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CLIMATIC CHANGES AND NUMERICAL MODELING

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PREFACE

The physical basis for modelling climatic change is considered in connection with the construction of global circulation models (GCM) for simulation of the climate itself and geophysical aspects of the interaction between man and climate. A retrospective review of the basic assumptions with respect to the nature of the major course of climate behavior in the past, is given with a brief survey of paleoclimatic approaches. The main features of the two advanced numerical climate models are discussed and the role of the world oceans in maintaining the climate is considered. The author's point of view on the geophysical aspects of global climate simulation for IIASA's purposes in studying the socio-economic effect of man-climate interactions is presented.

Climatic Changes and Numerical Modeling

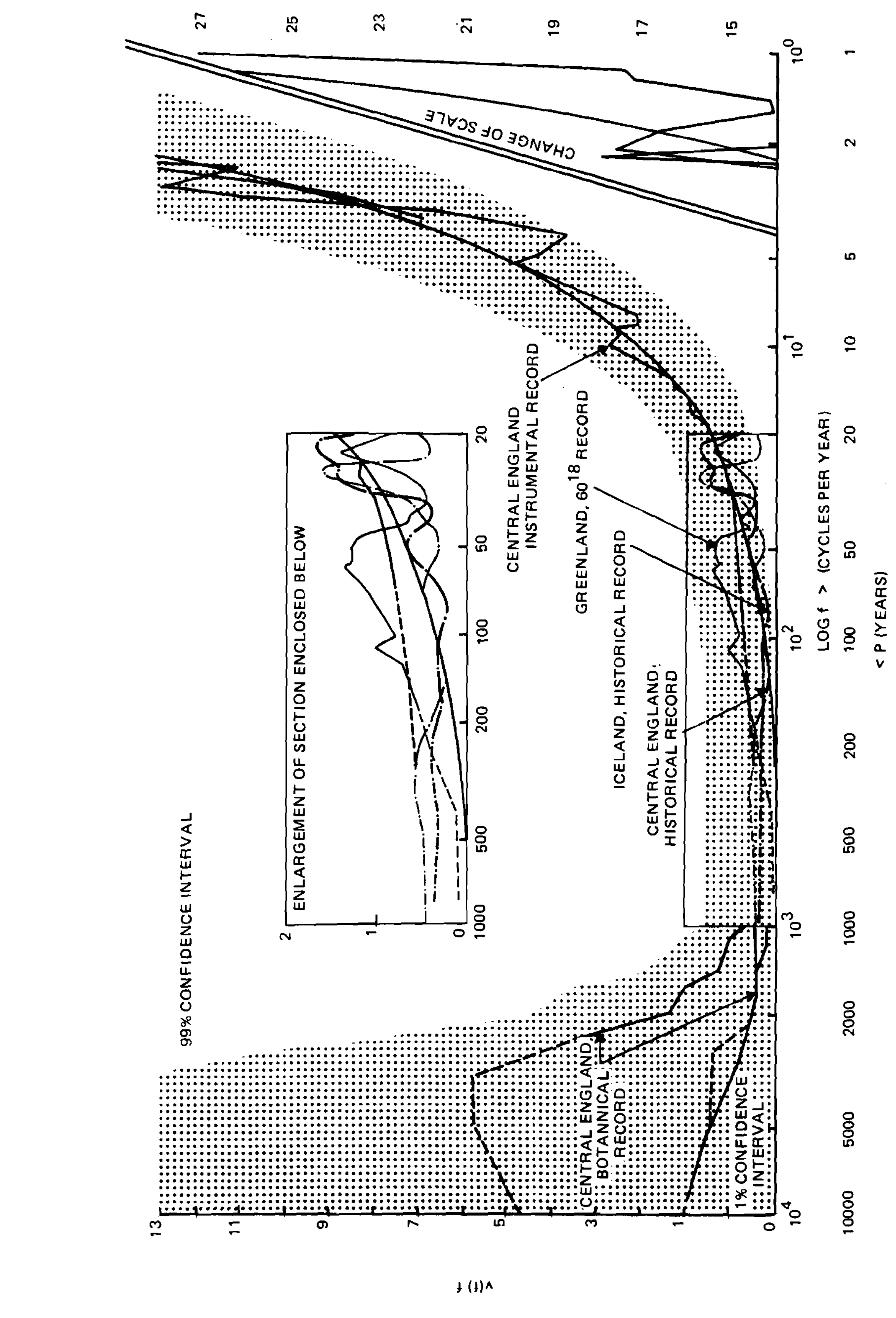
Rapid development of technology and agriculture during the past several decades has led to the obvious question of how our climate is being changed and what effect these changes have on human activity. Many data show that climate, as a geophysical system, is being continuously changed on entire geological, historical and "practical" time scales. Obviously the understanding of the main geophysical courses of such behavior is the first step. Without this step it is impossible to talk seriously about secondary effects, such as the human impact on climate and so on. Only by starting from a geophysical point of view, can one realize how man changes natural conditions. One of the most promising ways of simulating the behavior of the geophysical system is by numerical modeling with the aid of modern computer achievements. Changing the parameters of the imitated system can show the changes in the climates simulated in the model. One can then understand how dramatically human beings change climate. Are these changes really so dangerous? It may be that the climatic changes in the last century are not unique, but it is only that the image of a tragically changing climate has been brought into modern man's mind through the telegraph and radio communications and has given us the deep feeling that if anything is changed it is changed from bad to worse.

Let us look at the climate system using retrospective survey and start with some useful definitions. The following ideology is based mainly on Monin's approach to studying the climate as a geophysical problem [1]. Climate could be defined as a statistical ensemble of conditions passed by ocean-atmosphere-land system during the time scale of several decades. Ensemble is defined as the sum of elements, if all of them have been defined and if it is known how often each element would appear during certain time intervals. The instantaneous state of the ocean-atmosphere-land system is called weather. Weather is an element of climate.

The weather is known when one can measure or calculate the global and local field of components of wind velocity, temperature, humidity and so on. For measuring these quantities one has to use a worldwide mesh of observational stations. For such calculations the state of the ocean and the land is needed too. But more important is knowledge of weather "changes". In our climatic system it means: Which element goes after this one? One needs a full branch of fields, calculated or observed at this very moment to predict weather: temperature, pressure, concentrations of thermodynamically active mixtures, salinity of sea water, rate of evaporation and condensation, wind velocity and sea currents, heat fluxes through sea-air and air-land boundaries, cloudiness and so on. The time scale of system variability is very nonhomogeneous but, luckily, has a deep minimum within periods of 10-1000 years. So, averaging should be done within these limits. It is important that for such long periods, the momentary weather is insignificant; only the statistical behavior of the system is under consideration. Using mean variables from this scale will give us more stable behavior than any other possible type of averaging. It has been shown that averaging over one or several years gives a more variable and therefore less representative climatic picture for understanding the trend of changes. Even more intensive variability is found by averaging over thousands of years. This can easily be seen from Figure 1 where the spectrum of oscillations of the air temperature in the North Atlantic area was obtained by Kutzback and Bryson [2]. This curve gives the mean square of amplitude of temperature as a function of the periods of oscillation. It is clear that the most preferable time period for averaging would be 10-100 years. However the observed data dictates that it be less than 100 years due to the lack of data for such long time periods.

Climate depends on several variable conditions which could be roughly divided as follows (details on Figure 2):

1. Astronomical variables--brightness of the sun, movement of the earth and other planets in space,


99% CONFIDENCE INTERVAL
1% CONFIDENCE INTERVAL
CHANGE OF SCALE
ENLARGEMENT OF SECTION ENCLOSED BELOW
CENTRAL ENGLAND INSTRUMENTAL RECORD
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ICELAND, HISTORICAL RECORD
CENTRAL ENGLAND, HISTORICAL RECORD
CENTRAL ENGLAND BOTANNICAL RECORD
LOG f > (CYCLES PER YEAR)
< P (YEARS)
v(f) f

Figure 1.

