Geofísica Internacional (1994), Vol. 33, Num. 3, pp. 487-496

Global climate change in the context of global ecodynamics

K. Ya. Kondratyev[1,2] and I. Galindo[2]

[1] *Academician, Co-Chairman of the Board, Nansen International Environmental and Remote Sensing Centre (NIERSC), St. Petersburg, RUSSIA*

[2] *Centro Universitario de Investigaciones en Ciencias de la Tierra (CUICT), Universidad de Colima, Col., MEXICO.*

Received: January 12, 1994; accepted: February 24, 1994.

RESUMEN

Los problemas del cambio global del clima se podrán resolver solamente en el contexto de los problemas, mucho más amplios, de la ecodinámica global. Se presenta una revisión de los aspectos claves que incluye un breve resumen de la concepción actual de los cambios del clima basándose en observaciones y modelado numérico. Se enfatizan algunos conceptos así como nuevos resultados obtenidos en el campo del diagnóstico del clima, las posibilidades del efecto de fertilización producido por aumento del CO_2, cierto progreso en el modelo de la dinámica del clima de largo periodo y, una nueva estimación del impacto climático de los aerosoles. Se presentan un análisis del estado actual y las perspectivas del desarrollo del Sistema Global de Observación del Clima. Las prioridades de la futura investigación se discuten en las conclusiones.

PALABRAS CLAVE: Cambio climático global, ecodinámica.

ABSTRACT

It is now becoming clear that global climate change problems may be solved only in the context of much broader global ecodynamics problems. A survey of relevant key issues includes a brief summary of present-day understanding of climate changes on the basis of observations and numerical modelling. Issues such as new results in the field of climate diagnostics, possibilities of fertilization effect due to CO_2 increase, progress in modelling long-term climate dynamics, and new assessments of climatic impacts of atmospheric aerosols are surveyed. The present state and outlook of the Global Climate Observing System development is discussed, together with the priorities of future research.

KEY WORDS: Global climate change, ecodynamics.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) issued in 1990 a 3-volume report (Houghton *et al.*, 1990) summarizing the results of studies on the basic problems of climate change (volume I), as well as the possible effect of climate changes on the environmental and socio-economic development (volumes II, III). The Report was discussed and approved at the Second World Climate Conference (Kondratyev, 1990, 1991a, 1991b, 1992, 1993; Kondratyev and Kotlyakov, 1991; Kondratyev and Grassl, 1993), and at the 11th WMO Congress. The IPPC Report played an important role in the development of the Framework Convention on Climate Change approved by the Second U.N. Conference on Environment and Development (UNCED) in Rio de Janeiro, 4-14 June 1992 (Holmberg *et al.*, 1993; Kondratyev, 1993). While the final version of the Convention, signed in Rio and later ratified by many countries, has been seriously criticized (see, for instance, Holmberg *et al.*, 1993; Kondratyev, 1993), the fact is that the problems of global climate change were seriously considered by UNCED.

The key aspect of the problem is to evaluate the present understanding of the causes of global climate and its changes. Several years have gone by since the IPCC Report, and it may be worthwhile to analyze the progress recently achieved in this field. A recent supplement to the IPCC Report (IPCC, 1992) and other publications summarizing the results facilitate this task.

One cannot expect that a few years would bring about any major changes in our ideas about climate in general, and about the role of the greenhouse effect in particular. The following main assessments contained in the 1990 IPCC Report and in the supplement remain unchanged:

1. Anthropogenic emissions of the greenhouse gases (GHGs)–carbon dioxide, methane, chlorofluorocarbons (CFCs), nitrous oxide, carbon tetrachloride, tropospheric ozone– have substantially increased.
2. Observations and numerical modelling of climate suggest the following probable limits to the increase of the annual mean global surface air temperature (SAT) due to a CO_2 doubling: 1.5- 4.5 °C.
3. Our inadequate understanding of the causes of climate introduces many uncertainties in the prediction of possible changes in the future as to magnitude, time and regional spatial distribution.
4. During the last century the global mean warming varied within 0.3-0.6 °C.
5. Warming estimates agree, on the whole, with the predictions based on climate models, but they are about the same as natural changes due to the internal variability of the climatic system. Hence the observed SAT increase could have been caused by natural variability. On the other hand, this variability and other anthropogenic effects could have compensated for a more substantial assumed anthropogenic greenhouse effect.

An unambiguous confirmation of the increased greenhouse effect from observational data is not likely to occur before at least ten years.

It has recently been argued that the threat of ecologically and economically dangerous global warming is more remote than previously assumed (Michaels and Stooksbury, 1992). This suggests a re-examination of the reliability of predictions of climate change and associated consequences contained in the Framework Convention on Climate Change approved by the Second U.N. Conference on Environment and Development. Unfortunately, the Convention contains certain elements of what may be called "greenhouse" stereotypes which needed to be seriously revised.

The need to revise greenhouse stereotypes on global warming is based primarily on:

(i) Uncertainties in present theories of climate change and inadequate reliability of numerical modelling of anthropogenic climate changes, which formed the original basis of the greenhouse effect;

(ii) Contradictions between numerical modelling and observational data for SAT and other parameters.

The time has come to realize that adequate climate modelling is impossible without considering climate change and ecodynamics. The atmosphere-ocean-land-cryosphere-biosphere system has to be explored with consideration of all its complexities, including the potential impact of extraterrestrial inputs such as solar activity.

