I. The Winners of the Blue Planet Prize

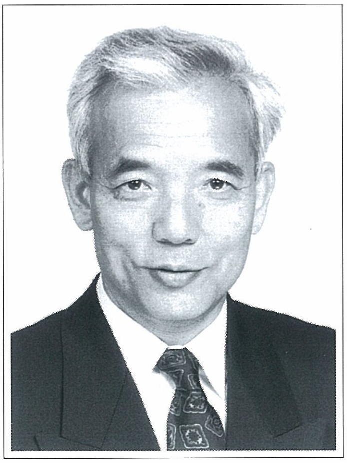
1992

1992

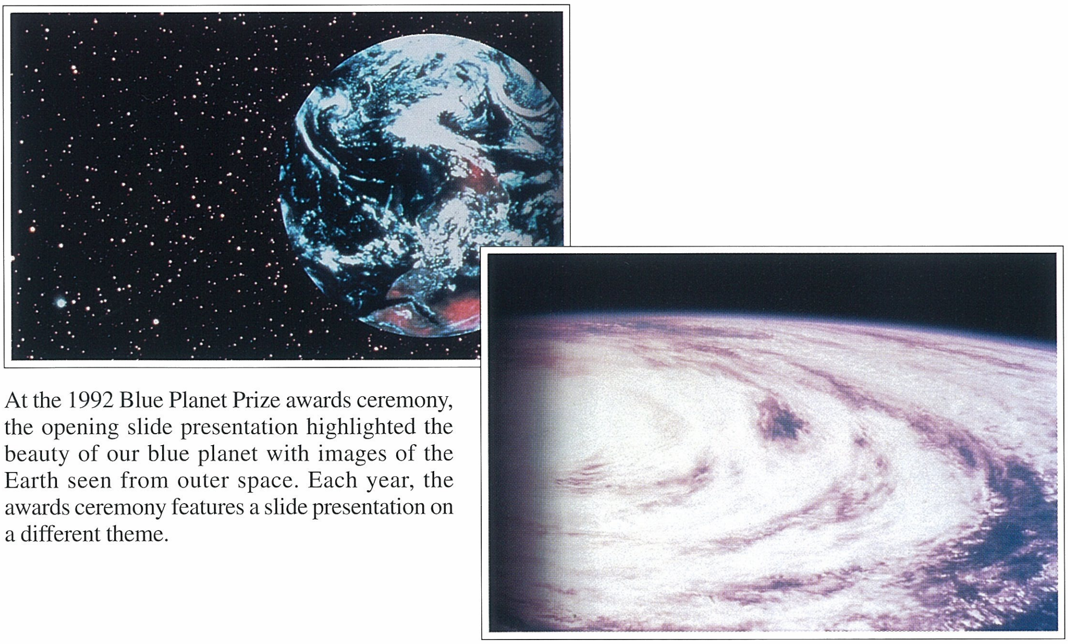
Blue Planet Prize

Dr. Syukuro Manabe (U.S.A.)

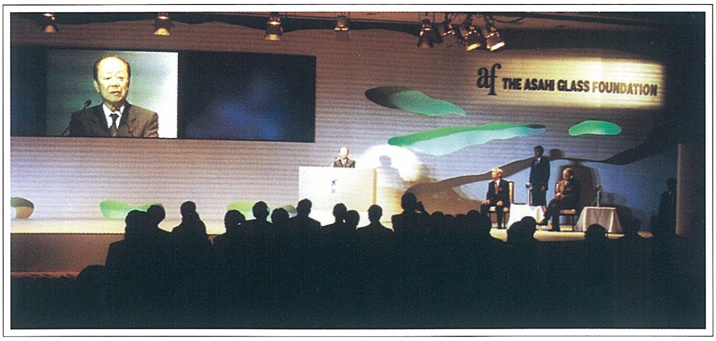
Member of the Senior Executive Service of the Geophysical Fluid Dynamics Laboratory at the National Oceanic and Atmospheric Administration



International Institute for Environment and Development (IIED) (Founded in the United Kingdom)

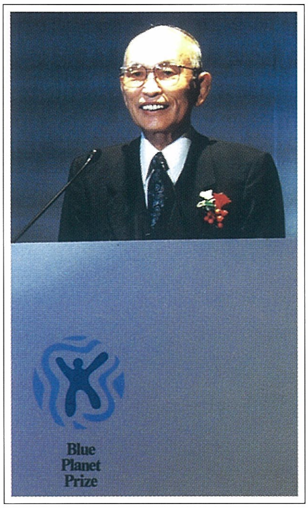


At the 1992 Blue Planet Prize awards ceremony, the opening slide presentation highlighted the beauty of our blue planet with images of the Earth seen from outer space. Each year, the awards ceremony features a slide presentation on a different theme.



Prime Minister Kiichi Miyazawa gives a congratulatory speech at the opening ceremony.

As the chaiman of the Presentation Committee, Dr. Saburo Okita reports on the selection process.



Hideaki Yamashita, chairman of the Asahi Glass Foundation, delivers the opening address.

Asahi Glass Foundation Chairman Hideaki Yamashita shakes hands with Michael Armacost, ambassador of the United States of America to Japan. Directly behind Mr. Armacost is Sir John Boyd, Her Britannic Majesty's ambassador.

On the day following the awards ceremony, a symposium was held on the topic of creating a new civilization in harmony with nautre. Symposium panelists, from left; Keiko Nakamura, Professor, School of Human Sciences, Waseda University; Takamitsu Sawa, head of Kyoto University's Institute of Economic Research; Symposium Coordinator Hirotada Hirose, Professor, College of Arts and Sciences, Tokyo Women's Christian University; Kenzaburo Oe, author; and Hiroyuki Ishi, Senior Staff Editor, Asahi Shimbun Publishing Company.

Seated with other members of the audience, the laureates participate in a panel discussion that followed the symposium.

Profile

Dr. Syukuro Manabe

Senior Scientist, Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, New Jersey

Education and Academic and Professional Activities

1953	Bachelor of Science, University of Tokyo
1955	Master of Science, University of Tokyo
1958	Doctor of Science, University of Tokyo
1958	Research Meteorologist, General Circulation Research Section, U.S. Weather Bureau, Washington, D.C.
1963–	Senior Scientist, Geophysical Fluid Dynamics Laboratory at the National Oceanic and Atmospheric Administration, Princeton, New Jersey
1966	Fujiwara Award, Japan Meteorological Society
1967	Mesinger Award, American Meteorological Society
1968–	Lecturer with rank of professor, Princeton University
1970	Gold Medal Award, Department of Commerce
1977	2nd Half-Century Award, American Meteorological Society
1979	Member of the Senior Executive Service, U.S.A., Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, New Jersey
1981–87	World Meteorological Organization/International Council of Scientific Union/United Nations Environmental Program, Joint Scientific Committee
1989	Meritorious Executive Award, President of the U.S.A.
1989–90	Intergovernmental Panel on Climate Change, Lead Author for Group I Report (Scientific Assessment)
1990	Elected Member, National Academy of Sciences
1992	Blue Planet Prize, Asahi Glass Foundation
1993	Revelle Medal, American Geophysical Union
1994	Elected Foreign Member, Academia Europaea
1995	Elected Foreign Member, Royal Society of Canada
1995	Asahi Prize, Asahi Shimbun Cultural Foundation

Dr. Syukuro Manabe, a naturalized U.S. citizen, was born in Ehime Prefecture, Japan, in 1931. Dr. Manabe received a doctor of science degree from the University of Tokyo in 1958, when he was invited to join a research group of the U.S. Weather Bureau as a research meteorologist. Dr. Manabe has since then continued to work at the same U.S. institution, which is currently called the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration.

Dr. Manabe is a leader in developing computer models for the study of climate. Using a one-dimensional model of climate which incorporates convective as well as radiative transfer of heat in the atmosphere, he successfully elucidated the role of greenhouse gases (e.g. carbon dioxide, water vapor and ozone) in maintaining the vertical thermal structure of the atmosphere. He and his collaborators made pioneering contributions to the projection of global warming through the imaginative use of the one-dimensional, radiative-convective model mentioned above and three-dimensional, general circulation models of the coupled ocean-atmosphere system. Their contributions had a profound impact upon the assessments of climate change which were conducted by the Intergovernmental Panel on Climate Change in 1990 and 1995. The scope of his modeling activity is very extensive, covering not only the present and future climates, but also the climate of the geological past. Dr. Manabe has played a leading role in the emergence of the modeling approach as one of the most promising avenues for the study of climate.

Essay

Model Assessment of Observed Global Warming Trend

Dr. Syukuro Manabe

April 1997

Prologue

When we discuss global warming, one of the questions which we ask frequently is, "Have we detected global warming?" In this essay, I would like to answer this question using a general circulation model of the coupled ocean-atmosphere system, which will hereinafter be called the "coupled model" for simplicity.

Since the basic structure of the coupled model was described in my commemorative lecture of the 1992 Blue Planet Prize contained in this volume, I shall not repeat it here. I would like to note, however, that the coupled model has become a very valuable tool for the study of climate, successfully simulating both its interannual and decadal variabilities (Manabe and Stouffer, 1996).