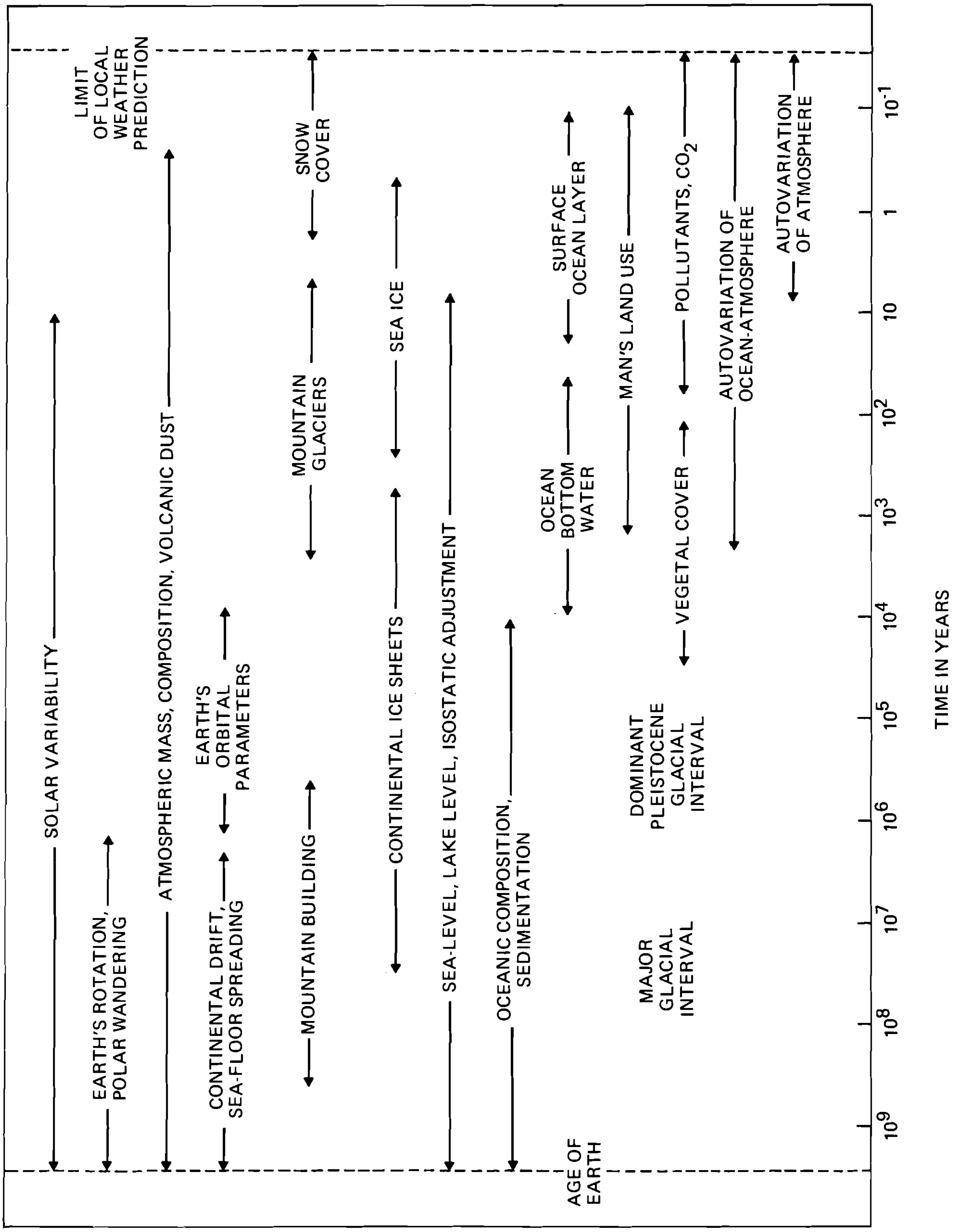
SOLAR VARIABILITY
EARTH'S ROTATION, POLAR WANDERING
ATMOSPHERIC MASS, COMPOSITION, VOLCANIC DUST
LIMIT OF LOCAL WEATHER PREDICTION
CONTINENTAL DRIFT, SEA-FLOOR SPREADING
EARTH'S ORBITAL PARAMETERS
MOUNTAIN BUILDING
MOUNTAIN GLACIERS
SNOW COVER
CONTINENTAL ICE SHEETS
SEA ICE
SEA-LEVEL, LAKE LEVEL, ISOSTATIC ADJUSTMENT
OCEANIC COMPOSITION, SEDIMENTATION
AGE OF EARTH
OCEAN BOTTOM WATER
SURFACE OCEAN LAYER
MAJOR GLACIAL INTERVAL
DOMINANT PLEISTOCENE GLACIAL INTERVAL
MAN'S LAND USE
VEGETAL COVER
POLLUTANTS, CO_2
AUTOVARIATION OF OCEAN-ATMOSPHERE
AUTOVARIATION OF ATMOSPHERE
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
TIME IN YEARS

Figure 2.

declination of the earth's axis, speed of the earth's rotation. This group of factors represents changes in insolation and other external influences.

2. Geophysical and geographical factors. The main idea here is that, for many reasons, global events primarily depend on the lower boundary of the atmosphere, the upper layer of the ocean and land, and their interaction. Of course climate depends on the geographical configuration of ocean and land also. The role of the ocean in maintaining climate will be discussed in detail below.
3. Atmospheric factors--mass and composition of the earth's atmosphere and its dynamics. The signs of modern times are easily seen here; it has become necessary to include the human impact on climate, at least for discussion, in the list of factors which could form climate or cause climatic changes.

The radiation from the sun is the most stable quantity in the astronomical group. (Stars of G-2 class have almost unchangeable brightness during 10^9 year intervals.) Gradual changes have taken place due to a deceleration of the earth's rotation. When rotation was faster, climate had more zonal features than it now has. Cyclones and anticyclones played a smaller role then, than they have in modern times. It is easily foreseeable that zonal contrasts will decrease more in the distant future.

Geochemical evolution of hydrosphere and atmosphere have also contributed to gradual climatic changes. The hydrospheric mass has grown non-monotonically in the past. More important for the earth's climate is the fact that the square area of ocean has enlarged and has begun to dominate the heat exchange between the atmosphere and the earth's surface.

Another kind of change is caused by continental drift and sea floor spreading. These changes have periods of 10^7-10^8 years and have been proven by paleoclimatic data [1]. They are slower than astronomically affected climatic changes.

The next group of paleoclimatological events is related to glacial ages in the earth's history. Details of the periods of changes can be found in the papers included in the GARP survey [3].

It must be pointed out, however, that the earth's history, which has seen many dramatic climatic and geophysical events, shows that climate, on the average, has been conservative enough to maintain the functions of life in the general sense. This fact could be formulated in three points:

1. Mean temperature of the earth's surface always was within the limits necessary for water to exist in its liquid state.
2. Climate has always been.
3. There have never been catastrophes in the earth's history severe enough to stop biological activity.

Thus it is the climatic stability of the earth rather than its variability which is most astonishing. During recent years many scientists have focused on the problem of environment destruction including air and sea pollution, the CO_2 problem and so forth. There are many advanced but rather simple models of the CO_2 cycle which represent the role of the biosphere. Many of them predict rapid growth of atmospheric CO_2 and moisture which would lead to a greenhouse effect. For example, Venus is a dramatic victim of this effect. The temperature of this planet's surface is $470^{\circ}C$. It must be remembered, however, that CO_2 could be dissolved in sea water, of which Venus has none. On the other hand, evaporation from the ocean increases cloudiness which affects the total sum of radiation reaching the earth's surface. So, even qualitative conclusions must be very carefully tested.

