NATURAL LONG-TERM CHANGES IN GLOBAL CLIMATIC ENVIRONMENT

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ABSTRACT

In comparison with man-made changes in the heat and water balance of the geophysical system atmosphere/ocean/ice, natural factors responsible for large-scale climatic changes will be discussed. Such natural factors are: possible fluctuations of the 'solar constant', volcanic eruptions causing stratospheric air pollution, surges of the Antarctic ice-sheet and fluctuations of the extension and thickness of Arctic sea-ice.

Evidence for regional and global instabilities (more precisely, intransitivities) of the geophysical system will be given. Finally, the future role of man's energy production and of man-made changes in the fresh-water budget will be discussed.

In recent years the geophysical system atmosphere–hydrosphere has received increasing attention even outside the relatively small roster of specialists in earth sciences. This is due to the fact that large-scale climatic variations are observed, frequently arousing speculations about a possible man-made pattern of these variations. This is in fact a matter of high concern among leading meteorologists and hydrologists, who have now succeeded in designing families of physico-mathematical models capable of simulating the most prominent features of the actual climate.

In searching for the most exciting examples of climatic variability, we have to take into account different time-scales, not only since the beginning of instrumental observations (about 1670) but also including the historical development of climate now rapidly emerging from obscurity with modern techniques such as isotope chronology and temperature measurements. There is no doubt that the world's climate is not stationary, that warming and cooling, droughts and wet periods are not completely compensating each other, but that the global balance itself is subject to change. This is especially true of temperature, the global warming trend of the years 1890–1940 having been replaced by global cooling. This cooling has reached a peak in the anomalous year 1972, with the greatest frequency of icebergs near Newfoundland since the beginning of this century. The cooling of the polar cap north of Lat. 50°N has been accompanied by the most disastrous drought in the Sahel belt of Africa since 1913, in India since 1918 and (in contrast) by a widespread anomaly of warm water and abundant rainfall reaching from the west coast of

South America (here devastating the fishery production of the world's largest fishery nation, Peru) along the Pacific equator over more than 12 000 km beyond the date-line. At isolated islands such as the Galapagos rainfall increased by a factor of 5–20, and the oceanic evaporation should also have increased by 30% or more, in a belt of about 12 000 × 600 km. Here evaporation and release of latent heat by precipitation cause an intensification of the Pacific trade-wind system (the so-called Hadley cell), more or less simultaneous with a weakening of the monsoon system of southern Asia and Africa. There are some indications that this coincidence is not random, but caused by a hitherto unidentified mechanism within the atmosphere–ocean system, the more so because of the coincidence with other anomalies such as the drought in the USSR.

It is generally agreed among experienced climatologists that the occurrence of such comparatively rare anomalies—rare in the scale of human lifetime—is mainly due to natural factors and only secondarily aggravated by man-made processes, such as the destruction of natural vegetation together with lowering of the groundwater level in the Sahel belt by excessive use of water. Among the most prominent climatogenetic factors are the following.

(1) The extraterrestrial direct radiation from the sun has been measured recently, above 80 km, with fair accuracy and found to be 1360 W/m^2 at a perpendicular surface: equally distributed over the horizontal surface of the rotating globe, the average is about one-fourth or 340 W/m^2. It is generally agreed to use the term solar constant in spite of the fact that it is not really a constant. Time fluctuations dependent (non-linearly) on the sun-spot cycle have been measured below 32 km—they hardly represent the true extraterrestrial radiation, because of the existence of volcanic particles and of ozone above the level, both varying with time. The observed time variations of the solar ultra-violet and Roentgen rays are large, but do not contribute significantly (less than 10^{-5}) to the solar energy. While their effect in the thermosphere (above 110 km) is very large, their effect in the weather-producing layers below 100 mb (about 16 km) can be detected only with statistical methods and is still controversial.