Figure 1 illustrates the time series of global averaged, annual mean surface air temperature (SAT) that Jones and Wigley (1991) constructed, based upon past observations of SAT. In addition to the low frequency fluctuations of global mean temperature at interannual to decadal time scales, this time series exhibits the global warming trend that began around the turn of this century. In this essay, I would like to discuss whether the sustained warming trend of global mean temperature during the 20th century is induced by thermal forcing, as a result of increasing greenhouse gases, or generated internally through the interaction among the

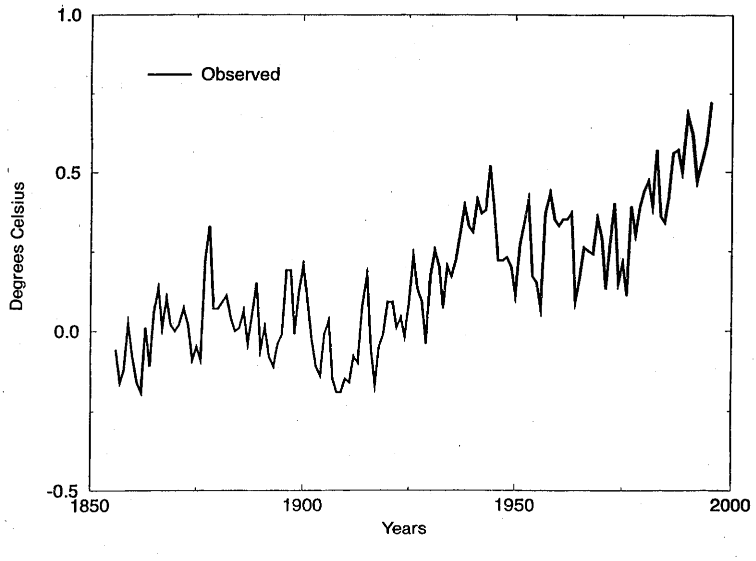


Figure 1 Time series of globally averaged, annual mean SAT anomalies (i.e., the departures from the 1880–1920 base-period means) obtained by Jones and Wigley (1991).

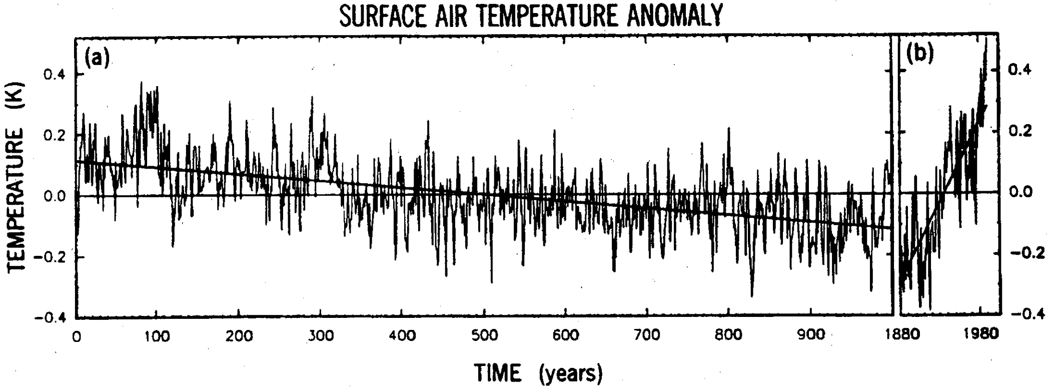


Figure 2 Time series of globally averaged, annual mean SAT anomaly from the long-term mean.
(a) 1,000-year time series from the coupled ocean-atmosphere model
(b) 110-year time series (1881–1990) of observed, globally averaged temperature.
The straight lines through both time series are such that the sum of squared distance between the time series and the straight line is minimized.

atmosphere, oceans, and land surface.

Simulated natural variability

In order to study the natural variability of climate internally generated in the coupled system, we conducted a 1,000-year integration of the coupled model at the Geophysical Fluid Dynamics Laboratory of NOAA. The 1,000-year time series of global mean SAT anomaly obtained from this time integration is illustrated in Fig. 2a and is compared to the time series of observed anomaly between 1881 and 1990 (Fig. 2b).

Stouffer et al. (1994) assessed the probability of finding in the simulated 1,000-year time series a century-scale warming trend such as that observed between 1881 and 1990 (Fig. 2b). They calculated the probability for linear trends exceeding 0.5 °C/century, which is the observed trend between 1881 and 1990 (Jones and Wigley, 1991). It was found that, for intervals longer than ~60 years, there are no trends as large as 0.5 °C/century. In other words, the observed warming trend of 0.5 °C/century is not found in the coupled model time series for any intervals longer than ~60 years. If our model behavior is realistic, it is not likely that the ocean-atmosphere-land interaction in the coupled model could randomly generate a substantial long-term warming trend such as that observed since the end of the last century.

To examine spectrally how realistic is the time series of global mean SAT anomaly shown in Fig. 2, the power spectrum of detrended and globally averaged, monthly mean SAT anomaly from the 1,000-year integration of the coupled model is compared in Fig. 3 with the spectrum of detrended, observed SAT compiled by Jones and Wigley (1991). (The detrending of the observed time series reduces the contributions from the fluctuations on time scales longer than 100 years.) This comparison indicates that, at multidecal and shorter time scales, the coupled model simulates the observed spectrum reasonably well.[1]

However, the coupled model fails to simulate any large warming trend of centennial time scale such as that observed during this century. This failure suggests that the observed warming trend was not generated internally in the coupled system, but was thermally forced.

Thermally forced response

As noted in my commemorative lecture of 1992, the coupled model overestimates the warming trend of the 20th century, if it were forced by greenhouse gases alone. Recently, Mitchell et al. (1995) of the U.K. Meteorological Office obtained a more realistic trend by forcing their coupled model with the effect of sulfate aerosols in addition to increasing greenhouse gases. At the Geophysical Fluid Dynamics Laboratory, we have conducted a similar experiment using the coupled model. The temporal variation of sulfate aerosols and the CO_2-equivalent concentration of greenhouse gases used for our experiment are practically identical to those used by Mitchell et al.[2] Starting from the initial condition, which is a snapshot of the 1,000-year control integration described in the previous section, Haywood et al. (1997) performed the integration of the coupled model over the period from 1765 to 2065 with thermal forcing of combined greenhouse gases and aerosols, as described above.

Figure 4 illustrates the temporal variation of the globally averaged, annual mean SAT anomalies of the coupled model from 1850 to 2000. For comparison, the time series of observed, global mean SAT anomaly compiled by Jones and Wigley (1991) is added to the same figure. This figure indicates that the simulated warming trend during the past 100 years is remarkably similar to the observed trend. The model also reproduces the magnitude of the observed decadal variability reasonably well, as discussed in the previous section.

In view of the large uncertainty in the estimation of the atmospheric loading of various aerosols and their radiative effect, the close agreement of the simulated and observed warming trends during this century could be fortuitous. For example, many radiative forcings other than sulfate aerosols are neglected in this experiment, including those due to ozone changes, other anthropogenic aerosols, indirect aerosol effects on cloud brightness, and changes in the solar irradiance. Furthermore, the climatic response to these forcings is also uncertain. It appears significant, however, that we are unable to simulate the observed warming during the last 100 years unless the combined effect of increasing greenhouse gases and sulfate aerosols is incorporated.

Concluding remarks

Based upon the comparison between the observed and simulated variability of global mean SAT, we suggest that the sustained warming trend of this century was not generated internally through the interaction among the atmosphere, oceans, and land surface. Instead, it appears to have been forced by natural and anthropogenic thermal forcing such as that resulting from the

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[1] The coupled model spectrum is inside the 95% confidence interval of the observed system, though the similarity between the two spectra does not hold too well at the time scale of 2–7 years. Because of its course computational resolution, the coupled model underestimates the amplitude of the Southern Oscillation with this time scale (see Knutson and Manabe, 1994; Knutson et al., 1997).

[2] The CO_2-equivalent radiative forcing of greenhouse gases from 1765 to 1900 was based upon the 1990 report of the Intergovernmental Panel on Climate Change (IPCC, 1990). After 1990, it was assumed to increase by 1% per year, following approximately the best guess IPCC 1992a scenario (IPCC, 1992). The direct effect of sulfate aerosols was added by increasing surface albedo at each grid box, yielding the 1990 global mean thermal forcing of ~-0.6 W/m^2.

increase of solar irradiance (Lean, 1991) and greenhouse gases in the atmosphere. A similar inference could also be drawn from analysis of the time series of global mean SAT obtained from the coupled model developed at the Hadley Centre of the U.K. Meteorological Office (Mitchell et al., 1995).

In addition to analyzing the time series of global mean SAT, other approaches have been employed for the detection of global warming. By comparing the pattern of the observed SAT models, Hegerl et al. (1996) concluded that statistically significant, externally induced warming has been observed. Saner et al. (1996) noted that the observed pattern of temperature change in the free atmosphere from 1963 to 1997 is similar to those obtained by climate models which incorporate various combinations of changes in carbon dioxide, anthropogenic sulfate aerosols and stratospheric ozone concentrations. The conclusions of these studies are clearly in support of the recent statement of the IPCC (IPCC, 1996): "The balance of evidence suggests a discernible human influence on global climate."

