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REVIEW

Status and Improvements of Coupled General Circulation Models

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Coupled general circulation models (CGCMs) integrate our knowledge about atmospheric and oceanic circulation. Different versions of CGCMs are used to provide a better understanding of natural climate variability on interannual and decadal time scales, for extended weather forecasting, and for making seasonal climate scenario projections. They also help to reconstruct past climates, especially abrupt climate change processes. Model intercomparisons, new test data (mainly from satellites), more powerful computers, and parameterizations of atmospheric and oceanic processes have improved CGCM performance to such a degree that the model results are now used by many decision-makers, including governments. They are also fundamental for the detection and attribution of climate change.

Numerical models integrate our knowledge of certain fields of science, but they can only be as good as our understanding of all the processes involved. For weather and climate models, large-field experiments regarding certain processes and continuous monitoring of three-dimensional (3D) dynamical and thermodynamical structure are required to increase understanding of the variability of the system studied. For long-term simulations of global climate variability and projections of its future changes, a realistic description of all climate system components is needed. Thus, a climate model simulating decades must contain at least a 3D general circulation model (GCM) of the global atmosphere coupled to the 3D world ocean, including sea ice dynamics and a representation of land surface processes (including vegetation). Whether the dynamics of the terrestrial and marine biosphere as well as of the land cryosphere are included depends on the time scale to which such a coupled model is applied. Here I review the status and recent improvements of coupled GCMs (CGCMs) that are now not only important for policy-making but are used for the evaluation of our understanding of many climate processes. They are also applied to make predictions of climate anomalies on seasonal time scales. Thus, we must continuously evaluate and improve the CGCMs we use.

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Historical Development

The development of atmospheric GCMs (AGCMs) for weather forecasting since the 1950s gives a good example of the growing number of processes that need to be included and the system parts needed when forecasting time scales grow.

The weather forecasting models based on

the barotropic vorticity equation that emerged in the early 1950s (*1*) neglected the ocean and all diabatic processes in the atmosphere that drive changes in weather. Nevertheless, they were able to give useful forecasts up to 48 hours in advance solely by analyzing the often rather realistic shift of decaying high- and low-pressure systems that were given as input from a mainly surface-based, synoptic, in situ meteorological network. In the 1960s, larger computers and a growing understanding of baroclinicity (*2*) allowed a breakthrough to the forecasting of newly developing mid-latitude atmospheric disturbances on time scales of up to about 3 days. As in the 1950s, only the dynamics of the atmosphere were modeled and diabatic processes were largely neglected, but in addition to the surface network, the models used the soundings of the troposphere and lowest stratosphere produced by the nearly global radiosonde network, as coordinated by the then-new World Weather Watch Programme of the World Meteorological Organization (WMO). From the radio soundings, differential advection of temperature and vorticity could be derived that determined the development of new low-pressure systems.

The continuous improvement of weather forecasting in the past two decades, which now includes all major diabatic atmospheric processes and thus also air-sea fluxes of radiation, heat, and momentum, has led to useful forecasts of about 8 days in winter. It has also had major consequences for climate modeling. Those improvements include the following:

1) Coupled atmosphere-ocean models such as the ECHAM model of the Max-Planck-Institute for Meteorology in Hamburg, Germany now often use a meteorological forecast center's model dynamical core and some parameterizations of subgrid-scale processes.

2) Through their reanalyses (*3, 4*), the weather forecasting centers provide the most consistent validation data sets for coupled climate models.

3) The breakthrough to predictions of seasonal climate anomalies that is already operational at several meteorological centers (*5*) [especially for areas affected by El Niño–Southern Oscillation (ENSO)] has to a large extent bridged the gap between weather forecast and climate models, because these forecasts combine the integration of nonlinear prognostic differential equations using initial values from observations (as used for weather forecasting) with probabilistic estimates of anomalous weather statistics (climate anomalies).

4) The application of seasonal forecasts in the developing and developed countries will boost the build-up of a global upper ocean observing system and thus will provide a long-needed data set for further improvements of climate models and of ocean GCMs (OGCMs), which will have many more applications than just being part of a climate model.