(2) The composition of the atmosphere is—as regards the main constituents such as nitrogen, oxygen and noble gases—very nearly constant. This is not true for the variable constituents: CO_2 has increased, since the end of the last century, by about 12%, and is still increasing, at a rate between 0.2 and 0.3% per year, owing to combustion of fossil fuel; O_3 is also increasing quite slowly, from unknown (probably natural) sources; while H_2O appears to be constant, at least within experimental error. Trace gases will be dealt with by other authors. The variations of O_2 caused by combustion are of the order of a few p.p.m.—it is unknown how far they are compensated (or not) by man-induced changes in the biosphere.

(3) The amount of aerosol particles varies considerably—in the lower troposphere (mainly below 3 km) due to man's activity, in the stratosphere (mainly in the Junge layer between 20 and 25 km) due to the strongly varying input from volcanic eruptions which are large enough to penetrate the tropopause (near 12 km). In a visible form, volcanic dust veils usually remain 1–3 years in the stratosphere; they are concentrated by a nearly permanent

circulation in the polar caps and can remain there somewhat longer. They scatter sun's radiation—to a small extent (according to Mie's law) backward—but they also absorb radiation and warm their immediate surroundings. Stratospheric aerosol layers have therefore a cooling effect on the lower troposphere amounting to 1–1.5°C in a hemispherical scale. This is not true for the low-tropospheric particle layer originating at the surface—here the average residence time is only a few days (in humid zones) or weeks (in arid zones). The cooling effect of scattering is apparently more than compensated by the warming effect of absorption intensifying the long-wave counter-radiation of the lower troposphere: this contributes substantially to the oppressive high night temperatures in dust-laden industrial cities or in deserts with loess-like soils, 2–4°C higher than in unpolluted air.

(4) One of the most influential climatogenetic factors is the varying extension of snow and ice—which is related to climate in a complex non-linear feedback mechanism difficult to simulate properly. The albedo (reflectivity) of all other natural surfaces—except yellow sand and gypsum dunes—varies only between 0.04 and 0.25; the albedo of fresh-fallen snow or pure (water-free) ice between 0.7 and nearly 0.9. This is the most important factor in the heat budget of all surfaces: snow and ice surfaces are a permanent source of cold air, and the weather-producing frontal zones between warm and cold (tropospheric) air show a strong tendency to fluctuate along the boundaries of large snow and ice areas. The extreme coolness and the circulation anomalies of the years 1971 and 1972 coincide with an increase in the northern hemisphere snow cover by 12%, as revealed by regular satellite observations—this is apparently more than a mere coincidence. It may be noted that in some periods (around 1840 and 1900) large numbers of enormous icebergs have surged from the existing Antarctic ice shelves, some of them as large as Belgium or the Netherlands, increasing the albedo and decreasing the temperatures of the southern hemisphere. The possible role of these Antarctic surges in the climatic history of the earth deserves much more attention than in the past, but events of this (or possibly much larger) intensity are obviously rare.

Outside the circle of specialists, the interest in climatic history has been aroused mainly because of the deleterious consequences of climatic anomalies in economy, especially in food production. Simultaneous occurrence of droughts in large grain-producing areas has caused a drop of the world's production by about 6% in 1972. There is no doubt that even more serious anomalies can occur—similar to those observed in the previous century. This situation is aggravated because of the rapid expansion of the world's population, which will reach 4 × 10^9 persons during 1975. Food production per capita is now not higher than 25 years ago, in several large countries even smaller—the world's grain reserves are certainly too small for a really severe famine.

Among climatologists and hydrologists the main emphasis has been placed on the quite novel concept of instability or—more precisely—of intransitivity of our climate which has been formulated from a purely theoretical viewpoint but which has been empirically confirmed at a regional scale and, as a rare event, even at a global scale. What has happened in the past can happen in the future: at present, we do not sufficiently understand the functioning of the whole system with its in-built positive and negative feedbacks to warrant a forecast of future climatic change.

The most sensitive and vulnerable feature is the Arctic sea-ice, which is in a highly delicate state of balance, and which has been subject to variations of area and thickness of 20% or more during the last 1000 years, of nearly 50% in the last 6000 years. Since about 1950 it has expanded slowly and has now reached a stage nearly similar to that at the beginning of this century. However, if and when anthropogenic warming outweighs other factors, and if the increasing need of food production forces a partial diversion of the great freshwater rivers from the Arctic into the arid irrigation areas of Central Asia and western North America, a drastic reduction and even a complete disappearance of the sea-ice is possible. This should have a dramatic effect in a shift of the large-scale climatic belts—in some areas beneficial, in others causing a catastrophic deterioration of the freshwater supply in densely populated regions. This is the more serious because a complete removal of Arctic sea-ice would be irreversible, even under present climatic conditions.