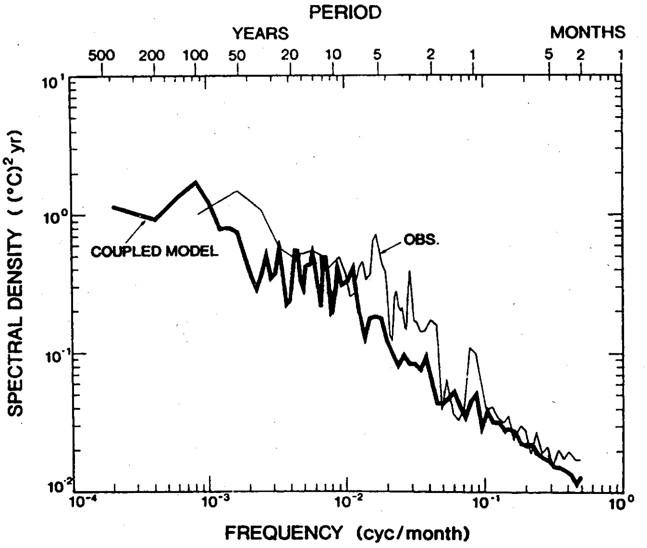

Figure 3 Power spectra of detrended globally averaged, monthly mean SAT anomaly. The thick solid line represents the spectrum of the coupled model time series shown in Fig. 2a, and the thin solid line represents the spectrum of the observed time series (obtained by use of the data compiled by Jones and Wigley (1991)). The spectra are the smoothed Fourier transform of autocovariance function using a Tukey window with a maximum of 2,400 lags (200 years) for the models and 480 lags (40 years) for the observed. They are smoothed by equally weighted averaging over the logarithmic (base 10) interval of 0.04 in frequency.

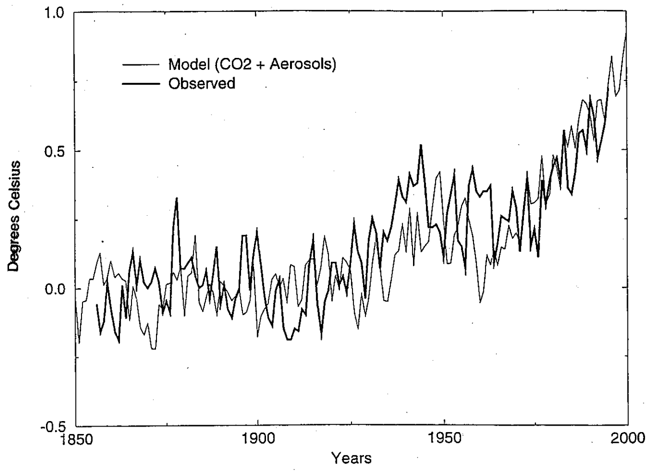

Figure 4 Time series of globally averaged, annual mean SAT anomalies (i.e., deviations from the 1880–1920 mean). Thick solid line: observed (Jones et al., 1991); thin solid line: simulated.

References

Haywood, J.M., R.J. Stouffer, R.T. Wetherald, S. Manabe, and V. Ramaswamy. "Transient Response of a Coupled Model to Estimated Changes in Greenhouse Gases and Sulfate Concentrations," *Geophys. Res. Letters*, (1997), (in press).

Hegerl, G.C., H. von Storch, K. Hasselmann, B.D. Santer, U. Cusbach, and P.D. Jones. "Detecting Greenhouse Gas-Induced Climate Change with an Optimum Fingerprint Method," *J. Climate*, 9 (1996), 2281-2306.

Intergovernmental Panel on Climate Change. Climate Change: *The IPCC Scientific Assessment*, edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums. Cambridge: Cambridge University Press, 1990.

Intergovernmental Panel on Climate Change. *Climatic Change, 1992: The Supplementary Report to the IPCC Scientific Assessment.* Cambridge: Cambridge University Press, 1992.

Intergovernmental Panel on Climate Change. *Climatic Change, 1995: The Science of Climate Change.* Cambridge: Cambridge University Press, 1996.

Jones, P. and T.M.L. Wigley. "Global and Hemispheric Anomalies." In *Trends '91: A Compendium of Data on Global Change*, edited by T.A. Boden, R.J. Sepanski, and F.W. Stoss. Oak Ridge: Oak Ridge National Laboratory, 512-517.

Knutson, T.R. and S. Manabe. "Impact of Increased CO_2 on ENSO-Like Phenomena in a Coupled Ocean-Atmosphere Model," *Geophys. Res. Letters*, 21/21 (1994), 2295-2298.

Lean, J. "Variation in the Sun's Radiative Output," *Rev. Geophys.*, 29 (1991), 505-535.

Manabe, Syukuro and R.J. Stouffer. "Low-Frequency Variability of Surface Air Temperature in a 1,000-Year Integration of a Coupled Atmosphere-Ocean-Land Surface Model," *J. Climate*, 9/2 (1996), 376-393.

Mitchell, J.F.B., T.C. Johns, J.M. Gregory, and S.F.B. Tett. "Climate Response to Increasing Levels of Greenhouse Gases and Sulphate Aerosols," *Nature*, 376 (1995), 501-504.

Santer, B.D., K.E. Taylor, T.M.L. Wigley, T.C. Johns, P.D. Jones, D.J. Karoly, J.F.B. Mitchell. A.H. Oort, J.E. Penner, V. Ramaswamy, M.D. Schwarzkopf, R.J. Stouffer, and S.F.B. Tett. "A Search for Human Influences on the Thermal Structure of the Atmosphere," *Nature*, 382 (1996), 39-46.

Stouffer, R.J., S. Manabe, and K.Y. Vinnikov. "Model Assessment of the Role of Natural Variability in Recent Global Warming," *Nature*, 367 (1994), 634-636.

Lecture

Future Projection of Global Warming by Climate Models

Dr. Syukuro Manabe

This lecture describes briefly my involvement in the development of climate models during the last 35 years and the application of these models to the study of global warming. The lecture concludes with a discussion of the strategy towards the reliable projection of the long-term change of climate in the future.

My involvement in the modeling study of climate began in the fall of 1958 when Dr. Joseph Smagorinsky of the U.S. Weather Bureau invited me to join his group and participate in a very ambitious project for the development of comprehensive models of climate. My initial assignment was the incorporation of the radiative effect of various greenhouse gases (e.g., water vapor, carbon dioxide and ozone) into a three-dimensional general circulation model of the atmosphere. As the first step towards this goal, we constructed a one-dimensional radiative-convective model of the atmosphere which included the effects not only of radiative transfer but also the convective restoration of the neutral, vertical temperature gradient due to cumulus convection and synoptical scale disturbances (Manabe and Strickler, 1964; Manabe and Wetherald, 1967).

Figure 1 illustrates the vertical distribution of the global mean temperature which is in radiative-convective equilibrium. The equilibrium state was approached asymptotically through a long-term integration of the radiative-convective model mentioned above. The heat balance of the convective troposphere is maintained between the convective heating and net radiative cooling, whereas the stably stratified stratosphere aloft is in radiative equilibrium without convective heating. The state of radiative equilibrium obtained compares favorably with the U.S. standard atmosphere which is added to Figure 1 for comparison.

To evaluate the response of the model atmosphere to changes in atmospheric CO_2 concentration, numerical experiments were performed with the radiative-convective model of the atmosphere. Figure 2 illustrates the vertical distribution of the simulated, global mean thermal equilibrium temperature of the atmosphere for the normal, half the normal, and twice the normal concentration of CO_2. In response to the doubling of atmospheric CO_2 from the normal to twice the normal concentration, for example, the equilibrium surface temperature of the model increases by about 2.3 °C. The figure also reveals that the magnitude of the cooling resulting from the halving of the CO_2 concentration (from the normal to half the normal concentration) is approximately equal to the magnitude of the warming from the doubling of CO_2 concentration.

The physical mechanism of the greenhouse effect may be understood by realizing that greenhouse gases such as CO_2 and H_2O can absorb and emit terrestrial radiation but absorb a

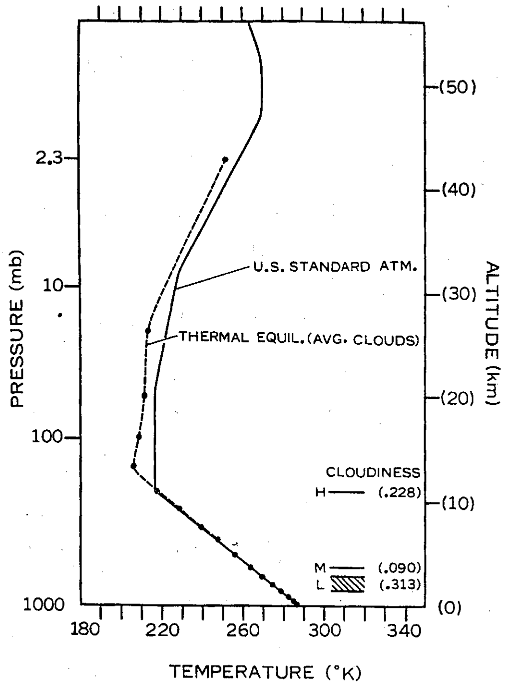

Figure 1. Dashed line shows the vertical distribution of global mean temperature of the atmosphere in radiative-convective equilibrium. (The prescribed cloudiness is indicated on the right-hand side of the figure.) The solid line shows the U.S. standard atmosphere. From Manabe and Strickler (1964).

