Analyses, (3) Analyses of Observed Climate, (4) Development of Analysis Methods, (5) Global Warming: Physics, Economics and Policy, (6) Participation in International Research Efforts, and (7) Publications.

1.1. Model Development and Testing

Our Climate Research Group has a suite of general circulation models (GCMs) of the atmosphere and ocean, as well as of simpler climate models.

Atmosphere General Circulation Models. Our 2-layer atmospheric GCM (AGCM) was initially developed by Arakawa and Mintz at UCLA, and subsequently developed and used by the PI during the past 23 years, first at the Rand Corporation from 1973 to 1976, second at Oregon State University (OSU) from 1976 to 1989, and since 1989 at the University of Illinois at Urbana-Champaign (UIUC). We have used the 2-layer GCM for many simulation studies, including that of the equilibrium climate change induced by doubling the CO$_2$ concentration (Schlesinger and Zhao, 1989). We are currently using the 2-layer model, together with our mixed-layer ocean-sea-ice model, coupled asynchronously to the ice-sheet/asthenosphere model of M. Verbitsky (Yale University), to simulate and understand the onset of the last Ice Age, 115,000 years ago (section 1.2). We have recently added a comprehensive photochemical subroutine to our 2-layer model to simulate and understand the tropospheric methane cycle (section 2.3).

In 1984 the PI and then-Ph.D. student, J.-H. Oh, developed a multi-layer (ML) version of the AGCM. The original 7-layer tropospheric version of this ML model was used by Oh (1989) for his Ph.D. research at OSU to develop and test a physically based parameterization of clouds and their radiative interactions, in which cloud water is a prognostic variable, fractional cloud amount is predicted semi-prognostically, stratiform and cumuliform clouds can coexist, clouds can consist of liquid water and/or ice, and cloud radiative properties depend on their predicted cloud water and ice amounts.

During the past 5 years we have revised in our AGCMs: (1) the surface-wind calculation, to improve the simulated sea-level pressure; (2) the planetary-boundary-layer (PBL) parameterization, to improve the simulated subtropical-ocean stratocumulus cloud cover; (3) the ML-model's radiation code, to include CH$_4$, N$_2$O, CFC-11 and CFC-12 (Entwistle, 1992); (4) the soil-moisture parameterization, to alleviate over-drying of the summer midlatitude continents (Smit, 1991); (5) the albedo of snow-covered surfaces, to include dependence on zenith angle and temperature; (6) the ML model's modified Arakawa-Schubert cumulus-convection parameterization, to correct its over-warming and over-drying of the lower troposphere, and to simulate tropical intraseasonal oscillations better (section 1.2); and (7) the ML-model's code, to reduce computer time, 41% for its 7-layer version. We developed a GCM parameterization for the evaporation of cloud (Schlesinger and Oh, 1993), and implemented it and uppermost-layer momentum drag in our ML model. We evaluated the cloud/radiation parameterization of the ML model (Oh and Schlesinger, 1992).

Two ten-year simulations have been performed with the 7-layer GCM for the Atmospheric Model Intercomparison Project (AMIP), a simulation with interannually varying monthly sea-surface temperatures (SSTs) and sea-ice extents (SIEs) prescribed from observations for 1979-1988, and a simulation with the corresponding 10-year-mean monthly SSTs and SIEs. These simulations were used to calculate the seasonal cloud-radiative-forcing for FANGIO, and the Caspian Sea level change (section 1.2) and cloudiness characteristics (Weare et al., 1995a,b) for AMIP; two perpetual-July simulations were also made for FANGIO to determine the GCM's climate sensitivity (section 1.2). The 7-layer GCM has also been coupled to a fixed-depth mixed-layer ocean model. The resulting coupled model simulates well the present-day distributions of SST and SIE. An 11-layer lower-stratospheric/tropospheric version of the ML model has been developed to simulate and understand tropical intraseasonal oscillations (section 1.2). A 24-layer stratospheric/tropospheric version of the ML model has been developed to simulate and understand the chemistry of climate (section 2.2).
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Ocean General Circulation Models. We have doubled the vertical resolution of our ocean GCM (Han, 1984a,b) to 12 layers, replaced its non-interactive sea-surface salinity boundary condition with an interactive evaporation-minus-precipitation boundary condition, replaced its convection scheme with that of Marotzke (1991), and replaced its thermodynamic sea-ice model with a dynamic-thermodynamic sea-ice model.

Simple Climate Models. We have developed a hemispheric version of our energy-balance climate/upwelling-diffusion-ocean (EBC/UDO) model to study the influence on climate of anthropogenic sulphate aerosols (Schlesinger et al., 1992) and putative solar-irradiance variations (Schlesinger and Ramankutty, 1992), and have discovered therewith a 65-70 year oscillation in observed surface temperatures for the North Atlantic Ocean and its bordering continental regions (Schlesinger and Ramankutty, 1994a,b; 1995). We have also developed a version of this model which explicitly calculates temperature changes over land and ocean in each hemisphere (Ramankutty, 1994); this model has been used to estimate the statistical significance of a 65-70 year oscillation in observed surface temperatures (Schlesinger and Ramankutty, 1995), and to study the influence on climate of putative solar-irradiance variations (Schlesinger et al., 1995a) and volcanic eruptions (Ramankutty, 1994; Schlesinger et al., 1995b). We have developed a 2-equation 'reduced-form model' of our EBC/UDO for use in integrated-assessment models. We have also developed a simple climate/ocean model (Schlesinger and Jiang, 1990) to represent simulations by our coupled atmosphere/ocean GCM (Schlesinger et al., 1985). We have developed an ML radiative-convective model using our ML radiative-transfer code and therewith verified our analytically determined vertical-temperature-profile change when there is no climate feedback (Entwistle, 1992; section 1.4).

Other Models. Under the auspices of our grant, M. Verbitsky has extended his ice-sheet/asthenosphere model to be global by including the Antarctic ice sheet. We have developed a time-dependent, latitude-altitude model for the formation, transport and optical properties of stratospheric aerosol to simulate and understand the role of volcanoes on climate (section 2.4).

1.2. Climate Simulations and Analysis

Glacial Onset. We have coupled our 2-layer atmospheric general circulation/mixed-layer-ocean model with Verbitsky's global ice-sheet/asthenosphere model and have simulated the onset of the last ice age, from 115,000 to 105,000 years ago (section 2.1).

Climate Sensitivity. From our 7-layer AGCM simulations (section 1.1) we obtain a climate sensitivity of 0.609°C/Wm⁻², with 0.500°C/Wm⁻² for the clear atmosphere. The total cloud feedback in the 7-layer AGCM is therefore positive. The seasonal cloud radiative forcing simulated for 1985-1988 compares reasonably well with the ERBE values. These results are reported in the paper by Cess et al. (1995).

Intraseasonal Oscillations. W. Wang has developed the 11-layer lower-stratospheric/tropospheric AGCM for his Ph.D. study of tropical intraseasonal oscillations (TIOs). Well-organized TIOs are simulated by the model only when penetrative convection, treated by our modified Arakawa-Schubert parameterization, is constrained to occur when the relative humidity at the top of the planetary boundary layer exceeds a threshold value, RHₑ. Well-organized, eastward-propagating TIOs with periods of 31 to 35 days and the observed amplitudes are simulated with RHₑ = 90% (Wang and Schlesinger; 1995).

Sulphate Aerosol Radiative Forcing. During his working visit with our Climate Research Group (section 1.6), M. Rajeevan calculated the spatial and seasonal distributions of the direct radiative forcing due to anthropogenic and natural sulphate aerosols using the radiative-transfer model of our 7-layer AGCM and the aerosol distributions simulated by Langner and Rodhe (1991). The simulated geographical distribution of annual-mean radiative forcing by anthropogenic sulphate aerosols has maximum negative values over southeastern Europe, eastern China, southeastern United States and south-central Africa, while that for the natural sulphate aerosols is predominantly located over the oceans. The annual global-mean forcing by anthropogenic sulphate aerosols is

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-0.50 Wm\(^{-2}\), while that for natural sulphate aerosols is -0.24 Wm\(^{-2}\) (Schlesinger et al., 1995c). This study is part of our collaboration in the IGAP TARFOX project (section 1.6).

