Global climate change: facts, hypotheses, and prospects of development

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Global climate change studies are reviewed in the context of Intergovernmental Panel on Climate Change Report (IPCC) 2001 and U.S. National Academy of Sciences "Climate Change Science." It is shown that these reports are incomplete because they overlook a number of key aspects of the problem (the concept of biotic regulation of environment, interaction of processes in the climatic system, unexpectedly strong paleoclimatic change, the role of solar activity, etc.). Priorities in future studies of the global climate change are outlined.

Introduction

Serious attention to the problem of global climate warming has not resulted yet in a consensus about the causes of contemporary climate change and, especially, climate prediction up to a century into the future (see, e.g., Refs. 1–93).

In this regard, of special concern is the fact that the existing observation systems still remain inadequate.[8,42,57,73] The discussion of the problem has already reached the level of such worldwide forums as the Second United Nations Conference on Environment and Development (COED) (Rio de Janeiro, 1992), and then the Special Session of United Nations General Assembly Rio+5 (New York, 1997), and World Summit for Sustainable Development Rio+10 (WSSD) (Johannesburg, August 26 – September 4, 2002).[8] It has been agreed to held the World Climate Conference in Moscow in 2003. A clear and right statement made by the U.S.A. president that the Kyoto Protocol (KP) is unacceptable, has further quickened the interest to the problem of global climate warming. Since the Kyoto Protocol has already been considered in detail earlier,[2,7,8] the discussion here will be restricted by two new documents,[28,31] which determine the necessity "to set all points over i" once again.

Some considerations and estimates contained in a conceptual memorandum prepared by Commission on Sustainable Development for discussion at WSSD as a key summit document, give rise to serious bewilderment. With reference to Millenium Declaration approved by United Nations, the memorandum calls for undertaking all necessary measures to ensure a sooner coming into force the Kyoto Protocol, desirably by 2002, the tenth anniversary of COED, including the KP requirements to reduce greenhouse emissions to the atmosphere.

Arguments, voiced earlier,[2,5,7,57] against the Kyoto Protocol, can be summarized as follows.

1. This document rests on misunderstanding that the contemporary climate change is mainly anthropogenically induced (sometimes it is claimed to be almost entirely anthropogenic); whereas it is undoubtedly realized that convincing *quantitative* estimates of how the observed climate forcing contributes into natural and anthropogenic factors are still absent. Estimates of internally caused changes of the climatic system, based on the use of numerical simulation, remain controversial.

2. To estimate future climate change, it is necessary to specify the growth of the CO_2 concentration (as most significant greenhouse gas) in the atmosphere. Generally, constant increase of CO_2 (until the end of the 21st century), of 1% per year, is arbitrarily assumed. However, a reliable prediction of the CO_2 dynamics can be made only on the basis of interactive numerical simulation of long-term global climate changes and carbon cycle. Unfortunately, this task is not accomplished yet, and only the first steps are taken in this direction. Rough estimates obtained by Demirchan et al.[2] taking into account the proposed growth of the global human population indicate that the assumed 1% increase of the CO_2 concentration is far overestimated. Undoubtedly, useless (and rather misleading) is the use of the notion of net emissions, introduced recently and taking into account not only greenhouse emissions, but also indirect influence on them of forest dynamics and land management, primarily because any reliable estimates of the net emissions are impossible (this means, in addition, that the reasoning on trade in emissions is fruitless).

3. As approximately estimated by Wigley,[91] complete fulfillment of recommendations of Kyoto Protocol will ensure only negligible reduction of globally mean near-ground air temperature (NAT). In this regard, a frequently used argument in favor of KP, justifying it as a first step, does not stand up, since even this first step (whose specific goals, above all, are unclear) is very costly for economics, with no justification of subsequent steps. A serious contradiction is contained in the fact that the document[31] defines the economic growth as a main factor of sustainable development. Quite in reverse, an

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observed consequence of economic growth is the increase of greenhouse concentration not only in such developing countries as China and India, but also in many industrially developed countries including United States. According to data of European Environmental Agency (EEA), the CO_2 emissions for period 1990–2000 have increased by at least 14%.

A change-over from coal to natural gas in Great Britain resulted in a considerable reduction of CO_2 concentration in the atmosphere (observed to be 7% lower in 2000 than in 1990); but, on the other hand, in 2000, the 1.2% increase of emissions took place. Nine countries of European Economic Community (EEC) are still far from achieving KP goals. For instance, CO_2 emissions in Spain in 2000 by 33.7% exceeded the 1990 level. Deindustrialization of East Germany furnished a 19.1% reduction of emissions in Germany. On the whole, it is quite obvious that EEC countries are incapable of implementing the KP recommendations. This clearly illustrates that the recommendations contained in Kyoto Protocol are unrealistic.

I. Most important questions concerning climate change

In the context of problems under discussion, of special interest is the conceptual document "Climate Change Science," prepared by Climate Change Science Committee of the U.S. National Academy of Sciences (chaired by professor Cicerone from University of California) on behalf of administration of U.S. president.[28] This document answers the questions posed by its authors and considered as most important. The authors[28] start with the following fundamental statement:

"As a result of economic human activity, greenhouse gases build up in the atmosphere, causing increase of near-ground air temperature and subsurface temperature of the ocean. Gradual temperature increases do occur. The changes observed during several recent decades seemingly are associated with economic human activity, though the fact that a certain significant part of these changes is also a reflection of naturally caused variability cannot be totally ruled out." Even though such modest statements are quite adequate (the main problem, as was already mentioned above, is that there are no quite reliable estimates of relationship between the natural and anthropogenic factors of climate change observed during last 100–150 years), the next phrase of the cited document arouses our bewilderment[28]: "It is expected that the anthropogenic warming and the associated increase of sea level will continue through the 21st century," indicating that the authors[28] actually rest upon the same wrong concept of greenhouse warming as does the UN document.[31]

Far more prudent estimates are made in the WMO Statement,[91b] where the importance of connection between climate change and El Niño/Southern Oscillation (ENSO) event is specially emphasized. Also of importance is the fact that 2001 was the last year of unusually long period of La Nina (cooling) phenomenon started in the middle of 1998. It is noted in Ref. 91b that, whereas since 1900 the globally mean NAT increased by 0.6°C per century, after 1976 the rate of the increase was approximately three times faster. In 2001, the globally mean NAT was 0.42°C higher than the 1961–1990 norm. The warming was most appreciable (0.67°C) at extratropical latitudes of the northern hemisphere (>20°N); at the same time, in some regions of the northern hemisphere a winter cooling was observed. The NAT was found to be no more than 1°C lower than the mean temperature on the most part of the U.S.A.; and in most regions of Russia this cooling anomaly exceeded 3°C. We, however, turn to discussion of the questions posed in Ref. 28.