In the upper layer of the ocean there are 50 ml of CO_2 in each liter of water. The total amount of CO_2 dissolved in the ocean goes as high as 140×10^{12} tons. This value is 60 times greater than the total amount of CO_2 in the atmosphere (2.6×10^{12} tons). There is a simple geochemical scheme which stabilizes the CO_2 concentration in the ocean. Sedimentation of $CaCO_3$ helps to maintain the CO_2 concentration sufficient for continuous transformation of $Ca(HCO_3)$ into $CaCO_3$ with CO_2 as a necessary material. Sedimentation occurs in deep water with a depth of approximately 4 km. Carbon sediments are accumulated at the speed of about $250 \cdot 10^6$ ton/year [4]. The total amount of sedimentated CO_2 is estimated at 5×10^{15} tons. The speed of this process when CO_2 is taken from the ocean depends mainly on the thermohydrodynamics of the ocean. Storage of CO_2 in sediments is 70 times greater than in the mass of modern atmosphere where it is estimated that a comparable amount emerged due to tectonic activity which in the past was much more intensive [5]. So, it may be stated that the amount of CO_2 in the atmosphere always varied by large values and, therefore, perhaps oscillated with significant amplitude. This leads to a more optimistic view on a slow increase of CO_2 in the atmosphere and could lead to more careful calculation of the effects of this process using highly developed models. The models have to be based on equations which properly represent the behavior of the whole ocean-atmosphere-land system with a time scale correspondent to oceanic time scale within the limits of the minimum in variability spectrum (see above).

Obviously, geophysical hydrodynamics are not developed enough to answer a question too delicate for our scientific ability today. There is no definite answer to the question: Is there only one possible climatic state due to fixed external factors or are there several different possibilities? For example, no significant changes have occurred in external conditions during the last one million years. But glacial ages came and went with periods of tens of thousands of years. Oscillations of such periods are successfully described with the aid of the theory of oscillations of the equatorial declination [6]. This theory predicts glacial ages after the next 170, 215, 260, and 335 thousand years with very strong glaciality after 505 thousand years. Presently, the earth seems to be in a typical interglacial state.

Another group of significant oscillations in climatic systems are oscillation interaction between the ocean and the atmosphere which is realized in different regimes of heat and mass exchanges. There are data that show oscillations which are called "little ice ages". The glacial blockade of the Icelandic shore which changed the development of civilization in this area in the XIII-XIX centuries is a dramatic example of human dependence on climate (see [3]).

The next well known oscillation in the ocean-atmosphere system have periods of several years. Byerknes [7] has presented a theory to explain the mechanism of these oscillations. The winds in the Atlantic differ from year to year. The movement of air masses to the south from the rather cold North Atlantic area cause a decrease in temperature in the upper layer of the ocean due to surface evaporation. Increasing the heat flux into the atmosphere at lower latitudes leads to intensification of cyclonic activity and more intensive transport of warm water masses by the Gulf Stream from the south to the north-east. The North Atlantic becomes warmer. This process has periods of several years. Another example is the anomalous motion of the equatorial masses of water of Passat to the south (El-Nino phenomena).

Kuroshio's meandering correlates with oscillations of basic pressure anomalies. This is realized in the form of 4-5 and 9-10 year periodical climatic variations. These are only a few examples of several year variations in the ocean-atmosphere system. The fact that the system returns to its previous condition shows that there is some kind of mechanism with negative feedback. So it is necessary to imitate such behavior with the aid of some kind of model, which is complicated enough to describe periodical features and climatic trends in the ocean-atmosphere-land system. As it goes from discussed above, behavior and time scale of interaction of ocean-atmosphere subsystem, main attempts should be done in direction of reasonable modeling this very subsystem. Its behavior could be described by using thermohydrodynamic model based on partial difference equations of fluid mechanics. The time scale of integration, if extended to decadal time, demands that the results be interpreted as statistical features.

A retrospective view of past climate and different speeds of the processes in the ocean and the atmosphere shows that the ocean dominates in climatic maintainance for decadal and longer time scales. The atmosphere is more responsible for the concrete realizations which we call "weather". A climatic model has to take into consideration all branches of significant principal factors which could influence the climate during time intervals of not less than a decade. Progress in constructing such numerical models has been impressive although we cannot yet say that we have a completely satisfactory climatic model. But it is possible to speculate on the degree of reasonability and direction of development and to predict probable success in this activity. The whole spectrum of these models could not be discussed here. Even the two models which will be presented in this survey are discussed as briefly as possible with the aim of showing the main ideas and differences in approaches only.

The bases for any geophysical numerical model are the laws of conservation of energy, momentum and mass in the system. The complexity of the model depends on the degree of simplification in the statement of the problem and the quality of the scheme for the numerical solution of the problem. This in turn depends mainly on the progress in computer technology. Some simplifications are reasonable, such as hydrostatic assumption, isotropical turbulence and others; others stem from our ignorance of the details of certain physical processes, the still others show our present weakness in numerical mathematics and computers. The history of relatively successful numerical modeling of atmospheric dynamics began as early as 1956 [8]. This is mentioned here simply to point up the speed of progress in numerical modeling since this pioneering study. The numerical climate models which will be discussed here are the model constructed in GFDL (Princeton, N.J., USA) by Manabe and Bryant with collaborators under Smagorinsky's leadership [9,10] and the model developed in the Institute of Oceanology (Moscow, USSR) by Chalikov, Turikov, Zilitinkevitch under A. Monin's leadership [11]. It has to be pointed out that there are other rather developed numerical geophysical models which could be used for climatic study, for example Marchuk's model [12] or NCAR's model. Discussions of these models might be found in publications listed for example in other publications (see, for example, [3,13]).

The mathematical basis for numerical models is stated as equations of geophysical hydrodynamics which has to be solved with consideration of all main processes significant for climate maintenance (such as baroclinic instability in the ocean and atmosphere, moist convection, heat and mass exchange between all components of the climatic system, glacial convection, poleward heat transport in the ocean and so on). The conservation of heat, mass and momentum leads to equations which represent thermohydrodynamics remarkably well but are very difficult to solve. Only with the development of computer technology has it become possible to use them for Global Circulation Models. Basically, they are as follows, in the great majority of numerical models.

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} + \omega \frac{\partial \vec{v}}{\partial Z} + 2\vec{\Omega} \times \vec{v} + \frac{1}{\rho} \nabla P = \vec{F} \qquad (1)$$

$$\frac{\partial \rho}{\partial Z} + \rho g = 0 \qquad (2)$$

$$\frac{\partial \theta}{\partial t} + \vec{v} \cdot \nabla \theta + \omega \frac{\partial \theta}{\partial Z} = Q \qquad (3)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} + \frac{\partial}{\partial Z}(\rho \omega) = 0 \qquad (4)$$

$$\frac{\partial q}{\partial t} + v \cdot \nabla \rho + \omega \frac{\partial q}{\partial Z} = D \quad (5)$$

$$P = \rho RT \quad (6)$$

where $\vec{v}$ is the horizontal velocity, ω is the vertical velocity, $\vec{\Omega}$ is the rotation vector of the Earth, ρ is the density, P is the pressure, g is the gravitational acceleration, θ is potential temperature, T is the ordinary temperature and $\theta = T(Po/P)^K$, P_o = 1000 mb, K = 0.286 is the ratio of the specific heats, q is the water vapor mixing ratio, R is the gas constant for air, D is the horizontal gradient operator. This system is in operation for the simulation of atmosphere dynamics.