No-Feedback Temperature Profile Change. For a change in CO\(_2\) the climate system cannot produce the no-feedback change in temperature profile, hence we have discovered a new feedback – emissivity/temperature feedback – heretofore completely overlooked, which exists in all simulations of GHG-induced climate change (Entwistle, 1992; Schlesinger and Entwistle, 1995).

Caspian Sea Level Change. With the assistance of A. Senatorsky (section 1.6), we have calculated the change in the level of the Caspian Sea implied by the hydrological quantities simulated over the Caspian catchment basin for 1979-1988 by 7 GCMs, the subset of models participating in AMIP that performed a control simulation with prescribed climatological SST and SIE. To remove any model bias we calculated the difference in Caspian-Sea-level change between that implied for a GCM's AMIP and control simulations, and compared the result with the observed Caspian Sea level rise for 1979-1988. Of the 6 GCMs that performed only a single simulation pair, 5 simulated a rise in the Caspian Sea. The seventh GCM performed 5 AMIP and 2 control simulations which differed only in their initial conditions. Of the possible 10 pairs of AMIP minus control, 6 displayed a rise, 3 a decrease and 1 essentially no change. Thus, pending further analysis, it appears that these GCMs may have simulated a statistically significant rise in the Caspian Sea level, in accord with the observations, as a result of their prescribed interannually varying surface-temperature frequencies and sea-ice extents.

Coupled Atmosphere-Ocean GCM Simulations. We have used our atmosphere-ocean GCM to simulate CO\(_2\)-induced climate change and the penetration into the world ocean of the passive tracers tritium, CFC-11, CFC-12, and a "passive CO\(_2\)-induced heating" – the CO\(_2\)-induced change in the ocean's temperature distribution in the absence of any corresponding change in the ocean's velocity and salinity distributions (Jiang, 1991). A simple inorganic carbon-cycle model was also included. The CO\(_2\)-induced active and passive temperature increases penetrate more deeply in the subtropics and high latitudes than in the tropics. Convective overturning and large-scale sinking are responsible for the large penetration in high latitudes. The North Atlantic thermohaline circulation is significantly weakened due to the penetration of the CO\(_2\)-induced heating. Associated with this change, the strength of North Atlantic conveyor belt is reduced, which results in a large warming in the upper ocean and cooling in the deep layers. The characteristic response time is 40-50 years for the active CO\(_2\)-induced climate change and 70-160 years for passive CO\(_2\)-induced climate change. Although no tracer penetrates into the ocean exactly like the active CO\(_2\)-induced heating, the CFCs are the best surrogate. The model-simulated ocean uptake of atmospheric CO\(_2\) due to inorganic processes alone is 2.61 GtC per year, which is 38.6±6.6% of the anthropogenic atmospheric CO\(_2\) released during the last decade.

1.3. Analyses of Observed Climate

65-70-Year Surface-Temperature Oscillation. Using our energy-balance climate/upwelling-diffusion-ocean model (section 1.1) to remove the anthropogenic greenhouse-gas and sulphate-aerosol contributions to four observed surface temperature records from 1858 to 1992, and using singular spectrum analysis (SSA) of the thus-detrended temperature records, we have discovered a surface-temperature oscillation in the global climate system having an irregular temporal character with a timescale of about 65-70 years (Schlesinger and Ramankutty, 1994a). SSA of the surface temperature records for 11 geographical regions shows that the 65-70-year oscillation is the statistical result of 50-88-year oscillations for the North Atlantic Ocean and its bounding northern hemisphere continents. (Our discovery was reported in Discover magazine as one of "The Top 75 Science Stories" of 1994 (Zimmer, 1995).) We performed two 'frozen-grid' analyses of the observed data, one for 1880 and another for 1920, in which the number of observing stations in each observational grid location was held constant in time at its value in 1880 and 1920, respectively. The oscillation is found to occur in these frozen-grid analyses. We have also changed the sulphate forcing in the simple climate/ocean model from its 'optimal' value of -0.35 Wm\(^{-2}\) to 0 Wm\(^{-2}\) and -1.1 Wm\(^{-2}\). Again, the oscillation is found. In response to criticism of our statistical-significance assessment (Elsner and Tsonis, 1994), we have used both our physical climate/ocean model and four statistical
autoregressive models to represent individually the response of the climate system to white-noise forcing, separately for the globe and the North Atlantic. For the global-mean temperature, all of the statistical models show statistical significance greater than 89.1%, and the physical model greater than 33.5%. For the North Atlantic temperature, all of the statistical models show statistical significance greater than 91.3%, and the physical model greater than 98.6%. Consequently, the hypothesis that the North Atlantic temperature oscillation is due to climatic noise can be rejected at a very high level of statistical confidence (Schlesinger and Ramankutty, 1994b, 1995). This oscillation has confounded detection of the greenhouse-warming signal.

Cloudiness. We have analyzed satellite-based cloudiness observations (Mokhov and Schlesinger, 1993), compared them with ground-based cloudiness observations (Mokhov and Schlesinger, 1994), and used both satellite-based and ground-based observations to evaluate the cloudiness simulated by six atmospheric GCMs (Mokhov and Schlesinger, 1995).

1.4. Development of Analysis Methods

CPMS Method. In collaboration with T. Karl (NOAA National Climatic Data Center) et al., we developed the Climatological Projection by Model Statistics (CPMS) method for downscaling GCM results to the regional and local scales required for climate impact analyses (Karl et al., 1990). The CPMS method uses observational data and statistical methods to relate the surface climatic quantities of interest at a location to the free-tropospheric quantities available from a GCM. The resulting relations are used with the free-tropospheric quantities simulated by the GCM for its grid cell nearest to the chosen location to infer the desired surface climatological quantities there. CPMS yields not only the mean and variance of the selected surface climatic quantities, but also the entire statistical distribution for each quantity. In collaboration with T. Karl and H. Pleym (Telemark College of Engineering in Porsgrunn, Norway), a former visitor for 6 months with our Climate Research Group, we have again tested the CPMS method for the present climate, and applied it for CO2-induced climate change (Pleym et al., 1995).

CEA Method. We have developed the Cause-and-Effect Analysis (CEA) technique to determine the sensitivity, stability and feedbacks of geophysical models. We have applied the CEA technique to photochemical and climate models to determine their sensitivity (Andronova and Schlesinger, 1991; Andronova et al., 1993; Andronova and Karol, 1993a), stability (Andronova and Schlesinger, 1992) and feedbacks (Andronova and Schlesinger, 1994a,b).

Adjoint Method. We have described the proper use of the adjoint method to analyze the sensitivity and uncertainty of climate model simulations (Cacuci and Schlesinger, 1994a,b).

Feedback Analysis Method. We have theoretically determined, and verified by our ML radiative-convective model (section 1.1), what the change in the vertical temperature profile is when there is no feedback – it is not the uniform profile which has heretofore been assumed (e.g., Arking, 1991).

1.5. Global Warming: Physics, Economics and Policy

We have used our energy-balance climate/upwelling-diffusion-ocean model, together with the observed surface temperature record from the mid-1850s to the present, to estimate the sensitivity of the climate system, ΔT<sub>2x</sub>, and the influence of external forcings due to anthropogenic sulphate aerosols, putative solar-irradiance variations, and volcanoes (section 2.4) (Schlesinger and Ramankutty, 1992; Schlesinger et al., 1992; Ramankutty, 1994; Schlesinger and Ramankutty, 1994a,b, 1995; Schlesinger et al., 1995a,b)

In follow-up to our projections to the year 2100 of the global warming for the IPCC 1990 report (Bretherton et al., 1990), and our participation in The White House Conference on Science and Economics Research Related to Global Change, we performed a calculation with our simple climate/ocean model as to the effect of a 10-year delay on the reduction of global warming in 2100, wherein we concluded that: "the penalty for a 10-year delay in..."
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initiating the transition to a reduced-GHG scenario is small" (Schlesinger and Jiang, 1991a). This paper fostered two debates in Eos, first with Riseby et al. (1991a,b) arguing for early abatement and we for a phased-in approach (Schlesinger and Jiang, 1991b,c), and second with further argument for early abatement by Bolin (1992), Harvey (1992) and Oeschger et al. (1992), together with our discussion of greenhouse economics and policy (Schlesinger, 1992). We were also invited to contribute an article to the global-warming debate in the National Geographic Research & Exploration magazine (Schlesinger, 1993), and an article on Decadal-to-Century Climate Prediction for the eighth edition of the McGraw-Hill Encyclopedia of Science and Technology (Schlesinger, 1994).