Evaluation of CGCMs

The second assessment report of the Intergovernmental Panel on Climate Change (IPCC) stated in 1996 (*6*), in an overall assessment of global CGCMs with adequate land surface representation, that those models were able to simulate many aspects of the observed climate with a useful level of skill. At that time, most models applied ocean surface flux adjustments in order to avoid a drift into unrealistic values of basic climate parameters during long-term simulations, and confidence in CGCMs was low. Model evaluation concentrated largely on the CGCM component models of the atmosphere, for which the Atmospheric Model Intercomparison Project, organized by the joint Working Group on Numerical Experimentation of the World Climate Research Programme (WCRP) and the Commission on Atmospheric Sciences of WMO, included virtually all AGCMs existing at this time. IPCC's Working Group I (*6*) therefore could conclude: "Current atmospheric models generally provide a realistic portrayal of the phase and amplitude of the seasonal march of the large-scale distribution of temperature, pressure and circulation." It was noted, however, that clouds and their seasonal cycle were not adequately simulated. The same was true for precipitation, but because almost no observations over oceans were available, it could not be assessed, as was the case for clouds.

If CGCMs had the following four capabilities, there would be greater confidence in the use of CGCMs for the projection of future climates: (i) Adequate representation of the present climate; (ii) reproduction (within typical interannual and decadal time-scale climate variability) of the changes since the start of the instrumental record for a given history of external forcings; (iii) reproduction of a different climate episode in the past as derived from paleo climate records for given estimates of the history of external forcings; and (iv) successful simulation of the gross features of an abrupt climate change event from the past.

If a CGCM reproduces the present climate [for example, does not show large systematic errors in sea surface temperature (SST)], especially the seasonal cycle, and does not need flux adjustments, it has successfully passed step one of the above evaluation but must still not be able to project future climate realistically for a given forcing. At present, many CGCMs, both flux-adjusted and non–flux-adjusted, pass step one; that is, they simulate mean climate and the annual cycle correctly on large scales and approach observed variability on time scales up to interannual.

Some models, when forced by scenarios of external parameters for the 20th century, reproduce the climate variability of recent decades, including the impact of volcanoes such as Pinatubo. Step (ii) of the evaluation is then passed within typical decadal time-scale variability. But the history of solar forcing and processes stimulated by solar forcing are still insufficiently known to justify more model studies.

The third step in evaluating CGCMs lies in simulating a past climate state, preferably one rather different from the present one. Such a test needs many paleo data of high quality, which are available for only a few time slices, such as the last glacial maximum (18,000 to 21,000 years ago) or the warmer period in the Holocene (roughly 6000 years ago). Although paleo data for model evaluation are more abundant for the Little Ice Age period of the Northern Hemisphere than for any other period in the past, this period is not so useful because its climate state differed from the present one far less than that projected in scenarios until the end of the 21st century. In the Paleo Climate Model Intercomparison for AGCMs (*7*), mid-Holocene (6000 years ago) simulations of 18 AGCMs at prescribed SSTs captured the northward extension and intensification of the African Monsoon in the Northern Hemisphere summer. The warmer-than-present conditions in high northern latitudes were also reproduced, but the paleo climate data do not support the modeled drier interior of Northern Eurasia and Northern America, and CGCM runs for the mid-Holocene (*8*) tend to intensify the African monsoon further than is actually seen.

The hardest test for a climate model is the simulation of an abrupt climate change. With the advent of quantitative paleo climate data, mainly the high temporal isotopic compositions of ice cores and sediments (*9*), this test came within reach. Because integrations of high-resolution CGCMs with grid sizes of about 100 km consume too much computer time, only models of intermediate complexity have been used for such tests until now. These models recently partially passed such a test. In addition, their components have to be tested by high-resolution component modules. In the ideal case, deposits with a yearly time resolution such as tree rings, lake varves, coral reefs, and ice cores would constitute the validation database for the evaluation of CGCMs under steps (iii) and (iv) above because isotope ratios in these deposits might even give us patterns that reveal circulation anomalies such as El Niño or the North Atlantic Oscillation. Therefore, a small group of scientists from both the climatological and the isotope community has started to enhance the Global Precipitation Network for Isotopes in Precipitation (GNIP), existing since 1961, to find locations that are especially suited to detect circulation anomalies and to help to better transfer isotope information into climate parameters and vice versa (*10*).

Two climate processes have been considered in particular that lead to abrupt climate change: A major rearrangement of the global thermohaline ocean circulation and the transformation of tropical and subtropical dry savannahs into deserts or even a hyperarid zone, now called the Sahara.

Improved Understanding of Climate Variability or Change

Cold Januarys and wet Julys are manifestations of climate variability that is driven by the nonlinear coupling of system components with strongly differing reaction times. The two most important interactions for climate variability on time scales of weeks to many centuries are ocean-atmosphere and soil-vegetation-atmosphere interactions. Although the first has been investigated intensively for years and coupled climate models are often abbreviated as AOGMCs, parameterization of the land surface processes remained comparably simple in most of these models. Only recently did a more sophisticated treatment of soil water content and the reaction of vegetation cover to changed meteorological parameters become central research topics in the debate over climate variability and change (*11*).