SOME NEW RESULTS IN THE FIELD OF CLIMATE DIAGNOSTICS

The Northern Hemisphere (NH) SAT increase observed after 1860 is known to have occurred until 1940 and not in the post-war years, when the GHG concentrations started growing intensively. The NH SAT linear trend after 1935 was close to zero. On the other hand, the data for the mostly water-covered Southern Hemisphere (SH), where the warming should have been slower and weaker, actually revealed a more distinct greenhouse signal. A statistical analysis of the global mean SAT values led to the conclusion that the warming had taken place mainly before 1945.

Long-term trends of SAT and sea surface temperature (SST) also revealed the presence of a short time lag between the land and the ocean. Taking into account the effect of urban heat islands on the data of some meteorological stations it was concluded that the SAT increase during the last 100 years was about 0.35-0.40°C.

Satellite microwave remote sounding data correlated well with the de-urbanized data, of the U.S. meteorological network. The correlation coefficient was 0.86. These data, plus radiosonde data suggested a global heating of only +0.04°C per decade for 1979-1990 (Christy *et al.*, 1991; Spencer and Christy, 1992). The combined results of satellite and ground observations led to the conclusion that the real increase of temperature between 1979 and 1990 was only 0.2°C in the Southern Hemisphere and was practically absent in the Northern Hemisphere.

Aerological soundings for North America of the average temperature (relative geopotential) for the 1000-500 hPa layer after 1948, plus indirect information for an earlier period (beginning 1885) revealed an increase of temperature during the first half of the 20th century which exceeded by a factor of 3 that obtained from surface observations, followed by a decrease of temperature. Temperature data for the same layer over the Northern Hemisphere after 1950 suggested a warming in the tropics and subtropics and a cooling at higher latitudes. On the average, for the entire hemisphere, the change in temperature for the 1000-500 hPa layer for 1950-1980 was close to zero.

These results do not agree with numerical modelling which predicts an increase of warming with latitude and a decrease of warming in the tropics, or a stronger polar warming in winter. Rather, the wintertime SAT observations in the North Atlantic Arctic revealed a strong secular temperature decrease. No such trend was detected during the polar night on the data for the South Pole station. The predictions of catastrophic climate warming have not been confirmed by data of diurnal temperature range in the USA, which definitely narrowed after 1950 as a result of decreasing maxima and increasing minima.

If we assume that anthropogenic warming should take place mainly during the night, this should entail a prolongation of the growth season, a reduction of the frequency of droughts, and an intensification of vegetation (due to fertilization by the increasing CO_2 concentration). Nocturnal warming would also weaken the process of ice melting, since at low temperature the enhanced greenhouse effect would not be sufficient for the temperature to rise above zero. Actually global warming should be favourable on the whole.

In evaluating the reliability of numerical modelling of the effect of increased GHGs concentrations on the climate we must bear in mind our inadequate understanding of two fundamental climate-forming factors:

(i) Atmosphere-ocean interaction (including the deep layers);

(ii) Cloud cover dynamics and cloud-radiation interaction.

Equally important (and much more difficult to take into account) is the interactive contribution of biosphere dynamics to global climate change (Kondratyev, 1992; Kondratyev and Grassl, 1993).

SOME COMMENTS ON THE FERTILIZATION EFFECT

Fertilization can be studied from the observational data. Thus, an increase of biomass in European forests was observed for two decades (the 70s-80s) despite acid rain damage to the forests. The increased assimilation of CO_2 by vegetation should markedly delay the rise in CO_2 concentration.

Note, however, that such conclusions about the fertilization effect need to be tested furhter. Studies by Idso (1991a,b) on the stimulating effect of increasing CO_2 concentration on vegetation were based on laboratory experiments with orange trees. For individual trees, with a CO_2 concentration twice as high as in the atmosphere, the amount of carbon accumulated by the tree in two years increased by a factor of 2.8. The global increase of CO_2 concentration was interpreted by Idso as an indicator of the fertilization effect. Thus with CO_2 doubling, the intensity of photosynthesis in the global biosphere should rise by a factor of 2.3 .

If one third of the global photosynthesis corresponds to forests and oceans, and if their productivity (assuming CO_2 doubling) increases by 33%, the forest productivity will rise by a factor of 2.8. Assuming that a doubling of the growth rate of closed forests is sufficient to compensate for anthropogenic emissions of CO_2, it turns out that at present levels of CO_2 emission its concentration of CO_2 will increase by at most 172 ppm by volume as compared to the pre-industrial level.

Opponents of Idso (1991c) suggest that these conclusions are based on some unacceptable assumptions:

(i) The complex dynamics of photosynthesis in conditions of increasing CO_2 concentrations (mainly, from the viewpoint of the balance between photosynthesis and respiration) should determine the total increase of carbon accumulation on land rather than the CO_2 concentration at a given rate of emission;

(ii) The net global primary production (NPP) of CO_2 should increase by 10% (this is equivalent to 50-60 GtC/year) if the anthropogenic emissions are to be balanced. Thus assimilation of carbon by closed forests should increase by 1 tC/m^2 in mid-latitudes and by 2.8 tC/m^2 year in the tropics. In undisturbed forests the assimilation of carbon is close to zero, since the heterotrophic respiration almost balances the NPP. The observed growth of CO_2 concentration during the last 200 years suggests that the effect of fertilization of the biosphere cannot be as high as Idso has supposed;

(iii) apparently, the effect of fertilization is largely compensated by deforestation.