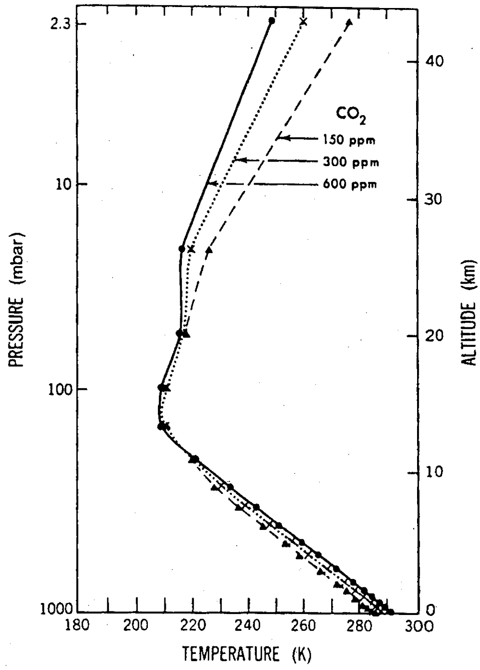

Figure 2. Vertical distribution of temperature in radiative-convective equilibrium for various values of atmospheric CO_2 concentration, i.e., 150, 300, and 600 ppm by volume. From Manabe and Wetherald (1967).

relatively small fraction of solar radiation. In the mid-troposphere, these gases absorb and re-emit a major fraction of the upward terrestrial radiation emitted from the Earth's surface and the lower troposphere. Thus, the effective source of emission of the outgoing terrestrial radiation at the top of the atmosphere is located in the mid-troposphere rather than the Earth's surface. On the other hand, in an atmosphere without greenhouse gases, the source of emission would be confined to the Earth's surface which is warmer than the mid-troposphere. In order to maintain the compensation between the net incoming solar radiation and outgoing terrestrial radiation at the top of the atmosphere, it is therefore necessary that the thermal equilibrium temperature of the troposphere with greenhouse gases be much higher than that of the greenhouse gas-free atmosphere. Thus, greenhouse gases help maintain the surface temperature of our planet at a level which sustains the biosphere. These discussions also imply that an increase in the atmospheric concentration of CO_2 raises the altitude of the effective source of emission and reduces the outgoing terrestrial radiation, thereby contributing to the global warming of the combined surface-troposphere system.

It is expected that, associated with global warming, the absolute humidity in the model troposphere increases because of the dependence of saturation vapor pressure upon air temperature. Since water vapor is a greenhouse gas which absorbs and emits terrestrial radiation very effectively, the increase in the absolute humidity of air raises the altitude of the effective

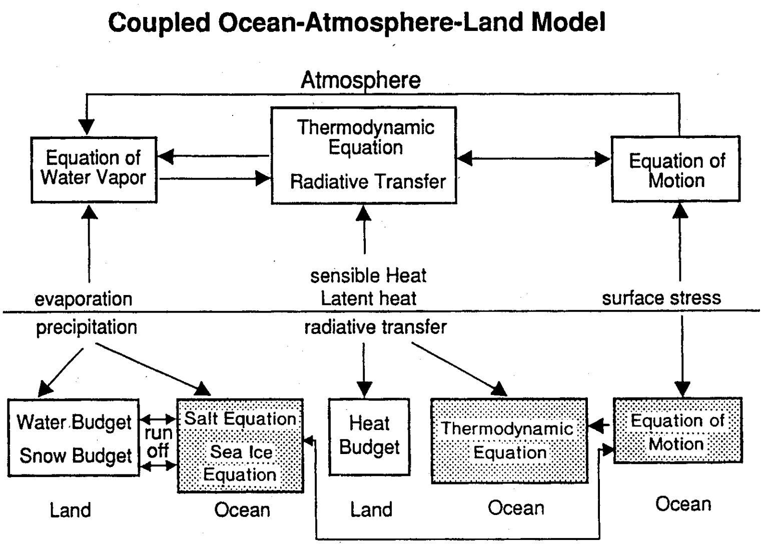

Figure 3. Box diagram which illustrates the structure of the coupled ocean-atmosphere model.

source of outgoing terrestrial radiation. Thus, the temperature of the model troposphere increases further, maintaining the radiation balance of the surface-atmosphere system as a whole. In addition, the increase of absolute humidity increases the fraction of solar radiation absorbed by the model atmosphere, thereby decreasing the planetary albedo and enhancing the CO_2-induced warming. In short, water vapor plays an important role in enhancing the CO_2-induced warming of the atmosphere. Using the radiative-convective model, we succeeded for the first time to correctly evaluate the positive feedback effect of water vapor (Manabe and Wetherald, 1967).

The development of the simple radiative-convective model described above was an important step towards the construction of the three-dimensional, general circulation model (GCM) of the atmosphere.[1] The success of the GCM in the 1960s and early 1970s in simulating many basic features of atmospheric circulation and climate (e.g., Manabe and Holloway, 1975) encouraged us to use the GCM for evaluating global warming (Manabe and Wetherald, 1975; Manabe and Stouffer, 1980).

One of the important factors which control the transient response of climate to a greenhouse forcing is the oceans. If the heat trapped by increasing greenhouse gases is stored in the upper layer of the oceans, or is sequestered into the deeper ocean through vertical mixing, it is possible that global warming could be delayed significantly. Thus, oceans can affect substantially the rate and distribution of global warming. This was one of the important reasons why we started developing the so-called coupled ocean-atmosphere models in the 1960s (Manabe and Bryan, 1969).

I would like to describe here the results from a recent numerical experiment which

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[1] For more detailed discussion on early developments in the model study of the greenhouse effect, see my recently published review paper :
Manabe, S. "Early Development in the Study of Global Warming: The Emergence of Climate Models." *Ambio* (1997, in press).

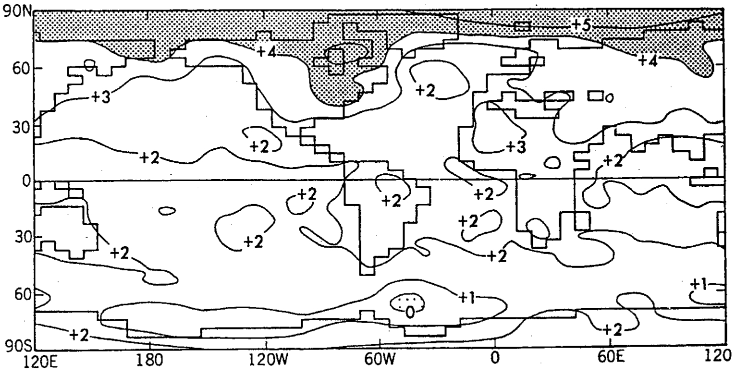

Figure 4. The geographical distribution of the changes in surface air temperature of the coupled ocean-atmosphere model in response to the 1%/year increase (compounded) of atmospheric CO_2. It represents the warming averaged over the 60th-80th year period when the CO_2 concentration is doubled (Manabe et al., 1991).

explored the transient response of a coupled ocean-atmosphere model to a gradual increase of atmospheric CO_2 (Stouffer et al., 1989; Manabe et al., 1991).[2] The coupled model consists of an atmospheric GCM, an oceanic GCM and a simple model of the continental surface that involves the budget of heat and water (Figure 3). It is a global model with realistic geography. The atmospheric component of the model has seasonal variation of insolation, and predicted cloud cover which depends only on relative humidity. It has nine vertical finite difference levels. To improve the accuracy of hydrodynamic calculations, the horizontal distributions of variables specified at grid points are represented by spherical harmonics at each time step. The oceanic GCM uses a finite difference technique and has a regular grid system with 4.5° × 3.75° (latitude × longitude) spacing and 12 vertical finite difference levels. The atmospheric and oceanic components of the model interact with each other continuously through the exchange of heat, water, and momentum, as illustrated by Figure 3.

The rate of increase in atmospheric CO_2 concentration chosen for this transient response experiment is 1%/year. This rate is approximately equal to the rate at which the total CO_2-equivalent concentration of all greenhouse gases (except water vapor) is increasing currently. Figure 4 illustrates the geographical distribution of the increase in annual mean surface air temperature when the atmospheric concentration of CO_2 is doubled (i.e., 70th year of the experiment). The doubling of the CO_2-equivalent concentration of greenhouse gases from the preindustrial level may realized around the middle of next century (IPCC, 1990). The figure indicates that the simulated response of surface air temperature is slow over the northern North Atlantic and the Circumpolar Ocean of the Southern Hemisphere, where the vertical mixing of the heat trapped by the increased greenhouse gas penetrates very deeply. However, in most of the Northern Hemisphere and low latitudes of the Southern Hemisphere, the distribution of the change in surface air temperature is very similar to the results obtained earlier without the delaying effect of the oceans. For example, surface air temperature increases with increasing latitudes in the Northern Hemisphere and is larger over continents than oceans. The increase is at a maximum over the Arctic Ocean and its surroundings in the early winter and is mini-

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[2] For more recent overview of climate change studies by coupled atmosphere models, see the review paper by Manabe et al. (1994).
Manabe, S., R.J Stouffer, and M.J. Spelman. "Response of a Coupled Ocean-Atmosphere Model to Increasing Atmospheric Carbon Dioxide." *Ambio*, 23 (1994), 44–49.