Thermohaline ocean circulation. At present, a major part of the water in the ocean interior had its last contact with the atmosphere up to hundreds of years ago in the Greenland-Iceland-Norwegian seas or the Labrador Sea. The high salinity of North Atlantic water and the cooling near the edge of the sea ice in winter and early spring lead to deep subsidence of dense surface waters. These waters then form North Atlantic Deep Water (NADW), a major portion of the global ocean. NADW reaches all ocean basins as part of the global ocean conveyor belt. In climate history, several events in which this deep convection was stopped abruptly (as revealed from ice cores and deep sea sediments) are known (*12*), and the strong climate shifts associated with it are documented for the North Atlantic region and beyond. Up to now, modeling of these events has generally been performed with coupled models of intermediate complexity (*13*, *14*) that have been calibrated in their system component modules by higher-resolution AGCMs and OGCMs. The harder test of a higher-resolution fully coupled model (a CGCM) is still not available. Whether current models of intermediate complexity can model abrupt climate change is answered by (*15*) with a partial yes: "The necessary physics are in these models and allow for thresholds and switches of the thermo-haline circulation. However, their location on the hysteresis now and in the past and the likely evolution in the future are unknown because we do not know whether there are additional stabilizing or destabilizing processes that we must take into account."

The strong interest in thermohaline circulation changes in the past arose with the observation in CGCM runs that deep water formation in the high-latitude North Atlantic would shrink or even stop if there were an enhanced greenhouse effect in the atmosphere (*16*). However, a mechanism not included in these models may dampen the entire discussion (*17*). Because most CGCMs used so far for such long-term integrations do not reproduce ENSOs as well as (*17*), mainly because of higher spatial resolution (0.5° latitude) in the tropics, the earlier studies underestimate increased evaporation in the tropical Atlantic for more El Niño–like events in the transient climate change runs, and thus also underestimate surface salinity in the Atlantic. Increased computing power may help solve this climate change research problem.

Positive vegetation feedback. Vegetation strongly modifies surface energy fluxes as compared to bare soil. Thus, it has the potential to strongly influence regional and global climate. Models of intermediate complexity have recently been used (*13*) in which vegetation is interactively modifying local, regional, and global climate.

One of the main results is a general enhancement of the monsoons during the warmer part of the Holocene about 6000 years ago, underlining the positive feedback of vegetation and explaining, for example, the dry savannah area in what is now the Sahara desert simply as the result of radiative forcing due to higher insolation in the Northern Hemisphere summer as compared to present conditions. Also, the interaction between earth orbital parameters, ocean, and vegetation can explain strong high northern latitude warming in the Eemian interglacial about 125,000 years ago (*13*). The main reason for the positive feedback of vegetation is the drastic surface albedo change of up to 50% during the snow-covered period of the year when tundra is replaced by taiga, as well as snow cover lasting into high-insolation springtime at these latitudes.

Projections of Global Climate Change

A realistic projection of future climate would need as input a scenario of anticipated human behavior in order to get realistic time series of emissions into the atmosphere and of land use changes as forcings of a CGCM. These time series ought to contain changes caused by human reactions to discussions about climate change and later to emerging climate change, as these feed back to emissions and land use patterns. The projections of 21st-century climate given in the scientific literature and the assessments thereof by IPCC (*6*) cannot come close to this goal because most existing emission scenarios apply either rather crude extrapolations [for example, a 1% increase of equivalent CO_2 concentration per year (combining the effect of all anthropogenic greenhouse gases)] or CO_2 concentration curves determined by choosing a climate management goal, such as that stipulated in the United Nations Framework Convention on Climate Change [for example, 550 parts per million by volume (ppmv) CO_2, not to be exceeded in the 21st century]. However, many relevant questions can be addressed by mere climate modeling, such as the sensitivity of the climate system to a given forcing, whether high-latitude areas will experience a doubled or even greater warming as compared to the global average, how precipitation—the most important climate parameter for most societies—will change, or whether sea level rise will accelerate.

The Coupled Model Intercomparison Project (CMIP) has helped to assess the performance of about 20 coupled models (*18*), giving a more reliable range of answers than was known for IPCC's second assessment report (*6*).