1. What is the range of naturally caused climate variability?

It is clear that the question of the range of naturally caused variability of globally mean climatic parameters (the near-ground air temperature (NAT) is commonly considered) cannot be answered because of absence of necessary observational data. However, it can be firmly concluded from the analysis of indirect paleoclimatic data that the climate changes in the past (on a timescale from a season to the whole period of the Earth evolution) exceeded by an order of magnitude those observed over the last 100–150 years. According to Ref. 29, the globally mean annually mean NAT has increased by (0.6±0.2)°C. An important conclusion from the recent paleoclimatic studies[75] is that not only large climatic changes, but also abrupt (fast) variations on a decadal (or lesser) time scale took place in the past. As noted in Ref. 29, the last ice-age was followed by global warming of 2°C per thousand years.

2. Do the rates of increasing the greenhouse gases concentration and other emissions into the atmosphere, affecting the climate, accelerate, and how do the corresponding rates differ? Is their increase anthropogenically induced?

Whereas in preindustrial era the concentration of such a significant greenhouse gas as CO_2 changed from approximately 190 ppmv during ice-age to 280 ppmv during interglacial eras, later on a monotonic increase of the CO_2 concentration of about 1% per year was observed until 1998. Then the CO_2 growth decelerated, and in nineties it became irregular. Presently, the CO_2 concentration is approximately 370 ppmv and increases at a rate of about 1.5 ppmv/yr under impact of anthropogenic CO_2 emissions into the atmosphere, primarily due to fossil fuel combustion. The other greenhouse gases to be taken into account include methane (two thirds of which have anthropogenic origin), tropospheric ozone, nitrous oxide, and chlorofluorocarbons.[5]

3. What is the contribution of other greenhouse gases (such as carbon oxide) and sulfate/soot aerosols in climate change?

In this regard, the contribution of aerosol is most uncertain; although it is assumed that, in the whole, aerosol is responsible for the effect of climate cooling. If the direct radiative forcing due to sulfate aerosol (the radiative forcing is defined as a perturbation of earth radiation balance) is estimated in the range from −0.6 to −1.0 W/m^2, then in the case of soot aerosol it is 0.1–0.2 W/m^2. Difficult to estimate, the indirect aerosol effect on climate (through a change of microphysical and radiative properties of clouds) may reach negative values of the radiative forcing of the order of more than −1.0 W/m^2. There is no doubt that organic and dust aerosols must be taken into account.

4. How much time will it take to mitigate the accumulation of greenhouse gases and other emissions in the atmosphere, and what are the corresponding characteristic times?

A partial answer to this question is contained in the data of Table characterizing the lifetimes of greenhouse gases and aerosol, as well as radiative forcing (until 2000).

Characteristic lifetimes of greenhouse gases and aerosol, as well as radiative forcing

Constituent	Lifetime*	Radiative forcing, W/m^2
Greenhouse gases:		
carbon dioxide	> 100 years	1.3–1.5
methane	10 years	0.5–0.7
tropospheric ozone	10–100 days	0.25–0.75
nitrous oxide	100 years	0.1–0.2
chlorofluorocarbons (including SF_6)	< 1000 years	0.01
Finely dispersed aerosol		
sulfate	10 days	−0.3 to −1.0
black carbon	10 days	0.1–0.8

* Lifetime of 100 years implies that most share of this constituent will be removed from the atmosphere during this period. For instance, 37% will remain by the end of the hundredth year, 14% after 200 years, 5% after 300 years, and 2% after 400 years.

5. Do any (and what if any) climate changes occur?

This question has, of course, a clear answer: the global climate changes always took place in the past and, undoubtedly, they will take place in the future.[4] As was already noted above, the global warming in the twentieth century was (0.6±0.2)°C; but, very importantly, it was not monotonic.[4] Most warming took place prior to 1940 and in a few last decades. In the period 1946–1975, a slight cooling was observed in the northern hemisphere, and, however, very strong in the eastern United States (with reasons not determined yet). Starting from the 1950s, the layer of 0–3 km of the world ocean was heated only by 0.05°C (Ref. 28).

According to the data of aerological observations, the free troposphere was heated in the 1970s much stronger than in two subsequent decades; whereas NAT varied in an opposite way (still unclear why). Analysis of data of the satellite microwave sensing initiated in 1979 has led to the conclusion about only slight tropospheric warming. During the last 35 years, the striking feature of the stratospheric climate change at altitudes of about 20–25 km was the cooling concentrated primarily in the region of the polar ice cap. The authors of Ref. 28 suggest that the difference between NAT and temperature over the last 20 years seems to be realistic, though, of course, the estimates of temperature trends over such short time interval cannot be considered climatically representative.

The trend of stratospheric cooling inferred from data of aerological observations since the 1960s and supported by results of the satellite microwave sensing (after 1979) cannot be attributed to only natural factors. Probably, this trend is due to total ozone decrease in the stratosphere and the greenhouse gas concentration growth (as is known from calculations, the latter also leads to stratospheric cooling). In response to radiatively driven variations of the temperature field, the stratospheric general circulation varied in such a way as to have maximal variations at high latitudes of the winter hemisphere, where a decrease of the stratospheric temperature as large as 5°C was observed.

During the last few decades, not only variations of the temperature field, but also changes of the general tropospheric circulation occurred. For instance, in 1976 over the Pacific ocean, climate changes similar to those in El Niño event were observed. At subpolar latitudes of both northern and southern hemispheres, a gradual increase of the winter western-eastern circulation took place. This dynamics of the general circulation requires careful monitoring, especially because it may reflect variations of natural circulation modes under impact of anthropogenically caused climate variations, though, of course, the problem of “filtering out” the anthropogenic contribution is very complex.