Subsequently we collaborated with J. Hammit and R. Lempert, both at the Rand Corporation, to examine a sequential-decision strategy for abating climate change wherein either moderate emissions reduction – energy conservation alone – or aggressive emissions reduction – energy conservation plus switching to non-fossil fuels – is begun in the near-term period, following which a least-cost abatement policy is chosen such that the temperature change never exceeds a target, defined implicitly as the global warming for which the marginal climate damage cost equals the marginal climate-change abatement cost. We found that the cost of abatement required to achieve any climate target increases rapidly with increasing climate sensitivity; that for any climate sensitivity there is a critical target beyond which the moderate near-term policy is less expensive than the aggressive near-term policy, and vice versa for targets less than the critical target; but that the difference in costs and emission rates between the moderate and aggressive near-term policies is much smaller than the difference in costs and emission rates between the different climate sensitivities and climate targets (Hammit et al., 1992). We next examined the effect on the near-term policy choice of abrupt changes in the sinks of carbon dioxide, the sources of methane, the circulation of the oceans, and the climate sensitivity. Although the abrupt changes increase the long-term costs of responding to climate change, they do not significantly affect the comparatively small cost difference between near-term strategies (Lempert et al., 1994). In our most recent collaboration, an adaptive-decision strategy was proposed which can make midcourse corrections based on endogenous learning from observations of the climate and economic systems. It was found that the adaptive-decision strategy outperforms ‘best-estimate’ policies based on minimizing projections of likely long-term costs (Lempert et al., 1995).

We are collaborating with several other groups in the integrated assessment of climate change. We have provided A. Manne and R. Richels of EPRI with geographical distributions of greenhouse-gas-induced temperature and precipitation changes – the mean of our GCM simulations, 2xCO2 minus 1xCO2 and 4xCO2 minus 1xCO2 – averaged for each of the 5 regions of their MERGE integrated assessment model, and normalized by the global-mean surface temperature change (Schlesinger and Andronova, 1994). These fields can then be applied to any scenario of greenhouse-gas emissions by multiplying them by the global-mean surface temperature change calculated by the MERGE model. We are also collaborating with C. Kolstad to incorporate learning formally into an integrated assessment model (Kolstad, 1993, 1994). We are continuing our collaboration with R. Lempert at Rand.

1.6. Participation in International Research Efforts

On a continuing basis we are participating in the Atmospheric Model Intercomparison Project (AMIP), the Paleoclimate Model Intercomparison Project (PMIP), the International Global Aerosol Program (IGAP) Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX), the Stanford Energy Modeling Forum 14 on Integrated Assessment of Climate Change, Working Group VIII of US/Russia Bilateral Agreement on Protection of the Environment, and the European Ice Sheet Modeling Initiative.

Under the auspices of US/Russia Working Group VIII we have had working visits by N. Andronova (5-6/90, 12/90, 6/91, 8-9/91), E. Rozanov (10/94-1/95) and A. Sokolov (12/90), Main Geophysical Observatory, St. Petersburg; S. Malyshnev (9-12/94) Institute of Experimental Meteorology, Obninsk; I. Mokhov (1/90-6/90, 9-10/91, 2-3/92, 10-11/93) and A. Senatorsky (6-8/94), Institute of Atmospheric Physics, Moscow; G. Stenchikov (11/89), Academy of Sciences Computing Centre, Moscow; and M. Verbitsky (1-6/90), Shirshov Institute of Oceanology, St. Petersburg. Under the auspices of the World Meteorological Organization we have had working visits by R. Kolli (7-11/93), Indian Institute of Tropical Meteorology, Pune, and M. Rajeevan (12/93-3/94), India Meteorological Department, Pune. We have also had working visit by C. Cuvelier (10-11/93), CEC Ispra Establishment, Italy; H. Pleym (7-12/91), Telemark College of Engineering, Norway; and H. Smit (6/90-2/91), Wageningen Agricultural University, Netherlands.
1.7. Publications

The papers and books published under NSF Grant ATM-9001310 are listed below.

Published in Refereed Literature


Schlesinger, M. E., and X. Jiang, 1990: Simple Model Representation of Atmosphere-Ocean GCMs and
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Estimation of the Timescale of CO$_2$-induced Climate Change. *J. Climate*, 3, 1297-1315.

Published in Non-Refereed Literature

Entwistle, C. B., 1992: Analysis of the Nature of Zero Feedback in the Climate System Using a Multilayer Radiative-Convective Model. M. S. Thesis, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, 201 pp.


2. Proposed Research

The research we propose to perform during the next 5 years is described below under 6 topics: (1) The Last Glacial-Interglacial Cycle, (2) Greenhouse-Gas-Induced Climate Change with Interactive Ozone Photochemistry, (3) Greenhouse-Gas-Induced Climate Changes with Interactive Tropospheric Methane Chemistry, (4) Estimation of the Climate Sensitivity, ΔTᵢ, (5) Anthropogenic Sulphate Aerosol Induced Climate Change for Integrated Assessments, and (6) Potpourri.

2.1. The Last Glacial-Interglacial Cycle

Objective. The objective of this research is to simulate and understand the last Glacial-Interglacial Cycle – 115kya (thousands of years ago) to the present – its initiation, continuation and termination.
Background. Despite more than 150 years of intensive study, the means by which ice sheets are periodically caused to be initiated and grow on the northern hemisphere continents has largely remained an unsolved mystery. The most widely accepted theory, the Milankovitch astronomical theory (Milankovitch, 1930), posits that such ice sheets will be initiated and grow during periods when northern summers are colder than at present, such that some winter snow can survive summer melting to accumulate year after year to form an ice sheet. The most recent such geological time was 115kya. Measurements of \( \text{CO}_2 \) and \( \text{CH}_4 \) in the Vostok ice core (Jouzel et al., 1993) indicate that the astronomical-insolation forcing at 115kya was enhanced by greenhouse forcing resulting from lower greenhouse-gas concentrations at 115kya. Simulation studies of the change in climate from the present or penultimate interglacial (125kya) to 115kya performed by atmospheric general circulation models (GCMs) with sea-surface temperatures and sea-ice extents either prescribed (Royer et al., 1984) or calculated by simplified ocean models (Dong and Valdes, 1994; Syktus et al., 1994) provide some support for the astronomical theory (Royer et al., 1984; Dong and Valdes, 1994) and for the combined astronomical/greenhouse theory (Syktus et al., 1994). Royer et al. (1984) obtained a decrease in annual-mean surface temperature over much of the northern hemisphere continents, while Dong and Valdes (1994) and Syktus et al., (1994) obtained northern hemisphere snow that survived summer melting. Furthermore, experiments with a two-dimensional (latitude-longitude) energy-balance/ice-sheet model (DeBlonde and Pelletier, 1993) and a two-dimensional (latitude-altitude) atmosphere/mixed-layer-ocean/ice-sheet model (Berger et al., 1994) demonstrated the possibility of simulating ice-volume changes consistent with geological data if the evolution of orbital insolation is accompanied by the corresponding observed change in \( \text{CO}_2 \) concentration. However, the atmospheric GCM simulations of Rind et al. (1989), with sea-surface temperatures and sea-ice extents either prescribed or calculated by a simple ocean model, with and without the \( \text{CO}_2 \) concentration reduced by 70 ppmv, failed to obtain northern hemisphere snow that survived summer melting, thereby calling the astronomical and combined astronomical/greenhouse theories into question. Accordingly, 5 years ago we began the study described below.