Many CGCMs now show ENSO events; that is, the irregular, interannual climate variability originating in the tropical Pacific, the more so if run with higher latitudinal resolution in the tropics (*19*). This lends more credibility to models used for projections of climate change because model variability approaches observed climate variability on seasonal-to-decadal time scales (*20*) that is mainly due to ocean-air interaction. However, because nearly all the models run without variable solar and volcanic forcing, they should not yet fully reach observed variability on time scales of up to decades. On the other hand, low model variability would give high probabilities for the detection of anthropogenic climate change too early.

The sensitivity of model equilibrium to an external forcing cannot be derived from a century time scale CGCM run because the full adaptation of the global ocean to such a forcing takes up to several millennia. Therefore, sensitivity is still derived from so-called equilibrium mixed layer models, in which an atmospheric GCM is reacting to doubled CO_2 concentration and only an ocean mixed layer model fully reacting over decades is coupled to the model atmosphere. In 1999, Le Treut and McAvaney (*21*) reconsidered 10 such model combinations and found an average warming of 3.3 ± 0.8 K and a precipitation increase of $6.3 \pm 3.6\%$ for a doubled concentration of CO_2 ($2 \times CO_2$). Compared to IPCC's second assessment report (*6*), mean temperature sensitivity decreased slightly from 3.8 K (for 17 models) to 3.3 K (for 10 models). Therefore, it is unlikely that this estimate will change greatly in the upcoming third assessment report of IPCC. The large range can only be reduced substantially if two questions are answered: How strong is the water vapor feedback on average? Will clouds, that cool on average now, give up part of this cooling and thus amplify the warming or will they damp? The answer is subject to better observations of the 3D distribution of liquid water, ice, and water vapor that could come only from new satellite sensors (*22*). Support for the large mean temperature reaction of about 3 K to 2 × CO_2 in model projections of future climate comes from another type of model experiment. Mixed layer ocean models coupled to atmospheric models for the last glacial maximum need a 2 × CO_2 sensitivity of about 3 K to bring ocean surface temperatures near the ones derived from paleo information (*7*).

There is, as already mentioned, agreement on increased mean global precipitation if the surface of the water planet Earth warms. However, of greater importance are the questions of where precipitation falls, at what rate, and when. An increased precipitation rate over many land areas is a general CGCM result, as is more precipitation in high northern latitudes and the inner tropics. An increased precipitation intensity and longer time periods without precipitation are of major consequence for many rural societies not only because they depend on rain-fed agriculture but also because the infrastructure protecting them against flash floods is often weak. In one model (*23*), the return period (the time needed on average for another extreme event of the same magnitude) for the present-day 20-year extreme of daily precipitation would shrink nearly everywhere and could reach 10 years over North America in a 2 × CO_2 climate.

If climate change were reducing the variability of precipitation and temperature, a mean global warming at the surface as the consequence of an enhanced greenhouse effect would not intimidate many people. Because variability changes are more important than shifts in mean values, the width and the shape of probability distribution functions must be assessed in climate change scenarios. As Fig. 1 shows, even a stable shape of the distribution function must cause new extremes on one side when the mean value shifts. Because our infrastructure is normally not adapted to these new extremes, dikes and dams could break more often. However, if the distribution function broadens—that is, the standard deviation grows—even more new investment in better infrastructure would be needed, and so-called natural disasters such as flooding and drought would more often be human-made. For precipitation, most models (*6*, *21*, *24*) and observations show a broadening of the distribution function, leading to more frequent major precipitation events. Because most impact studies (for example, those treating agricultural yield) do not include a changed precipitation rate distribution that is shifted to more extreme single events with nearly none or a moderate increase in total amount, they need to be repeated.

We also still have to wait for answers to the following questions on weather extremes in a changed climate: Will northern midlatitude storms intensify, and how will their main tracks shift? Will tornadoes and thunderstorms become less frequent but more violent or vice versa? Will tropical cyclones be less frequent but more intense if the ocean surface warms in the tropics?

Regional Modeling

The highest spatial resolution of CGCMs is still coarse at present (≥100 km), and many small-scale processes will remain unresolved for many years to come. Thus impact studies, especially in areas with strongly varying topography or a mix of surface types, are hampered. Therefore, regionalization of global model data via empirical-statistical, statistical-dynamical, and dynamical downscaling (*25*) will not only be necessary but will become even more important with the growing reliability of global models. Regionalization of climate anomaly predictions and of climate change projections is now in a stage of rapid development because CGCMs have improved and more downscaling methods are available. A major push in this context has been reanalyses by the major numerical weather prediction centers (*3*, *4*) because they allow the consistent empirical-statistical, statistical-dynamical, or dynamical downscaling of large-scale variables to local surface variables. These regression relations or imbedded regional climate models can then be used for the regionalization of global climate change projections that is needed to derive a certain more localized impact. If these strongly differing local or regional variables under a changing climate are used to run an impact model, we have created added value by regionalization.