In his comments, Idso (1991c) emphasized that intensified photosynthesis, taking place with increasing CO_2 concentration, reduces respiration. As a result, the primary productivity of forests grows substantially. Further studies are needed, but there is little doubt that an increasing CO_2 concentration may produce a strong increase of primary productivity. This problem illustrates the necessity of simulating the dynamics of the biosphere as a coupled component of the climatic system, including the global biogeochemical cycles of carbon, sulphur and nitrogen.

SOME ADVANCES IN LONG-TERM CLIMATE DYNAMICS MODELLING

Progress achieved in numerical climate modelling favours a better understanding of long-term climate variability. The increased power of computers has improved numerical climate modelling for very long time periods (of the order of centuries), which makes possible a more adequate appraisal of internal variability of the climatic system. Thus, we may obtain reliable data to detect anthropogenic signals (AS) in climate change.

The first results of numerical modelling for a period of hundred years (Barnett *et al.*, 1992) turned out to be very interesting. The global mean SAT slowly increased during the first 50 years and fell by 0.4°C during the next 25 years, especially after the 50th year. Then the process of warming began again. The change of temperature on a ten-year time scale is slightly less (though opposite in sign) than the observed global warming during the last hundred years.

Assuming a chaotic internal variability of the climate system, we may invert the curve of the SAT secular trend which will then be similar to the observed (plus a time shift). This is a further indication of the difficulty of a reliable identification of AS as it suggests that the SAT increase observed between 1900 and 1940 and its subsequent decrease between 1940 and 1965 may be due to the internal variability of the climatic system. Of course, external non-greenhouse factors (variability of extra-atmospheric insolation, tropospheric aerosol, etc.) cannot be excluded. The SAT variability on a ten-year scale not connected with external factors could be due to variations in heat transport in the oceans and to the associated ocean-atmosphere heat exchange.

Barnett *et al.* (1992) undertook a numerical modelling of climate using the GISS 9-level coupled model of the atmosphere and the ocean over a 8° latitude by 9° longitude grid. The model features a 1-D oceanic mixed layer and takes account of the observed geographic variability. The annual change of depth and the advection in the ocean is prescribed by the annual variation of heat transport in the ocean. This provides good agreement with the observed climate.

For a period of hundred years the low-frequency variability of climate is comparable with that observed during the last 100 years. The variability of the modelled climate turned out to be barotropic in the atmosphere and concentrated in the tropical belt with a maximum near the equator in the Pacific Ocean.

An application of the technique of principal components to the analysis of the curve of the SAT secular trend from the temperature field in the troposphere has shown that:

(i) The climatic signal is not really global in the lower and middle troposphere but is confined mainly to the tropics: 90% of the variability is determined by the contribution from the ± 30° latitudinal belt.

(ii) Near the equator the signal is coherent within the tropical atmosphere and more concentrated close to the surface than at the 200 hPa level where horizontal transport takes place.

(iii) At every altitude and over the globe the first mode explains 20% of the variability of temperature and the second mode 4%. The signal of cooling increases with altitude.

The greenhouse signal is characterized (according to earlier numerical modelling) by polar enhancement, but this fails to appear in control integration. Hence polar enhancement is one of the indicators to detect the greenhouse signal. The cause-and-effect analysis of the secular variability of model climates cannot be considered realistic because of the approximate character of the model. This kind of analysis reveals, however, an important and complicated influence on climate of the interaction between the structure of the SST field and atmospheric general circulation in the tropics and the role in the atmosphere-ocean system of lower cloudiness and moisture.

The uncertainty in the numerical modelling is mainly the effect of general circulation on the parameterized lower and upper cloudiness and on the optical properties of clouds at different spatial and temporal scales: the cloudiness-convection-ocean interaction is, no doubt, still insufficiently considered as a factor of climate change.

Meehl, Washington, and Karl (1993) have performed numerical modelling of climate with a gradual (1% per year) linear increase of CO_2 concentration in the atmosphere, in order to evaluate:

(i) The contribution of CO_2 to climate change;

(ii) The internal variability of the climate system at various time scales.

The 9-layer spectral coupled model R15, which approximately corresponds to 4.5° lat by 7.5° long feature a mixed 4-layer ocean and thermodynamic parameterization of the ice cover over the 5°x5° grid. Its can simulate, for example, phenomena such as the El Niño/Southern Oscillation (ENSO), characterized by the Pacific Ocean and accompanied by a long-range effect on the atmospheric general circulation in mid-latitudes. However, since flux corrections are not introduced the model contains systematic errors. SAT differences with respect to the control experiment for the 60th year of integration show that the maximum SAT increase takes place in high latitudes, except for the North Atlantic. The land surface is heated more rapidly than the ocean, with a minimum of ocean heating in high latitudes of the Southern Hemisphere and in the equatorial zone. The initial 15 years of weakly decreasing global mean SAT is followed by warming at the rate of 0.03°C/year during the next 30 years. By the end of the 100-year interval of integration, CO_2 is doubled and the total global warming reaches 2.3 °C.

The computed variability from one 5-year interval to the next is similar to that observed at the maxima in high latitudes over the continents in the winter hemisphere. There is no substantial agreement between the seasonal variabilities of SAT differences from one 5-year period to another. Thus, the spatial structure of the wintertime SAT anomalies for the period 20th-to-30th year of integration closely corresponds to the observed SAT trends in the Northern Hemisphere: cooling in the NH Atlantic and Pacific Oceans, but warming over the rest of the globe.