What We Have Done. We have coupled our 2-layer atmospheric general circulation/mixed-layer ocean (AGC/MLO) model with the global ice-sheet/asthenosphere (ISA) model of M. Verbitsky (section 1.1) to simulate and understand the initiation and growth of northern hemisphere ice sheets at 115kya, that is, to simulate the onset of the last ice age with a comprehensive climate model. The AGC/MLO model has been run to equilibrium for the present climate and the simulated snowfall, surface insolation and other quantities used as external conditions for a 71-ky simulation by the ISA model to obtain its present-day equilibrium distributions of ice-sheet volume and asthenosphere displacement. The AGC/MLO model was then run to equilibrium for the insolation of 115kya with \( \text{CO}_2 \) reduced from its present-day AGC/MLO-model value of 326 ppmv to its 115kya concentration of 275 ppmv. Next, starting from its present-day equilibrium ice-volume and asthenosphere-displacement distributions, the ISA model was run from 115kya to 105kya using external conditions from the AGC/MLO-model 115kya/275ppmv simulation. Ice sheets were nucleated along the Arctic coasts of North America and Siberia. The AGC/MLO–ISA 115kya simulation was then repeated with only the insolation changed. As before, ice sheets were nucleated along the Arctic coasts of North America and Siberia in this 115kya/326ppmv simulation, but at fewer locations and to smaller volumes than in the 115kya/275ppmv simulation. A third AGC/MLO–ISA 115kya simulation was then performed with both \( \text{CO}_2 \) and \( \text{CH}_4 \) reduced to their 115kya concentrations, the combined radiative forcing of which was represented by an equivalent \( \text{CO}_2 \) amount of 246 ppmv. An ice sheet was nucleated along the Arctic coast of Europe in this 115kya/246ppmv simulation, as well as along the Arctic coasts of North America and Siberia. In the three 115–105kya ISA-model simulations, the ice volume of Antarctica either decreased or was unchanged while the ice volume of Greenland either increased or was unchanged. The net increase in ice volume in the 115kya/246ppmv simulation was only 31% that given by the SPECMAP reconstruction. When, however, the accumulation of rain was allowed - on the premise that rain over the new ice sheets would have been calculated to be snow had the climate been recalculated by the AGC/MLO model to take into account the presence of these new ice sheets, their volumes increased significantly. The resultant net increase in ice volume at 105kya was 86% that given by the SPECMAP reconstruction. From our findings we conclude that the Milankovitch mechanism alone is not sufficient to grow ice sheets on the northern hemisphere continents as large as those that have been reconstructed by SPECMAP, and that the concurrent decrease in greenhouse-gas concentrations was essential to this
What We Will Do. We will simulate the last glacial-interglacial cycle, 115kya-present, in three phases: I. Glacial Onset (Year 1), II. Glacial Continuation (Years 2 & 3), and III. Glacial Termination (Years 4 & 5).

As described above, we have already simulated the onset of the last glacial. In this initial study, however, we did not recalculate the climate at any time between 115kya and 105kya, but instead kept the climate constant at that calculated by the AGC/MLO model at 115kya when there were no ice sheets on the northern hemisphere continents. By keeping the climate fixed in this manner, we missed an important positive feedback, the ice-albedo/temperature feedback. Had this feedback been included by rerunning the AGC/MLO model at intermediate times, the higher albedo of the growing ice sheets would have further cooled the earth, and this, in turn, would have enhanced the growth of the new ice sheets. Accordingly, in Phase I we will again simulate the time interval 115kya to 105kya, but we will recalculate the climate with our AGC/MLO model at intervals of 2ky, with the ice sheets, sea level and continental boundaries for each recalculation time given as simulated by the ISA model for that time. We will continue this asynchronous coupling of the AGC/MLO and ISA models with a 2ky period until at least 105kya, and as far beyond that as necessary to incorporate the existing positive ice-albedo/temperature feedback. (We cannot use our coupled atmosphere/ocean general circulation model [sections 1.1, 1.2] for these simulations because the thousands of years required for the deep ocean to achieve equilibrium makes such simulations computationally impossible.) In doing so, we will test our current parameterization that precipitation falling as rain over the newly formed ice sheets would fall as snow, and thus accumulate on these ice sheets, if the climate were recalculated to take into account the presence of these new ice sheets. We will publish results of Phase I in a scientific journal.

In Phase II we will simulate the continuation of the glacial. In this phase we will increase the period of the asynchronous coupling to be as large as possible – at least 10ky – commensurate with inclusion of the ice-albedo/temperature feedback, and continue the simulation to about 25kya. Since the paleotopography of the Last Glacial Maximum ice sheets is a subject of considerable discussion, we will compare the ice geography generated by our model with the CLIMAP and ICE-4G (Peltier, 1994) reconstructions. We will publish results of Phase II in a scientific journal.

In Phase III we will simulate the termination of the glacial. We expect this stage to be the most difficult one, because the reasons for the collapse of the Pleistocene ice sheets are even more mysterious than the reasons for their onset. In this phase we will first examine whether the physical mechanisms incorporated in our model are capable of generating a major ice-sheet retreat. These physical mechanisms represent three leading theories of the Ice Ages: (i) seasonal insolation changes due to changes in orbital configuration, i.e., the astronomical theory; (ii) changes in CO$_2$ concentration; and (iii) vertical movements of the underlying bedrock under the ice load. We will run our model under the combined influence of these factors, as well as under their individual influence. In this phase we will reduce the period of our asynchronous coupling back to 2ky. We will check the sensitivity of the results obtained to the changes in physical parameters involved. We will publish results of Phase III in a scientific journal.

In this study we will generalize the standard climate paradigm such that it not only correctly predicts the change in global-mean surface temperature resulting from annual-global radiative forcing, but also the temperature change for the seasonal-latitude radiative forcing of the Milankovitch mechanism. This simulation and analysis study of the last glacial-interglacial cycle will help solve the mystery of the Ice Ages and, thereby, increase confidence in the ability of climate models to simulate a future greenhouse-gas-induced climate different from the present climate.

**Personnel:** Verbitsky, Schlesinger, Ghanem, new graduate student (A).

2.2. Greenhouse-Gas-Induced Climate Change with Interactive Ozone Photochemistry

**Objectives.** The objectives of this research are to simulate and understand: (1) the influence of interactive ozone photochemistry on greenhouse-gas-induced climate change, and (2) the influence of greenhouse-gas-induced climate
change on ozone, including the distribution of ultraviolet radiation at the earth's surface.

Background. The two most societally-relevant problems in the atmospheric sciences are 'global warming' and 'ozone depletion', the former projected on the basis of increasing anthropogenic contributions to greenhouse-gas concentrations, and the latter on the basis of anthropogenic use of CFCs. Despite the interdependence of these two problems, with ozone being a greenhouse gas whose concentration is likely to change as a result of the stratospheric cooling accompanying global tropospheric warming, ozone and global warming have been studied either separately (e.g., Schlesinger and Mintz, 1979; Manabe and Wetherald, 1980; WMO, 1991) or with simplified and/or idealized models (e.g., Mahlman and Moxim, 1978; Callis et al., 1983; Kaye and Rood, 1989; Kaye et al., 1990; Ramaroson et al., 1994; Larry et al., 1994; Folkins et al., 1994; Austin and Butchart, 1994), but not with a stratospheric/tropospheric general-circulation model having comprehensive and interactive photochemistry. It is for this reason, in large part, that two recent international workshops were held to discuss GCM studies of climate-chemistry interactions, which concluded that: "Due to the complex nature of the anthropogenically induced changes of O3 and sulfate particles and our limited knowledge of their impact on climate change, reliable calculations of the climatic impact of O3 and sulfate particles require the GCMs to include coupling between their atmospheric distribution and climate impact" (Wang and Isaksen, 1994). Accordingly, we propose to implement this recommendation as described below using our stratospheric/tropospheric general-circulation/photochemical (GC/PC) model.

What We Have Done. To simulate and understand atmospheric ozone, we have developed a 24-layer stratospheric/tropospheric version of our ML model, with top at the stratosphere (1 mb), which has an optimized comprehensive photochemical algorithm consisting of 26 species [O₃, O(¹D), O(¹P), N, NO, NO₂, NO₃, N₂O₅, HNO₃, HNO₄, N₂O, H, OH, HO₂, H₂O₂, H₂O, H₃, Cl, Cl₂O, HCl, HOCl, Cl₂NO₃, CFC-11, CFC-12, CO, CH₄] and 90 reactions (Schlesinger et al., 1995d; Rozanov et al., 1995). In preparation for extended simulations with this GC/PC model, we have tailored its code to run on the SGI 16-processor Power Challenge computer at the National Center for Supercomputer Applications (Schlesinger et al., 1995d). Comparison of integration results with observations show that the GC/PC model is capable of simulating the three-dimensional distributions of its dynamical, thermodynamical and chemical quantities reasonably well (Schlesinger et al., 1995d; Rozanov et al., 1995).

What We Will Do. This research will be conducted in 3 phases: I: Development and testing of the GCM without heterogeneous chemistry (Years 1 & 2); II: Development and testing of the GCM with heterogeneous chemistry (Year 3); and III: Performance of doubled-CO₂ simulations and their analysis (Years 4 & 5).

