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The biosphere and climate

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RESUMEN

Una revisión de los resultados de estudiar el papel de la biosfera en la formación del clima, indica que ha empezado una nueva etapa del desarrollo de la teoría del clima que muestra la necesidad de tomar en cuenta procesos biosféricos. Por lo tanto, hay la necesidad de considerar en forma más adecuada los procesos en la superficie de la tierra así como, por razones evidentes, tomar en cuenta la interacción entre los ciclos bioquímicos y el clima. Se discuten varios enfoques para incluir la biosfera como un factor que forma el clima, así como algunos resultados de modelado numérico y posibilidades de utilizar datos combinados de observaciones de superficie y de satélites, para determinar aquellos parámetros que caracterizan la interacción entre la atmósfera y biosfera.

ABSTRACT

A review of the results of studying the role of the biosphere in the climate formation has been made which shows that a new stage of the climate theory development has been started which demonstrates the necessity to take into account biospheric processes. This has been demonstrated by the need to more adequately consider land surface processes as well as by obvious requirements to take into account the interaction between biogeochemical cycles and climate. Various approaches to the consideration of the biosphere as a climate-forming factors have been discussed as well as some results of numerical modelling and possibilities to utilize data of combined surface and satellite observations to determine those parameters which characterize the interaction between the atmosphere and biosphere.

Introduction

Variations in the atmosphere, which determine both the incoming solar radiation (the primary source of energy for the formation of climate) and atmospheric greenhouse effect (the basic mechanism for anthropogenic impact on climate), are one of the key factors of climate change. Studies of the recent years (it concerns, in particular studies by Gorshkov (1982), Gorshkov and Sherman (1986), Gorshkov *et al.* (1989) and Lovelock (1986) convincingly demonstrate the decisive contribution of the biosphere (both continental and marine biota) to the formation of the chemical composition of the atmosphere. It is exemplified, particularly, by the global carbon cycle.

There is an urgent need now for a climate theory with an interactive account of the biosphere as a component of the "atmosphere-hydrosphere-cryosphere-lithosphere-biosphere" climate system. Thus, the biosphere is not only an indicator of climate change (through dendrochronology, in particular) but also a major component of the climate system. The latter means that the correct interpretation of dendroclimatic data is impossible without the interactive multi-factor formation of climate taken into account.

From the viewpoint of climate theory (and, hence, analysis of the causes of climate change), one more important aspect of the problem consists in the development of techniques to parameterize the biosphere as a climate system component. This aspect includes the solution of the complicated problem of the atmosphere-surface interaction with realistic account of processes which take place in vegetation cover (evapotranspiration, heat exchange, mixing, etc.). No doubt, further development of climate theory with an interactive account of the biosphere will create the basis not only for a better understanding of the factors of climate formation but also for a more reliable interpretation of dendroclimatic data.

The important role of the biosphere in the formation of climate has determined the priority of studies of land surface processes and of the use of space-based observation means to assess the respective climatically important parameters (albedo, phytomass, evapotranspiration, heat balance components, etc.). The latter has determined an adoption of the International Satellite Land Surface Climatology Project - ISLSCP (ISLSCP, 1985; Kondratyev, 1985a; Sellers *et al.*, 1988). The problems of the biosphere (and especially biogeochemical cycles of various elements) occupy the key place in the International Geosphere-Biosphere Program: Global Change (Kondratyev, 1985b).

Numerical climate modelling

Analysis of available results of numerical modelling of the sensitivity of atmospheric general circulation (AGC) to the parameters characterizing the land surface processes has shown that AGC is very sensitive to surface albedo and upper soil layer moisture content (Kondratyev, 1985a; Kondratyev, 1986). In this connection the following should be taken into account and parameterized in climate models: (i) the spatial extent and optical properties of snow cover; (ii) type and density of vegetation cover; (iii) rate of soil moisture increase due to infiltration of water into the soil; (iv) rate of soil moisture decrease resulting from evapotranspiration and exfiltration of water. Since the connection between moisture fluxes in soils, soil moisture and vegetation cover thickness is characterized by strong non-linearity, while rain rate, properties of soil and vegetation cover are characterized by substantial sub-grid variability, calculations of averaged (with account of a grid size) moisture fluxes are the most difficult and important problem of parameterization. The solution for this problem may be based on a 1-D parameterization of the respective physical processes depending on observed physical quantities and on an adequate technique for spatial averaging.

In this connection of great importance are numerical experiments on the sensitivity of soil moisture and other substantial parameters to the parameterization of hydrological processes, whose reliability should be tested from the data of complex field observations on the scale of watershed area of the size of a spatial grid cell or more. Though present AGC models (AGCMs) are constructed in a way to ensure the moisture balance in the soil, this problem is solved without account of the dependence of the field moisture capacity of soils on their type. Since, however, this dependence is very strongly expressed, its account is an important objective of further development of parameterization schemes.

An inadequate account of snow cover in most of the AGCMs is manifested through an inadequate description of the heat balance for the soil - snow cover system in the regions with seasonal snow cover, of the runoff due to snow melting, of solar radiation absorption by the snow layer, as well as of snow cover albedo.

Most of the available AGCMs do not take into account the effect of vegetation cover on the land surface processes, though an interactive consideration is needed of the soil-vegetation-atmosphere system.