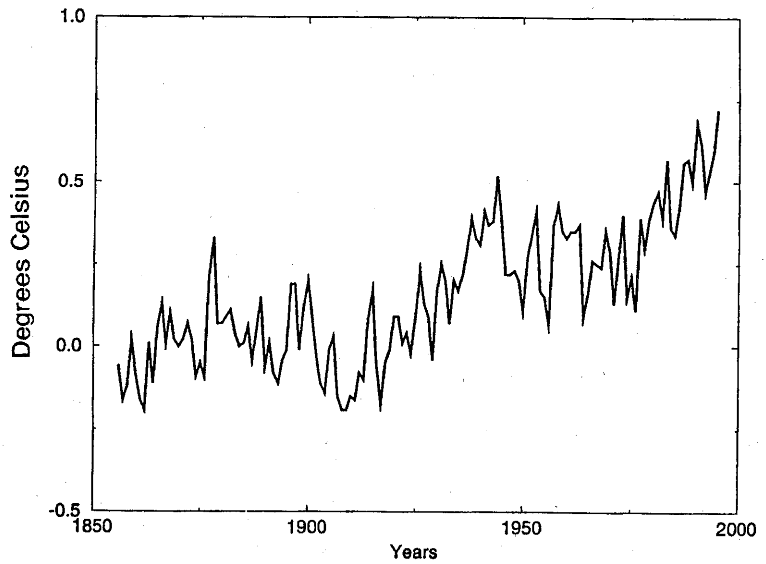

Figure 5. Time series of globally averaged, annual mean surface air temperature anomalies (i.e., the departures from 1961-1990 base-period means) obtained by Jones and Wigley (1991).

mum in summer. The enhanced heat conduction through thinner sea ice is responsible for the early winter maximum, whereas sea ice prevents the temperature of the oceanic mixed layer and the overlying air to rise substantially above the freezing point in summer, and is responsible for the summer minimum in warming. Although the Arctic sea ice loses its thickness in winter as mentioned above, it becomes less extensive as well as thinner in summer.

The increase of a greenhouse gas affects not only the thermal structure of the coupled system but also the hydrologic cycle. For example, the global mean rates of both precipitation and evaporation increase (Manabe and Wetherald, 1975). Because of the increase in the poleward, atmospheric transport of water vapor associated with the increase in the moisture content of air, the increase of precipitation rate in high latitudes far exceeds that of evaporation rate, markedly increasing runoff and reducing the surface salinity in the Arctic and surrounding oceans. This capping of the oceanic surface by relatively fresh water reduces the convective activity in high latitudes and weakens the thermohaline circulation which advects warm and saline surface water northwards, further reducing the greenhouse warming in the northern North Atlantic and surrounding regions (Manabe et al., 1991). It has also been noted that the soil moisture is reduced in summer over extensive mid-continental regions of both the Eurasian and North American continents of the model (Manabe et al., 1981). Thus, it is likely that summer droughts may become more frequent as the greenhouse warming intensifies.

Figure 5 illustrates the temporal variation of the globally averaged, annual mean surface air temperature anomaly compiled by Jones and Wigley (1991) during the last 140 years.[3] The figure shows that the global mean temperature has increased by about 0.6 °C since the begin-

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[3] For the recent model assessment of the temporal variation of the global mean surface air temperature shown in Figure 4, see recent review article by Manabe and Stouffer:
Manabe, S. and R.J. Stouffer. "Climate Variability of a Coupled Ocean-Atmosphere-Land Surface Model: Implication for the Detection of Global Warming." *Bull. Amer. Meteor. Soc.* (1997, in press).

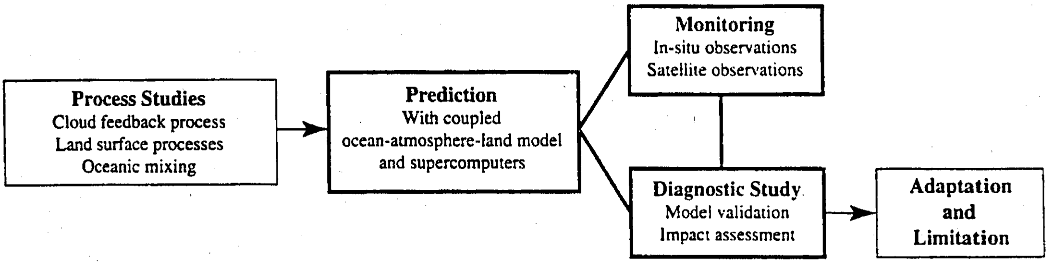

Figure 6. Diagram which illustrates the strategy for the projection of future climate change.

ning of the century. We found that, in response to the observed increase of greenhouse gases, the coupled model generates an increase of global mean surface air temperature which is larger than observed by the factor of about 1.5. This overestimate of global warming may result from our neglect of the cooling effect of sulfate aerosols which reflect incoming solar radiation. Because of fossil fuel combustion, the atmospheric loading of sulfate aerosols has increased rapidly during the last several decades (Charlson et al., 1990). It is therefore very urgent to monitor the temperature variation of various thermal forcings, such as those due to the increase of aerosols, as well as greenhouse gases.

The overestimate of global warming mentioned above may also be attributable to the excessive sensitivity of the coupled model which we constructed. It is therefore desirable to evaluate the sensitivity of the model by comparing the simulated and actual changes of climate. The agreement between these climate changes should enhance our confidence in our ability to project the future change of climate.

A comprehensive strategy for the successful validation of a climate model is illustrated by the box diagram in Figure 6. It involves:

1. reliable, long-term monitoring of climate and its thermal forcings such as changes in the concentration of greenhouse gases and aerosols in the atmosphere;
2. simulation of observed climate change by a coupled model;

and

3. comparative assessment of the simulated and observed changes of climate.

The insight gained from this comprehensive effort is indispensable for the reliable projection of future climate change and successful adaptation to and mitigation of anthropogenic climate change in the future.

The execution of the comprehensive strategy identified above requires the construction of supercomputers and the development of artificial satellites, in which the contribution of Japanese engineers is increasing rapidly. I hope that Japanese scientists will also play an increasingly important role in modeling and observing the future change of global environment by using these powerful tools.

References

Manabe, S., and R.F. Strickler. "Thermal Equilibrium of the Atmosphere with a Convective Adjustment." *J. Atmos. Sci.*, 21 (1964), 361-385.

Manabe, S., and R.T. Wetherald. "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity." *J. Atmos. Sci.*, 24 (1967), 241-259.

Manabe, S., and J.L. Holloway, Jr. "The Seasonal Variation of the Hydrological Cycle as Simulated by a Global Model of the Atmosphere." *J. Geophys. Res.*, 80 (1975), 1617-1649.

Manabe, S., and R.T. Wetherald. "The Effect of Doubling the CO_2 Concentration on the Climate of a General Circulation Model." *J. Atmos. Sci.*, 32 (1975), 3-15.

Manabe, S., and R.J. Stouffer. "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentrations in the Atmosphere." *J. Geophys. Res.*, 85 (C10), (1980), 5529-5554.

Manabe, S., and K. Bryan. "Climate Calculation with a Combined Ocean-Atmosphere Model." *J. Atmos. Sci.*, 26 (1969), 786-789.

Stouffer, R.J., S. Manabe, and K. Bryan. "Interhemispherical Asymmetry in Climate Response to a Gradual Increase of Atmospheric Carbon Dioxide." *Nature*, 342 (1989), 660-662.

Manabe, S., R.J. Stouffer, M.J. Spelman, and K. Bryan. "Transient Response of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2. Part I: Annual Mean Response." *J. Climate*, 4 (1991), 785-818.

Intergovernmental Panel on Climate Change. *Climate Change: The IPCC Scientific Assessment*, edited by J.T. Houghton, G.J. Jenkins and J.J. Ephraums. Cambridge University Press, 1990.

Manabe, S., R.T. Wetherald, and R.J. Stouffer. "Summer Dryness due to an Increase of Atmospheric CO_2 Concentration." *J. Climate Change*, 3 (1981), 336-376.

Jones, P., and T.M.L. Wigley. "Global and Hemispheric Anomalies." In *Trend '91: A Compendium of Data on Global Change*, edited by T.A. Boden, R.J. Sepanski, F.W. Stoss, Oak Ridge National Laboratory, 1991, 512-517.

Charlson, R.J., J. Languer, and H. Rodhe. "Sulfate Aerosol and Climate." *Nature*, 348 (1990), 22.

Major Publications
Dr. Syukuro Manabe

Articles

Manabe, Syukuro. "On the Development and Energetics of the Westerly Waves." *J. Meterol. Soc. Japan*, 33/2 (1955), 76–88.

Gambo, K., K. Katow, S. Manabe and M. Aihara. "Numerical Forecasting over the Far East by the Double Fourier Series Method." *J. Meterol. Soc. Japan*, 33/3 (1955), 133–139.

Syono, S., M. Gambo, K. Miyakoda, M. Aihara, S. Manabe and K. Katow. "Report on the Numerical Prediction of the 500-mb Contour Height Change with Double Fourier Series Method." *J. Meterol. Soc. Japan*, 33/4 (1955), 174–176.