The lack of agreement may mean that the observed SAT trends are caused by the internal long-term variability of the climate system. The computed annual mean SAT differences for each of the three decades suggest, however, a small but steady warming in the tropics and sub-tropics, less warming around the Antarctic, and a strong warming in high latitudes of the Northern Hemisphere. These results are like those obtained with the same model for a sudden CO_2 doubling in the 30th year of integration. Essentially, however, this structure of spatial distribution of mean SAT anomalies does not become more intense with gradually increasing CO_2. It reflects a low-frequency variability on a 10-year scale in the coupled model.

When averaging over 30 years the results are even more similar to those of the ($2xCO_2$) case. This suggests that the climatic CO_2 signal is characterized by a specific spatial and temporal variability. An examination of zonal mean values brings out, for all periods, warming in the troposphere and cooling in the stratosphere. This might be used as a way to recognize the CO_2 signal. The results cannot, however, serve as a scientific basis for political decisions on regional climate change. They merely testify to the need of further studies on the interdecadal climate changes.

AEROSOL CLIMATIC IMPACT

Of great concern are the assessments of climate cooling foreseen as a result of increasing anthropogenic sulphate aerosols in the atmosphere, due to emissions of sulphur dioxide and subsequent gas-to-particle reactions of aerosol formation (Jennings, 1993; Kondratyev, 1991; 1991; Penner *et al.*, 1992a,b). Some indirect data show, for example, that at present the content of sulphates in the NH atmosphere can be compared with that observed after the Tambora eruption, when a SAT decrease of about 1-2 °C took place during a short time period.

Theoretical estimates show that the global mean radiative forcing (cooling) due to aerosols should amount to -1.5 to-2.0 W/m^2. This is comparable with the impact of the greenhouse effect, estimated at 1.5 - 2.5 W/m^2. Therefore the aerosol-induced cooling can explain that, despite an accelerating increase of CO_2, during the second half of the 20th century, the SAT almost stopped rising in the Northern Hemisphere, where the principal mass of anthropogenic sulphate aerosol forms. The SAT continued increasing but slowed down.

An intensified gas-to-particle conversion of anthropogenic sulphate aerosols should have increased the low-level cloudiness. In this case, the following consequences should be expected:

i) Increased nocturnal warming due to the intensified greenhouse effect and cloudiness;

ii) Reduction of day-time warming due to the increased cloud albedo;

iii) The cloud-induced nocturnal warming should be stronger during long nights in winter, and weaker during short nights in summer;

iv) The strongest cooling (day-time albedo effect) should be expected in the summer, when the day duration is at a maximum;

v) Cloudiness and other climatic effects mentioned above should be stronger in the regions such as North America and Eurasia, where the sources of anthropogenic aerosols (condensation nuclei) are more highly concentrated.

These predictions are qualitatively confirmed by observational data.

Intensified emissions of sulphur dioxide with formation of sulphate aerosols during the second half of the present century have called attention to the need of assessment of the aerosol effects on climate. These effects mainly produce an increase of the albedo of the surface-atmosphere system, due to the following two processes:

i) More backscattering with increasing aerosol content.

ii) Higher concentrations of condensation nuclei, which leads to the increase of small droplets and, hence, of the albedo.

The effect of anthropogenic aerosols on climate should be strongest in summer, with maximum insolation, and in regions of concentrated industry (e.g., Galindo, 1965, 1984, 1992).

Novakov and Penner (1993) have pointed out that the albedo and the radiative properties of marine stratus clouds depend largely on the density of cloud condensation nuclei (CCN) over the oceans. Modelling studies suggest that most of these nuclei are sulphate aerosols from both anthropogenic and natural sources. Novakov and Penner (1993) have presented evidence that organic aerosols may also play a key role in cloud nucleation. This conclusion was derived from observational data obtained in March-April 1992 as part of a field project on El Yunque, Puerto Rico peak (18° 19'N, 65° 45'W, elevation ~ 1000 m), where earlier observations had discovered high concentrations of SO_4^{2-} (from ~300 to ~2000 ng/m^3) and CN (from ~250 to ~3400 cm^{-3}. The higher concentrations indicate that anthropogenic aerosols may often strike the site. Not all CN acts as CCN, but sulphate particles are known to be efficient CCN.

The following aerosol parameters were measured on El Yunque peak:

i) The mass distributions of aerosol sulphur, chlorine, and organic carbon (OC), used to calculate the aerosol size distribution and aerosol number concentrations.

ii) CCN concentrations at 0.5% supersaturation.

iii) CN concentrations, and

iv) Total non-sea salt SO_4^{2-} mass concentrations determined concurrently with CN and CCN measurements.

The data show that:

1) Most of the Cl (or sea salt) is associated with large particles (D > 0.8 μm).

2) The aerosol sulphur is confined to a relatively narrow range of smaller particles.

3) The OC size distribution is more evenly spread over the entire size range. It contributes significantly more than sulphate aerosols to the number concentrations of small particles (D < 0.08 μm), despite the fact that total SO_4^{2-} mass is about twice the OC mass.

Novakov and Penner (1993) conclude that organic aerosols play a key role in cloud nucleation. In the present case the OC accounts for the major part of the CCN fraction. Thus, in regions that are affected by anthropogenic pollutants, organic aerosols may play at least as important a role as sulphate aerosols in causing cloudiness. This demonstrates the complexity of climate impact of aerosols and the possibility of surprises.

Table 1 from Penner *et al.*, (1992a, b) describes the principal types of anthropogenic aerosols enumerated in order of their probable importance and of the reliability of

Table 1

Principal types of anthropogenic aerosol, their sources and associated consequences. After Penner *et al.*, (1992b).