Ocean currents may be described by a simpler system. Equations (1) and (3) principally are unchanged. Equations (3)-(6) give their places to the following

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T + \omega \frac{\partial T}{\partial Z} = Q_1 \quad (7)$$

$$\nabla \cdot \vec{v} + \frac{\partial \omega}{\partial Z} = 0 \quad (8)$$

$$\frac{\partial S}{\partial t} + \vec{v} \cdot \nabla S + \omega \frac{\partial S}{\partial Z} = Q_2 \quad (9)$$

$$\rho = \rho(T,S,P) \quad . \quad (10)$$

Here S is the salinity. The terms $\vec{F}$($\vec{F}_1$ for oceanic system), D, Q_1 and Q_2 on the right sides of equations written above represent the sources and sinks of momentum, heat, water vapor for the atmosphere, heat and mass for the ocean due to several physical processes such as turbulent friction, latent heat release during condensation, heating due to long and short wave radiation and heating the atmosphere by turbulent heat fluxes from the lower surface. The net moisture rate S represents the difference between the evaporation and condensation rate. Q_1 shows the heating of the ocean due to heat flux from the atmosphere, cooling due to evaporation, and the radiative balance between the ocean and the atmosphere; Q_2 shows the mass exchange due to evaporation from the ocean and condensation from the atmosphere which are recognized by salinity changes. Both Q_1 and Q_2 must be capable of representing the formation and melting of ice in the ocean. There are some lows which show moisture and water exchange between the atmosphere and the land as well as between the land and the ocean. Boundary conditions for (1)-(6) and (1), (2), (7)-(10) must be used in a form which represents main large scale heat, momentum, and mass exchanges in order to simulate the global features of the feedbacks which are responsible for maintaining climate.

The details of GFDL's model can be found in recently published papers [9,10]. Here only a brief list of its main feature is presented and some of its significant results are discussed.

The atmospheric part of the model (see Figure 3) is based on a primitive equation of motions (1) in a spherical coordinate system. For vertical finite differencing, nine levels are used and regular latitude-longitude grid covers the globe in a horizontal direction. The space step of the grid is approximately 500 km. For computation of radiative transfer the distribution of water vapor is used. This distribution is obtained from the prognostic equation, similar to (6). The distributions of CO_2, ozone and cloudiness are prescribed and assumed to be constant in time. The temperature of the land is calculated in such a way that heat exchange is in balance. The prediction of soil moisture and snow depth is based upon the budget of water, snow and heat in case of much larger abedos of snow and sea ice than that of the soil or the sea surfaces. Time integration of the model is based on the so-called "leap frog" method. It must be mentioned that this scheme in operating only with time steps of less than 10 min. To avoid the development of a computational mode, predicted values are averaged once every 40 time steps.

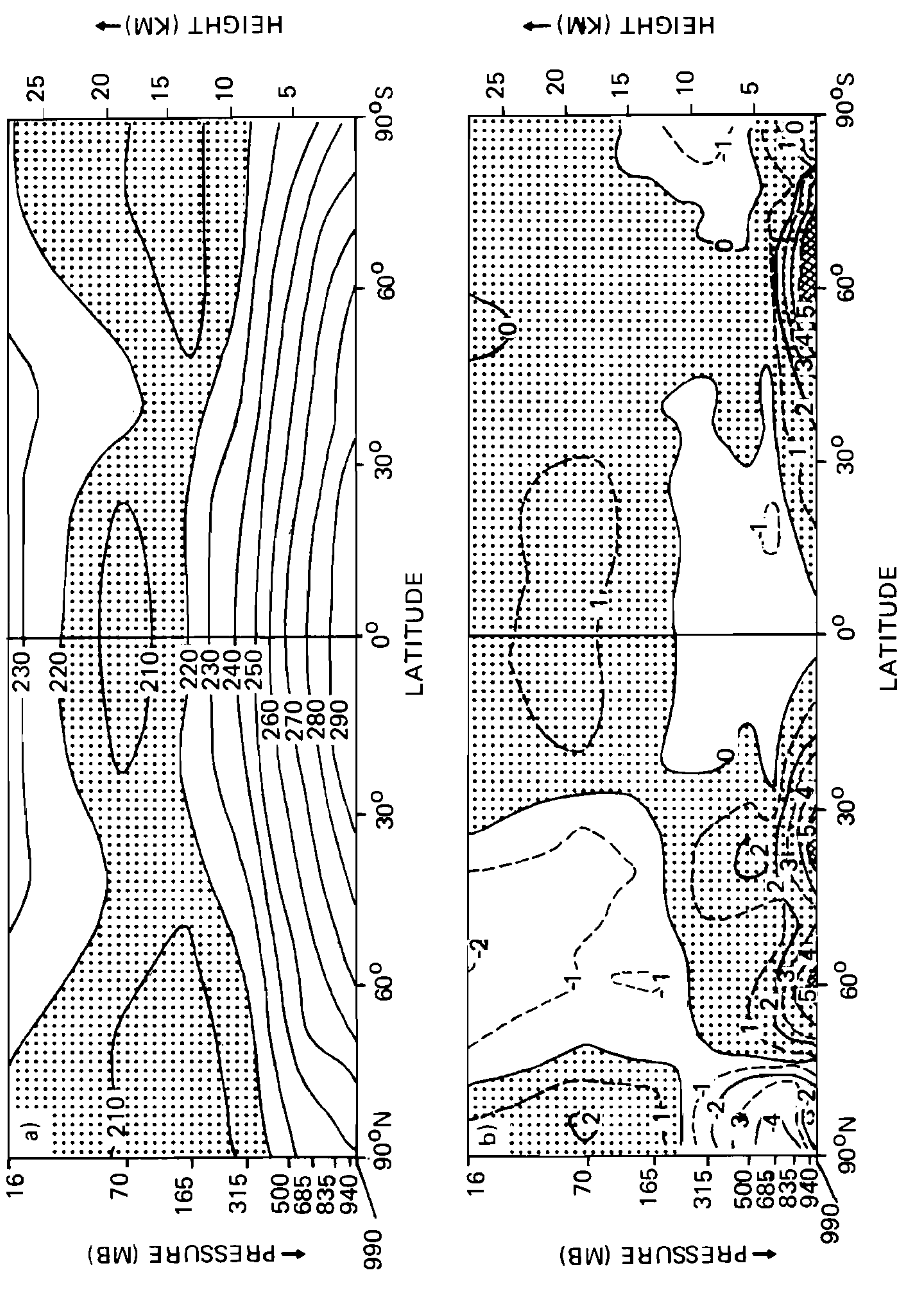
a)
b)
PRESSURE (MB)
HEIGHT (KM)
LATITUDE
16
70
165
315
500
685
835
940
990
25
20
15
10
5
90°N
60°
30°
0°
30°
60°
90°S
210
220
230
240
250
260
270
280
290

Figure 3.

Furier space filtering is used to prevent instability due to conversion of longitude-latitude grid. One of the serious difficulties in constructing GCMs is the parametrization of moisture convection. Simple adjustment mechanism is used. It is based on the assumption that there is redistribution of vapor and heat in case of hydrostatic instability with conservation of humidity and energy. Horizontal mixing is included in nonlinear form. The coefficient of turbulent friction is a function of the components of the stress tensor (Smagorinski, 1963, Monin, Yaglom, 1965).