As for the account of physical processes and their parameterization, the unsolved problems of paramount importance are the following (Dickinson, 1984; Dickinson and Henderson-Sellers, 1988; Sellers *et al.*, 1986; Sellers *et al.*, 1988): (i) development of probabilistic techniques to describe the spatial variability of "forcing" parameters (rains, in particular) and parameters characterizing the physical processes on land surface; (ii) improving the parameterization of hydrothermal processes in snow cover (first of all, it concerns snow albedo); (iii) development of techniques which permit an establishment of relationships between substantial hydraulic and thermal properties of the soil and classes of soil texture presented on global soil maps (the first-priority properties are: effective porosity and hydraulic conductivity of moisture-saturated soil, the dependence of the conductivity logarithm on soil moisture; heat conductivity and specific heat capacity of the soil); (iv) similar relationships can also be established between the depth of the plant's root zone, soil moisture and classes of vegetation cover (with account of the vegetation phase) presented on global maps of vegetation; (v) development of techniques to parameterize the state of natural and cultural vegetation (without irrigation and with it) from the point of view of the dependence of the type and thickness of vegetation cover, albedo, rate of transpiration on the moisture and roughness of soil surface, the depth of the root zone, and vegetation phases.

In substantiating the parameterization of processes in soils and vegetation cover it is important to take into account the features of plants' biology, bearing in mind an account of the interaction between the atmosphere, soil and vegetation cover. Of great importance are further numerical experiments on an assessment of the sensitivity of AGCMs to the parameterization of land surface processes, with account of the following order of priority for the effect of different factors (Nemani and Running, 1989; Schimel *et al.*, 1989; Sud *et al.*, 1988; Wilson *et al.*, 1987): (i) the choice of the model of precipitation on horizontal scales characteristic of soil moisture anomalies (and, in general, the choice of AGCMs and parameterization of hydrological processes in soils); (ii) the effect of regional-scale anomalies of the snowless surface albedo (including an account of feedbacks with soil moisture and vegetation); (iii) the effect of the winter snow cover, its interannual variability and anomalies of snow cover extent manifested through albedo and respective effect on soil moisture; (iv) the sensitivity to variations in surface roughness, especially that caused by deforestation; (v) the effect of the soil heat content on the diurnal and annual change.

The forthcoming new stage of the development of climate modelling will be, undoubtedly, connected with the consideration of the role of biogeochemical cycles in climate change. This is true not only for the land biosphere but also for marine biosphere. The latter deserves special attention as a critically important contributor to the formation of global biogeochemical cycles and, consequently, to a change in atmospheric composition. It is enough to mention two illustrations of the importance of marine biosphere: (i) its role in the formation of the global carbon cycle (Gorshkov *et al.*, 1989); (ii) its possible role in emission of dimethylsulfide (produced by phytoplankton into the atmosphere, further gas-to-particle conversion into cloud condensation nuclei, a change in the cloud droplets size distribution, as well as cloud albedo and, eventually, the global climate change which may surpass the impact of increasing CO_2 concentration (IAMAP, 1989).

The ISLSCP

Under the auspices of several international organizations (COSPAR, IAMAP, UNEP) the ISLSCP was developed aimed at further advancement and application of techniques for retrieving the land surface parameters interesting from the viewpoint of studies of climate and climate change as well as studies of the role of climate change in affecting the surface properties (soil, vegetation, ice cover) from satellite data (ISLSCP, 1985).

To meet the objectives of the ISLSCP, the following has been planned: (i) retrospective studies of surface variations on the key sites with the use of available data of surface and satellite observations (albedo, vegetation cover, surface temperature); (ii) search studies to determine the key sites, where surface variations are most sensitive to climate variations, and an accomplishment of complex (satellite, aircraft, ground) observations on these sites. H.-J. Bolle and S. I. Rasool (ISLSCP, 1985) performed a detailed analysis of the possibility to retrieve various parameters and emphasized the important role of combining satellite and ground observations on the key sites. Substantial difficulties of data interpretation are connected with the solution of the problems of filtering out the partial cloudiness in the field of view of the radiometers and the problems of atmospheric correction.

Principal criteria for the choice of the key site to perform complex observational programs within the ISLSCP are as follows: (i) high sensitivity of respective regional climates to the past or possible future changes of the surface properties; (ii) anthropogenically induced large-scale transformations of the surface; (iii) strong natural variability of regional climates; (iv) a variety of the types of the surface and their great importance for agriculture; (v) the key site must be well studied.

Complex observations of two scales are planned: local (largely, to ensure the calibration of satellite data) and covering large territories (to substantiate different techniques for parameterization). There have been planned local key sites in north-eastern Brazil, Senegal, South Sudan, North Africa (Tunisia or Egypt), Argentina, Canadian tundra, different regions of the USA, France, Austria, India, and other countries. As large-scale key sites, the following were suggested: north (Canada) and south (USA) parts of Great Plains, central Niger, Sonoran desert (near the boundary of the USA and Mexico), the region of Amazon. H.-J. Bolle and S. I. Rasool (ISLSCP, 1985) discussed the requirements to the program of observations on key sites and their realization.

The Scientific Steering Group organized by the Joint Scientific Committee (JSC) on WCRP discussed the problems and ways of realization of the program of studies of the role of land surface processes in the formation of climate and its changes (such processes are defined as phenomena which determine the heat, moisture and momentum exchange between the land surface and the atmosphere). To compare the results of numerical climate modelling (from the point of view of parameterization of land surface processes), it would be worthwhile to develop a 1-D model which would provide an interactive description of the processes on the surface, in the atmospheric boundary layer (ABL), and of cloud formation, as well as a simulation of the steady diurnal and annual change independent of initial conditions.