6. Are the greenhouse gases responsible for climate changes?

This is one more rhetorical question (in the absence of atmospheric greenhouse effect, whose major contributor is the water vapor, the life on Earth would not be possible). In fact, the question is how strongly did the growth of the greenhouse gas concentration determine the global warming in the past century. According to Intergovernmental Panel on Climate Change (IPCC) report,[29] “the warming observed during the last 50 years probably is caused by growth of concentration of greenhouse gases, and this conclusion reflects the modern views of scientific community" (note in this regard that, instead of absurd reference to "consensus" commonly used some time ago, now it is changed to the mention of opinion of "scientific community," again, of course, demonstrating an inexhaustible desire to ignore the opinion of opponents of the "orthodox" viewpoint).

It was reasonably noted by the authors of Ref. 29 that whilst the confidence level of IPCC conclusions is now higher than it was 5–10 years ago, significant uncertainties still remain because (1) there are no sufficiently reliable estimates of internally caused variations of the climate system on timescales from decades to centuries; (2) there is no confidence about ability of climate models to reproduce adequately such a variability; and (3) there is a need to estimate critically the reliability of indirect paleoclimatic data.

A conceptually important conclusion about interpretation of observational data, made in Ref. 29, is that "because of still large uncertainty concerning the naturally caused climate variability, as well as concerning time evolution of different (especially aerosol) forcings of climate, the growth of greenhouse gas concentrations in the atmosphere, observed in the twentieth century, and climate change cannot be uniquely related." The fact that the observed climate warming is large as compared with the model-calculated naturally-caused climate variations, indicates that this relation is possible, but it by no means can be considered as a proof of this relation, because the numerical simulations fail to reproduce reliably the naturally caused climate variations on timescales from decades to centuries.

Summarizing the discussion of observational data, the authors of Ref. 28 reasonably note that "despite uncertainty, there is a general consensus about the fact that the observed warming does occur and is the strongest in the last 20 years.

Consistence of this warming with climate changes, to be expected if anthropogenic factors are taken into consideration, depends on assumptions about time evolution of greenhouse gas concentrations in the atmosphere and other (especially atmospheric aerosol) forcings."

7. How strong and where will be temperature changes in the next 100 years?

According to Ref. 29, by the end of the twenty first century the globally-mean annually-mean NAT should increase by 1.4–5.8°C, i.e., by somewhat wider range than predicted in the Second report of IPCC (1.5–4.5°C). Of course, the accuracy of estimates of the global climate warming depends on the adequacy of used scenarios of the greenhouse gas concentration growth with time, whose reliability is ultimately determined by realism of scenarios of global social and economic development. For instance, numerical climate simulations typically assume CO_2 growth rate of 1% per year; whereas in the last decade of the twentieth century, CO_2 increased by 0.6% per year, and its subsequent variations are almost unpredictable. Of course, the global climate warming cannot be estimated reliably without adequacy of climate models, still being rather limited. For instance, calculations revealed an increase of climate warming with latitude, especially in winter and spring; but the actual spatiotemporal NAT variability in Arctic is much more complex.[8]

8. To what extent the expected climate changes are a consequence of processes caused by climatic feedbacks?

Again, this is a rhetoric question, because the key role of diverse feedbacks in climate formation has long been in common knowledge. It is more important to estimate contribution of different feedbacks to climate change.[4–8]

9. What will be the consequences (such as extreme weather conditions, and influence on human health) of different anthropogenic impacts?

It can be expected that in the near future, the increase of CO_2 concentration will favorably influence agriculture and forest growth (because of enhancement of "fertilization," caused by the CO_2 increase, and growth of efficiency of water consumption by vegetation[5]). Uncertainty in predictions of regional climatic conditions (especially drying or moistening anomalies), gives no way of predicting quite reliably the influence of climate change on dynamics of ecosystems. However, a very detailed such analysis was performed for the territory of the USA (see Ref. 6).

10. Is there any scientific justification of any "acceptable" level of greenhouse gas concentration?

This question, dealing with solution of the problem of risks and economic losses, is still unanswered, though, undoubtedly, it is clear that the stronger the climate changes, the greater the risks.

11. What are significant discrepancies between the content of IPCC reports and their summaries for decision makers?

Authors of Ref. 28 reason that "full IPCC Working Group 1 report[29] is a good result of research in climate science, and that the technical summary is its adequate characteristic. The full report and technical summary were not intended to discuss specially the ecological policy issues. The summary for policy makers (SPM) pays less attention to the problem of uncertainty of estimates, while is more concerned about anthropogenically induced climate change."

Regarding this general opinion on IPCC 2001 report,[29] it is worth noting that (1) despite thoroughness of the review made in the report, it is essentially incomplete and inadequate (e.g., practically, it does not even mention the important Russian publications on the subject); and (2) although an important new feature of the document[28] is a prudence of its statements, underlining the uncertainty in estimates of causes of the current global climate change and, moreover, future climate variations (the documents deal with "projects" rather than with predictions), SPM is formulated in the spirit of the conception of anthropogenic nature of the contemporary climate change and, hence, apologetics of Kyoto Protocol, contrary to the real state of affairs. Thus, there is a serious contradiction between full IPCC 2001 report and SPM.

12. What are scientific areas (in their priority order) requiring further development for better understanding of climate change?

In this regard, Ref. 28 calls for working fundamental problems related to accumulation of greenhouse gases in the atmosphere and studying the dynamics of the climate system. Individual aspects of the problems include: (1) predictions of future fossil fuel exploitation; (2) estimates of possible future emissions to the atmosphere; 3) estimates of a fraction of fossil-fuel-derived carbon dioxide, remaining in the atmosphere, as well as the relationship between associated radiative forcing and exchange between the atmosphere, ocean, and land biosphere; (4) analysis of feedbacks in the climate system, determining the magnitude and rate of energy assimilation by the ocean, which ultimately control the energy evolution (for a given radiative forcing); (5) study of regularities of the climate change on regional and local scales against the background of global climate change; (6) determination of the nature and causes of naturally caused climate variations and their interaction with different forcings; and (7) estimation of direct an indirect effects of atmospheric aerosol on climate. Unfortunately, a characterization of priority problems, briefly presented in Ref. 28, is obviously made in the context of anthropogenic hypothesis of the global climate change, i.e., the "greenhouse" warming. This conclusion will be discussed further in more detail.