In Phase I we will develop our GC/PC model to: (1) revise the numerical scheme for chemical-species advection from its current finite-difference formulation, which is diffusive (Schlesinger, 1976), to a semi-Lagrangian scheme; (2) include vertical transport of chemical species in our formulation of the Arakawa-Schubert cumulus convection parameterization (sections 1.1 and 1.2); (3) refine the set of chemical species and reactions as required by any modernization of chemical knowledge, for example, inclusion of iodine and bromine chemistries (Solomon et al., 1994; Anderson et al., 1989), and (4) include the distribution of surface sources of the chemical species, namely, CFC-11 and CFC-12 for chlorine, N₂O for NO₂, and CH₄ for stratospheric water vapor. We will test the GC/PC model by simulating the present ozone distribution and comparing its results with the observed ozone distribution, not including the ozone hole, and other chemical species, both long-lived (CH₄, HNO₃, H₂O and others) and short-lived (OH, NO, NO₃ and others). We will then revise the model as required to diminish its errors until the model satisfactorily simulates the ozone distribution, as well as the dynamics and thermodynamics of the atmosphere. We will publish results of Phase I in a scientific journal.

In Phase II we will develop our GC/PC model to: (1) incorporate Type II (nitric acid) polar stratospheric clouds (PSCs); and (2) include heterogeneous chemistry on Type I and II PSCs for species N₂O₅, ClONO₂, Cl₂NO₂, Cl₂O₂, Cl₂, HOCl, HNO₃, HCl (Hanson et al., 1994; Danilin and McConnell, 1994), and any other heterogeneous chemistry which may be discovered to be important. We will test the GC/PC model by simulating the present ozone distribution and comparing its results with the observed ozone distribution, particularly the ozone
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hole, and with other chemical species, including HNO₃, HCl, N₂O₅ and ClONO₂. Again we will revise the model as required to diminish its errors until the model satisfactorily simulates the ozone distribution, as well as the dynamics and thermodynamics of the atmosphere. We will publish results of Phase II in a scientific journal.

In Phase III we will perform 4 tasks. In Task 1 we will couple the GC/PC model, having both heterogeneous and homogeneous photochemistry, to our mixed-layer ocean (MLO) model (sections 1.1, 1.2, 2.1) and will use this GC/PC/MLO model to simulate the present climate (1xCO₂). In Task 2 we will use the GC/PC/MLO model, with its atmospheric photochemistry turned off and the distributions of chemical species prescribed as simulated for the present climate in Task 1, to simulate the equilibrium climate change resulting from a doubling of the CO₂ concentration without interactive photochemistry (2xCO₂/NIPC). In Task 3 we will use the GC/PC/MLO model, with its homogeneous and heterogeneous photochemistry turned on, with the surface sources of the chemical species prescribed as in the 1xCO₂ simulation, to simulate the climate change resulting from a doubling of the CO₂ concentration with interactive photochemistry (2xCO₂/IPC). In Task 4 we will compare and analyze the CO₂-induced climate changes with and without interactive photochemistry to determine the effect of the interactive photochemistry on the CO₂-induced climate change. We will also analyze the differences between the 2xCO₂/IPC and 1xCO₂ simulations to determine the CO₂-induced changes in ozone, other chemical species and the distribution of surface ultraviolet radiation. We will publish results of Phase III in a scientific journal.

Personnel: Rozanov, Schlesinger, Andronova, Ghanem, new graduate student (B).

2.3. Greenhouse-Gas Induced Climate Changes with Interactive Tropospheric Methane Chemistry

Objectives. The objectives of this research are to determine: (1) the role of anthropogenic sources in the recent decline in the rate of tropospheric methane increase; (2) the role of wetlands in the changes of methane concentration and temperature during a glacial-interglacial transition; and (3) the role of 'stratospheric-total-ozone/temperature', 'tropospheric-water-vapor/temperature' and 'wetlands/methane/temperature' feedbacks in changes of tropospheric composition and climate.

Background. Atmospheric photochemistry plays an important role in the maintenance of the present climate by helping to control the atmospheric contents of greenhouse gases – water vapor, carbon dioxide, ozone, methane, nitrous oxide, non-methane hydrocarbons (NMHC) and halocarbons – and particulate matter – aerosol and clouds drops. Conversely, climate change can influence the rate of atmospheric photochemical reactions by changing atmospheric temperature, winds and water vapor.

Among all of the atmospheric chemical species, methane is a key compound in the chemistry of both the troposphere and the stratosphere. Tropospheric methane plays an important role in determining the concentration of hydroxyl radical (Taylor et al., 1991) which is involved in the chemistry of most tropospheric trace gases (Prinn, 1994). Methane, carbon monoxide (CO) and NMHC contribute to tropospheric ozone photochemistry, which depends on the tropospheric concentrations of nitrous oxides (NOₓ). The non-uniform distribution of the surface sources of NOₓ ultimately determines whether tropospheric ozone is produced or destroyed (Prinn, 1994), and allows subdivision of tropospheric chemistry into 'coherent regions' (Thompson, 1992).

It is well known that methane is a major contributor to greenhouse warming. Furthermore, feedbacks between temperature and tropospheric greenhouse gases – methane, water vapor and ozone – influence the sensitivity of the tropospheric photochemical system to anthropogenic activity, particularly to anthropogenic methane sources (Callis et al., 1983; Rind et al., 1991; Andronova et al., 1993). Global surface-based measurements of atmospheric methane have revealed a recent marked decrease in its growth rate, the cause of which is not well understood (Bekki et al., 1994). One possible reason could be a decrease in the intensity of anthropogenic surface sources.

All sources of methane are located at the Earth’s surface, and the major sink – reaction with hydroxyl – is located in the atmosphere. Methane sources have both anthropogenic and natural (mostly biogenic) origin, and are non-uniformly distributed over the globe. Wetlands are a major natural biogenic methane source (Fung et al., 1991). The intensity of methane emission from wetlands strongly depends on climate, hence climate change could
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considerably change tropospheric methane content (Chappellaz et al., 1993; Andronova and Karol, 1993b). Because methane is a greenhouse gas and is an important sink of reactive hydroxyl, the wetlands/methane/temperature feedback can influence climate and the chemical composition of the troposphere. Paleo-data from Antarctic and Greenland ice cores show, in fact, that changes in temperature, methane and carbon dioxide during the last 160 ky were positively correlated (Chappellaz et al., 1993; Jouzel et al., 1993). Therefore, it is important to determine the contribution of the wetlands/methane/temperature feedback to this observed correlation.

As recently estimated (Prinn, 1994), methane is a compound with a chemical lifetime of 9-13 years. Because of this long lifetime, it is necessary to take into account in any regional budget of methane, the time-dependent vertical and horizontal transports of methane by atmospheric motions. To study the evolution of the chemical composition of the troposphere, it is also critically important to take into account changes in stratospheric ozone, which buffers the penetration of UV radiation into the troposphere (Bekki et al., 1994), and chemical and radiative processes in clouds, which provide upward transport of surface-emitted trace gases (Lelieveld and Crutzen, 1990; Toumi et al., 1994).

Consequently, to be able to correctly simulate greenhouse-gas-induced climate change and change in the chemical composition of the troposphere, it is necessary to couple tropospheric photochemical, dynamical and climatic processes in a single three-dimensional climate model (Wang and Isaksen, 1994).

What We Have Done. The problems we will study can be investigated with a tropospheric GCM using prescribed column ozone amounts in the overlying atmosphere and prescribed sources of the chemical species at the earth's surface. Accordingly, we have developed a photochemical algorithm for our tropospheric GCMs. This tropospheric photochemical algorithm has 20 species (O$_2$, O($^1$D), O($^3$P), NO, NO$_2$, HNO$_2$, HNO$_4$, H, OH, HO$_2$, H$_2$O$_2$, H$_2$O, CO, CH$_4$, CH$_3$, CH$_2$O, CH$_2$O, CH$_3$O, HCO) and 36 reactions. We have introduced the chemical algorithm into our 2-layer tropospheric GCM for testing (Rozanov et al., 1995; Andronova, 1995). Simulation results show that the 2-layer GC/PC model is capable of simulating the altitude-latitude-longitude distributions of the chemical species reasonably well (Rozanov et al., 1995). We have also compiled the distributions of recent surface emissions of CH$_4$, CO and NO$_x$ for use as boundary conditions for our atmospheric GCMs (Andronova, 1995). We reconstructed the distribution of methane emission from wetlands using the surface air temperature simulated by our 2-layer GCM for 1xCO$_2$, together with the temperature-dependent model of Andronova (1991) for the transformation of organic matter into methane and the data from Matthews and Fung (1987) for the distribution of wetland area (Andronova, 1995).