Boundary conditions at the earth's surface are formulated in the following form. Surface stress in the model is computed as

$$\tau = - \rho(h)\ C_D(h)\,|\vec{v}(h)|\,\vec{v}(h) \qquad (11)$$

where $C_D(h)$ is the drag coefficient for wind at height h. Heat flux H at the surface of the earth goes from balance the relation due to wind and temperature difference between the earth's surface and the air near the surface. The flux of latent energy LH from the ocean is obtained from the balance between latent heat of evaporation and sublimation. To obtain H and moisture flux it is necessary to know the surface temperature T_*. This temperature is computed in the oceanic part of the model. The equation of heat balance is as follows.

$$S_* + DLR = \delta_{SB} T_*^4 + H + LH \qquad (12)$$

where S_* and DLR are the net downward insolation and downward longwave radiation at the earth's surface, respectively, and δ_{SB} is the Stefan-Boltzmann constant. The ocean part of the model predicts horizontal velocity, temperature, and salinity for the 12 level in the world ocean. Vertical velocities and density are obtained from diagnostical equations of continuity and state. The model includes effects of bottom topography and

and sea-ice formation and melting processes. The coefficients of the turbulent heat and momentum exchange are chosen constants in space. The "so-called rigid-lid" approximation for filtering out surface gravitational waves was used. The sense of this term is that vertical velocity vanishes at the ocean surface. The ocean part of the model differs from the atmospheric one in the case of rigid meridian and parallel boundaries where no fluxes of water, heat and salinity exist. The sea ice model can be expressed in one equation

$$\frac{\partial I}{\partial t} = - \nabla(\delta_I \vec{v} I) + A_H \nabla^2 I + S_* - E_* - (Q_a + Q_b)/(\rho_I L_f) \tag{13}$$

where I is the local ice thickness (assumed to be uniform), Q_a, Q_b are the heat flux received at the base of floating ice from above and below, S_* and E_* are the contribution to ice gain and loss due to snowfall and evaporation, ρ_I and L_f are the density of ice and the latent heat of freezing, $\delta_I = 1$ if $I < 4$m and $\delta_I = 0$ if $I > 4$m.

$$Q_a = K(T_* - 271.2)/(I + 1.7) \quad . \tag{14}$$

This is empirically derived equation where calculated T_* is set equal to 273 K if it is greater than 273 K. Q_a is obtained from heat balance equation mentioned when the atmospheric part of the model was discussed. So, (14) gives T_* for area covered by ice.

The major objective of the study mentioned above using this GCM was to identify the effects of ocean currents in maintaining the climate. Two experiments were performed. The first one was carried out by using the so-called "A-model". In the A-model, oceans were treated as wet swampy surfaces without any heat capacity. The second experiment was done with oceans and this version of the model is called the joint model.

Starting from the initial conditions of an isothermal and dry atmosphere, and uniformly stratified ocean at rest, the A-model and joint model were conducted and a comparison between two kinds of climate was made. Although many unrealistic features of climate appeared, there was qualitative agreement in observation of the main features. It is not possible to discuss the results in detail here. The only conclusions which we want to underline in this survey are those connected to the role of the ocean in a climatic system. To show the difference between two models it is at first useful to look at the difference of the zonal mean temperature of the atmosphere (Figure 4). In higher latitudes the tropospheric temperature of the joint model is warmer than that of the A-model. Heat transport toward the poles is responsible for these differences. The cooling effects of the ocean in the tropics is also essential for climate and is easily seen. It is indicated by lower temperature in the tropics, obtained from the joint model. The global distribution of temperature (not presented here) is also affected greatly by the ocean.

The second objective here is demonstration of rather good qualitative agreement in distribution of sea surface temperature which is of greatest interest for climate simulation when heat exchange between the ocean and the atmosphere were considered. Figure 5 shows the distribution of observed and calculated temperature of the ocean surface.

This model is so successful in simulating climate that we cannot stress its deficiencies which are insignificant in comparison with the advantages of the study. But there is one main deficiency which leads to seeking the alternative solution of the climate simulation problem. This model is too complicated for nowaday numerical experimentation for understanding variability of climate.

The experience obtained from running the GFDL model shows that it is practically impossible to complete the experiment using modern computers if the equilibrium of the ocean has to be reached. The inertia of the deep ocean layers demands large amounts of computer time. Physically this comes from the weakness of the turbulence and vertical advection as mechanisms for

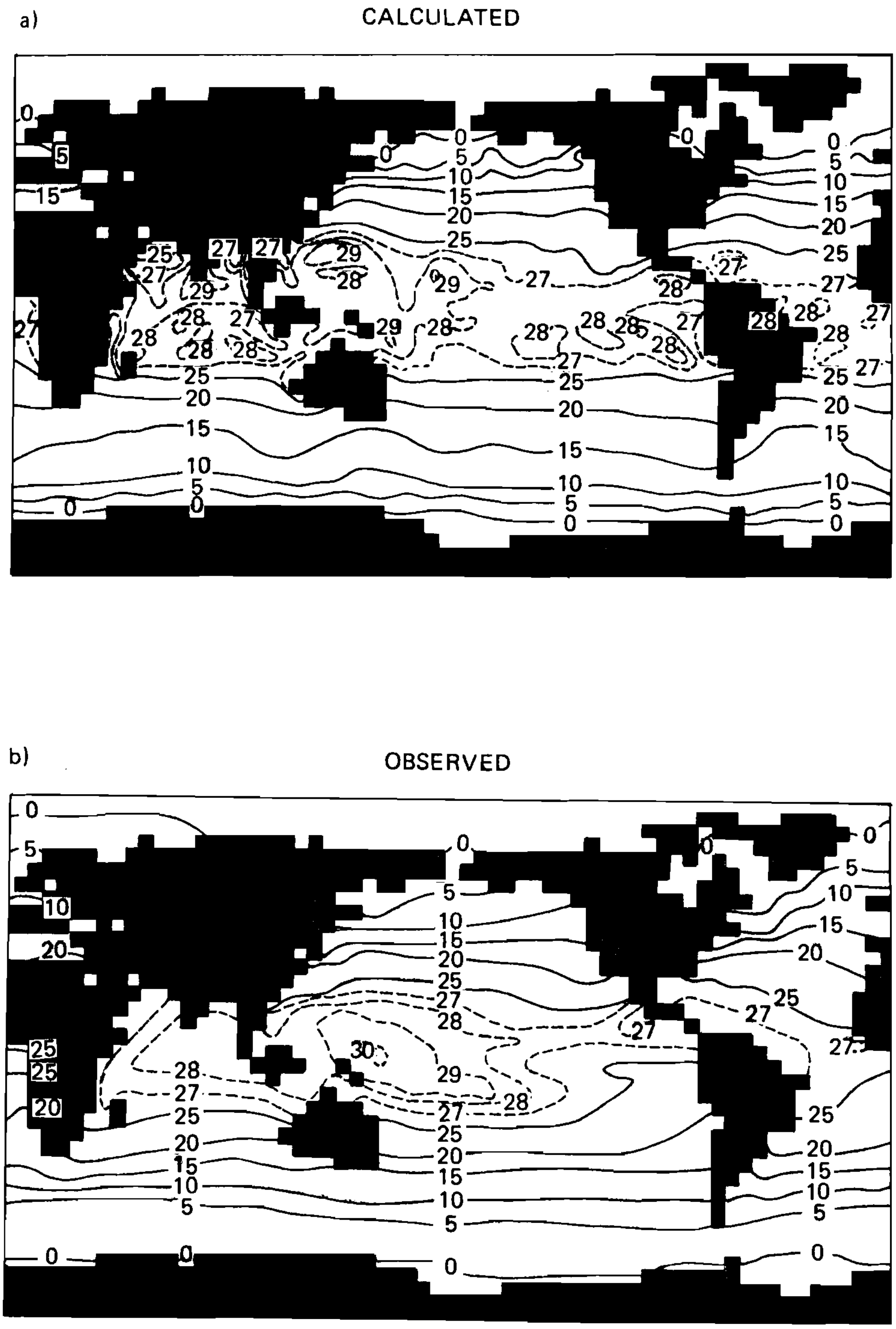

Figure 4.

transferring the impulses from the atmosphere to the deep. On the other hand, when it is necessary to imitate seasonal or annual variability this fact becomes convenient because of the possibility of regarding the deep ocean as a climatically non-variable barotropic layer. It is then possible to simulate the behavior of the upper layer and seasonal thermocline only. This assumption gives basis for another climatic model developed at the Institute of Oceanology (IO model) [11]. It goes without saying that this model is much simpler than the GFDL model but it permits a complete series of experiments using a reasonable amount of computer time. The model has three major parts--an atmospheric, an upper ocean, and a deep ocean part (see [11]).