Komabayashi, M., K. Miyakoda, M. Aihara, S. Manabe, and K. Katow. "The Quantitative Forecast of Precipitation with the Numerical Prediction Method." *J. Meterol. Soc. Japan*, 33/5 (1955), 205–216.

Manabe, Syukuro. "A Note on the Barotropic Forecast Using a Moving Coordinate System." *J. Meterol. Soc. Japan*, 33/7 (1955), 164–168.

—. "On the Contribution of Heat Released by Condensation to the Change in Pressure Pattern." *J. Meterol. Soc. Japan*, 34/6 (1956), 308–320.

—. "On the Modification of Air-Mass over the Japan Sea When the Outburst of Cold Air Predominates." *J. Meterol. Soc. Japan*, 35/6 (1957), 311–326.

Syono, S., K. Miyakoda, S. Manabe, T. Matsuno, T. Murakami and Y. Okuta. " Broad-Scale and Small-Scale Analyses of a Situation of Heavy Participation over Japan in the Last Period of Baiu Season 1957." *Japan J. Physics*, 2/2 (1959), 59–103.

Manabe, Syukuro. "On the Estimation of Energy Exchange Between the Japan Sea and the Atmosphere During Winter Based upon the Energy Budget of Both the Atmosphere and the Sea." *J. Meterol. Soc. Japan*, 26/4 (1958), 123–133.

Moller, F. and S. Manabe. "Uber das Strahlungsgleischgewicht der Atmosphare" Sonderdruck aus, *Zeitschrift fur Meterologie*, 15/1-6 (1961), 3–8.

Manabe, Syukuro and F. Moller. "On the Radiative Equilibrium and Balance of the Atmosphere." *Mon. Wea. Rev.*, 89/12 (1961), 503–532.

Manabe, Syukuro and R.F. Strickler. "Thermal Equilibrium of the Atmosphere with a Convective Adjustment." *J. Atmos. Sci.*, 21/4 (1964), 361–385.

Smagorinsky, Joseph, S. Manabe and J. L. Holloway, Jr. "Numerical Results from a Nine-Level General Circulation Model of the Atmosphere." *Mon. Wea. Rev.*, 93/12 (1965), 727–768.

Manabe, Syukuro, J. Smagorinsky and R.F. Strickler. "Simulated Climatology of a General Circulation Model with a Hydrologic Cycle." *Mon. Wea. Rev.*, 93/12 (1965), 769–798.

Manabe, Syukuro and Smagorinsky, Joseph. "Simulated Climatology of a General Circulation Model with a Hydrologic Cycle: II. Analysis of the Tropical Atmosphere." *Mon. Wea. Rev.*, 95/4 (1967), 155–169.

Manabe, Syukuro and R.T. Wetherald. "Thermal Equilibrium of the Atmosphere with a Given

Distribution of Relative Humidity." *J. Atmos. Sci.*, 24/3 (1967), 241–259.

Manabe, Syukuro. "General Circulation of the Atmosphere, Transactions." *Am. Geophys. Union.*, 48/2 (1967), 427–431.

Smagorinsky, J., R.F. Strickler, W.E. Sangster, S. Manabe, J.L. Holloway and G.D. Hembree. "Prediction Experiments with a General Circulation Model." Proc. IAMAP/WMO International Symposium on Dynamics of Large-Scale Processes in the Atmosphere. (Moscow, USSR, 1965) (1967), 70–134.

Manabe, Syukuro and B.G. Hunt. "Experiments with a Stratospheric General Circulation Model: I. Radiative and Dynamic Aspects." *Mon. Wea. Rev.*, 96/8 (1968), 477–502.

Hunt, Barrie G. and S. Manabe. "Experiments with a Stratospheric General Circulation Model: II. Large-Scale Diffusion of Tracers in the Stratosphere." *Mon. Wea. Rev.*, 96/8 (1968), 503–539.

Stone, Hugh M. and S. Manabe. "Comparison Among Various Numerical Models Designed for Computing Infrared Cooling." *Mon. Wea. Rev.*, 96/10 (1968), 735–741.

Hunt, B.G. and S. Manabe. "An Investigation of Thermal Tidal Oscillations in the Earth's Atmosphere Using a General Circulation Model." *Mon. Wea. Rev.*, 96/11 (1968), 753–766.

Manabe, Syukuro and K. Bryan. "Climate Calculations with a Combined Ocean-Atmosphere Model." *J. Atmos. Sci.*, 26/4 (1969), 786–789.

Manabe, Syukuro. "Climate and Ocean Circulation: I. The Atmospheric Circulation and the Hydrology of the Earth's Surface." *Mon. Wea. Rev.*, 97/11 (1969), 739–774.

—. "Climate and Ocean Circulation: II. The Atmospheric Circulation and the Effect of Heat Transfer by Ocean Currents." *Mon. Wea. Rev.*, 97/11 (1969), 775–805.

Manabe, Syukuro, J. Smagorinsky, J.L. Holloway, Jr. and H.M. Stone. "Simulated Climatology of a General Circulation Model with a Hydrologic Cycle: III. Effects of Increased Horizontal Computational Resolution." *Mon. Wea. Rev.*, 98/3 (1970), 175–212.

Manabe, Syukuro, J.L. Holloway, Jr. and H.M. Stone. "Tropical Circulation in a Time-Integration of a Global Model of the Atmosphere." *J. Atmos. Sci.*, 27/4 (1970), 580–613.

Manabe, Syukuro and J.L. Holloway, Jr. "Simulation of the Hydrologic Cycle of the Global Atmospheric Circulation by a Mathematical Model." Proc. Reading Symposium on World Water Balance, International Association of Scientific Hydrology. (1970), 387–400.

Manabe, Syukuro. "Cloudiness and the Radiative, Convective Equilibrium." Proc. AAAS Air Pollut. Session Dallas, Texas. In *Global Effects of Environmental Pollution*, edited by S. Fred Singer. D. Reidel, 1970, 156–157.

—. "The Dependence of Atmospheric Temperature on the Concentration of Carbon Dioxide." Proc. AAAS Air Pollut. Session Dallas, Texas. In *Global Effects of Environmental Pollution*, edited by S. Fred Singer. D. Reidel, 1970, 25–29.

Manabe, Syukuro and J.K. Holloway, Jr. "Climate Modification and a Mathematical Model of Atmospheric Circulation." Proc. of Joint Symposium Commemorating the Centennial of the US Weather Service and Golden Anniversary of the Am. Meterol. Soc., Wash., D.C., *A Century of Weather Progress*, edited by James E. Caskey, Jr. Lancaster Press, 1970, 157–164.

Holloway, J. L. Jr. and S. Manabe. "Simulation of Climate by a Global General Circulation

Model: I. Hydraulic Cycle and Heat Balance." *Mon. Wea. Rev.*, 99/5 (1971), 335–370.

Manabe, Syukuro. "General Circulation of the Atmosphere." *EOS, Transactions Am. Geophys. Union (Meterol.: US National Report, IUGG Fifteenth General Assembly)*, 52/6 (1971), 313–320.

—. "Estimates of Future Change of Climate Due to the Increase of Carbon Dioxide Concentration in the Air." *Man's Impact on the Climate*, edited by W.H. Matthews, W.W. Kellog and G.D. Robinson. Cambridge, MA: MIT Press, 1971, 250–264.

Wetherald, Richard T. and S. Manabe. "Response of the Joint Ocean-Atmosphere Model to the Seasonal Variation of the Solar Radiation." *Mon. Wea. Rev.*, 100/1 (1972), 45–59.

Mahlman, Jerry D. and S. Manabe. "Numerical Simulation of the Stratosphere: Implications for Related Climate Change Problems." *Proc. Survey Conference on the Climatic Impact Assessment Program, Dept. of Transportation Report DOT-TSC-OST-72-13*, (1972), 186–193.

Holloway, J. Leith Jr., M.J. Spelman and S. Manabe. "Latitude-Longitude Grid Suitable for Numerical Time Integration of a Global Atmospheric Model." *Mon. Wea. Rev.*, 101/1 (1973), 69–78.

Manabe, Syukuro and T.B. Terpstra. "The Effects of Mountains on the General Circulation of the Atmosphere as Identified by Numerical Experiments." *J. Atmos. Sci.*, 31/1 (1974), 3–42.

Manabe, Syukuro, D.G. Hahn, and J.L. Holloway, Jr. "The Seasonal Variation of the Tropical Circulation as Simulated by a Global Model of the Atmosphere." *J. Atmos. Sci.*, 31/1 (1974), 43–83.

Holloway, J. Leith Jr. and S. Manabe. "Numerical Simulation of the Seasonal Variation of the Atmospheric Hydrologic Cycle." *J. Phys. Oceanogr.*, 5/1 (1975), 3–29.

Bryan, Kirk, S. Manabe and R.C. Pacanowski. "A Global Ocean Atmosphere Climate Model: Part II. The Oceanic Circulation." *J. Phys. Oceanogr.*, 5/1 (1975), 30–46.

Manabe, Syukuro and R.T. Wetherald. "The Effects of Doubling the CO42554 Concentration on the Climate of a General Circulation Model." *J. Atmos. Sci.*, 32/1 (1975), 3–15.