In conclusion, the authors of Ref. 28 reasonably note that a greater attention must be paid to projects dealing with regularities of interaction between the nature and human activity, namely: (1) interdisciplinary studies of interactive physical, chemical, and biological processes, interacting with dynamics of social-economic development; (2) extension of possibilities of integration of scientific knowledge, including estimates of corresponding uncertainties in the decision support systems; (3) support of regional-scale and sector-scale projects, allowing one to estimate the behavior of anthropogenic and natural systems in response to different forcings.

Also, the efficient strategy of our understanding of climate change requires (1) to create a global observational system for long-term climate monitoring and furnishing the climate prediction models with appropriate information; (2) to concentrate efforts on the numerical climate modeling with use of supercomputers; and (3) to provide adequate support necessary for increasing the efficiency and innovation potential of the projects connected with climate study.

Summarizing, note that the very comprehensive document[28] lacks completeness and is somewhat biased. Therefore, we turn to more systematic and extended discussion of the problem.

II. Conceptual aspects of the problem of global climate change

Key questions of the present-day climate studies, including the analysis of the corresponding contradictory reasonings and estimates, have been recently discussed in sufficient detail.[7,8] Concise, but very comprehensive analysis of the problem is given by Ellsaesser.[34a] To avoid repetition, we will consider only most important aspects of the problem. As it was reasonably noted in Ref. 30a, the proponents of the anthropogenic ("greenhouse") hypothesis of "global warming" rest upon three main assumptions:

1. Current temperature variations are mostly anthropogenic and determined by the growth of greenhouse gases concentration (primarily CO_2 and CH_4) in the atmosphere.

2. According to results of numerical simulation, the near-ground temperature by 2100 may increase in the range 1.4–5.8°C. We should point out to the uncertainty of estimates of this range. The sensitivity of global climate (defined as an increase of globally mean near-ground temperature due to CO_2 doubling in the atmosphere) first published by Arrenius in 1896 was $\Delta T_{2x} = 5.4$°C. According to later estimates, obtained with models of different complexities,[18] ΔT_{2x} varies in a wide range from 0.24 to 9.6°C. In the Second Assessment Report of IPCC 1996, the range 1.5–4.5°C is recommended as most probable; while in the Third Assessment Report of IPCC 2001, it is 1.4–5.8°C. The estimates, based on paleoclimatic and instrumental NAT data, suggest that ΔT_{2x} interval may be even wider, from 0.7 to 10°C. In all these cases, however, estimates of the corresponding probability distribution functions (pdf) for ΔT_{2x} values were not obtained.

Calculations by Andronova and Schlesinger,[18] based on the approximate climate model for the atmosphere–ocean system, have shown that, if natural climate variability and uncertainty of estimates of climate forcings are properly taken into account, the interval of ΔT_{2x} values (at 90% confidence level) is 1.0–9.3°C. This means that ΔT_{2x} values are beyond the range of ΔT_{2x} values recommended by IPCC 1996 report with probability of 54%. The numerical simulation under discussion uses 16 models of radiative forcing by greenhouse gases, sulfate aerosol (taking into account both direct and indirect effects), and tropospheric ozone. Given 90% confidence level, the estimates of aerosol radiative forcing range from 0.54 to 1.30 W/m^2.

3. The climate stability is possible only through reducing greenhouse gas emission to the atmosphere.

The invalidity of this claim was demonstrated in many publications including Refs. 7, 8, 30a, and 34a. In this regard, here we consider some recent publications.

The failure of the Sixth Session of Conference of the Parties (COP-6) signed the UN Framework Convention on Climate Change (FCCC) in Hague in November 2000, was not unexpected, because its participants had not sufficient scientific information in hand and strategically they were not adequately prepared. Very important problem of uncertainty of estimates of greenhouse gas reservoirs and fluxes turned out to be ignored. Subsequent to COP-6, the problem became even more acute after President Bush rejected the Kyoto Protocol. On the other hand, the published Third Assessment Report of Intergovernmental Panel on Climate Change (2001) states that the available information allows one to say with even more confidence that greenhouse gases significantly contribute in the contemporary climate change, as well as to predict the future climate changes with even more probability.

As it was reasonably noted in this regard by Nilsson et al.,[72] the estimates of uncertainties of those estimates, upon which conclusions on climate changes and mitigating measures rest, acquire a key meaning. It is especially important to verify the levels of greenhouse gas emissions to the atmosphere. Obviously, without reliable verification, any discussion concerning ecological advantages of different measures and financial estimates, is abstract. For example, it is difficult to justify the penalties for those who do not follow the Kyoto recommendations to reduce greenhouse gas emissions, because it is impossible to prove that the 2012 emission level will differ from the 1990 level.

Until very recently, political discussions concerning the Kyoto Protocol ignore quantitative estimates of uncertainties of greenhouse gas sinks, particularly, biospheric. The uncertainties of estimates of total CO_2 fluxes are, however, very significant (exceeding 100% in conditions of Russia). The errors of estimates of total greenhouse gas fluxes were calculated to lie approximately in the range 5–25%; whereas the reduction of greenhouse gas emissions under Kyoto Protocol average approximately 5%. The globally-mean situation, for example, is illustrated by the fact that the uncertainties of estimates of greenhouse gas emissions due to energy production systems are nearly equal to uncertainty of estimates of CO_2 assimilation by the land biosphere. In such a situation, attacking the problems of uncertainty of estimates (primarily in terms of reliable information on hydrogen cycles) and verification becomes most important. To solve the second problem, the verification mechanisms must be agreed upon, what is very important from the financial viewpoint as well. The results of numerical simulation, for example, indicate that, if the confidence interval of 5.2% reduction of greenhouse gas emission is increased from 5 to 95%, the corresponding cost of measures intended to reduce the greenhouse gas emission increases by a factor of 3–4. The main conclusion is that science must serve as a guide in elaboration of the measures in the ecological policy. In this regard, the failure of COP-6 may serve as a healing shock.

According to mandate of Intergovernmental Panel on Climate Change, the main goal of IPCC is to prepare a review of "any temporal climate variations, both natural and anthropogenic." Pielke[76] has shown, however, that at least two climate forcing agents turned to be overlooked: (1) influence on global climate of anthropogenic variations of land surface characteristics; and (2) biologic impacts of carbon dioxide growth (including "fertilization effect") in the atmosphere. If the both factors are truly significant, we have to conclude that the agreement between the results of numerical simulations of global climate (in fact, primarily in terms of the globally-mean annually-mean near-ground air temperature) is accidental.