An impressive example of the possibilities that regionalization of GCM results opens up was recently given (*26*). Statistical downscaling was used to convert large-scale circulation parameters from the global European Centre for Medium Range Weather Forecasting (ECMWF) reanalysis (*4*) into local meteorological variables in a Scandinavian mountain area. The resulting parameter values compared well with local observations. Then these local variables were derived again, but from a 10,000-year run of an AGCM coupled to a mixed layer ocean, and were fed into a glacier model simulating the mass balance and length of several glaciers over thousands of years. The conclusion of this study is, as demonstrated in Fig. 2, that the length variations of the Nigaardsbreen and Rhone-Gletscher glaciers were outside the internal variability range only for the recent major retreat since 1850. But all fluctuations, including those during the Little Ice Age in Europe, as partly recorded for the two glaciers mentioned, were not significantly different from mere natural internal climate variability.

Detection of Change and Attribution to Causes

The detection of climate change caused by a certain external forcing factor is made difficult by large internal variability. Although detection only requires that observed changes be significantly above natural variability, ideally attribution should be the result of careful experimentation, including variable forcing histories. A less demanding minimum requirement for attribution is to show that the observed change in patterns and seasonal cycles is reproduced in CGCMs given all forcings. Despite numerous statistical detection studies available until 1995 that only evaluated observed temperature time series and a few studies using CGCMs together with fingerprint methods, the second assessment report by IPCC (*6*) could only conclude that "the balance of evidence suggests a discernible human influence on global climate." The main reasons for this "soft" statement were, first, an inadequate history of the forcing by volcanoes, the sun, and anthropogenic aerosols needed to drive climate models; second, lack of thorough assessment of modeled climate variability on time scales up to several decades; third, gaps in long-term global observations of

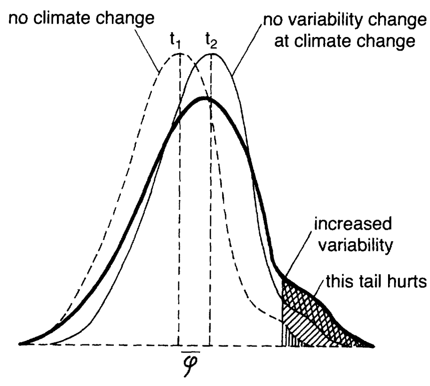

Fig. 1. Schematic representation of changes in the frequency distribution of a meteorological parameter caused by climate change. Even if the distribution (variability) does not change at time t_2, new weather extremes must be observed on one side (hatched portion). If variability increases, as observed for precipitation, rare earlier events become much more frequent and many more new extremes will be observed (double-hatched portion).

key climate parameter time series; and fourth, the wide span of climate system sensitivity estimates of responses to external forcing. The rare application of the optimal fingerprint method (*25*), which detects patterns of change that are due to a certain influencing factor, also contributed to the cautious statement.

Has the situation changed? The answer is yes because improved data and methods can be reported now:

1) CGCMs have been run with forcings by solar and volcanic variability (*27*), different greenhouse gases, and sulfate aerosols. All results point to an anthropogenic contribution, especially in the latter part of the 20th century.

2) Both paleoclimatic reconstructions of the past millennium and new estimates of climate variability in CGCMs show that the observed average warming in the 20th century is significantly above natural variability (*20*, *28*).

3) Several studies applying fingerprinting with both fixed and time-dependent multiple signal patterns (*29*) to CGCM runs with natural plus anthropogenic forcings conclude that only the combined action of greenhouse gases and tropospheric sulfate aerosols can explain the observed record, especially during the recent decades.

Obviously, the uncertainties surrounding the detection of climate change and the attribution of the observed change to certain forcings have shrunk since 1995.

Remaining Uncertainties

Understanding of the evolution of a complex system will always be incomplete, especially if the system shows large state changes caused by minor shifts of external forcing or small internal fluctuations. Earth's climate has experienced such changes in recent history (during the past few million years), which were to a large extent stimulated by small changes in Earth's orbit around the sun that were mainly caused by the neighboring large planets Jupiter and Saturn (*30*). Concerning rapid changes—that is, state transitions within decades or centuries, called bifurcations in mathematics—we know of several events of one type (cessation of NADW formation, caused by freshwater pulses entering the northern North Atlantic from melting or surging of ice sheets), and we have ourselves inadvertently started and then tried to stop another one: stratospheric ozone depletion by catalytic chemical reactions involving the chlorine freed from chlorofluorocarbons when dissociated by solar ultraviolet radiation in the stratosphere (*29*). The observed depletion of ozone has caused a cooling of the lower stratosphere that has repercussions for the debate on warming caused by increased greenhouse gas concentrations (*30*).