Type of anthropogenic aerosol	Principal sources	Forcing mechanisms
1. Water soluble inorganic substances (e.g., sulphates, nitrates, ammonia)	Industrial pollution and (for ammonia) fertilizers and stock-breeding.	a) SW radiation backscattering; b) Indirect effect of CN on could albedo; c) Indirect effect of CN on the cloud droplets life-time.
2. Organic condensed components	Industrial pollution and biomass burning	a), b), c)
3. Elemental carbon	Industrial pollution and biomass burning	d) Solar radiation absorption; d) Effect on the vertical temperatura profile
4. Mineral dust	Soil (desertification and deforestation)	a), b), c), d), as well as absorption and emission of LW radiation.

the information. Mixed aerosols (i.e., different types of "internal" mixtures of aerosols) are typical. Table 2 summarizes the factors which determine the direct climate forcing of sulphate and organic aerosol due to biomass burning. The total uncertainty, taking account of all the factors enumerated in Table 2, is 1.9. If globally averaged radiative forcing (RF) due to sulphate aerosols is assumed to be 0.6 W/m^2, the range of variability lies within 0.3 - 1.1 W/m^2. An assessment of the contribution of organic anthropogenic aerosols from biomass burning yields a global mean RF value of 0.8 W/m^2, with an uncertainty of 0.3 to 2.0 W/m^2. Information about elemental carbon as a radiation absorber is fragmentary, but, it may affect the transfer of longwave (LW) greenhouse effect and short-wave (SW) radiation. Increased radiation absorption produces additional heating of the atmosphere.

The effect of scattering and absorption due to mineral dust is rather complicated. The silicon-containing substances are known to be strong absorbers in the atmospheric transparency window of 9-14 μm. In this case information about the size distribution and chemistry of aerosols may become very important.

As Penner *et al.*, (1992b) emphasized, the effect of CN on the size distribution and optical properties of clouds involves many uncertainties. This problem can be solved only through a coordinated programme of numerical modelling and complex field experiments. Because of strong spatial and temporal variability of the aerosol content and properties, the space-borne monitoring of aerosols in the atmosphere is extremely important (Table 3).

GLOBAL CLIMATE OBSERVING SYSTEM

The present situation in the field of global climate studies appears to be paradoxical:

i) In spite of years of continued attempts by many experts to substantiate greenhouse global warming (e.g., Budyko, 1991, 1992; Budyko *et al.*, 1991), the IPCC has come to the conclusion that there is no convincing evidence from observations of a greenhouse effect on global warming during the last century, and that paleo-analogies cannot be used for climate predictions (Houghton *et al.*, 1990; IPCC, 1992).

ii) Studies of the internal variability of the climatic system have priorized the climate-forming role of cloud cover dynamics (especially cloud-radiation interaction), atmosphere-ocean interaction, and the role of the biosphere as an interactive component of the climatic system (Kondratyev and Cracknell, 1994; IPCC, 1992).

iii) A number of recent publications on climate diagnostics have substantially modified our understanding and assessment of the SAT secular trend during the last century.

The paradox consists in that, as Wigley and Raper (1992) note, the degree of uncertainty in climate prediction has increased, the main factor of uncertainty being the poorly-known climatic sensitivity to external forcings.

To ensure further progress in climate studies, it is critically important to implement a global climate observing system. The draft plan for a Global Climate Observing System (GCOS) developed by the WMO Scientific-Technical-Committee (Houghton, 1993) describes the strategy. The first stage of GCOS should be implementation and development of the Initial Operational Observing System (IOOS) based on the available operational observing systems by adding new components and expanding data processing and capabilities. Operational observations are those with clearly formulated requirements, substantiated needs of reliable and continuous data, well-developed technology and long-term support.

The principal GCOS objectives consist in providing documentation on the present state of the climate, monitoring the factors determining climate changes, and a deeper understanding of the evolution of climate. Together with numerical modelling, the GCOS data allow reliable techniques of short-range predictions to develop.

Of the highest priority are the following GCOS problems:

i) Seasonal and interannual climate change predictions (most importantly the dynamics of the ENSO events).

ii) Early detection of climatic trends and anthropogenic climate changes. A deeper understanding is needed of the causes of climate change and, in particular, the contribution of natural changes.

iii) Reducing the uncertainty of climate predictions by assessing the reliability of climate models by comparing with more complete observational data. Improving the techniques of data assimilation in climate models plays an important role here.

The GCOS should be based on a systems approach that includes every component of the atmosphere-ocean-land-cryosphere-biosphere climatic system and their interactions. The IOCS is planned to develop over the next decade. Obviously GCOS should be based on coordination and cooperation with programs such as World Weather Watch (WWW), Global Atmosphere Watch (GAW), Integrated Global Ocean Service System (IGOSS), Global Sea Level Observing System (GLOSS), Global Environmental Monitoring System (GEMS), World Climate Research Program (WCRP), and the International Geosphere-Biosphere Program (IGBP). Cooperation with the Global Ocean Observing System (GOOS) under the auspices of the International Oceanographic Committee, and with the newly developed Global Terrestrial Observing System (GTOS), should be especially close.

Among available observing systems we may mention the Global Observing System (GOS), part of WWW, and the Global Telecommunications System (GTS). So far, many regions lack conventional observations, including parts of Africa and South America and vast areas of the SH ocean.