Testing the reliability of different parameterization techniques could be based on the realization of a Hydrological-Atmospheric Experiment (HAPEX) aimed at: (i) better understanding of hydrometeorological processes on land surface and of meteorological processes on horizontal scales from several kilometers to characteristic sizes of the climate models' grid, to improve the parameterization techniques; (ii) checking the reliability of the technique for the parameterization of the heat-and moisture-exchange, of soil moisture and runoff; (iii) complex interpretation of the results of remote sensing with the use of *in-situ* measurements data. For an adequate account of the spatial and temporal variability of processes, an accomplishment is needed of the programs of the HAPEX type in different climatic conditions on test areas from 50 × 50 to 500 × 500 km^2, covering a certain watershed territory during, at least, one year (with the periods of more frequent observations, with a 1-hr repeatability, to obtain the data on the diurnal change).

The requirements of observation accuracies, substantiated with the WCRP scientific plan, necessitate an estimation of monthly mean energy fluxes on a $2 \times 2^{\circ}$ grid (about 200 × 200 km^2) with an accuracy of 10 $\mathrm{W/m}^2$, which is equivalent to the precipitation uncertainty 10 mm/month. For the territory 100 × 100 km^2 it means that the error in estimating the total fluxes and runoff must not exceed 10^8 m^3/month and 40 m^3/s, respectively. To reach the HAPEX objectives, errors in the hourly mean values of the surface heat budget components about 10 $\mathrm{W/m}^2$ are considered acceptable, and those in monthly mean precipitation about 5%.

The complex of the quantities to be measured should comprise: (i) sensible and latent heat fluxes; (ii) heat flux in the soil; (iii) radiation budget components (including surface albedo and temperature); (iv) precipitation; (v) standard meteorological parameters (temperature, relative humidity, wind speed, cloud amount) near the surface and in ABL; (vi) hydrological characteristics of soil (moisture content, level of ground waters); (vii) runoff within the watershed basin; (viii) surface characteristics (topography, vegetation cover, type of soil, land use).

The adequacy of account of land surface processes in climate models is determined by correct simulation of internal dynamics of the atmosphere, radiative regime, ABL structure (from the point of view of temperature, wind, and fluxes of heat, moisture and momentum), and of hydrological processes. An accomplishment of HAPEX will make it possible to obtain information on all these aspects.

At present, observations have been made within the HAPEX program in south-west France (André *et al.*, 1988) and in the basin of Vashita river (south part of the Great Plains, USA). It is supposed to accumulate data bases of two types needed to test the reliability of climate models: (i) a data base which would provide testing of the reliability of parameterization of various processes on a scale of the spatial grid cell: (ii) a data base meeting the requirements of testing of the models of global climate (global data sets on albedo, surface roughness, soil properties, etc.).

The directly observed parameters containing information about land surface processes are the following: runoff, precipitation, cloud distribution, vegetation and snow cover, etc. Almost all this information can be obtained from satellite observations realized or planned within the ISLSCP programs.

Surface albedo is one of the most important input parameters in numerical modelling of AGC and climate. The correct prescription (and parameterization of variability) of albedo is very difficult because of a wide range of albedo variations and inadequacy of the data base on albedo, which determines the urgency of surface albedo retrieval from satellite observations.

Though the surface albedo retrieval from satellite observations is of great interest (and due to natural spatial averaging close to the grid scale used in numerical modelling), there is no doubt that the only satellite information is not enough (for instance, it is impossible to estimate surface albedo from satellite data in conditions of overcast cloudiness). Of interest are considerable differences between global maps of albedo drawn from satellite or conventional data, determined by different reasons (largely, difficulties in surface albedo retrievals). All this suggests the conclusion that the available data on surface albedo cannot be considered reliable, though successful efforts have recently been undertaken to accumulate data on albedo and to substantiate the global data bases of surface albedo.

The parameterization of the biosphere and land surface processes

Evapotranspiration is one of the most important climate-forming factors. Sellers *et al.* (1986, 1988) pointed out that, although it is difficult to assess the effect of evapotranspiration on the weather and climate from the observational data, the numerical modelling of AGC confirmed the substantial role of this effect. A decrease of heat expenditure on evaporation on land surface is approximately equalized by an increase of the sensible heat exchange. However, the latter causes a local heating of only relatively thin ABL, whereas the latent heat released by water vapour condensation leads to the heating of the whole atmospheric thickness and, due to an advection, can be manifested, with a time lag, in remote regions. This difference in the features of the spatial and temporal manifestation of the two types of heat flux divergence determines the sensitivity of the thermally induced large-scale AGC to evapotranspiration.

Based on the use of an AGCM developed in the Goddard Laboratory for Atmospheric Sciences (GLAS), a generalization of this model has been suggested with account of the atmosphere-biosphere interaction manifested through evapotranspiration (Sellers *et al.*, 1988). The transfer of water and energy through the underlying surface depends on the morphological features (spatial structure) and vegetation cover physiology in the biospheric model considered, the morphology of vegetation cover is determined by dependences of specific leaf area on height, $L_D(z)$, calculated per unit volume, and of specific length of the root system on depth, $RT_D(z)$, which is determined as total length of roots per unit volume, represented in the discrete form for each of the spatial grid cells of the AGCM.