The main differences in the atmospheric part compared with the GFDL model are as follows: The parametrization of the physical processes are widely used in the IO model. For example, a simple parametrization of the Ecman's layer is used. The planetary boundary layer was put into the lower layer of the numerical model. Only horizontal and time structures are computed. The vertical structure is assumed to be universal. The surface temperature T_s for continents and heat flux M_o to the ocean are computed using the balance equation,

$$(1 - A)\ F_s^{\downarrow}(0) + F_L(0) - B(T_s) - H - LE = M_o \qquad (15)$$

where $F^{\downarrow}(0)$ and $F_L(0)$ = downward fluxes of the long and short wave radiation, $B(T_s) = \delta T_s^4$ = radiation from the surface (δ = Stephan-Boltzmann constant), H and E vertical fluxes of the heat and moisture, A = albedo, and L = latent heat of evaporation. Heat flux H_o is used in the ocean part of the model. There is no heat capacity for the lake.

Humidity near the ocean surface is assumed to be critical (the same is true for the land when it is raining). Two hours from the moment when the rain stops, the humidity above the land drops to half of the critical value and remains in this condition until the next rain. The calculations were carried out on rough numerical grid (four levels in the atmosphere).

A simplified method for computing radiative heat fluxes was incorporated. Nevertheless, the presence of aerosols in the atmosphere was taken into consideration.

Cloudiness was obtained similarly to the GFDL approach, but assumptions were made on two-dimensional clouds due to the rough vertical approximation permitted in the four-level model.

The structure of the upper layer of the ocean is computed using the prognostic equations for surface temperature T_s and thickness of the layer h with advection of heat in horizontal direction and turbulence. At the lower boundary of this layer h_a = 350 m the temperature T_a which is calculated with aid deep ocean part of the model was used as boundary condition. Vertically averaged velocity components are represented as the sum of climatic mean and Ecman's velocity is given by wind stress at the surface. Algorithm which gives rough approximation of the ice formation works with the assumption that if the temperature of the sea water is lower than -1.8^{o}C the ice appears. Ice isolates the upper layer from the thermal or dynamic influence of the atmosphere on the ocean. From that moment the ice-covered area is treated as a land until the temperature increases above -1.8^{o}C limit.

The deep ocean is simulated with the aid of the two-layer model proposed by Kagan et al. [14]. There are no temperature or salinity changes in a layer deeper than 2 km. The equation for total stream function together with heat balance equation was used with no heat or mass flux through lateral boundaries. These boundaries roughly approximate the geographical distribution in the ocean-land subsystem. The deep ocean equations were integrated with 5^{o} grid size. On Figure 5 there is stream function. There is qualitative agreement with our knowledge of the World Ocean current system which goes from observations and some diagnostical calculations [15,16]. The equations of four-level atmospheric and upper ocean were solved using non-divergent numerical scheme for spherical grid with the grid size approximately equal to 1000 km. Time step was equal to

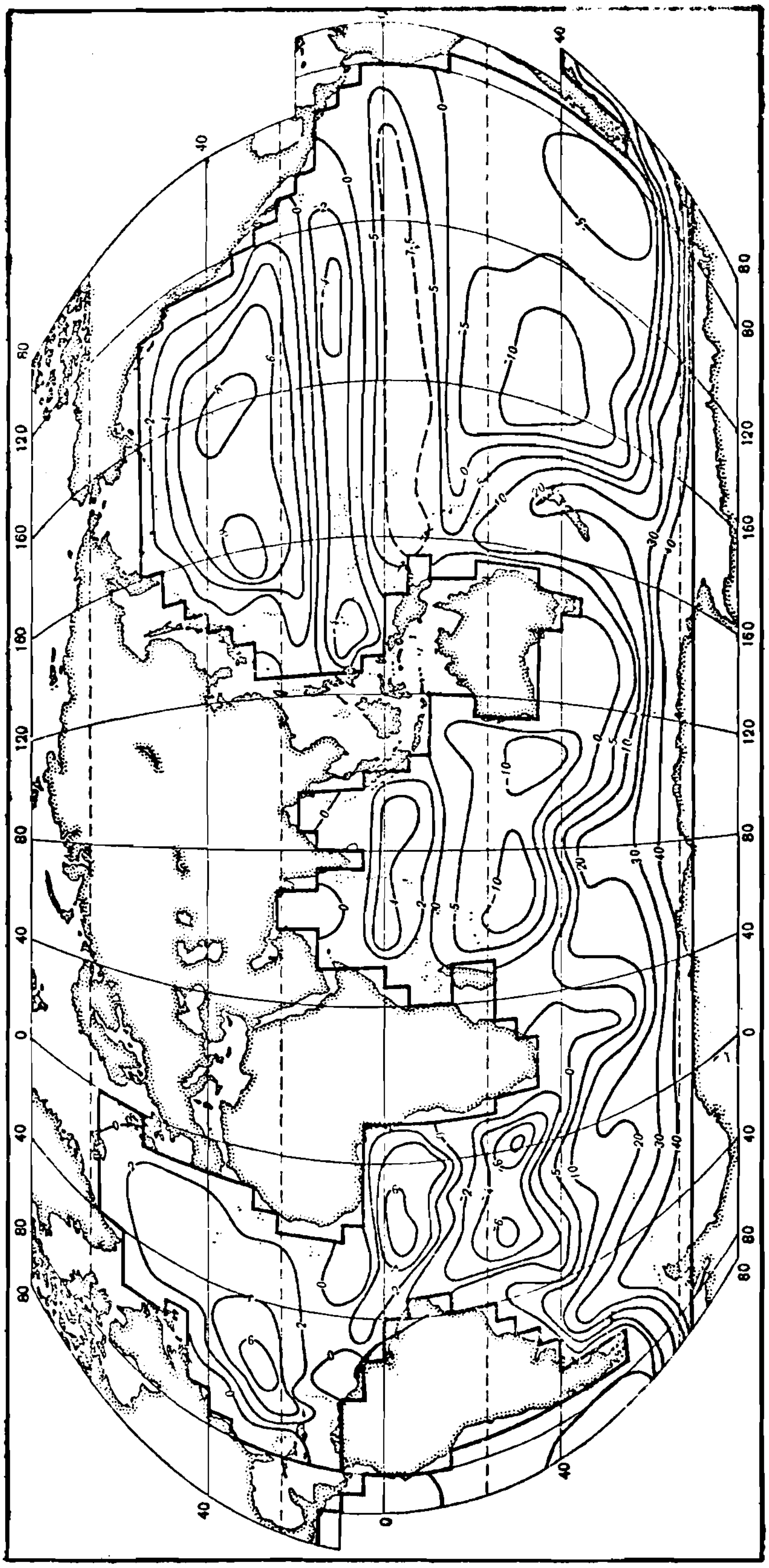

Figure 5.