For both abrupt climate change processes we have at least a qualitative understanding, [that is, we can model the principal features of the events (*31*) or processes], but concerning NADW formation, we do not know how near we are to such an event or whether we are driving toward it (*32*). Another major uncertainty lies in the broad range still given for climate sensitivity to long-wave radiative forcing by increasing greenhouse gas concentrations in the atmosphere. I see no indication that the next IPCC assessment will strongly reduce the range given in 1996 (*6*): that the full reaction of the climate system to a doubling of CO_2 (from 300 to 600 ppmv) will lie between a 1.5 and 4.5 K increase in global mean near-surface air temperature. Unless we have measurements of the vertical profiles of liquid water, ice, and aerosols in the atmosphere, we will not be able to improve cloud parameterizations used in CGCMs to such a degree that a significantly smaller range would emerge. We may see better CGCM simulations due to strongly improved cloud parameterizations in about 5 years when new satellite sensors will allow profiling in the atmosphere (*22*). However, if one looks at the response of CGCMs to a transient forcing, differences between models are smaller.

A further major uncertainty remains the substantiation of the indirect aerosol effect on clouds in models (*33*); that is, the change in optical and precipitation properties of clouds caused by a changed spectrum of cloud condensation nuclei. This indirect effect is mainly due to the emission of precursor gases such as sulphur dioxide (SO_2), nitrogen oxides ($NO + NO_2$), ammonia (NH_3), and hydrocarbons, which are transformed chemically into

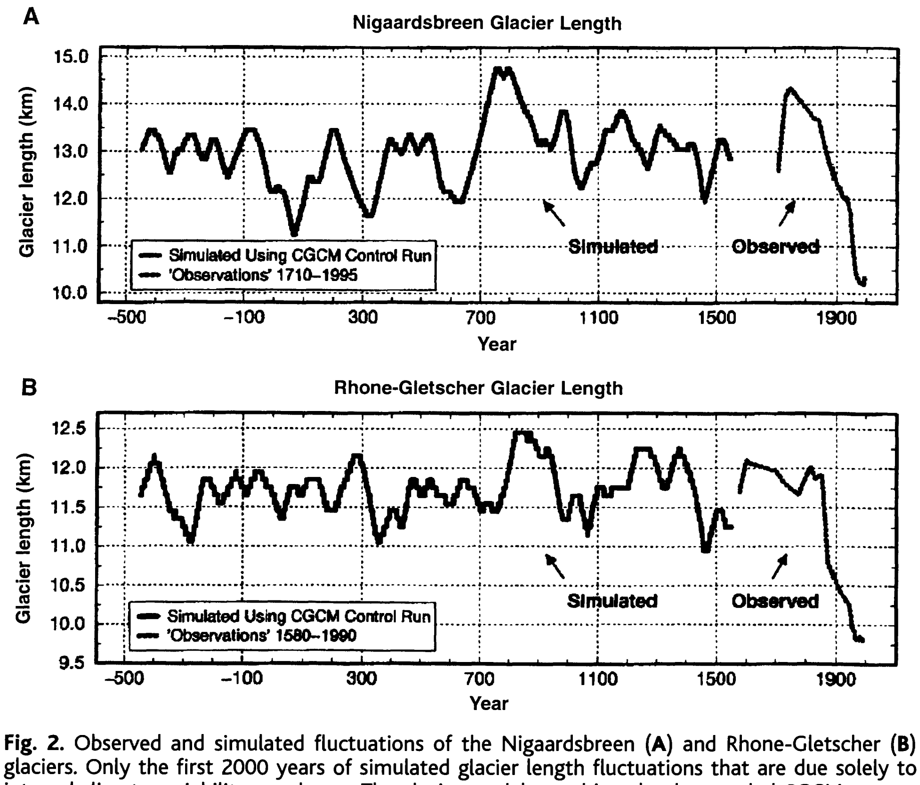

Fig. 2. Observed and simulated fluctuations of the Nigaardsbreen (**A**) and Rhone-Gletscher (**B**) glaciers. Only the first 2000 years of simulated glacier length fluctuations that are due solely to internal climate variability are shown. The glacier model was driven by downscaled CGCM output.