What We Will Do. In this investigation we will use both our 2-layer and 7-layer GC/PC models, the 7-layer model for its higher vertical resolution, and the 2-layer model for its computational economy. We will perform our research in three phases: I. Implementation of the photochemical module into our 7-layer tropospheric GCM and improvement of the chemical, radiative and dynamical modules in both the 2-layer and 7-layer GC/PC models (Years 1 & 2); II. Testing of the 2-layer and 7-layer tropospheric GC/PC models with interactive and comprehensive photochemistry via simulations of the present concentrations of tropospheric species and temperature, and their sensitivity to changes in the intensity of surface sources, particularly of CH$_4$, CO, NMHC and NO$_x$ (Years 2 & 3) and III. Performance of equilibrium and transient climate simulations to: (a) determine the role of wetlands and anthropogenic sources in tropospheric chemistry and climate, and (b) evaluate 3 feedbacks contributing to changes of tropospheric methane and climate (Years 4 & 5).

In Phase I we will: (1) use the semi-Lagrangian scheme for chemical-species advection that will be developed in Phase I of the ozone project (section 2.2); (2) include additional nitrogen and NMHC chemistry; (3) test partitioning of the chemistry into "coherent regions" – urban, rural and marine – (Thompson, 1992), each with comprehensive regional chemistry; (4) use published results from other photochemical models and results from numerical simulations made with our 24-layer PC/GC model to develop a parameterization for the relationship between greenhouse-gas-induced climate change and changes in total stratospheric ozone, whereby allowing inclusion of the influence of climate change on the rates of tropospheric photodissociation resulting from the change of UV radiation entering the troposphere; (5) include the dependence of the intensity of the transformation of organic matter into methane on the GCM-simulated soil-water content and develop a parameterization for the change of wetland area on climate change, thereby allowing a more accurate calculation of the dependence on climate change of the methane...
emission from wetlands; and (6) compile and update information about the recent evolution and distribution of the surface sources of methane, nitrogen oxides and carbon monoxide, thereby facilitating more-accurate transient simulations of the changes in climate and tropospheric composition caused by anthropogenic influences.

In Phase II we will: (1) use our 2-layer and 7-layer tropospheric GC/PC models to simulate the present climate and tropospheric distribution of methane, carbon monoxide and nitrogen oxides; (2) compare the simulated distributions of tropospheric species with observations and estimates of simpler models; and (3) revise the models as required such that they satisfactorily simulate the distribution of tropospheric chemical species, as well as the dynamics and thermodynamics of the troposphere.

Phase III has three tasks: (1) We will use our 7-layer tropospheric GC/PC model coupled to our mixed-layer ocean model (sections 1.1, 1.2, 2.1, 2.2) to evaluate quantitatively the wetlands/methane/temperature feedback, the water-vapor/temperature feedback, and the stratospheric-total-ozone/temperature feedback. Four pairs of 1xCO2-control and 2xCO2-experiment simulations will be performed, one with all feedbacks turned off, and three with only one of the 3 feedbacks turned on. We will analyze the feedbacks using the approach described by Schlesinger (1988).

(2) We will use our 7-layer tropospheric GC/PC model coupled with our ocean general circulation model (sections 1.1 and 1.2) to determine the contributions to the observed decline in rate of tropospheric methane increase resulting from changes in: (a) the regional anthropogenic methane sources, and (b) the observed stratospheric ozone depletion. Three 10-year transient simulations will be performed, a control simulation and two experiment simulations. In these simulations the wetlands/methane/temperature and stratospheric-total-ozone/temperature feedbacks will be turned off. In the control simulation the intensity of all regional anthropogenic methane sources will be time invariant, with values taken equal to their average values during 1970-1980 (e.g., Andronova et al., 1986). In the first experiment simulation, the intensity of the regional anthropogenic methane sources – rice paddies, cattle, coal and gas mining – will be time varying, with values taken equal to their rate of development during 1982-1992, which we will assume to be proportional to the rate of economic development of the specific source (area of paddies, number of cattle, volume of gas and coal production) in each specific geographical region. The second experiment simulation will differ from the first in that the amount of stratospheric ozone will be decreased according to observations.

(3) We will use our 2-layer GC/PC model coupled to our mixed-layer ocean model (sections 1.1, 1.2, 2.1, 2.2) to determine the role of wetlands in the change of tropospheric methane concentration and climate during a glacial-interglacial transition. We will simulate the equilibrium climate and methane concentration at 150 kya, when the reconstructed methane concentration was a minimum, and at 130 kya when it was a maximum (Jouzel et al., 1993). For each paleo-time the CO2 concentration and orbital parameters will be prescribed (sections 1.1, 1.2, 2.1). We will turn off the anthropogenic part of the surface sources of methane, carbon monoxide and NOx, and we will keep the stratospheric-total-ozone/temperature and water-vapor/temperature feedbacks turned on. Then a control simulation and an experiment simulation will be performed. In the control simulation the wetlands/methane/temperature and wetland-area/temperature feedbacks will be turned off, and in the experiment simulation these feedbacks will be turned on. Comparison of the experiment and control simulations for each paleo-time will show the role of wetlands in establishing the methane concentration and climate. This study will complement the paleoclimate study described in section 2.1.

We will publish the results of the second and third phases in a scientific journal.

**Personnel:** Andronova, Rozanov, Schlesinger, Ghanem, new graduate student (C).

**2.4. Estimation of the Climate Sensitivity, ΔT_{2x}**

**Objective.** The objective of this research is to obtain the best-possible estimate of the sensitivity of the climate system, ΔT_{2x}.

**Background.** According to the IPCC, the sensitivity of the climate system, ΔT_{2x}, lies within 1.5-4.5°C, with a best-guess value of 2.5°C (Houghton et al., 1990, 1992). Although this estimate is based on GCM simulations, some GCMs have obtained ΔT_{2x} values larger than 4.5°C (Mitchell et al., 1989; Li and Le Treut, 1992), while a
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non-GCM estimation has given a much smaller value, \( \Delta T_{2x} = 0.5^\circ C \) (Lindzen, 1990). Our collaborative studies (section 1.5) on estimating the cost of the fossil-fuel abatement required to meet a climate-warming target using sequential-decision strategy (Hammitt et al., 1992) and adaptive-decision strategy (Lempert et al., 1995), with or without abrupt climate changes (Lempert et al., 1994, 1995), show that the abatement cost increases dramatically with increasing climate sensitivity, \( \Delta T_{2x} \). Similarly, value-of-information studies have found that the most important climatic quantity influencing greenhouse policy for which the uncertainty should be reduced is \( \Delta T_{2x} \) (e.g., Peck and Teisberg, 1993). But, how can the uncertainty in \( \Delta T_{2x} \) be reduced?

It is most unlikely that the uncertainty in \( \Delta T_{2x} \) can be reduced via GCM studies alone, because the value of \( \Delta T_{2x} \) generated by these models depends strongly on their parameterizations of the subgrid-scale physical processes which they cannot resolve because of severe computing limitations. Moreover, even if all GCMs produced the same value of \( \Delta T_{2x} \), we would not know whether or not this value is correct or merely the result of systematic errors in the models (Schlesinger and Mitchell, 1987). Thus it is likely that the uncertainty in \( \Delta T_{2x} \) can be reduced only by using climate models, both simple and complex, to reproduce the observed difference between the present climate and one or more past climates. This approach has been employed by Hoffert and Covey (1992) using palaeoclimates – the Last Glacial Maximum and the Cretaceous, by us (see below) and by Wigley and colleagues (e.g., Kelly and Wigley, 1992) for the instrumental temperature record since the mid-1850s, and by Hansen et al. (1992) for the post-Pinatubo eruption period. There are problems common to using models to estimate \( \Delta T_{2x} \) based on reproducing either paleo or past climates, in particular the representativeness and quality of the temperature data and the lack of perfect knowledge about all the radiative-forcing factors. This notwithstanding, we must confront and overcome these problems if we are to reduce the uncertainty in \( \Delta T_{2x} \) before nature does so sometime in the next century as a result of greenhouse-gas-induced climate change.