Table 2

Factors affecting the direct climate forcing of anthropogenic aerosols. After Penner *et al.* (1992b)

Parameter	Average	Range of variations	Ucertainty coefficient
Emission contribution, g/kg C in fuel	32	18-56	1.750
Efficiency of sulphate aerosol scattering, m^2/g	5	3.6-7	1.400
Efficiency of sulphate aerosol from the products of burning, m^2/g	0.7	0.5-0.9	1.286
Lifetime of smoke from the products of burning, days	5	3.6-7	1.400
Average lifetime of atmospheric SO_4^{2-}, years	0.016	0.012-0.022	1.375
Globally averaged share of backscattering	0.15	0.12-0.19	1.267
Share of SO_2 oxidized to SO_4^{2-}	0.5	0.4-0.6	1.200
Proportionality coefficient, W/m^2	489	406-589	1.204
Amount of burnt biomass, TgC/year	3800	3200-4500	1.197
Relative intensification of the efficiency of backscattering by sulphate aerosol due to its hygroscopic growth	1.7	1.4-2.0	1.176
Power of anthropogenic soot sources, Tg/year	71	62-81	1.141
Share of the cloud-free Earth	0.39	0.35-0.44	1.128

Table 3

Planned or proposed space-borne instruments to monitor aerosols. After Penner *et al.* (1992b)

Instrument/ Satellite	Time of launch	Spatial resolution km	Spectral channels	Parameters to be retreaved	Probable resolution by optical thickness	Remarks
SeaWIFS	1994	4	443, 500, 565, 665, 765, 865 nm	Optical thickness, size distribution	0.05	Data only over the ocean; two IR channels to filter out clouds
AVHRR/ NOAA-K	1994	4	630, 845 nm, 1.59-1.78 μm	Optical thickness	0.1	Narrow channel No. 2 outside H_2O bands; new channel No. 3 for the day- time side.
POLDER/ ADEOS	1996	7	443, 490, 565, 665, 762, 765, 865, 910 nm	Optical thickness, size distribution, type of aerosol		
MODIS/ EOS-AM, PM	1998	0.025 0.05 1	659, 865 nm 470, 555 nm 1.24,1.64,2.13μm 415, 443, 490,531 865,905,936,940 nm	Optical thickness, size distribution	0.05	Reliable filtering out of clouds using the multichannel information
MISR/ EOS-AM	1998	2	440, 550, 670 860 nm	Optical thickness, size distribution	0.05	9 multi-channel "comb-like" scanners-multi-level data.
SAGE-III/ EOS-AERO	2000	200	290-1020 nm resolution 1 nm, 1.55 μm	Vertical profile of aerosol extinction, size distribution		Vertical resolution 0.5 km in the stratosphere and the upper troposphere (up to 4km) without clouds
EOSP/ EOS-AM2	2003	8	410, 470, 555 615, 675, 750 880, 950 nm; 1.25, 1.60, 1.05, 1.25 μm	Optical thickness size distribution refraction index (?), type of aerosol (?)	0.03	Measured not only brightness but also polarization degree at every channel.

The GOSS incorporates the polar-orbiting and geostationary satellites. According to the WMO a system of two polar-orbiting and five geostationary satellites is needed. A large volume of satellite information has made it possible to achieve such WCRP components as the International Satellite Cloud Climatology Project (ISCCP), International Satellite Land Surface Climatology Project (ISLSCP), and International Global Precipitation Climatology Project (IGPCP).

The observing system GAW is nearly operational and includes a global system for ozone observations (about 140 stations) and a network of background stations to monitor atmospheric pollution (about 200 stations), which provides information about the atmosphere and precipitation chemistry, solar radiation and atmospheric transparency, the content of some greenhouse gases, etc. Within the IGCS system about 150 ships and 450 buoys are regularly functioning, and GLOSS controls about 300 permanent stations, where the ocean level is monitored. Satellite observations are the principal source of information.

Of great importance are the data from more than 100,000 hydrological stations for observing such parameters as precipitation, evaporation, surface run-off, water level, water quality, sediment transport, ground water level, glacier mass, extent, thickness and water equivalent of snow cover, etc. The problem is, however, that the hydrological observations are still inadequately coordinated on a global scale even as to measurement techniques. There is still only a small number of long series of reliable observations.

The available observing systems are planned to be extended, bearing in mind the following objectives:

i) Provision of continuity and homogeneity of space-borne observation series.

ii) Increasing the number of stations for conventional observations (including sea buoys), improving the reliability of observations and increasing the number of parameters to be measured.

Of the first priority is the implementation of programs for observing the key parameters characterizing the processes in the atmosphere, at the atmosphere-ocean interface, in the ocean, at the atmosphere-land interface, and on land.

The principal parameters of the atmosphere needed for studying natural and anthropogenic causes of climate change and the possibilities of climate prediction include: air temperature near the Earth's surface and in the free atmosphere, wind speed and relative humidity. This satisfies the WWW requirements. In the context of the WCRP objectives, an optimal observing system should be implemented from the viewpoint of locating the stations and the needed measurement accuracy.

Particularly important are the long-term space-borne observations with scatterometers (retrieval of wind speed near the ocean surface); broadband precise radiometers (measurements of the Earth's radiation budget and its components); pyrheliometers to monitor the solar constant; multi-channel scanning microwave radiometers (assessment of ice and snow cover, moisture and water content of the atmosphere, rainfall, etc.)

Even more urgent is the monitoring of atmospheric chemistry parameters (water vapour, ozone, greenhouse gases, aerosols, etc.) The development of a complex observing system for tropospheric aerosols is particularly important.