The simplest version of the biospheric model foresees fixed (for each cell) values of $L_D(z)$ and $RT_D(z)$ depending on season prescribed from the data of phenological observations. In a more advanced model, an interactive relationship is taken into account between these values and precalculated atmospheric parameters and soil moisture. Therefore, on a time scale of phenophases $L_D(z)$ and $RT_D(z)$ depend, for instance, on droughts and temperature extrema.

The most adequate model foresees a differentiation of vegetation cover (tropical forests, mid-latitude forests, deserts, grass cover, etc.) and its interactive connection with conditions in the atmosphere and soil. The specific leaf area affects: (i) the aerodynamic resistance to the transfer of sensible and latent heat; (ii) radiation transfer through the vegetation cover; (iii) evaporation off the surface, and precipitation. The principal physiological factor is an effect of the internal structure of the roots, stems and leaves on the water and energy transfer,

It is assumed that the climate model with an interactive account of the biosphere will be realized first with the use of the FGGE data base as the background for prescribed SST. At a later stage an interactive model "atmosphere-ocean-biosphere" with account of heat transfer in deep layers of the ocean is planned to be developed. A realization of such a model is of particular importance in the use of anthropogenic effects on climate.

Dickinson (1984) suggested a technique for parameterizing evapotranspiration in 3-D climate models, which makes it possible to take a separate account of contributions of soil surface and vagetation cover into evaporation. It is assumed that soil moisture is concentrated in the upper 1-m layer, but, separately, the 10-cm upper layer is considered, too. To test the reliability of this parameterization, comparisons were made with a multi-layer model of evaporation off the soil surface. The parameterized evaporation off the soil is estimated as the possible rate of evaporation or maximum rate at which water can suffer diffusion up to the surface depending on which of the rate values is less. Maximum rate is estimated empirically from the data on the soil hydrological parameters.

The evapotranspiration of vegetation cover (VC) is described as evaporation of water accumulated on the surface of VC elements, or as transpiration of water extracted by the roots from the soil. The water vapour flux from the external surface of VC elements to the atmosphere over VC is determined by the difference of water vapour concentrations near the surface and in the atmosphere as well as by the incoming water through molecular boundary layers of VC and VC on the whole (aerodynamic resistance of VC). The transpired water suffers an additional resistance in the process of its transition from the internal to the external part of VC elements whose temperature and saturating water vapour pressure is calculated with the use of a model of the VC heat budget.

The soil moisture determines maximum rate of extraction of water from the soil by the roots, and, if the needed evapotranspiration exceeds this maximum rate, they become narrower till the respective equilibrium is reached. The feasibility of the described technique for parameterizing the evapotranspiration off the land surface may be needed for a realistic simulation of the diurnal change of surface temperature and evapotranspiration in mesoscale and global climate models, the resulting increase of the reliability of numerical modelling should, first of all, exhibit its effect near the surface, and on the estimates of the climatic parameters of the surface and soil. The increase of reliability is only possible under condition of reliable description of the vertical transport of the ABL, precipitation processes, cloud cover formation and radiation budget.

Practical application of the technique under discussion is complicated by the consideration of small-scale processes, lack of reliable input parameters (hydrological characteristics of the soil, vegetation cover properties), which should be prescribed for the spatial grid, and by the necessity of simultaneous adequate parameterization of some other processes. In this connection, detailed numerical experiments on the sensitivity to different factors are required.

Improving the climate models determines the need for parameterization of not only the heat and moisture fluxes from the vegetation covered surface but also (in future) the processes of dry deposition on the surface of various geseous and aerosol components. For instance, of particular interest is an account of the fluxes of carbon dioxide, sulphur dioxide and nitrogen dioxide, depending, in particular, on stomatal resistance in the leaves of plants as determining the sinks on the surface of the various components of atmospheric composition. The parameterization of related processes can be made with the use of schemes similar to that described.

As Dickinson (1984) noted, various changes are possible in the VC characteristics under the influence of climate changes which can generate the albedo-climatic feedbacks. The changes manifested through the growth of albedo are as follows: the southward retreat of the northern boundary of forests (substituting the coniferous forests with the tundra), transformation of pastures into deserts, and of tropical forests into savannahs.

Though during the last millennium an anthropogenically induced deforestation has taken place, the associated change of albedo has not substantially affected the global climate. Probably, the processess of deforestation have only led to comparatively small changes in global albedo. Therefore, naturally, a numerical modelling performed within the CLIMAP program revealed only a 0. 22% decrease of global mean annual albedo of the surface-atmosphere system during the last 18 thousand years (from the time of Wisconsin glaciation), which is equivalent to a $0.75 \mathrm{W/m^2}$ decrease of reflected radiation.