What We Have Done. For our climate-sensitivity studies we have used our energy-balance climate/upwelling-diffusion-ocean model, for which \( \Delta T_{2x} \) must be prescribed, to simulate the instrumental temperature record from the mid-1850's to the present. This also requires specification of the external forcing, hence we have examined the role of anthropogenic sulphate aerosols (Schlesinger et al., 1992), putative solar-irradiance variations (Schlesinger and Ramankutty, 1992; Schlesinger et al., 1995a), and volcanic forcing (Ramankutty, 1994; Schlesinger et al., 1995b).

We have found that the value of \( \Delta T_{2x} \) which best represents the instrumental temperature record depends nonlinearly on the highly uncertain value of the anthropogenic sulphate-aerosol forcing (Schlesinger et al., 1992), hence our effort to simulate the clear-air component of this forcing (section 1.2). This dependence is so strong that, if the forcing by anthropogenic sulphate and biomass-burning (Penner et al., 1992) tropospheric aerosols is as large negative as some scientists have stated (e.g., Penner et al., 1992), then \( \Delta T_{2x} \) could be as large as 10\(^\circ C\) or even larger, with the global-warming abatement problem then likely being acute, if not catastrophic. Moreover, we have found (Schlesinger et al., 1995a) that if this negative aerosol forcing is large, and if the solar irradiance has changed as suggested by Friis-Christensen and Lassen (1991) or Hoyt and Schatten (1993), then the sun may have played a significant, but not dominant, role in the observed surface temperature changes of the last 130 years, as (over)stated by some scientists (Jastrow et al., 1992); and, regardless of the magnitude of the sulphate forcing, it appears that the sun may have played a dominant role in the pre-instrumental temperature record compiled from proxy data by Bradley and Jones (1993). Our studies (Ramankutty, 1994; Koshelkov, 1994; Schlesinger et al., 1999) using the volcanic atmospheric depths simulated at our request by Khmelevtsov et al. (1995) indicate, however, that volcanoes have not significantly influenced temperature over the last 130 years, except during the 1-2 years immediately following the largest volcanoes.

Our studies have impressed upon us the difficulty of estimating \( \Delta T_{2x} \) using the instrumental record from the mid-1850's to the present because of our lack of knowledge of the radiative forcing due to anthropogenic sulphate and other aerosols, including those due to biomass burning; putative solar-irradiance variations; and volcanoes prior to Pinatubo. This is made even worse by our lack of knowledge about the natural internal variability of the atmosphere-ocean system on decade-to-century timescales, which makes it impossible to partition the observed temperature changes into the part due to anthropogenic forcing and the part due to natural internal variability. And, we are skeptical that \( \Delta T_{2x} \) can be estimated more accurately using paleoclimate proxy data than by using
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instrumental data, as has been claimed (Hoffert and Covey, 1992), all the more so because our 115kya/550ppmv and 115kya/275ppmv paleoclimate simulations (section 2.1) show that ΔT2x is not a constant, but instead varies with the climate that is being perturbed. There is one way to estimate ΔT2x from the observed temperatures, however, which largely circumvents the confounding problems, namely, use of the natural 'climate-change experiment' performed by the eruption of the Pinatubo volcano on 15 June 1991. This volcano caused a decrease in annual global-mean surface temperature during the next year of about 0.5°C, which is 3 times the interannual standard deviation of the observed temperature (Hansen et al., 1992). It has been concluded (McCormick et al., 1995) that: "Observations of the Mt Pinatubo aerosol, various chemical species, and the radiative consequences during the most heavily loaded period and the subsequent recovery provide data needed to test dynamical, chemical and radiative modelling of the atmosphere" and "...much more work is needed to exploit fully the opportunity provided by nature to enhance our knowledge of how this complex atmosphere and climate system works, and to provide us with a glimpse of the future."

The increase in stratospheric aerosol optical depths resulting from Pinatubo was measured by both the limb-sounding Stratospheric Aerosol and Gas Experiment (SAGE) II on ERBS at 0.385, 0.453, 0.525, 1.02 μm (McCormick and Veiga, 1992), and the nadir-sounding Advanced Very High Resolution Radiometer (AVHRR) on NOAA-11 at 0.5 μm (Long and Stowe, 1994). We have compared the 0.525 μm SAGE and 0.5 μm AVHRR measurements (Ramankutty, 1994; Koshelkov, 1994). We used latitude-time interpolation to fill-in the SAGE observations, which are quite sparse in space and time owing to the nature of limb sounding. We subtracted from SAGE its 2-year-average pre-Pinatubo stratospheric background optical depth of 0.005, and from AVHRR its 2-year-average, monthly pre-Pinatubo tropospheric-plus-stratospheric background. Confining the comparison to between 40°S and 40°N to conform to the latitude band for which radiative forcing was determine by Minnis et al. (1993), we found that the maximum optical depth and space-time optical-depth gradients are much larger for AVHRR than for SAGE, particularly during the 6 months after the eruption. The optical depths calculated by Khmelevtsov et al. (1995) agree with the AVHRR optical depths.

In preparation for our investigation, described below, of the post-Pinatubo temperature changes, we have developed our 24-layer stratospheric/tropospheric GCM with interactive photochemistry (sections 1.1, 2.2), and we have, in collaboration with S. Malyshev (Institute of Experimental Meteorology, Obninsk, Russia), developed a simpler model to simulate the formation and spread of aerosols (Malyshev and Schlesinger, 1995). This time-dependent, two-dimensional aerosol-layer model incorporates chemistry of sulfuric-acid production, aerosol formation and growth, and aerosol transport by the large-scale circulation, diffusion and sedimentation. The model has 11 irregularly spaced levels from 7 to 50 km, and 25 grid points equally spaced in the sine of latitude from pole to pole. The size distribution of the aerosol particles is resolved by 12 discrete size intervals covering a range of particle radii from 0.01 to 2.5 microns. Sulfuric gases reaching the stratosphere by volcanic injections or diffusion from ground sources are oxidized by a series of reactions into sulfuric acid. Droplets of aerosol are formed by heterogeneous nucleation and then grow by heteromolecular condensation of acid and water vapor. The droplets also undergo diffusive coagulation and gravitational sedimentation, and are transported by the seasonal residual circulation and diffusion deduced from the results of GCM simulations. Below the tropopause the particles are removed by rainfall. The model has been tested by simulating the global dispersion of the products of the Pinatubo eruption.

What we propose below has not been done before. Studies have been performed with two-dimensional models to simulate the El Chichón aerosol (Tie et al., 1994) and the influence of Pinatubo on stratospheric ozone (e.g., Pitari and Rizi, 1993). Investigations have been made using atmospheric GCMs with fixed sea-surface temperatures of the volcano-induced winter warming in the northern hemisphere (Graf et al., 1993), and circulation changes (Graf et al., 1992). The pioneering study by Hansen et al. (1992) of the post-Pinatubo temperature change used a GCM with no photochemistry, coupled to a non-dynamic mixed-layer ocean having diffusive heat transport to the deeper ocean, and with distributions of volcanic optical depths prescribed on the basis of observations available only within 6 months following the Pinatubo eruption. This atmosphere GC/mixed-layer ocean model has also been used to investigate volcano-induced global cooling not specifically related to Pinatubo (Pollack et al., 1993; Robock and Liu, 1994).
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What We Will Do.

Phase I (Years 1-2): We will incorporate in our 24-layer stratospheric/tropospheric PC/GC model the aerosol physics presently implemented in the two-dimensional aerosol-layer model described above, and the chemistry of DMS, H2S, SO2, COS, in both gaseous and solid phases. We will couple the 24-layer stratospheric/tropospheric GC/PC model with our 12-layer ocean GCM (section 1.1). We will increase the ocean GCM’s horizontal resolution in the tropics and vertical resolution in the upper ocean (Nagai et al., 1995) to better simulate the 1992 El Niño, whose occurrence likely partially offset the Pinatubo-induced cooling.

Phase II (Years 3-5): We will use the coupled atmosphere-ocean GCM to simulate the geographical distributions of volcanic and background aerosol concentrations, optical depths, radiative forcing and climate for two years following the Pinatubo eruption. We will perform at least 5 experiment simulations including the eruption, and at least 5 control simulations excluding it, the members of each simulation set differing only in their atmospheric initial conditions. In this way we will be able to estimate the contribution of natural internal variability to the post-Pinatubo temperature changes.