In this regard, Ref. 76 discusses information, supporting the significance of both climate forcing agents mentioned above, and suggests possible ways to verify this conclusion. This can be done using data on the influence of anthropogenic variations of land surface characteristics on local, regional, and global climates, which illustrate that this influence is at least as important in climate simulations as the influence of CO_2 doubling in the atmosphere (as well as the growth of concentration of other greenhouse gases). No less important is the fact that the atmosphere–surface interaction is characterized by the presence of different nonlinear feedbacks (see Ref. 34), sometimes making impossible the climate prediction on a longer than seasonal timescale.

As to potential biological impacts of the CO_2 growth, they manifest themselves in the form of short-term (biophysical), medium-term (biogeochemical), and long-term (biogeographic) effects of landscape-changing processes on the weather and climate. The biophysical effect includes, for example, the influence of transpiration on the ratio of latent and sensible heat fluxes as components of heat balance of the underlying surface. Among the biogeochemical effects is the influence of vegetation growth ("fertilization effect") on the leaf area, from which transpiration occurs, as well as on the surface albedo and carbon accumulation. A manifestation of the biogeographic effects can be, in particular, a change of species composition in vegetation with time.

The results of numerical simulation clearly indicate that the estimates of climate changes cannot be considered adequate without biophysical and biogeochemical effects taken properly into account. A further development of climate models must incorporate, among others, the following climate-change aspects: (1) direct and indirect impacts of landscape dynamics through the biophysical, biogeochemical, and biogeographic processes; (2) consideration of anthropogenic changes due to land use practices on different (local, regional, and global) spatiotemporal scales; and (3) assessment of possibilities of the climate prediction on a longer than seasonal timescale, taking into account numerous nonlinear feedbacks determining the atmosphere–surface interaction. As long as these and other problems are unsolved, the mission of IPCC 2001 report and U.S. National Academy of Sciences report is restricted only by estimates of sensitivity of global climate to changes of some climate-forming factors.

MacCracken[66] has noted that, in the course of prolonged preparation of three already published (1990, 1996, and 2001) IPCC reports, an increasingly full analyses of climate forcings (atmospheric aerosol in addition to greenhouse gases) and different feedbacks have been performed. Despite this, the recent climate models, which have already reached very high level of sophistication, still cannot be considered as quite complete from the viewpoint of inclusion of all significant climate forcings. A new step forward in the IPCC 2001 report was the inclusion of the climate forcing due to changes in anthropogenic land use practices, restricted, however, to discussion of effect of land use dynamics since 1750 on the surface albedo. In this regard, the mean climate forcing was estimated to be 0.2 W/m^2 for an uncertainty range of 0 to −0.4 W/m^2. Thus, these estimates are characterized by high uncertainty even in the sign of the climate forcing (after the biophysical, biogeochemical, and biogeographical effects of land use evolution on climate were taken into account, it has been concluded that climate forcing is > 0 in this case).

In this regard, it is important that IPCC 2001 report accepted a new range (1.4–5.8°C) of possible global warming by 2001, justified only by numerical simulation results (and therefore will be inevitably changed in the future). The problem is that the new range cannot be directly compared with analogous estimates obtained earlier. For more reliable estimates of climate changes, the IPCC report should use in the future the term “projections” instead of the term “predictions” because the latter means that the factors not accounted for at present will not be significant in the future. Just the unacceptability of the last speculation is the reason why none of modelers will guarantee the possibility of a 100-year climate prediction.

A key aspect of the numerical climate simulation in the context of accounting for anthropogenic consequences is the development and application of the interactive model of climate and carbon cycle. An important step in this direction was made by Harvey and Huang.[51]

In interactive one-dimensional models of atmosphere–ocean system, widely used earlier, one of the most important parameters is the coefficient of vertical diffusion in the ocean, characterizing the intensity of heat and mass exchange between the atmosphere and ocean. Both in one- and three-dimensional models, this parameter is *a priori* specified with “fitting” through comparison of numerical simulation results and observational data. However, even with such a fitting, serious discrepancies existed in k_v estimates. In this regard, Harvey and Huang[51] have developed a relatively simple interactive model of the system “atmosphere–ocean–carbon cycle,” which can be used to simulate numerically the processes of heat and CO_2 assimilation by ocean and to estimate variations of the ocean level due to thermal expanding.

The prime objective of the model developing was the study of the atmosphere–ocean interaction in context of carbon cycle dynamics and, then, application of the model to analysis of climatic consequences of different scenarios of anthropogenic emissions of greenhouse gases and aerosol. At the same time, its important task is to reproduce naturally occurring climate changes and carbon cycle on geological time scales.

The model under discussion is considered as diagnostic rather than prognostic, with emphasis on global-scale processes. The latter dictates distinguishing of three regions on the globe (two polar and one nonpolar) with specific vertical resolution. The model allows one to reproduce such parameters of the ocean as concentration of dissolved inorganic carbon, phosphates and dissolved oxygen, alkalinity, temperature, as well as to describe the operation of “biologic pump,” causing formation of organic tissues, calcite, and aragonite. Formation of bottom waters occurs in one of the polar regions due to interaction with the atmosphere and convective mixing in the ocean with a subsequent transport of waters to the lower part of the nonpolar region. Bottom waters formed in the region of polar downwelling then suffer upwelling in one nonpolar region; though a part of them is transported from intermediate depths to another nonpolar region.

Harvey and Huang[51] discussed in detail the characteristic features of climate, formed under conditions of their interactive model. In this regard, they justify the determination of relative effective diffusion coefficient k_v for different tracers. The calculations showed that k_v is minimal for temperature, intermediate in the case of carbon, and maximal for dissolved oxygen. Compared with values used earlier in one-dimensional models, they obtained much less value of k_v for temperature (~0.2 cm^2/s versus 0.6–1.0 cm^2/s), as well as a less maximal rate of upwelling (2 m/yr versus 4 m/yr). A consequence of accounting for convective mixing in an explicit form was a considerable influence of intensity variation of thermohaline circulation on nonstationary response of surface temperature and rise of ocean level. For this reason, calculations gave a significantly different (a faster) response of the ocean level and surface temperature to decrease of thermohaline circulation than that obtained earlier from the classic one-dimensional model. This means, in particular, that the climate sensitivity to external forcings consistent with last 140 years of observations, is approximately 10% lower than the classic model predicts.