In 1977, with participation of the NCAR scientists, the development of techniques was started to parameterize land surface processes as applied, first, to the NCAR community finite-difference model and then to the spectral climate model (Dickinson *et al.*, 1986) with emphasis on the parameterization of vegetation cover as a factor of transformation of heat and moisture balances at the surface level. The respective unit of the climate model reflecting the processes taking place in the biosphere-atmosphere transfer scheme (BATS), is responsible for: (i) an account of the type of the surface and soil characteristics for each cell of the grid; (ii) calculations of the temperature of soil, snow and sea ice cover as a function of the heat balance conditions and with account of heat capacity and heat conductivity of the snow and ice cover; (iii) calculation of soil moisture, evaporation, surface and sub-surface runoff; (iv) prescription of the characteristics of vegetation cover which determine the shadowing of land surface, as well as of the part of the surface with the transpiring and non-transpiring vegetation (depending on the land use features); (v) prescription of the dependence of surface albedo on soil moisture, type of vegetation and snow cover (with account of the effect of the shadowing of this cover by forests); (vi) an account of the water balance of vegetation (considering the dew, trapped precipitation and transpiration which depends on the stomatal resistance and moisture of the soil); (vii) an account of the coefficient of surface stress (depending on the Richardson number and vegetation cover characteristics); (viii) determination of the temperature of foliage depending on the conditions of heat and moisture exchange between the atmosphere and leaves.

Dickinson *et al.* (1986), discussed the physical processes and their parameterization considered in the BATS unit, in order to describe the exchange in momentum, heat and moisture between the surface and the atmosphere, inside the vegetation cover, and at the surface level. Of particular importance is a realistic presentation of the diurnal course of the fluxes of latent and sensible heat on land surface, since usually even the sign of these quantities changes during 24 hours. Since the fluxes of latent and sensible heat are non-linear functions of the characteristics of the lower layers of the atmosphere, and the moisture content of the upper soil layer depends non-linearly on surface temperature, an estimation of these parameters with the use of daily-averaged temperature values leads to serious errors. Therefore, an adequate retrieval of the diurnal course of temperature, which depends on the features of vegetation cover, is one of the most important objectives of numerical modelling.

In this connection, the most substantial physical characteristics of vegetation involve: (i) absorbed solar radiation and the degree of soil surface shadowing; (ii) the latent and sensible heat exchange between vegetation cover and the atmosphere, which can exceed the exchange between the soil surface and the atmosphere; (iii) water content of vegetation cover (dew or trapped precipitation; the effect of the latter is particularly strong in the case of forests).

The discussed parameterization of the processes with account of vegetation cover is based on consideration of 10 types of natural formations with prescribed vegetation cover within each square of the 4.5° × 7.5° grid. Based on the data of the two available global-scale archives and published information, techniques have been substantiated to parameterize the dependence of the albedos of the various types of surface on its determining factors (in the case of vegetation, albedo is considered in the wavelength interval below and above 0.7 μm). A prescription of roughness as well as of thermal and hydrological characteristics of the soil has been substantiated in Dickinson *et al.* (1986).

Henderson-Sellers *et al.* (1986) analyzed the sensitivity of the NCAR community climate model unit of parameterization of processes in the 1-layer vegetation cover and 2-layer soil system to different input parameters, with prescribed sinusoidal diurnal change of air-surface temperature and global radiation, and with calculated (from surface temperature and prescribed specific humidity) longwave radiation fluxes (this model is called a zero-dimensional one). The use of a 2-layer soil model makes it possible to consider the dependence of the extent of the plant's root system on the depth and provides, thereby, a more adequate simulation of soil moisture.

Numerical modelling was carried out for the following five types of the ecosystems: ever-green forests in the summer low latitudes; coniferous forests in the spring northern high latitudes; the spring-time tundra with melting snow cover; snow cover accumulated in winter over grass-covered surface in the Northern Hemisphere. Calculations have shown that the discussed parameterization unit is most sensitive to variations in soil texture, especially to those connected with variations in the hydraulical conductivity and diffusion. There is only a weak sensitivity to the dependence of surface albedo on soil moisture. Much more substantial (and predictable) is the role of surface roughness and snow cover depth.

Varying of the thickness of the upper soil layer is more substantial than that of the total thickness of the active soil layer, since the degree of water saturation of the upper layer strongly affects the parameterization of hydrological processes. The response of the parameterization unit to variations in the leaf area index and stomatal resistance was often masked by the presence of dew or precipitated water catched by leaves. From the point of view of the prospects for future studies, the most important is an accomplishment of complex observational programs which will enable one to obtain the data needed to test the parameterization schemes with the spatial averaging over 4.5° lat. × 7.5° long.

Climate sensitivity to land surface processes

Numerical modelling of climate has demonstrated a high sensitivity of climate to such parameters as surface albedo and upper soil layer moisture, as well as to variations in the hydrological regime caused by deforestation (tropical forests, in particular). In this connection, Dickinson (1987) characterized the schemes of parameterization of land surface processes applied in the NCAR community climate models, as well as the numerical modelling results in order to assess the climatic impact of deforestation in the Amazon basin (it is assumed that in South America the grass cover substitutes the forests).

The effect of tropical deforestation

Preliminary results of calculations show the absence of marked changes in the annual course of precipitation in the region (0°-14°S; 49°-71°W), which can be explained by strong natural variability of precipitation and convective clouds in the tropics. In conditions of deforestation, the river runoff intensifies (especially in the dry-season period) and soil watering increases (for lack of trees catching precipitation). The period of soil drying increases (from one to several months in the Southern Amazon basin), air and soil temperatures rise by several degrees (especially during the dry season), the sensible heat exchange intensifies, and evapotranspiration weakens. To obtain reliable results, the parameterization of land surface processes must further be improved.