20 min. The smoothed orography of the surface was introduced in the model directly.

The initial conditions represent annually averaged temperature for the atmosphere and upper ocean layer. Initial value of upper homogeneous layer h was simply specified as 50 m. The stratification of the atmosphere assumed to be adiabatic. Quasi-periodical equilibrium state was reached after one year of simulation time and characteristic values were as follows:

Mean (averaged over the whole stratosphere) wind velocity is 17 m sec^{-1}.
Wind velocity in upper atmospheric layer is 40 m sec^{-1}.
Mean temperature of the atmosphere is 29^{o}C.
Minimal monthly averaged temperature is -39^{o}C (in the Antarctic).
Maximal temperature is 35^{o}C (North Africa).
Mean humidity is 1.6 g/kg.
Cloudiness is 0.47.

These values seem to be reasonable. So, in spite of roughness of the approximation and significant simplification of the model in comparison with the GFDL model, there are results obtained with much less effort and agreeable with known physics processes in the atmosphere and upper ocean. The evaporation and condensation, as well as cloudiness and heat flux through ocean surface, are in good agreement with empirical data, and represent annual variations (Figures 6 and 7).

These results allow to say that the IO-model seems to be a perspective for further numerical experiments for simulating the climatic variability. The ways for development of the IO-model are the same as for GFDL. They lead to better parametrization of significant but rather unknown processes of turbulent exchange to increase the effectiveness of numerical scheme which could lead to using more detailed approximation of geometry and orography and so on.

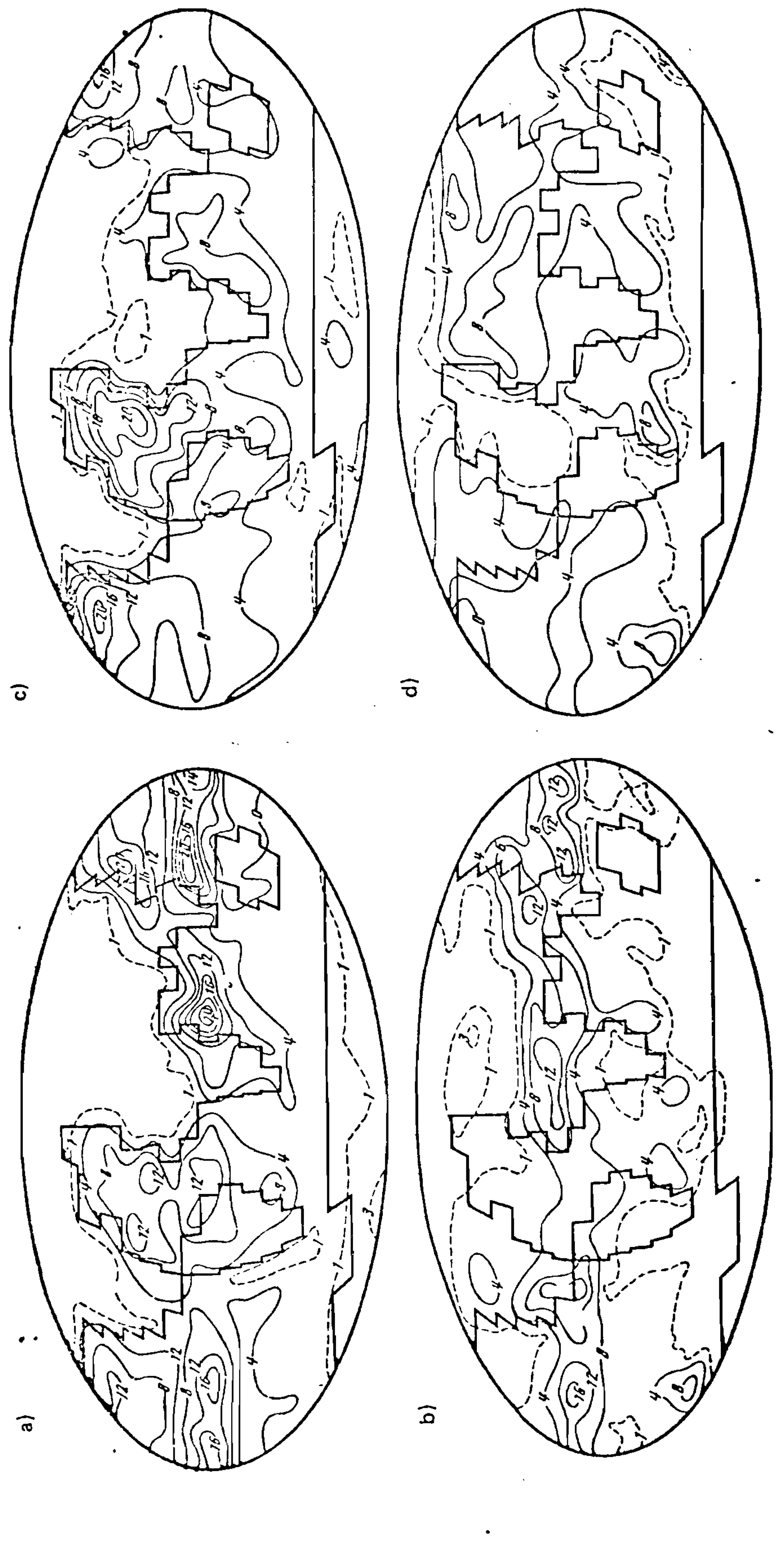

Figure 6.