A comparison of numerical simulation results on vertical profiles of different tracers (including ratios of isotope concentrations) obtained with one-dimensional interactive model of the system "atmosphere–ocean–carbon cycle" and observational data has shown that there is a need in reproducing the following characteristics[52]: (1) upwelling rate in a nonpolar region, reaching a maximum of about 2 m/yr at a depth of 1 km and gradually decreasing above and below this depth level; (2) unequal values of the effective vertical diffusion coefficient for temperature and different tracers in the upper 0.5-km layer of the ocean; and (3) ratio of formation rates of carbonate carbon and organic carbon equal only to 0.09. In particular, from observational data (along with information on the mixing along isopycnic surfaces and numerical simulation results) it follows that the effective coefficient of vertical mixing in the upper ocean layer must be minimal for temperature and maximal for dissolved oxygen, at somewhat less values for alkalinity and phosphate concentration than for dissolved inorganic carbon (DIC).

Harvey[52] showed that setting of model parameters, which fit the preindustrial observations of the tracers' distribution, gave the best agreement with observations of isotope concentration variations. Taking into account of alkalinity–DIC interaction (earlier, as a rule, disregarded by such models) mitigates the influence of variations of model parameters on the stationary pCO_2 level in the atmosphere. The calculations have shown that the assimilation of anthropogenic CO_2 by ocean and CO_2 variations in the atmosphere, calculated for the period extending to 2200 (with all parameters kept constant throughout this period), are insensitive to the mixing parameters used in the model. Estimates of sensitivity of the calculated pCO_2 concentrations to temperature changes of warm ocean surface well agree with analogous calculations using the tree-dimensional model of carbon cycle in the ocean.

Despite quite popular reasoning that there exists some consensus on estimates of causes of modern climate change, the rapid development of both empirical diagnostics and numerical simulation of global climate has led to many surprising and often contradictory results. Among them are the conclusions about regularities of the earth radiation budget (ERB) change, inferred by Wielicki et al.[90] from the analysis of satellite data on ERB. It is agreed that, on a large scale of spatiotemporal averaging, the variability of ERB and its components, absorbed solar and outgoing longwave radiation (OLR), is insignificant. However, processing of two-decade satellite observations for the tropics has revealed much stronger variability than estimated earlier. The reason for such variability, unpredictable by the present-day climate models, lies in the cloud dynamics. Quite surprisingly, OLR decreased by about 2 W/m^2 during the period from the end of 1970s to the mid-1980s, and then increased by about 4 W/m^2 from the late 1980s to 1990s. Since the variations of radiative forcing of the order of 1 W/m^2 are climatically significant, the natural OLR variability in the tropics, reaching 4 W/m^2, should be considered as very strong and unexplainable as a direct consequence of global warming.

Analysis of data from Tropical Rainfall Measuring Mission (TRMM) satellite (in operation since 1998) and Terra satellite (in operation since 2000) performed by Chen et al.[27] and consistent with conclusions of Wielicki et al.,[90] has revealed that the OLR flux was 5–10 W/m^2 (2–4%) larger than obtained from the Earth Radiation Budget Satellite Narrow Field of View broadband scanning radiometer (1985–1989), unexplainable only by a difference in instruments. The data from wide field-of-view ERBS sensor, covering a longer time period (1985–1995), suggest the presence of a positive OLR trend, most clearly seen in the first half of the 1990s. For entire period 1985–2000, an OLR increase in excess of 5 W/m^2 was observed in the tropics; whereas in the case of outgoing shortwave radiation (OSR), a decrease of less than 2 W/m^2 took place.

After minimization of the El Niño/Southern Oscillation (ENSO) effect on variability of OLR and OSR fields, some information on "residual" long-range variability of OLR and OSR was obtained. A similar analysis of the moisture content of the upper troposphere, cloud amount, near-ground air temperature, and vertical velocity has shown that the long-range change of OLR and OSR were associated with decade-scale variations of Walker and Hadley circulation in the tropics. They manifested themselves in convection intensification in the equatorial belt, accompanied by enhancement of upward motions and increase of atmospheric moisture content; whereas the regions of equatorial and subtropical downward motions were characterized by a decrease of atmospheric moisture content and cloud amount. The observed intensification of Walker–Hadley circulation cells was most probably caused by the influence of natural long-term variability on as long as decadal or longer timescales. The final conclusion, however, is difficult to make because of insufficient length of the observational series. Thus, there is a considerable variability of ERB components on decadal time scales in the tropics, whose nature requires a further study (see Refs. 27 and 50).

The effect of solar activity on climate remains very poorly understood.[4,14,46,57,62] Study of this problem was restricted primarily to estimates of influence of extraterrestrial insolation variations. As is well known, the variability of integrated extraterrestrial solar radiation – solar constant (SC) – is characterized by the presence of 11-year cycle and, possibly, longer-term variations. It follows from data of satellite observations that in the periods of maximal solar activity (1981 and 1989), SC was 0.08% higher than during the minimal solar activity (1986). Since the Mounder minimum in the seventeenth century, SC increased, probably, by 0.2% or larger. The SC variations are accompanied by considerable changes in the spectral composition of extraterrestrial solar radiation.[62] During last cycles of solar activity, UV radiation varied by 1.2% in the wavelength range 200–295 nm, and by 0.36% in the range 295–310 nm.

Analysis of data on ice cores has led to a conclusion that, on centennial timescale, the near-ground air temperature changed by about 0.5°C, what can be explained (using numerical climate modeling) by SC variations in the range 0.2–0.3%. Solar-induced temperature variations near the earth surface in the troposphere, as well as variations of ozone, atmospheric pressure, and temperature in the stratosphere were observed on the decadal time scales. If during reduction of greenhouse gases emission to the atmosphere the radiative forcing decreases to 1 W/m^2 for the coming 50 years, this will suggest an increase of significance of the solar-induced radiative forcing. In 1996, the twenty third cycle of solar activity started. In 2000 (near the maximum of activity), the annually mean SC was approximately 1 W/m^2 higher than in the years of minimal activity (1986 and 1996). This increase is comparable with that observed in the course of the twenty first and twenty second cycles.