From the viewpoint of the atmosphere-ocean interaction, the following parameters should be observed: sea surface temperature SST (the problem of comparing SST satellite and ship observations to characterize the temperature of the upper layer of the ocean remains unsolved); the speed and direction of winds near the ocean surface; momentum and heat fluxes (the combined use of conventional and satellite observations is essential); evaporation and precipitation over the ocean; fluxes of CO_2 and other GHGs; colour of the ocean; the level and topography of the ocean surface (space-borne radio altimetry is particularly important); the extent and characteristics of the sea ice cover. To study the interior of the oceans, parameters should be observed such as : temperature, salinity and currents in the upper layer of the ocean; assessment of the cycles of heat, fresh water and carbon in the ocean; and biogeochemical processes (the Joint Global Ocean Fluxes Study JGOFS; World Ocean Circulation Experiment WOCE; hydrographic, hydrochemical and biological sections).

The need of information for studies of land surface processes and atmosphere-land interaction has been adequately described in the ISLSCP program. The first priority is for observations of the shortwave radiation budget. It is important to attain a spatial resolution of 250 km, to be further improved to 50 km with an accuracy of 10 W/m^2. Also absorbed photosynthetically active radiation observations are required, for which space-borne observing means are needed.

It is necessary to have more adequate information about the types of surface (including land use) improving resolution from 250 km (at present) to 50 km (in the near future), with more detailed descriptions up to 5 km (slopes) and 20-300 km (catchment areas) for individual limited regions. The source of such information may be the data of AVHRR, Landsat, and SPOT satellites, as well as radar images (ERS-1, Almaz-1). It is important to enlarge the AVHRR data base with a 1 km resolution (there is already such a data base for 1992-93). One problem is to obtain and accumulate data on soil moisture and river runoff, as well as ice formations (ice sheets and shelves, glaciers).

A complex problem is the processing, storage and distribution of the data classified into three categories:

i) Results of *in-situ* observations.

ii) Satellite information

iii) Secondary data (results of 4-D assimilation and numerical modelling, calculation of fluxes, etc.).

The 4-D assimilation is particularly important. The user-oriented system of GCOS data is planned to be distributed on CD-ROM.

Further development of space-borne observations should be focused on improving:

i) Techniques to retrieve precipitation and cloud cover data (passive and active microwave sounding, including the millimeter wave-range, etc.).

ii) Accuracy and vertical resolution of the profiles of wind, temperature and humidity (including lidar sounding).

iii) Techniques to retrieve the optically active minor gaseous components, ozone and aerosol (especially in the troposphere).

iv) Monitoring of glacier dynamics (including an application of interferometric observations with synthetic-aperture radars).

v) Scanning radioaltimeters to monitor the central Antarctic.

Of extreme importance are further developments of various conventional observations. This refers, for example, to the instruments for studying the chemical and photochemical processes (especially in the troposphere), physical properties of clouds and aerosols; the development of acoustic tomography of the ocean to monitor the temperature field, etc.

CONCLUSIONS

The following problems should be considered as of first priority:

1. Implementation of the Global Climate Observing System (GCOS) on the basis of existing experiments and numerical modelling, including:
   1.1 Priorization of climate parameters.
   1.2 Requirements of spatial and temporal resolution.
   1.3 Specification of observational errors.
   1.4 Optimization of combined conventional and satellite systems, including focussed field experiments.

2. Consideration of those significant processes that are most important from the viewpoint of uncertainties in climate modelling:
   2.1 Ocean-atmosphere interaction (including CO_2 and DMS exchange); the notion of energy-active zones; climate- cryosphere coupling.
   2.2 Parameterization of cloud dynamics, cloud-radiation interaction; dedicated field experiments, and nested models.
   2.3 Colloidal components of the atmosphere; aerosols and climate; global aerosol models, information between aerosols and clouds (gas-to-particle conversion processes); aerosols versus greenhouse climate impacts.
   2.4 Biogeochemical cycles (primarily carbon and sulphur), and their coupling with climatically significant processes.

3. Principal causes of uncertainties in climate modelling and the problem of predictability:
   3.1 Parameterization of subgrid processes; applications of the nested grid approach; mesoscale models.
   3.2 Possibilities of model verification: cases of satellite data and focused field experiments.
   3.3 Perspectives of coupled climate-biosphere models.
   3.4 Computational aspects; application of conjugated equations and splitting techniques.

4. Substantiation of a revised concept of the Framework Convention on Climate Change, coupled with future conventions on biodiversity, forestry and desertification.

BIBLIOGRAPHY

BARNETT, T. P., A. D. DEL GENIO and R. A. RUEDY, 1992. Unforced decadal fluctuations in a coupled model of the atmosphere and ocean mixed layer. *J. Geophys. Res., C97, 5,* 7341-7354.

BUDYKO, M. I., 1991. Analogy technique to assess future climate change. *Meteorol. and Hydrol., 4,* 39-50 (in Russian).

BUDYKO, M. I., 1992. An accuracy of estimates of future climate conditions. *Meteorol. and Hydrol., 5,* 5-13 (in Russian).

BUDYKO, M. I., A. ISRAEL Y. and A. I. YANSHIN, 1991. Global Warming and its Consequences. *Meteorol. and Hydrol., 12,* 5-10 (in Russian).

CHRISTY, J. F., R. T. McRIDER and F. R. ROBERTSON, 1991. Comparison of MSV and CCM1 tropospheric temperatures for 1979-1986. Fifth Conf. on Climate Variations. Amer. Meteorol. Soc., Raston, MA., pp. 28-31.

GALINDO, I., 1965. Turbidiometric estimations in Mexico City using the Volz Sun Photometer. *Pure and Appl. Geophys., 60,* 189-196.