Manabe, Syukuro and J.L. Holloway, Jr. "The Seasonal Variation of the Hydrologic Cycle as Simulated by a Global Model of the Atmosphere." *J. Geophys. Res.*, 80/12 (1975), 1617–1649.

Manabe, Syukuro. "The Use of Comprehensive General Circulation Modeling for Studies of the Climate and Climate Variation." *The Physical Basis of Climate and Climate Modeling Report of the International Study Conference in Stockholm*, GARP Publication Series 16 (1975), 148–162.

Hahn, Douglas G. and S. Manabe. "The Role of Mountains in the Southeast Asian Monsoon Circulation." *J. Atmos. Sci.*, 32/8 (1975), 1515–1541.

Wetherald, Richard T. and S. Manabe, "The Effects of Changing the Solar Constant on the Climate of a General Circulation Model." *J. Atmos. Sci.*, 32/11 (1975), 2044–2059.

Manabe, Syukuro and J.D. Mahlman. "Simulation of Seasonal and Interhemospheric Variations in the Stratospheric Circulation." Climate of an Ice Age." *J. Atmos. Sci.*, 33/11 (1976), 2185–2217.

Hahn, Douglas G. and S. Manabe. "Reply." *J. Atmos. Sci.*, 33/11 (1976), 2258–2262.

Manabe, Syukuro and D.G. Hahn. "Simulation of the Tropical Climate of an Ice Age." *J. Geophys. Res.*, 82/27 (1977), 3889–3911.

Manabe, S., K. Bryan and M.J. Spelman. "A Global Ocean-Atmosphere Climate Model with Seasonal Variation for Future Studies of Climate Sensitivity." *Dynamics of Atmospheres and Oceans.*, 3 (1979), 393–426.

Hahn, Douglas G. and S. Manabe. "Simulation of Atmospheric Variability." Proc. Fourth Annual Climate Diagnostics Workshop, Inst. for Environ. Studies, Univ. of Wisconsin (1979), 398–402.

Kurbatkin, G.P., S. Manabe and D.G. Hahn. "The Moistening of Continents and the Intensity of Monsoon Circulation." *Meterol. and Hydrol.*, 11/6 (1979), 5–11.

Manabe, Syukuro and R.J. Stouffer. "A CO_2 -Climate Sensitive Study with a Mathematical Model of the Global Climate." *Nature.*, 282 (5738) (1979), 491–493.

Manabe, Syukuro, D.G. Hahn and J.L. Holloway, Jr. "Climate Simulations with GFDL Spectral Models of the Atmosphere: Effect of Spectral Truncation." Proc. JOC Study Conf. on Climate Models: Performance, Intercomparison and Sensitivity Studies, Wash., D.C., edited by W. Lawrence Gates, Garp Publication Series, 22/1 (1979), 41–49.

Manabe, Syukuro and R.T. Wetherald. "On the Horizontal Distribution of Climate Change Resulting from an Increase in CO_2 Content of the Atmosphere." *J. Atmos. Sci.*, 37/1 (1980), 99–118.

Wetherald, Richard T. and S. Manabe. "Cloud Cover and Climate Sensitivity." *J. Atmos. Sci.*, 37/7 (1980), 1485–1510.

Manabe, Syukuro and R.J. Stouffer. "Sensitivity of a Global Climate Model to an Increase of CO_2 Concentration in the Atmosphere." *J. Geophys. Res.*, 85/C10 (1980), 5529–5554.

—. "Study of Climatic Impacts of CO_2 Increase with a Mathematical Model of the Global Climate." *Report from AAAS-DOE Workshop on Environmental and Societal Consequences of a Possible CO_2-Induces Climate Change*, Annapolis, MD: Dept. of Energy, 1980, 127–140.

Wetherald, Richard T. and S. Manabe. "Influence of a Seasonal Variation upon the Sensitivity of a Climate Model." *J. Geophys. Res.*, 86/C2 (1981), 1194–1204.

Manabe, Syukuro, R.T. Wetherald and R.J. Stouffer. "Summer Dryness Due to an Increase of Atmospheric CO_2 Concentration" *Climate Change.* 3/4 (1981), 336–376.

Manabe, Syukuro and D.G. Hahn. "Simulation of Atmospheric Variability." *Mon. Wea. Rev.*, 109/11 (1981), 2260–2286.

Bryan, K., F.G. Komro, S. Manabe and M.J. Spelman. "Transient Climate Response to Increasing Atmospheric Carbon Dioxide." *Science*, 215, (1982), 56–58.

Manabe, Syukuro. "Simulation of Climate by General Circulation Models with Hydrologic Cycles." In *Land Surface Processes in Atmospheric General Circulation Models*, edited by P.S. Eagelson. Cambridge: Cambridge University Press, 1982, 19–66.

Manabe, Syukuro and R.J. Stouffer. "Seasonal and Latitudinal Variatudinal Variation of the CO_2 Induced Change in a Climate of an Atmosphere-Mixed Layer Ocean Model." Proc. DOE Workshop on First Detection of Carbon Dioxide Effects, June 8–10, 1981, Harpers

Ferry, West Virginia, 1982, 79–94.

Manabe, Syukuro. "Comments on Paper—Simulating Seasonal and CO_2-Induced Climate Change with Mathematical Climate Models: Capabilities, Limitations and Prospects by Michael E. Schlesinger." PrO_2 Research Conference and Workshop, Sept. 19–23, 1982, Coolfont, West Virginia, III, 1983, 145–159.

—. "Carbon Dioxide and Climate Change." In *Advances in Geophysics, 25, Theory of Climate*, edited by Barry Saltzman. New York: Academic Press, 1983, 39–84.

Yeh, T.C., R.T. Wetherald and S. Manabe. "A Model Study of the Short-Term Climatic and Hydrologic Effects of Sudden Snow-Cover Removal." *Mon. Wea. Rev.*, 111/5 (1983), 1013–1024.

Spelman, M.J. and S. Manabe. "Influence of Oceanic Heat Transport Upon the Sensitivity of a Model Climate." *J. Geophys. Res.*, 89/C1 (1984), 571–586.

Yeh, T.C., R.T. Wetherald and S. Manabe. "The Effect of Soil Moisture on the Short-Term Climatic and Hydrology Change—A Numerical Experiment." *Mon. Wea. Rev.*, 112/3 (1984), 474–490.

Manabe, S. and A.J. Broccoli. "Ice-Age Climate and Continental Ice Sheets: Some Experiments." *Annals of Glaciology*, 5 (1984), 100–105.

—. "Influence of the CLIMAP Ice Sheet on the Climate of a General Circulation Model: Implications for Milankovitch Theory." In *Milankovitch and Climate, Part 2*, edited by A.L. Berger et al. D. Reidel, 1984, 789–799.

—. "The Influence of Continental Ice Sheets on the Climate of an Ice Age." *J. Geophys. Res.*, 90/C2 (1985), 2167–2190.

Bryan, K. and S. Manabe. "A Coupled Ocean-Atmosphere and the Response to Increasing Atmospheric CO_2." Proceedings of the Liege Colloquium (1984), World Climate Research Programme. *Coupled-Ocean Atmosphere Models*, edited by J.C.J. Nihoul. Amsterdam: Elsevier, 1984, 1–6.

Manabe, S. and R.T. Wetherald. "CO_2 and Hydrology." In *Advances in Geophysics (28), A Climate Dynamics*, edited by B. Saltzman. New York: Academic Press, 1985, 131–156.

Manabe, Syukuro and K. Bryan, Jr. "CO_2-Induced Change in a Coupled Ocean-Atmosphere Model and Its Paleoclimatic Implications." *J. Geophys. Res.*, 90/C11 (1985), 689–707.

Manabe, S. and A.J. Broccoli. "A Comparison of Climate Model Sensitivity with Data from the Last Glacial Maximum." *J. Atmos. Sci.*, 42 (1985), 2643–2651.

Wetherald, R.T. and S. Manabe. "An Investigation of Cloud Cover Change in Response to Thermal Forcing." *Climatic Change*, 8 (1986), 5–23.

Manabe, S. and R.T. Wetherald. "Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide." *Sciences Magazine*, 232 (1986), 626–628.

Broccoli, A.J. and S. Manabe. "The Influence of Continental Ice, Atmospheric CO_2, and Land Albedo on the Climate of the Last Glacial Maximum." *Climate Dynamics*, 1, Berlin: Springer, 1987, 87–99.

Manabe, S. and R.T. Wetherald. "Large Scale Changes of Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide." *J. Atmos. Sci.*, 44 (1987), 1211–1235.

Broccoli, A.J. and S. Manabe. "The Effects of the Laurentide Ice Sheet on North American

Climate during the Last Glacial Maximum." *Geographie Physique et Quaternaire*, XLI/2 (1987), 291–299.

Wetherald, R.T. and S. Manabe. "Cloud Feedback Processes in a General Circulation Model." *J. Atmos. Sci.*, 45/8 (1988), 1397–1415.

Bryan, K., S. Manabe and M.J. Spelman. "Interhemispheric Asymmetry in the Transient Response of a Coupled Ocean-Atmosphere Model to a CO_2 Age Forcing. "*J. Phys. Oceanogr.*, 18/6 (1988), 851–867.