The anthropogenically induced transformation of the surface in low latitudes (deforestation, bush cutting and overgrazing) manifests itself, first of all, through varying albedo, emissivity, soil moisture and roughness. Rowntree and Sangster (1985) analyzed the variability of these characteristics (mainly, albedo) as well as the results of numerical modelling of the effect of the transformation of albedo and soil moisture on climate (with emphasis that care should be taken in assessing the reliability of the results since the available climate models are still far from an adequate account of all substantial feedbacks in the climate system).

The data of Table 1 for the summer Northern Hemisphere characterize the results obtained by various authors. All the models take an interactive account of hydrological processes on the surface, and the radiation transfer depends on the pre-calculated air humidity and cloudiness. As seen from Table 1, the regional growth of albedo leads to the following regional-scale effects: (i) decrease of evaporation; (ii) reduction of precipitation; (iii) decrease of moisture convergence (except for Picon's data). It follows from the data of the last column that 10.1 increase of albedo leads to a decrease of precipitation by about 20%. If the albedo of all snow-free land surface increases from 0.1 to 0.3, then the following changes take place: (i) average evaporation off the land decreases from 3.65 to 2.7 mm/day; (ii) average precipitation on land decreases from 4.6 to 3.4 mm/day, but increases over the ocean from 2.9 to 3.25 mm/day; (iii) atmospheric pressure near the land surface increases (up to 12 hPa in the center of the NH continents).

Table 1. Results of numerical modelling of the effect of albedo increase (δA) on variations in evaporation δE), precipitation (δP) and other parameters (P^+ is precipitation for control experiment).

Experiment	δA	δE mm/day	δP mm/day	P^+	$\frac{\delta P/P^+}{\delta A}$
Charney *et al.* (Sahel)	0.21	-0.9	-3.4	-0.46	-2.2
Sud and Fenessi	0.12	-0.7	-1.5	-0.26	-2.1
Chervin (Sahara)	0.22		-2.5	-0.4	-1.8
Picon (Sahel)	0.19	-1.2	-0.8	-0.30	-1.6
Carson and Sangster (the globe)					
0.1 → 0.3	0.2	-0.95	-1.22	-0.27	-1.8
0.2 → 0.3	0.1	-0.26	-0.4	-0.14	-1.4

A decrease of emissivity by about 0.2 taking place after the liquidation of vegetation cover practically does not affect the surface radiation budget. The effect of variations in soil moisture on global scales on precipitation is very strong. All numerical experiments revealed a decrease of precipitation when evaporation decreases.

Experiments with a prescribed local negative anomaly of soil moisture similar to that observed in the Sahara in summer have revealed: (i) a decrease of evaporation (from 3 to 0 mm/day); (ii) surface heating (up to 20K) and increase of the sensible heat flux (from 30 to 120 W/m^2); (iii) warming of the lower atmospheric layer (up to a level of about 600 hPa) and cooling (about 2K) of higher tropospheric layers; (iv) a decrease of atmospheric pressure near the surface, whereas at the level 700 hPa and higher the geopotential grows when the anti-cyclonic circulation intensifies; (v) a reduction of precipitation (from 5 to 2 mm/day), which favours the soil moisture anomaly; (vi) upward motions, confined to low altitudes, which excludes the possibility of substantial precipitation. A strong decrease of roughness (from 45 cm to 0.2 mm) leads to a weakened convergence due to friction and associated precipitation.

Numerical experiments performed by the scientists of the Great Britain Meteorological Service to analyze the effect of soil drying in the Sahel region revealed a substantial impact of drying on the climate of the Sahel and adjacent regions. Partial liquidation of vegetation cover (albedo increase) may be considered one of the reasons of precipitation reduction in the Sahel region, starting from 1968, with the subsequent effect of the biogeophysical feedback. This feedback could show itself through the SST anomalies affecting the aridization of the Sahel climate. To assess the reliability of the results obtained, of great importance is a prolonged monitoring of the dynamics of the surface properties from satellite-derived data.

Desertification processes

The recent studies have shown that the causes of the continuous drought in the Sahel region with a maximum in 1973 can be understood in terms of a strong positive feedback, partially caused by changing properties of the surface. The key factor of this mechanism is variations of albedo and soil moisture which cause variations in the radiation budget manifesting themselves both directly and indirectly (through changing expenditures of heat on evaporation). In this connection, Courel *et al.* (1984) studied variations in the surface albedo in the Sahel region during the period, starting from 1972. Analysis of observational data has shown that in the periods of dry seasons in the Sahel (especially in the regions of Ferlo and Gondo) the albedo values decreased from a maximum of about 0.30 in 1973 to 0.20 in 1979. This decrease of albedo agrees with the data on variations in vegetation cover recorded from spectral brightnesses observed from Landsat as well as from ground-based observations. In conditions of decreasing albedo, the vertical motions and precipitation intensify, and the cloud amount grows. The result obtained contradicts the hypothesis of the biogeophysical (albedo) mechanism for the formation of the drought suggested by J. Charney, 1975.

M'Rabet and Planton (1984), Planton (1985), applied the 10-level spectral AGCM developed by the French National Center of Meteorological Research, to analyze climate changes caused by the surface albedo anomalies in the Sahel-Sahara region (16°N-34°N; 12°W-45°E), which consists in a 10% growth of albedo compared to the albedo in the control experiment. An integration was made for 15 months, starting from December.

The data of Table 2 illustrate variations in the differences between zonal mean (12°W-45°E) characteristics of climate averaged over two winters (December-February) and over summer seasons (July-August). During the first winter, the effect of the biogeophysical feedback mechanism suggested by J. Charney, 1975 (precipitation reduction with increasing albedo) manifests itself particularly strongly. The difference of climatic response at the two considered latitudes is determined by different radiation budgets of the surface.