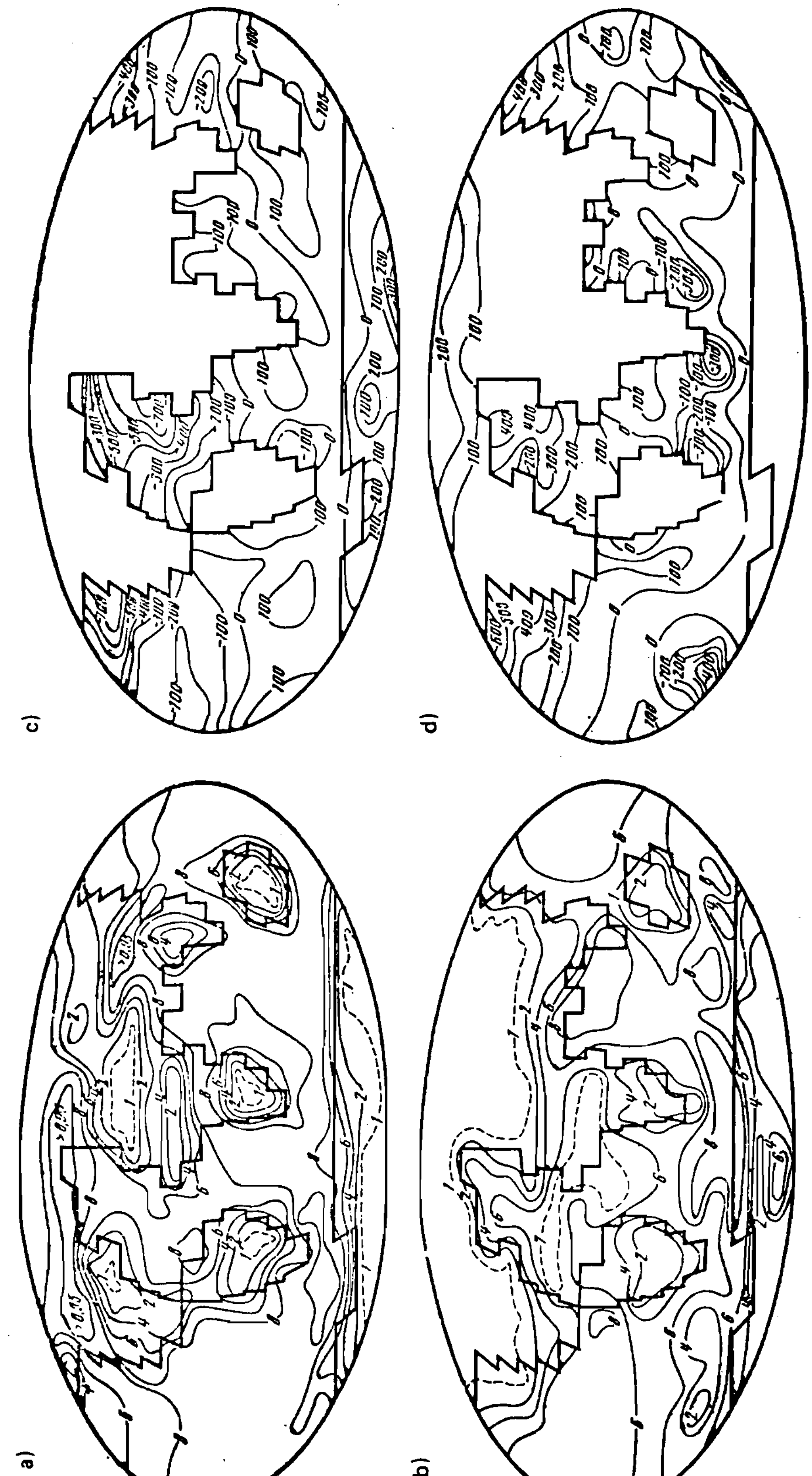

Figure 7.

Discussion of two climatic models shows that only highly developed numerical GCM models could simulate geophysical system behavior. Any other problem could be incorporated in such models in geophysical terms. It is necessary to have a link between other nongeophysical models and discussed above, but the main idea is that it is impossible to simulate climate without GCM's models at all.

It has to be mentioned also that many have to be done for the development of the ocean parts of climatic models. Only one example on this matter to show how fast our knowledge of the oceans circulation develops. The mesoscale phenomena has to be included directly or by proper parametrization into the models. Energetics of ocean currents show that at least half of energy is storaged in mesoscale motion. The models which deal with simulation of dynamics of the large-scale currents with interaction between mean currents and eddies are under development now [17,18,19].

But even a simple climatic model needs too much money to be spent and too much manpower is needed. There are years of hard work to construct such a model and years to run it with relative success. This fact could be easily transferred to the statement that only the largest word scientific centers could practice this activity.

The question is--how IIASA could do the study of the climate variability or even more special problems--the human impact on climate? (We think that splitting the problem of climate-man interactions is artificial, but let us state the problem in the simplest way.) It is clear that the geophysical model is the vital part of any socio-economic consideration.

Is it possible to study the climate changes at IIASA? We studied the possibility of this activity and could make the proposals on this subject. It has to be pointed out that it is only our own opinion and perhaps our experience is not sufficient for estimating whole difficulties in organizing such work. Nevertheless we will try to formulate the possible steps in approaching the solution of the climate variability geophysical aspects needed for socio-economic studies.

As soon as IIASA is interested in this socio-economic aspect of interaction between man and climate it is necessary to simulate different types of climate variability using developed geophysical models with parameters that represent the human impact on climate and the results of climate effects on man's activity.

There are several possibilities for solving this problem from the point of view that says that IIASA has not enough manpower, resources and budget for constructing its own numerical climatic model which would be rather sophisticated in description of feedback mechanisms in climatic system with desirable accuracy (for example, accuracy needed for solving the CO_2 problem and so on).

1. It is possible to use resources of one of the large scientific centres (in the USSR or USA) for simulation of climatic changes. On the other hand, some hypothetical climatic changes could be introduced into other special models constructed at IIASA in other projects--energy, water and others--as initial conditions. In this case there will not be any feedback and simulation will be noncomplete. Deficiencies of such an approach seem to be obvious.

a. Uncertainty in capability of chosen climatic model in describing the reality of the behavior of climatic system (because any model has its advantages and weak parts) from the socio-economic point of view. (In other words, there will be no security in the choice that was made.)

b. The human impact on climate and the influence of climatic changes on man's activity could be missed from the model which has no geophysical prognostic part (or approximated in a wrong way).

c. The objects under consideration (namely, plants, polluting system and so on) will not affect climate directly in experiments.

d. The initial conditions may be too undefinitely chosen.

e. Final cost of the numerical experiment in large centers may grow rapidly if the model will be too complicated or computer time becomes more expensive (at least it could not be planned by IIASA itself).

2. The second main possibility is to ask for the help of large national centers (Computer Center of the Siberian Branch of the Academy of Sciences, Institute of Oceanology of the Academy of Science in the USSR, Geophysical Fluid Dynamics Laboratory, National Center for Atmospheric Research in the USA and others) in constructing rather simple but reasonable versions of the climatic model suitable for IIASA. IIASA's model should be compiled using the parts of the models prepared in national centers. However, it seems to us that the solution of the problem which leads to choosing the appropriate feature of concrete models cannot be solved without intensive cooperation of involved scientists on IIASA basis (preferably for short-term meetings).

The following hypothetical steps seem to be reasonable (but it is again only our point of view).

a. Small scientific staff (2-3 persons) should be appointed at IIASA for a one-year period for coordinating activity in the framework of Climate Project.

b. The workshop should be held for development of a strict program for action, discussion of terms of the collaboration, schedule the activity of involved scientists, and so on. The workshop should make a list of scientific and logistic problems and make a proposal to IIASA's leaders.

c. In case the proposal is approved by IIASA, different small groups of scientists should come to IIASA with their parts of the model already prepared at their countries for adopting these parts at IIASA. These groups of scientists of one or two modelers should come to stay at IIASA for a period of one month (it leads to careful preparation of the adopted part at their home institutes so the preliminary work has to be carefully planned by the permanent staff).

d. The whole group of participating modelers should take up a meeting for final steps of work at IIASA (probably for two or three weeks) to run and test the joint geophysical model.

e. One or two scientists will stay after that for a needed period of time (one or two months) to provide help for first experiments with the model with a socio-economic program of investigation. From this moment the socio-economic problems become of main interest and the geophysical model could be only corrected from time to time in order to keep it up-to-date.

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Captions

Figure 1. Composite variance spectrum at temperature on time scales of 1 to 10^4 years. The ordinate is v(f) times f in $(^{o}C)^2$, and the abscissa is a logarithmic frequency scale (from [2]).

Figure 2. Characteristic climatic events and processes in the atmosphere, hydrosphere, cryosphere, litosphere and biosphere and possible factors of global climate change (from [13]).

Figure 3a. Latitutde-height distributions of the zonal mean temperature (in K) in GFDL-model for the joint model atmosphere.

Figure 3b. The difference between the joint model and the A-model (from [9]).

Figure 4. The annual average ocean surface temperature (in ^{o}C):

a. simulated by the joint GFDL-model

b. observed temperature based on Navy Hydrographic Office data.

(from [10]).

Figure 5. The annual average total stream function for the baroclinic World Ocean (from [11]).

Figure 6. (a,b) The distribution of percipitation (in mm day^{-1}) simulated by IO-model.

a. for January; b. for July.

(c,d) The distribution of evaporation (in mm day^{-1}) simulated by IO-model.

c. for January; d. for July.

(from [11]).

Figure 7. (a,b) The distribution of cloudiness in IO-model

a. for January; b. for July.

The distribution ofheat flux from the atmosphere to the ocean (in Watt m^{-2}) in IO-model

c. for January; d. for July.

(from [11]).