Delworth, T. and S. Manabe. "The Influence of Potential Evaporation on the Variabilities of Soil Wetness and Climate,." *J. Climate*, 1/5 (1988), 523–547.

Manabe, S. and R.J. Stouffer. "Two Stable Equilibria of a Coupled Ocean-Atmosphere Model." *J. Climate*, 2/9 (1989), 841–866.

Delworth, Thomas and S. Manabe. "The Influence of Soil Wetness on Atmospheric Variability." *J. Climate*, 2/12 (1989), 1447–1462.

Stouffer, R.J., S. Manabe and K. Bryan. "On the Climate Change Induced by a Gradual Increase of Atmospheric Carbon Dioxide." *Nature*, 342 (1989), 660–662.

Manabe, S. and A.J. Broccoli. "Mountains and Arid Climates of Middle Latitudes." *Science*, 247 (1990), 192–195.

Manabe, S. and T. Delworth. "The Temporal Variability of Soil Wetness and its Impact on Climate," *Climatic Change*, 16/2 (1990), 185–192.

Manabe, Syukuro, K. Bryan and M.J. Spelman. "Transient Response of a Global Ocean-Atmosphere Model to a Doubling of Atmospheric Carbon Dioxide." *J. Phys. Oceanogr.*, 20/5 (1990), 722–749.

Wetherald, R.T. and S. Manabe. "Hydrologic Sensitivity to CO_2-Induced Global Warming." *Civil Engineering Practice*, 5/1 (1990), 33–36.

Broccoli, A.J. and S. Manabe. "Can Existing Climate Models be Used to Study Anthropogenic Changes in Tropical Cyclone Climate?" *Geophysical Research Letters*, 17/11 (1990), 1917–1920.

Wetherald, R.T., V. Ramaswamy and S. Manabe. "A Comparative Study of the Observations of High Clouds and Simulations by an Atmospheric General Circulation Model." *Climate Dynamics, 5*, (1991), 135–143.

Manabe, Syukuro. "Studies of Glacial Climates by Coupled Atmosphere-Ocean Models: How Useful Are Coupled Models?" In *Global Change of the Past*, edited by R.S. Bradley. Boulder, CO: UCAR/Office for Interdisciplinary Earth Studies, 1989.

Mitchell, J.F.B., S. Manabe, V. Meleshko, and T. Tokioka. "Equilibrium Climate Change and Its Implications for the Future." In *Climate Change, The J.T. Houghton, Scientific Assessment*, edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums. Cambridge: Cambridge University Press, 1990.

Manabe, Syukuro, R.J. Stouffer, M.J. Spelman, and K. Bryan. "Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2, Part I: Annual Mean Response," *J. Climate*, 4/8 (1991), 785–818.

Manabe, Syukuro, M.J. Spelman, and R.J. Stouffer. "Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2, Part II: Seasonal

Response," *J. Climate*, 5/2 (1992), 105–126.

Broccoli, A.J. and S. Manabe. "Reply to Comment by L.L. Evans on 'Can Existing Models Be Used to Study Anthropogenic Changes in Tropical Cyclone Climate?'," *Geophys. Res. Letters*, 19/14 (1992), 1525–1526.

Delworth, T.L., S. Manabe, and R.J. Stouffer. "Interdecal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmospheric Model." Proc. of the Principal Investigators' Meeting, Atlantic Climate Change Program, Miami, March 9–11, 1992. NOAA Climate and Global Change Program, Special Report No. 7, 1992.

Broccoli, A.J. and S. Manabe. "The Effects of Orography on Midlatitude Northern Hemisphere Dry Climates," *J. Climate*, 5/11 (1992), 1181–1201.

Manabe, Syukuro and R.J. Stouffer. "Reply," *J. Climate*, 6/1 (1993), 178–179.

Delworth, T.L. and S. Manabe. "Climate Variability and Land Surface Processes," *Advances in Water Resources*, 16 (1993), 3–20.

Manabe, Syukuro and R.J. Stouffer. "Century Scale Effects of Increased Atmospheric CO_2 on the Ocean-Atmosphere System," *Nature*, 364 (6434) (1993), 215–217.

Delworth, T.L., S. Manabe, and R.J. Stouffer. "Interdecal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmospheric Model," *J. Climate*, 6/11 (1993), 1993–2011.

Broccoli, A.J. and S. Manabe. "Climate Model Studies of Interactions between Ice Sheets and the Ocean-Atmosphere System." In *Ice in the Climate System*, NATO ASI Series, edited by W.R. Peltier. Berlin: Springer, 1993, 271–290.

Manabe, Syukuro and R.J. Stouffer. "Multiple-Century Response of a Coupled Ocean-Atmosphere to an Increase of Atmospheric Carbon Dioxide," *J. Climate*, 7/1 (1994), 5–23.

Manabe, Syukuro, R.J. Stouffer, and M.J. Spelman. "Response of a Coupled Ocean-Atmosphere Model to Increasing Atmospheric Carbon Dioxide," *AMBIO*, 23/1 (1994), 45–49.

Stouffer, R.J., S. Manabe, and K.Y. Vinnikov. "Model Assessment of the Role of Natural Variability in Recent Global Warming," *Nature*, 367 (1994), 634–636.

Knutson, T.R. and S. Manabe. "Impact of Increasing CO_2 on the Walker Circulation and ENSO-Like Phenomena in a Coupled Ocean-Atmosphere Model." Preprints from 6th Conference on Climate Variation, Nashville, TN, 23–28 January, 1994. Boston: American Meteorological Society, 1994.

Knutson, T.R. and S. Manabe. "Impact of Increased CO_2 on ENSO-Like Phenomena in a Coupled Ocean-Atmosphere Model," *Geophys. Res. Letters*, 21/21 (1994), 2295–2298.

Manabe, Syukuro, R.J. Stouffer, and M.J. Spelman. "Interaction between Polar Climate and Global Warming," Fourth Conference on Polar Meteorology and Oceanography, Dallas, TX, 15–20 January, 1995. Boston: American Meteorological Society, 1995.

Delworth, T.L., S. Manabe, and R.J. Stouffer. "Interannual to Interdecal Variability in a Coupled Ocean-Atmosphere Model." Proc. of International Workshop on Numerical Prediction of Oceanic Conditions, Tokyo, Japan, March 7–11, 1995.

Knutson, T.R. and S. Manabe. "Time-Mean Response over the Tropical Pacific to Increased CO_2 in a Coupled Ocean-Atmosphere Model," *J. Climate*, 8/9 (1995), 2183–2199.

Manabe, Syukuro and R.J. Stouffer. "Simulation of Abrupt Climate Change Induced by

Freshwater Input to the North Atlantic Ocean," *Nature*, 378 (1995) 165–167.

Broccoli, A.J. and S. Manabe, J.F.B. Mitchell, and L. Bengtsson. "Global Climate Change and Tropical Cyclones," *Bull. Am. Meteor. Soc.*, 76/11 (1995), 2243–2245.

Wetherald, R.T. and S. Manabe. "The Mechanisms of Summer Dryness Induced by Greenhouse Warming," *J. Climate*, 8/12 (1995), 3096–3108.

Manabe, Syukuro and R.J. Stouffer. "Low-Frequency Variability of Surface Air Temperature in a 1,000-Year Integration of a Coupled Atmosphere-Ocean-Land Surface Model," *J. Climate*, 9/2 (1996), 376–393.

Vinnikov, K.Y., A. Robock, R.J. Stouffer, and S. Manabe. "Vertical Patterns of Free and Forced Climate Variations," *Geophys. Res. Letters*, 23/14 (1996), 1801–1804.

Knutson, T.R., S. Manabe, and D. Gu. "Simulated ENSO in a Global Coupled Ocean-Atmosphere Model: Multi-Decal Amplitude Modulation and CO_2 Sensitivity," *J. Climate*, 9/10 (1996).

Manabe, Syukuro. "Early Development in the Study of Greenhouse Warming: The Emergence of Climate Models," *AMBIO* (1997), (in press).

Milly, P.C.D. and S. Manabe. "The Reduction in Summer Soil Wetness Caused by Increased Atmospheric Carbon Dioxide: Sensitivity to Change in Plant Rooting Depth," *Nature*, (1996).

Broccoli, A.J. and S. Manabe. "Mountains and Midlatitude Aridity." In *Global Tectonics and Climate Change*, 1997.

Manabe, Syukuro and R.J. Stouffer. "Coupled Ocean-Atmosphere Model Response to Freshwater Input: Comparison to Younger Dryas Event," *J. Paleo-Oceanography*, (1997), (in press).

Delworth, T.L., S. Manabe, and R.J. Stouffer. "Multidecal Climate Variability in the Nordic Seas and Surrounding Regions: A Coupled Model Simulation," *Geophys. Res. Letters*, 24 (1997), 257–260.

Manabe, Syukuro and R.J. Stouffer. "Climate Variability of a Coupled Ocean-Atmosphere-Land Surface Model: Implication for the Detection of Global Warming," *Bull. Am. Meteor.* Soc., (1997), (in press).

Haywood, J.M., R.J. Stouffer, R.T. Wetherald, S. Manabe, and V. Ramaswamy. "Transient Response of a Coupled Model to Estimated Changes in Greenhouse Gases and Sulfate Concentrations," *Geophys. Res. Letters*, (1997), (in press).