Table 2. Variations in different characteristics of climate caused by positive anomalies of albedo in the Sahel-Sahara region.

Paramenter	First winter		Summer		Second winter	
	30°N	20°N	30°N	20°N	30°N	20°N
Absorbed solar radiation, W/m^2	-14.4	-18.5	-33.8	-27.4	-25.2	-22.9
Effective emission, W/m^2	2.3	-1.9	14.7	6.0	14.3	6.7
Evapotranspiration, mm/day	-0.06	-0.08	-0.14	-0.08	0.11	-0.02
Precipitation, mm/day	-0.08	-0.15	-0.18	-0.30	0.35	-0.06
Soil surface temperature deg.	-2.7	-5.5	-0.6	-2.5	-0.8	-3.3
Sea level pressure, hPa	2.6	2.8	0.7	1.7	1.3	1.8
Vertical velocity at 500 hPa level, hPa/s	0.9	1.2	-0.2	1.4	-0.1	1.1
Cloud amount, %	-0.3	-1.4	2.6	-3.5	13.0	2.0
Temperature at 800 hPa, deg.	-1.7	-2.9	-0.5	-1.7	-0.9	-1.7
Temperature at 500 hPa, deg.	-0.6	-0.8	-0.4	-0.7	-1.2	0.0

The discussed calculations reveal a substantial effect of the soil moisture anomalies on the atmospheric general circulation on a time scale of several months and the seasonal dependence of this effect.

Based on the use of the 11-level AGCM developed by the British Meteorological Service, Rowntree and Sangster (1986) performed numerical modelling in order to analyze the role of feedbacks due to land surface processes in the formation of drought in the Sahel region. Withing the 4-year control experiment, calculations for nine months (starting from 1 March) were made for two different years, with prescribed soil moisture content in Africa, south of 10°N, decreasing from 15 cm to 1 cm (this is equivalent to a substitution of scarce vegetation cover for multi-year deep-root vegetation). This change has led to a substantial decrease of summer rainfall over the western part of the Sahel but to an intensification of precipitation in Sudan and Ethiopia.

In the subsequent pair of experiments, apart from decreasing evaporation, the albedo was prescribed to increase in the band 10°-17.5°N to values corresponding to semi-desert conditions. In this case a decrease of precipitation was more homogeneous spatially (in the Sahel region) and somewhat exceeded that observed during the last drought. The effect on precipitation and atmospheric circulation was not confined to the region of Sahel. So, for instance, precipitation decreased up to the equator (especially in September and October), reflecting the effect of advection from the north on the atmospheric water content, as well as in the zone of the Atlantic, where it was followed by the southward shift of the ITCZ rainfall band and by substantially varying tropospheric circulation (all these variations were statistically significant). The latter closely corresponds to variations in circulation observed in the transition from arid to moist periods. This suggests the conclusion that the circulation variations have followed the droughts but not caused them.

Thus, the results of the numerical experiments point to the existence of a positive feedback manifested in that the decreasing rainfall in the Sahel leads to the loss of the multi-year vegetation cover which promotes further intensification of the drought. This feedback can intensify due to such effects as a decrease of rainfall due to SST anomalies as well as liquidation of vegetation cover by people and domestic animals.

The role of the cryosphere

The cryosphere is, no doubt, an important component of the climate system. This is confirmed by the data tabulated by Henderson-Sellers and McGuffie (1984) (Table 3) which reflect the spatial and temporal variability of cryospheric components.

Table 3. The spatial and temporal scales of the cryospheric components.

Component	Characteristic scales	
	Area, km^2	Time, years
Ice sheets	16×10^6	$10^3 - 10^5$
Permafrost	25×10^6	10^4
Mid-latitude glaciers	0.35×10^6	$10 - 10^3$
Sea ice	23×10^6	$10^{-1} - 10$
Snow cover	19×10^6	$10^{-2} - 10^{-1}$

As is seen, the sea ice cover and continental snow cover play the leading role, but permafrost is also very important. A typical feature of the cryosphere consists in a rapid variability of its components in the annual course. So, for example, the extent of sea ice varies from 20 x 10^6 km in September to 2.5 x 10^5 in March in the Southern Hemisphere and within (15-8.4) x 10^6 km^2 in the Northern Hemisphere.

Still more substantial is the variability of the extent of snow cover: the difference between maximum and minimum values reaches 80%. Rapid changes in the snow and ice cover connected with melting are one of the key factors of climate change mainly manifesting itself through the so-called "albedo" feedback. Though available information about permafrost is fragmentary, one can believe that this cryospheric component is the most sensitive indicator of climate change.

All hemispherical and global climate models take into account the high-latitude processes, but the parameterization schemes are very diverse. Numerical climate modelling for the polar regions is seriously hindered by several factors. One of them is radically different climates of the Arctic (largely the ocean covered with ice whose dynamics is controlled by temperature, salinity and convective mixing) and Antarctic (continental ice sheet 4 km high), with rather scarce observational data. Another factor is an inadequacy of finite difference models near the poles (the presence of singularities), which leads to seriously distorted results (in this case the spectral models are more adequate).