GALINDO, I., 1984. Anthropogenic aerosols and their regional scale climatic factors. *In:* Aerosols and their Climatic Effects. H.E. Gerber and A. Deepak, Eds., A Deepak Publ., pp. 245-259.

GALINDO, I., 1992. Cambios climáticos regionales como componentes del cambio climático global. *Ciencia, 43,* 21-27.

HOLMBERG, J., K. THOMSON and L. TIMBERLAKE 1993. Facing the Future, Beyond the Earth Summit. Intern. Inst. for Environ. and Develop., London, 48 p.

HOUGHTON, J. T., Ed., 1993. Draft Plan for the Global Climate Observing System. WMO, Geneva.

HOUGHTON, J. T., G. J. JENKINS and J. S. EPHAUMS, Eds., 1990. Climate Change. The IPCC Scientific Assessment. Cambridge Univ. Press, 3 Vols., 365 p.

IDSO, S. B., 1991a. The aerial fertilization effect of CO_2 and its implications for global carbon cycling and maximum greenhouse warming. *Bull. Amer. Meteorol. Soc.*, *72*, 7, 962-966.

IDSO, S. B., 1991b. Carbon dioxide and the fate of the Earth. *Global Environ. Change*, *1*, 3, 178-182.

IDSO, S. B., 1991c. Reply. *Bull. Amer. Meteorl. Soc. 72*, 12, 1910-1913.

IPCC, 1992. Supplement Intergovernmental Panel on Climate Change. WMO/UNEP, Geneva. 70 p.

JENNINGS, S. G., Ed., 1993. Aerosol Effects on Climate. The University of Arizona Press. 350 p.

KONDRATYEV, K. YA., 1990. Key Problems of Global Ecology. Itogi Nauki i Techniki. Theoretical and General Problems of Geography. Vol. 9, Moscow, VINITI Press. 454 p. (in Russian).

KONDRATYEV, K. YA., Ed., 1991. Aerosols and Climate. Leningrad, Gidrometeoizdat. 542 p. (in Russian).

KONDRATYEV, K.YA., 1991a. The Second World Climate Conference. I. General survey and conception of climate studies. *Izvestiya of Russian Geograph., Soc.*, *123*, 5, 401-408 (in Russian).

KONDRATYEV, K.YA., 1991b. The Second World Climate Conference. II. Assessments of global climate change and measures to prevent it. *Izvestiya of Russian Geograph. Soc.*, *123*, 6, 473-480 (In Russian).

KONDRATYEV, K. YA., 1992. Global Climate. St. Petersburg. Nauka Press, 359 p. (in Russian).

KONDRATYEV, K. YA., 1993. The Second UN Conference on Environment and Development: some results and perspectives. *Izvestiya of Russian Geograph. Soc.*, *125*, 3, 1-8 (in Russian).

KONDRATYEV, K. YA. and V. M. KOTLYAKOV, 1991. Polar regions and their contribution to global ecological change. *Izvestiya USSR Acad. Sci.*, *Geograph. 1*, 36-46 (in Russian).

KONDRATYEV, K.YA. and H. GRASSL, 1993. Global Climate Change in the Context of Global Change. St. Petersburg, Acad. Sci. Publ., 195 p. (in Russian).

KONDRATYEV, K. YA. and A. P. CRACKNELL, 1994. Observing Global Climate Change. Taylor and Francis, London (in press).

MEEHL, G. A., W. M. WASHINGTON and T. R. KARL, 1993. Low-frequency variability and CO_2 transient climate change. Pt. 1. Time-averaged differences. *Climate Dynam. 8*, 3, 117-134.

MICHAELS, P. J. and D. E. STOOKSBURY, 1992. Global warming: a reduced threat?. *Bull. Amer. Meteorol. Soc.*, *73*, 10, 1563-1567.

NOVAKOV, T. and J. E. PENNER, 1993. Large contribution of organic aerosols to cloud-condensation nuclei concentrations. *Nature 365*, 825-827.

PENNER, J. E., S. J. CHAN and J. J. WALTON, 1992a. The role of biomass burning in the budget and cycle of carbonaceous soot aerosols and their climatic impact. Global Biomass Burning. Atmospheric, Climatic, and Biospheric Implications. Ed. by J.S. Levine. The MIT Press Cambridge, MA, pp. 387-393.

PENNER, J. E., R. J. CHARLSON, J. M. HALES *et al.*, 1992b. Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols. DOE/NBB-00921. UC-402. Contr. NW-7405-Eng-48, U.S. Department of Energy, Washington, D.C. 53 pp.

SPENCER, P. W. and J. R. CHRISTY, 1992. Precision and radiosonde validation of satellite gridpoint temperature anomalies. Pt. II: A troposphere retrieval and trends during 1979-1990. *J. Climate*, *5*, 858-866.

WIGLEY, T. M. L. and S. C. B. RAPER, 1992. Implications for climate and sea level revised IPCC emissions scenarios. *Nature*, *357*, 293-300.

K. Ya. Kondratyev[1,2] and I. Galindo[3]

[1] *Academician, Co-Chairman of the Board, Nansen International Environmental and Remote Sensing Centre (NIERSC), 18, Korpusnaya str., 197042 St. Petersburg, RUSSIA*

[2] *K.Ya. Kondratyev is at present Visiting Professor at the University of Colima.*

[3] *Centro Universitario de Investigaciones en Ciencias de la Tierra (CUICT), Universidad de Colima, 28000 Colima, Col., MEXICO.*