Using an empirical dependence of SC on solar radio-frequency radiation at a wavelength of 10.7 cm, Lynch[27] obtained predictive estimates of SC variations up to 2018. In the twenty fourth cycle, the maximum of SC is expected to occur in 2010, at the same or somewhat lower SC than it was during maxima in 2000, 1989, and 1981. Minimal values of SC are expected in 2006 and 2016. The long-term SC trend superimposed on the 11-year cyclicity should not exceed that observed during the last 350 years. It makes less than ± 0.4 W/m^2 per decade. In case of UV radiation, it is expected to be ± 0.1 W/m^2 (295–310 nm) and ± 0.04 W/m^2 (200–295 nm). If the combined effect of cyclicity and trend is taken into consideration, the solar radiative forcing for the period between minima of the 11-year cycle dated to 1996 and 2016 will be in the range ± 0.1 W/m^2; whereas the total anthropogenic radiative forcing for the 22-year period may reach 0.5–0.9 W/m^2.

Unexpected results were recently obtained in the course of paleoclimatic studies at high time resolution. They revealed abrupt and large variations of air temperature in the past. For instance, it follows from the analysis of data on ice cores, collected in Greenland, that large and fast variations of near-ground air temperature took place in the period of the last ice age.[80] The NAT variations in Greenland reached 10°C during the time period of several tens of years. Quite naturally, analogous synchronous variations occurred in the entire Northern Atlantic region, because NAT variations in Greenland were connected with migration of Atlantic polar front, i.e., a boundary between water masses of polar and middle latitudes (in the region from Greenland to the south coast of Portugal). Data of analysis of Antarctic ice cores cover somewhat longer time period than the Greenland ice cores (several ice ages).

Recently, it has been evident (from data on Antarctic ice cores) that substantial NAT variations were observed on millennial or shorter timescales. In this regard, a comparison of paleoclimatic data for both hemispheres holds much promise, because it may answer the following questions: (1) whether the millennial-scale NAT variations manifest themselves over whole globe; (2) whether the temperature varies synchronously in both hemispheres, or the functioning of “polar swing” entails heat transfer from one hemisphere to another; and (3) what factors are responsible for such a great variability. Reference 20a partially answers these questions using data on variations of the methane concentration allowing a quite close time reference to NAT paleovariations between both hemispheres. Just these data made it possible to justify the presence of correlation between NAT variations in both hemispheres during the last ice age.

In the low temperature period in Greenland, NAT in Antarctic gradually increased and then decreased when NAT in Greenland appeared to be relatively high. It is important that the change from cold to warm climate conditions in Greenland was very rapid (over a few decades); and the change from gradual warming to cooling in Antarctic was also very rapid (on about decadal timescale) every time during abrupt warmings in Greenland. Thus, it is clear that the NAT variations in the northern and southern hemispheres differ in phase. However, some synchronism exists in variations of the ocean surface temperature in the North Atlantic and NAT over the Greenland ice sheet. At the same time, deep waters in North Atlantic are characterized by the presence of “a signal” of NAT variations in Antarctic. The mechanism of “polar swing” is still unclear.

In contrast to the last ice age, characterized by rapid climate variations on millennial timescales, the climate of the middle Holocene period was generally considered as a classic example of stability. These opinions, however, were somewhat changed after analysis of ice cores from Greenland and Antarctic, as well as cores of bottom marine sediments from regions of North Atlantic and Arabian Sea. The analysis shows that, during Holocene, climatic cycles of centennial to millennial timescales took place. Presumably, they were a continuation of the well-known fast climate changes during last ice ages, when, in particular, significant changes of El Niño/Southern Oscillation (ENSO) event occurred.

One of the regions, for which the geologic data on paleoclimate change are available, is the mid-latitude region of Chile where very strong atmospheric pressure gradient is determined by the latitudinal position of the west-eastern transfer zone in the south hemisphere. Lamy et al.[60a] discussed results of analysis of sea bottom sediments taken from the continental slope of Chile (41°S), which allowed them to obtain information on variability of precipitation over the last 7.7 thousand years. It can be concluded from the data, containing information primarily on the iron concentration, that there exists a variation of precipitation with time scales from many centuries to millennia. They are superimposed on the background climate being more arid in the middle Holocene period (7.7 thousand years ago) than during late Holocene (4 thousand years ago or less).

Comparison with data of analysis of ice cores from the South American belt and coastal Antarctic have shown that this region had similar "bands" of climate variations. The climate variations in the tropics of South America were determined by shifts of the west-east transfer zone, whereas the nature of climate variations in Antarctic was more complex and characterized by the presence of phase shifts at the beginning of the late Holocene, coinciding in time with the beginning of establishment of the modern ENSO state. Thus, the results considered here confirm that the well-known climate variability on millennial scales, observed in the last ice age period, has been continued into the Holocene period.

From the middle of the sixteenth century to the early seventeenth century, a minimum of solar activity, the so-called Mounder period, was observed. In this period, the near-ground air temperature in the northern hemisphere had dropped to its minimal values over the last millennium (in West Europe in winter, NAT decreased by 1–1.5°C). Using the Goddard Institute for Space Studies (GISS) Global Climate Middle Atmosphere Model (GCMAM), which takes carefully into account the stratospheric processes, Shindell et al.[81] performed a numerical simulation of climate to estimate the climatic effect of extraterrestrial insolation variations over the period from the Mounder minimum to the last century, when the level of extraterrestrial insolation was high during a few last decades. The calculations have revealed a presence of small (about 0.3–0.4°C) variations of globally mean NAT, consistent with available observational data.

However, the regional globally mean NAT variations were quite large and occurred primarily due to an induced shift toward decrease of the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) index during decline of extraterrestrial insolation. Under these conditions, NAT over continents of the northern hemisphere decreased, especially in winter (up to 1–2°C), consistent with NAT variations from data of *in situ* measurements and indirect NAT indicators. Thus, even small variations of the solar radiative forcing can play a significant role as an important factor of climate variations in the northern hemisphere in winter on about centennial timescale. In this regard, it is naturally to hypothesize that the NAT decrease on continents of the northern hemisphere in winter in the XV–XVII centuries (named the Small Ice Age) and climate warming in the XII–XIV centuries (Middle-Ages warming period) were caused by long-term variations of extraterrestrial insolation.