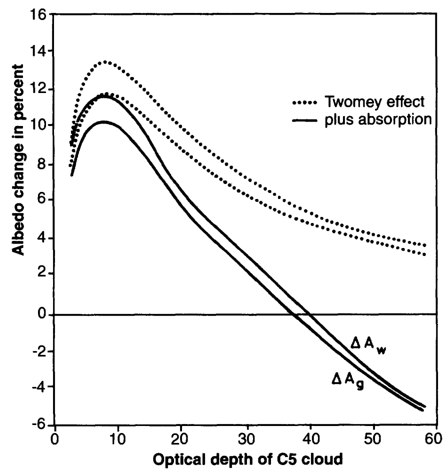

Fig. 3. An "old" simulation of the indirect aerosol effect (here, cloud albedo change) from 1978 (*34*), including both the Twomey effect (higher albedo caused by more cloud droplets at unchanged liquid water content) and increased absorption by soot. The transition from a marine low-level water cloud (C5) to a continental one (C1) can lead to lower albedo at increasing geometrical or optical depth because of increased absorption. Not yet included in CGCM runs, increased absorption could strongly reduce the overall indirect aerosol effect, largely depending on the amount of soot and how soot absorbs in clouds.

small aerosol particles that grow by coagulation into the cloud condensation nucleus range. But directly emitted black carbon (soot) particles and other carbonaceous particles that absorb solar radiation are also important (*34*). Typical shifts from maritime to continental water clouds (*35*), which mimic a pollution effect (Fig. 3), could reduce cloud albedo for clouds exceeding a vertical extent of about a kilometer, counteracting the cloud albedo increase for less thick clouds.

Looking at global climate evolution from a very long-term perspective, it is surprising that despite major glaciations, an Earth mostly without continental ice sheets, a sun with increasing luminosity, and a 10-fold variation in atmospheric CO_2 content mean surface temperature has remained in comparably narrow bounds of about ± 5 K as compared to the present mean. We need to understand the negative feedback that stabilizes climate and thus keeps Earth a living planet.

Outlook

In about a decade, coupled atmosphere-ocean-land models (CGCMs) assimilating near–real-time data from the global observing system (including the ocean interior) will (i) predict the probability of certain climate anomalies, to the extent possible, for many regions over season(s), year(s), and possibly even a decade; (ii) allow the attribution of a large part of observed climate variability and change to natural and/or anthropogenic causes; (iii) project future climate more realistically and thus allow better regional projections of climate change impacts; and (iv) be a firmer basis for Earth system models that describe the feedbacks of societies to climate anomaly predictions and emerging climate change patterns.

The improvement process for climate models that is needed for such applications will continue as it rests on pillars needed for other purposes. These pillars, roughly ordered according to their strength, are:

1) More and as well as more precise global observations of the composition, thermodynamic structure, and dynamics of the atmosphere as well as of ocean and land surface parameters through satellite remote sensing, partly offsetting the often shrinking in situ network. These data sets (*36*) are ideal for model evaluation and will soon also allow the testing of climate model performance in an event-based mode, not only for time averages.

2) Improved parameterizations of physical and chemical processes in the atmosphere and at the global surface, especially for clouds and vegetation. Examples of where we need strong improvements are in determining mean cloud albedo as a function of the amount of liquid water or ice in a model grid volume, depending on aerosol type and loading, and determining evapotranspiration from a mixture of surface types in complex terrain.

3) The growth of computing power by about an order of magnitude every 6 years, if current trends continue. More oceanic and atmospheric processes will thus become resolved and need no longer be parameterized.

4) Assimilation of all, including asynoptic, observations into forecast or climate models that not only assign values to grid points without nearby observations and discard observations exceeding prescribed error limits but also create a physically consistent starting field for a forecast or a validation data set for a climate model. This holds for land surfaces, the atmosphere, the upper ocean, and the cryosphere.

5) More sophisticated numerical techniques that need less computer time despite improved descriptions of advection and diffusion, thereby not requiring 16 times more computing power if the grid size is halved, but only about 10 times more.

CGCMs will become a primary tool delivering policy-relevant information to many types of decision-makers, including governments. We scientists should create networks of climate research centers across national borders and intensify cooperation with operational weather and climate forecasting centers in order to accelerate progress in understanding the functioning of the Earth system and to better exploit the possibilities for disaster prevention and management. The existing Global Change Research Programmes (*35*) need not only to cooperate, as they do already to a large extent, but they need the infrastructure to do so effectively. This cooperation and networking would facilitate worldwide dissemination of information and foster further progress.