To initialize the ocean in the coupled GCM, we will first run the uncoupled ocean GCM for 100 years using observed climatological atmospheric forcing to ensure that the upper ocean reaches quasi-equilibrium, following which the uncoupled ocean GCM will be run for five years using the observed atmospheric data before the Pinatubo eruption. The final state of this five-year run will be used as the initial condition of the ocean in the coupled ocean-atmosphere model. The atmosphere in the coupled ocean-atmosphere model will be initialized with the observed descending easterly shear of the stratospheric Quasi-Biennial Oscillation to capture the tropical stratospheric reservoir phenomenon (Trepte and Hitchman, 1992).

We will compare the aerosol concentrations, optical depths and radiative forcing obtained by the initial experiment simulation with the corresponding satellite and ground-based measurements, and will revise the model as required to obtain a satisfactory reproduction. In this way we will also obtain the post-Pinatubo aerosol concentrations, optical depths and radiative forcing where these quantities were not measured.

We will compare the ensemble of experiment simulations with the ensemble of control simulations to determine the Pinatubo-induced temperature changes at the surface and in the atmosphere within the uncertainty of the model’s natural variability. We will compare these simulated temperature changes with the ground-based and satellite temperature measurements. The ratio of the observed and simulated global annual-mean surface temperature changes will define the correction factor for the model’s ΔT2x, the latter which will be determined in Phase III of the Ozone Project described in section 2.2.


2.5. Anthropogenic Sulphate Aerosol Induced Climate Change for Integrated Assessments

Objective. The objective of this research is to simulate the equilibrium climate change induced individually and collectively by the radiative forcing of 4 regional sources of anthropogenic sulphate aerosols for use by integrated assessment models.

Background. Integrated assessments of climate change are beginning to investigate the inter-regional aspect of emissions abatement, viz: if region A reduces its emissions of greenhouse gases and fossil-fuel-generated sulphur dioxide, but region B does not, how will this affect climate change and its impacts, both globally and regionally, and thus influence international policy-making. While the emitted greenhouse gases (GHGs) become uniformly mixed because of their long residence times in the atmosphere, 50-100 years for CO2 and 9-13 years for CH4, the tropospheric sulphate aerosol generated by a chain of chemical transformations from SO2 is not uniformly mixed because its residence time is only about a week. The radiative forcing by sulphate aerosol therefore has a much more regional distribution than the radiative forcing by greenhouse gases (Kiehl and Briegleb, 1993). Consequently, although the regional breakdown of GHG-emissions abatement has a negligible affect on global and regional climate change and impacts, the regional breakdown of the collateral SO2 abatement can have a major...
impact on climate change and impacts regionally, and perhaps even globally. It is likely that this 'regionality' of sulphate-aerosol-induced climate change, in contrast to the 'globality' of GHG-induced climate change, will make achieving international agreement on abatement more difficult.

What We Have Done. We have calculated the spatial and seasonal distributions of the direct radiative forcing due to anthropogenic and natural sulphate aerosols using the radiative-transfer model of our 7-layer AGCM (section 1.2).

What We Will Do. We will use our coupled 7-layer tropospheric GC/mixed-layer-ocean model (section 1.1) to simulate the equilibrium climate change induced separately and collectively by the regional sulphate-aerosol radiative forcing by North America, Europe, Asia, South America and Africa. For these 6 simulations we will again use the aerosol distributions simulated by Langner and Rodhe (1991). Following the method we used to provide GHG-induced equilibrium climate change results for the 5 regions of the MERGE integrated-assessment model (section 1.5), we will normalize the simulated geographical distributions of equilibrium surface temperature and precipitation changes by the global-mean surface-temperature change. We will also normalize the simulated geographical distributions by the simulated characteristic clear-sky aerosol radiative forcing. Under the assumption that the cloudy-sky (indirect) aerosol radiative forcing and any opposing carbohydrate-soot radiative forcing are proportional to the clear-sky (direct) aerosol radiative forcing (Haywood and Shine, 1995), an integrated-assessment model will multiply the doubly normalized geographical distributions by its prescribed characteristic aerosol forcing and by its calculated time-dependent global-mean temperature change (for prescribed $\Delta T_{2x}$). In this way, an integrated-assessment model will be able to calculate the temperature and precipitation changes for its regions for any scenario of future regional GHG and SO$_2$ emissions. By varying the prescribed characteristic aerosol forcing, an integrated-assessment model can take into account, in a simple way, the large uncertainty inherent in the sulphate/carbohydrate-soot radiative forcing.


2.6. Potpourri

Currently, we have a backlog of 10 papers in progress which need to be completed. We also have in progress several projects that we will continue, including our investigation of tropical intraseasonal oscillations (sections 1.1, 1.2), our participation in the IGAP Tropospheric Aerosol Radiative Forcing Observational Experiment, TARFOX (sections 1.2, 1.6), and our participation in the Atmospheric Model Intercomparison Project (AMIP) and its subprojects (sections 1.1, 1.2, 1.6). We will also use our 11-layer atmospheric GCM to simulate the climate of the Last Glacial Maximum at 18kya, and the Climatic Optimum at 6kya, as part of our participation in the Paleoclimate Model Intercomparison Project (PMIP, section 1.6). One additional project deserves special mention.

We have used our 2-layer tropospheric GC/mixed-layer-ocean model simulations for 2xCO$_2$ and 4xCO$_2$-induced equilibrium climate changes, together with our ice-sheet/asthenosphere model, to simulate the response of the Greenland and Antarctic ice sheets to these greenhouse-gas-induced climate changes. For the warmer climates, the volume of the Greenland ice sheet decreases, but the volume of the Antarctic ice sheet increases. We have used the nonlinear time-dependent evolutions of the volume of the Greenland and Antarctic ice sheets for the two greenhouse-gas-induced equilibrium climate changes to derive a step response function (SRF) for each ice sheet. When we complete this study, the SRFs for the Greenland and Antarctic ice sheets can be used with our energy-balance-climate/upwelling-diffusion-ocean model to calculate the change in sea level for any scenario of future greenhouse-gas and sulphate-aerosol emissions. The calculation therein of the contributions to sea-level change by the Greenland and Antarctic ice sheets should be a substantial improvement over the conventional linearized-time-dependence approach used by the IPCC (Warrick and Oerlemans, 1990) and follow-on studies (Wigley and Raper, 1993).

BIBLIOGRAPHY


Bradley, R. S., and Jones, P. D., 1993: 'Little Ice Age' summer temperature variations: Their nature and relevance to recent global warming trends. The Holocene, 3, 4, 367-376.


Chappellaz, J., I. Y. Fung, A. M. Thompson, 1993: The atmospheric CH₄ increase since the last glacial


Dong, B., and P. Valdes, 1994: Sensitivity studies of the glaciation using the UGAMP GCM. *Annales Geophysicae*, 12 (Supplement II), C374.


Entwistle, C. B., 1992: Analysis of the Nature of Zero Feedback in the Climate System Using a Multilayer Radiative-Convective Model. M. S. Thesis, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, 201 pp.


Graf, H. F., I. Kirchner, A. Robock, I. Schult, 1993: Pinatubo eruption winter climate effects: model versus observations. *Climate Dynamics*, 9, 81-93.


BIBLIOGRAPHY


Wang, W., and M. E. Schlesinger, 1995: Simulation of tropical intraseasonal oscillations by the UIUC 11-layer lower-stratospheric/tropospheric GCM. Climate Research Group internal report, University of Illinois at Urbana-Champaign, 18 pp.


BIOGRAPHICAL SKETCH

Provide the following information for the senior personnel on the project. Begin with the Principal Investigator/Project Director. DO NOT EXCEED 2 PAGES PER PERSON.

A. Vitae, listing professional and academic essentials and mailing address.
B. List up to 5 publications most closely related to the proposed project and up to 5 other significant publications, including those being printed. Patents, copyrights, or software systems developed may be substituted for publications. Do not include additional lists of publications, invited lectures, etc. Only the list of up to 10 will be used in merit review.
C. List of persons, other than those cited in the publication list, who have collaborated on a project or a book, article, report or paper within the last 48 months, including collaborators on this proposal. If there are no other collaborators, please indicate that fact.
D. Names of graduate and post-graduate advisors and advisees. The information in C and D is used to help identify potential conflicts or bias in the selection of reviewers.

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5 Publications Most Closely Related to the Proposed Project
5 Other Significant Publications

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