Studies of past climates are of great interest in the context of prediction of the future climate. In this regard, the history of Antarctic glaciers is of the special concern.[63]

A consequence of the possible collapse of the Western Antarctic Ice Sheet (WAIS) can be a probable increase of sea level by about 5 m. Mass media interpret this collapse as an inevitable result of anthropogenic impact on the global climate. Glaciologists, however, discuss some other reasons for the WAIS destruction. Possibly, the ice sheet is still at the state of recovering after changes occurred during the last ice age. Many specialists believe that the collapse is impossible during the contemporary interglacial period. The absence of solution of the WAIS problem and difficulties in solving it have motivated the following thesis in the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC): "estimates of the probability of collapse in the next century are still impossible." In such a situation, it is important to estimate the risk of collapse (defined as an event caused by a combination of probability and consequences of this hazard).

An analysis of WAIS risk using Delfi technique of interrogating the specialists is presented in Ref. 87. The main conclusion drown from such an approach is that, as the predominating opinion (among which quite opposite ones exist) suggests, the WAIS collapse is unlikely to occur during a few nearest centuries. We can state that, with probability of 5%, the rise of sea level due to WAIS collapse will be less than 10 mm/yr during the time interval of the order of 200 years. To reduce the uncertainty of estimates, it is important to answer the following questions:

(1) What is the present day balance of WAIS mass?

(2) Whether or not the loss of the shelf ice will lead to a stronger ice discharge to the ocean?

(3) Whether or not the contribution of precipitation intensification due to global warming will exceed the level of ice discharge?

(4) Whether or not the decay of thermohaline circulation will be a consequence of atmospheric warming, and whether or not its effect will exceed the influence of the shelf ice melting due to increase of temperature?

(5) How important is the mechanism of "ice streamers," and what is its nature?

(6) What are the continuous consequences of the glacier-interglacial transition?

(7) Can the "ice streamers" exist sufficiently long for to cause the WAIS collapse?

(8) Had any WAIS collapse been occurred during preceding interglacial periods?

The recent analysis of WAIS mass balance has led to a paradoxical conclusion that, on average, a thickening of the glacier took place.[17]

Conclusion

The main conclusion of our review is that we still know very little about regularities of the present-day climate variations. Undoubtedly, there are no firm grounds to believe in anthropogenic character of the present-day climate change. This is because of the serious uncertainty of results in the region of empirical diagnostics and numerical climate simulation. Promising and priority areas should include:

1. Validation and realization of the global system of long-term climate observations with the use of both usual and satellite observation facilities. Despite the existence of the programs like Global Climate Observing System (GCOS), Global Ocean Observing System (GOOS), Global Terrestrial Observing System (GTOS), and Integrated Global Observing Strategy (IGOS), even validation of the problem-oriented observation systems is absent up to present (the problem of biogeochemical cycles, greenhouse effect of the atmosphere, dynamics of ozone layer, and many others).

On the one hand, this leads to redundancy of observational data (for instance, only a negligible portion of satellite data are in use presently) and, on the other hand, to their deficiency.[57,59a] It is recognized, for instance, that one of the main uncertainties in the numerical climate modeling is caused by inadequate taking into account of direct and, especially, indirect aerosol effect on climate.[29,58] So far, however, there is no even a program of such a system of observations of properties of different atmospheric aerosols, whose implementation in the future would provide the necessary information.[9a,b] At the same time, it is encouraging that an interest grows to the study of aerosol properties under conditions of the real atmosphere, which is illustrated by publication of two topical issues of the Journal of Geophysical Research (2002, Vol. 59, No. 3, Parts 1, 2). A series of new works[12,13,33,33a,34] argue for a more justified statistical analysis of long observational time series (in particular, for trend identification) than used earlier. Based on new findings in the paleoclimate study, special attention should be paid to indirect indicators of the paleoclimate change.[24,31a,35]

2. Diagnostics of global climate still rests upon primarily temperature data. It clearly underestimates the analysis of these data on regional scales. A more full diagnostics is, of course, impossible without a greater amount of long observational series. However, extended arrays of data on clouds and earth radiation budget are now available, the possibility of analysis of which are still little used.[40a,49,77b,84a,89a,92] Interesting ideas about recognition of anthropogenic variations of hydrologic cycle components were reported by Wood.[91c] Temperature variations are an important source of information about the stratosphere[26a,76a]; for example, about cooling, but, as noted by Ramaswamy et al.,[76a] they do not allow uniquely interpretation of the causes of the cooling.

3. A key aspect of studying the greenhouse effect of the atmosphere is the biotic environmental regulation; nevertheless, the concept of biotic regulation[42a] still remains not properly understood, although recently it has been actively discussed in the context of the Gaia hypothesis.[56a,62a,78a] In this regard, the necessity of interactive taking into account the biosphere, as the most important component of the climatic system "atmosphere–hydrosphere (ocean and inland waters)–lithosphere–cryosphere–biosphere," still remains inadequately understood. It is very important, however, that first steps are made in development of interactive climatic models accounting for the dynamics of the biosphere and carbon cycle.

4. Undoubtedly, partly because of the lack of observational data, the role of numerical global climate models in adequate understanding of regularities in real climate (such as internally caused variations of the climate system) is overestimated. Despite its complexity, undoubtedly, the numerical climate modeling makes only its first steps, primarily because it still disregards the interactive character of many processes determining the dynamics of the climate system (in particular, interrelation between variations of stratospheric and tropospheric ozone and climate[19a,59]). The problem of analysis of limitations of numerical climate modeling and prediction becomes more and more urgent.[8,78b] There is an obvious necessity to take into account the social and economic dynamics of society in prognostic models. This, in its turn, imposes so heavy demands on the models that there appears a need, yet poorly understood, to analyze possible limits of the numerical simulation.

5. The problem of influence of solar activity on climate still remains unsolved.[4,5,14,46,57,60,62,77a]

The considerations presented above are only a fragmentary comment. During preparation of the World Climate Conference to be held in Moscow in 2003, it is important to develop a realistic international program of the promising projects, which can be discussed and approved at the conference. Of course, this work should be performed in a close collaboration with the new IPCC administration.

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