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35. WCRP, the International Geosphere/Biosphere Programme (IGBP), and the International Human Dimensions Programme (IHDP) on Global Environmental Change already jointly sponsor the Global Change System for Analysis, Research and Training, which establishes research networks in large regions (such as Southeast Asia, northern Africa, and southern Africa) and promotes projects such as Climate Predictions for Agriculture. However, the infrastructure (an international secretariat and international project offices) is weak for IHDP, and IGBP is also weak in terms of project offices. A fourth program, called DIVERSITAS and devoted to biodiversity, does not yet have what one can call a functioning infrastructure.
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REVIEW

Is El Niño Changing?

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Recent advances in observational and theoretical studies of El Niño have shed light on controversies concerning the possible effect of global warming on this phenomenon over the past few decades and in the future. El Niño is now understood to be one phase of a natural mode of oscillation—La Niña is the complementary phase—that results from unstable interactions between the tropical Pacific Ocean and the atmosphere. Random disturbances maintain this neutrally stable mode, whose properties depend on the background (time-averaged) climate state. Apparent changes in the properties of El Niño could reflect the importance of random disturbances, but they could also be a consequence of decadal variations of the background state. The possibility that global warming is affecting those variations cannot be excluded.

The two most intense El Niño episodes in more than a century occurred during the past two decades, in 1982 and 1997. Whether these exceptional warmings of the eastern tropical Pacific Ocean and the associated changes in global weather patterns were manifestations of global warming and how the continual rise in the atmospheric concentration of greenhouse gases will affect El Niño in the future are issues currently being debated. The disagreements mainly concern the causes of the irregularities in the continual climate fluctuation, the Southern Oscillation, between complementary El Niño and La Niña states. This natural mode of oscillation, attributable to ocean-atmosphere interactions in which the winds create sea surface temperature gradients that in turn reinforce the winds, plus negative feedbacks involving the dynamical response of the oceans to changes in the winds, is neutrally stable, so that random disturbances contribute to its irregularities. Other causes for variations in the properties of this mode (and more generally of a spectrum of possible modes including those involved in the seasonal cycle) include changes in the background climate state, which is described by factors such as the intensity of the time-averaged trade winds, τ, and the spatially averaged depth of the thermocline, H. Changes in that state can explain why El Niño has different properties in paleorecords from different times and why it appears to be changing gradually in response to the decadal fluctuation that modulates the background state in records for the past century. That fluctuation, which brought relatively weak trade winds and unusually warm surface waters to the eastern equatorial Pacific in the late 1970s, is of uncertain origin, but it could be under the influence of global warming. Different climate models differ in their assessment of how that warming will affect El Niño because they reproduce different background states for the future.

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Atmospheric Aspects

The Southern Oscillation, the dominant signal in Fig. 1A, shows sea surface temperature variations as measured on the equator to the west of the Galapagos Islands. (The seasonal cycle and higher frequency variations are filtered out.) Figure 1, B and C, depicts conditions at the peaks of particularly intense El Niño and La Niña episodes. Such changes in sea surface temperature have a profound effect on climate throughout the tropics because, in low latitudes, the correlation between sea surface temperature and rainfall patterns is almost perfect: Moist air rises spontaneously into cumulus towers over the warmest regions, which therefore have plentiful rainfall; aloft, the air that has been drained of its moisture diverges from these regions and subsides over the colder regions that get little precipitation. Surface winds, the trades in the case of the Pacific, restore moisture to the air by means of evaporation while returning it to the warmest regions. These direct thermal circulations are controlled by surface temperatures, so changes such as those in Fig. 1 substantially alter rainfall, winds, and other atmospheric variables.

During La Niña, the trade winds are intense, and heavy rains fall mainly over the far western tropical Pacific; during El Niño, the winds relax and the heavy rains move eastward, so that the coastal zones of Ecuador and Peru have severe floods, whereas New Guinea and Indonesia experience relatively dry conditions. The expanse of warm waters in the Pacific during El Niño is so vast and causes such a huge increase in evaporation from the ocean (and hence in the release of latent heat in the atmosphere when the water vapor condenses to form clouds) that weather patterns are affected globally. Numerical models of the atmosphere that are used to predict the weather (those with forecast skills that are limited to a few days at most) are capable of reproducing realistically and deterministically the atmospheric aspects of the Southern Oscillation over extended periods of several decades, provided that the observed sea surface temperature variations of the tropical Pacific are specified as boundary conditions. (Calculations in which the boundary conditions correspond to the climatological seasonal cycle fail to simulate the Southern Oscillation.) This means that it is possible to predict certain time-averaged atmospheric conditions indefinitely into the future, provided that we know how sea surface temperatures will vary (*1, 2*). From an atmospheric perspective, the problem appears to be oceanographic.