What about man's impact on this highly sensitive system with its partial instabilities? Today this most important aspect can only be tentatively answered with reasonable estimates of the energy contribution of natural and anthropogenic climate-producing effects (*Table 1*). Each comparison of these contributions should not start from the energy value of the solar constant or from the similarly high value of the radiation balance (net radiation) at the earth's surface: both quantities are mainly needed to maintain a given state of equilibrium. The dynamics of the atmosphere–hydrosphere system are controlled by the production of available potential energy, which is estimated to about 1000 TW. All natural effects connected with global-scale climatic variations are of the order of 100–300 TW—except those responsible for the (apparently sudden) transition into a glacial epoch, which amount to about 1000 TW.

Man-made climatogenetic processes contribute, at present, between 16 and 20 TW, including the direct release of fossil and nuclear energy of nearly 8 TW. Since this last-mentioned quantity will further rise exponentially, as a consequence of many unavoidable economic and social processes, we ought to expect, near the middle of next century, man-made processes to reach the same level as the natural factors. Then the risk of irreversible climatic changes will become intolerable.

There is no immediate danger of such a development, which is expected to happen after two or three generations. But the present expansion of the Arctic ice leads to an increased frequency of extreme anomalies (positive and negative), with unavoidable economic and social consequences. This outlook, based on all available evidence from the last millenium, commits us to intensified research on climate which is now under preparation within the framework of the Global Atmospheric Research Program (GARP) and its sub-programmes. Such research should include empirical investigations as well as model computations, which have reached a fairly advanced level. However, an advanced model, designed at a simplified 'real' earth with a fairly realistic distribution of oceans and continents (and mountains), and taking into account the non-linear feedback between atmosphere, ocean and ice as well as the hydrological cycle including soil moisture, needs a prohibitively large

Table 1. Energetics of large-scale climatic changes

(A) *External parameters*	TW (10^{12} W)	W/m^2
Solar constant	173 000	340
Input earth + atmosphere	123 000	241
Net radiation, earth surface	52 000	102
Geothermal heat	+32	0.063
Volcanic dust, stratosphere	max. 2 000? (1–3 years)	
Antarctic ice surges	50–100 per 10^6 km^2	
(B) *Internal parameters* (non-linear feedback)		
Absorption in the atmosphere	45 000	88
Production of available pot. energy	1 000	2.0
Change in cloudiness (1 %)	350	0.67
Change in evaporation equat. oceans	300	0.59
Photosynthetic processes	±92	0.18
Change in snow cover (12 %)	110	0.22
Change in Arctic sea-ice	50 per 10^6 km^2	
(C) *Anthropogenic parameters*	*1970*	*2000*
Increase in CO$_2$	+ 1.5 TW = 3 mW/m^2	+ 2.4 TW
Energy production	+ 8 TW = 15 mW/m^2	+ 40 TW
Savannah bush-fires, heat	+ 3 TW = 6 mW/m^2	?
Tropospheric dust, total	+ 40 TW (northern hemisphere)	
Tropospheric dust, industry, cities	+ 1.7 TW = 3 mW/m^2	+ 2·5 TW
Tropospheric dust, vegetation destruction	+ 5 = 10 mW/m^2	6
Water consumption (evaporated)	+ 140 TW = 270 mW/m^2	+ 380 TW
Conversion tropical rain-forest		− 17 TW per 10^6 km^2

computer time. It is therefore a matter of greatest concern to develop models far beyond the range of weather forecasting, without dealing explicitly with each individual cyclone and anticyclone, but including their effect on energy transports and conversions.

Looking far ahead, the stability of climate (more exactly, the freshwater budget) will be among the first and most important handicaps for economic growth, with serious consequences for humanity—not now, but in the generation of our children and grandchildren.