One more difficulty is a reliable reproduction of specific conditions of cloudiness in high latitudes. In the presence of snow cover the formation of overcast cloudiness causes a surface warming (independent of the cloud height), whereas in the case of snow-free surfaces the overcast low-level cloudiness causes a cooling, and the upper-level cloudiness causes a warming (the greenhouse effect of cirrus clouds).

Of great importance is the effect of the permafrost dynamics on the hydrological regime. Estimates have shown, for instance, that with permafrost liquidated in the regions of rivers Lena and Enissey the runoff of these rivers will halve, which will affect the salinity regime and the annual course of the ice cover extent of the arctic seas (the process of ice formation must slow down). A change in the albedo of snow and ice cover caused by its contamination can play an important role, too. This effect must particularly be taken into account in analysis of the possible impact of a nuclear war on climate. A more reliable account of further improvement of climate models.

Though the response of the form of snow-falls to AGC variations is characterized by a relatively small time constant of the order of several days and more, a subsequent effect of stronger snow-falls on climate can be prolonged. To analyze the short-period effects of snow-melting and snow cover, Ji (1986) undertook a numerical modelling with the use of 1-D climate model, which takes into occount the heat-and moisture-exchange between the upper soil layer and the atmosphere.

With snow cover anomalies taking place either in winter or in spring (the cases were considered of initial snow cover thickness less than the climatic one and the beginning of snow melting earlier than the climatic time), variations happen in such characteristics of the surface as albedo and soil moisture which affect the fluxes of latent and sensible heat as well as moisture cycle. Due to these processes, prolonged anomalous situations occur, especially from the viewpoint of variability of the hydrological characteristics which remain for a long time after snow melting. An anomalous snowfall can be an important factor of either cold and moist or warm and dry climate in spring and in summer. Variations in the zonal mean temperature calculated for different latitudinal belts agree well with the annual change of the snow cover extent on the continents of the Northern Hemisphere.

Conclusions

Studies of the global distribution of vegetation cover are a very important problem. In this connection, Matthews (1985) substantiated the global data base on the distribution of vegetation cover, land use and surface types for a $1^\circ \times 1^\circ$ grid, from the data of about 100 publications supplemented with the results of processing satellite imagery. This data base is aimed at a prescription of the input parameters on the global distribution of albedo in numerical climate modelling.

The whole data base archived at NASA (USA) consists of six parts. The first part (VENTYPE) characterizes the distribution of natural vegetation with the use of the classification scheme adopted by UNESCO. The second part (COLTINT) contains data on land use presented as a share (%) of the area of cultivated soils for each cell of the grid. The other four parts are global data bases (also presented as maps) on total land surface albedo for the four seasons (January, April, July, October) without snow cover (except for the regions of continental ice with persistent snow cover). Data on albedo were obtained with account of both natural and cultivated vegetation. A scheme of the data formats on magnetic tape is given and brief descriptions of albedo maps for the USA territory. The considered natural formations totalled 32, with the annual course of albedo expressed weakly or absent altogether. So, for instance, for the albedo of the snow-ice surface a constant value of 75% is assumed.

Starting from April 1962, a regular processing of data has been carried out which were obtained with the NOAA-7 AVHRR, to draw daily mean global maps of the vegetation index determined from the relationship:

$$VI = B_2 - B_1; \quad NVI = (B_2 - B_1)/(B_2 + B_1)$$

where B_1, B_2 are the brightnesses of the surface-atmosphere system for AVHRR channels No. 1 (wavelength interval 0.58-0.68 um) and No. 2 (0.73-1.10 um). Use of the normalized vegetation index NVI as a characteristic of vegetation cover is preferable, since in this case the effects of varying conditions of illumination, viewing angle and surface slope is partly excluded. NVI 0 for clouds, water and snow, when B_1 B_2, and is close to zero for bare soil and mountains.

In the case of vegetation cover the NVI varies within 0.1-0.6 (higher values correspond to larger density and greenness of vegetation cover). The effect of the atmosphere markedly decreases the contrasts $B_1 - B_2$, especially, at large angles of viewing.

A serious problem is the filtering out of cloudiness by prescribing a threshold value of brightness in the visible and selecting only maximum values of vegetation index.

The key role in the formation of climate and biospheric functioning is played by global water cycle in which, due to unique position of the Earth in the solar system, which determines the observed thermal regime water in all three phases participates. In this connection, the most important problems of hydrology are as follows:

- development of new techniques to determine the water stress of the soil and evapotranspiration on the scales from individual fields to continents;
- a quantitative estimate of precipitation and its distribution over the watershed territory;
- global monitoring of snow cover extent and its water equivalent;
- development and testing of the reliability of hydrological models which are compatible with possibilities to obtain information by remote sensing from space (spatial and temporal resolution, repeatability) for the phenomena of different scales, from floods on small rivers to general circulation models;
- further studies of the laws of global water cycle.

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Резюме

Сделан обзор результатов исследований роли биосферы в формировании климата, который свидетельствует о наступлении нового этапа в развитии теории климата, демонстрирующего необходимость учета биосферных процессов. Это проявляется как в необходимости более адекватного рассмотрения процессов на поверхности суши, так и в очевидной потребности принимать во внимание взаимодействие между биогеохимическими круговоротами и климатом. Обсуждены различные подходы к учету биосферы как климатообразующего фактора, некоторые результаты численного моделирования, и возможности использования данных комбинированных спутниковых и наземных наблюдений для определения параметров, характеризующих взаимодействие атмосферы и биосферы.