quite likely that the model fails to quantitatively evaluate feedback processes related to sea ice, and will produce some errors when predicting possible future climate changes due to increasing CO_2.

In this report, we describe some results of a simulation of the transient response of climate to gradually increasing CO_2 with a climate model which has been improved with respect to the aspects mentioned above. The work presented in this report is partly based on Tokioka *et al.* (1995), JMA (1995), Motoi *et al.* (1995), Noda *et al.* (1995) and Yukimoto *et al.* (1995).

2 Description of the model

The coupled atmosphere-ocean general circulation model (CGCM) used for this study consists of a general circulation model of the world ocean (OGCM) coupled to a general circulation model of the atmosphere (AGCM) together with a sea ice model and a land surface model, all developed at the MRI. The method of coupling the models is an important consideration for climate modeling, because it controls the exchange of momentum, heat and water between atmosphere and ocean and thus influences the simulated fields of the model. Each component of the CGCM and the method of coupling them will be described in this section.

2.1 Atmospheric model

The atmospheric part of the model is identical to that used for the Atmospheric Model Intercomparison Project (AMIP; see Phillips, 1994) and its performance is described in Kitoh *et al.* (1995).

The horizontal resolution of this AGCM is 5° by 4° in the longitudinal and latitudinal directions, respectively. In order to allow different horizontal resolutions between the AGCM and the OGCM, the fractional coverage by different types of surface characteristics (ocean, land, sea ice and ice sheet) are considered in each AGCM grid cell (Fig. 1).

The vertical resolution of the AGCM is 15 hybrid levels between the surface and the model top at 1hPa. Log-pressure coordinates were used for altitudes above 100 hPa and modified sigma coordinates were used for altitudes below that level (Fig. 2).

Shortwave radiation was calculated based on the parameterization of Lacis and Hansen (1974). Rayleigh scattering and absorption by ozone and water vapor were calculated. The calculations of

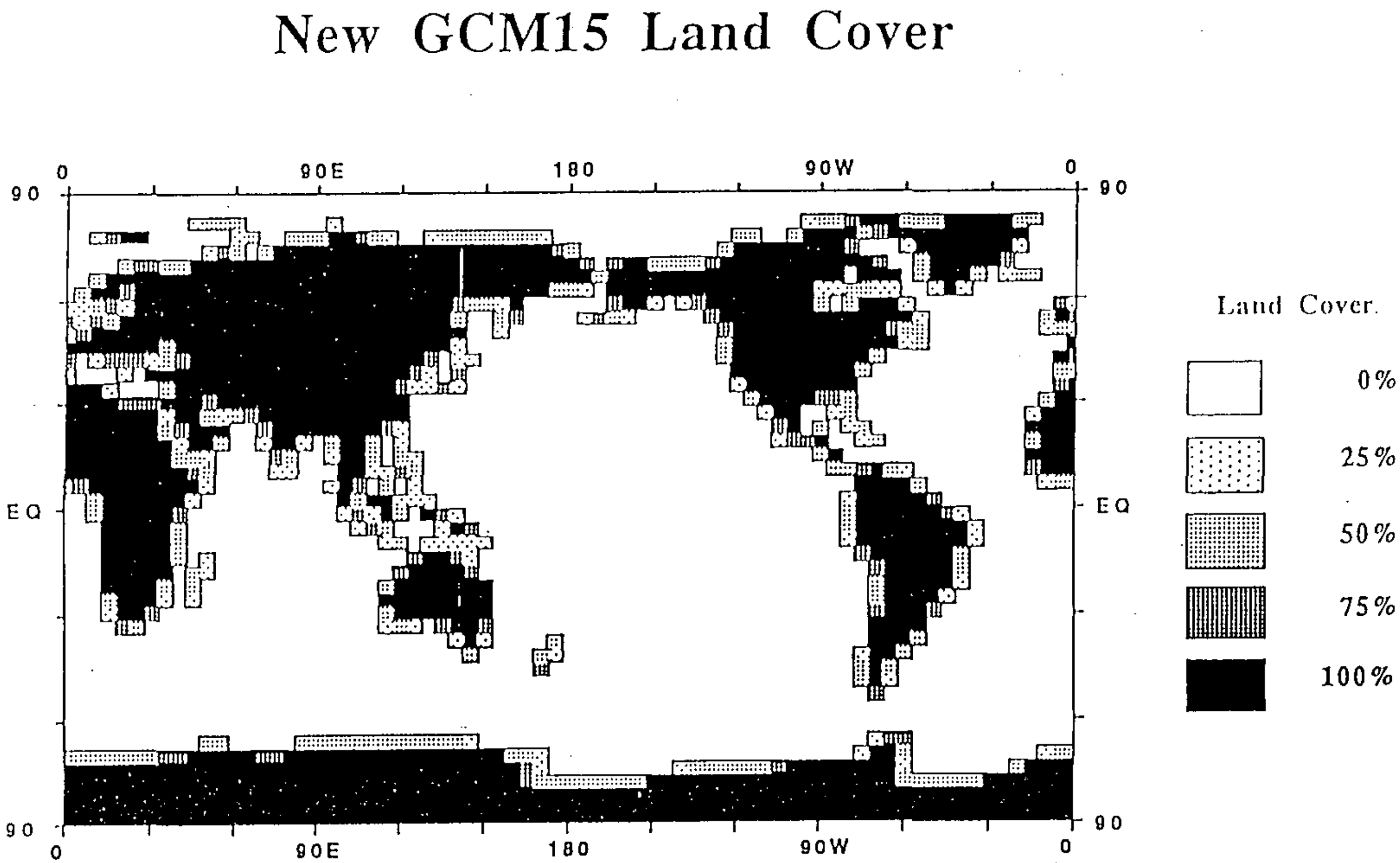

Fig. 1 The percentage of land coverage in the AGCM grid points.

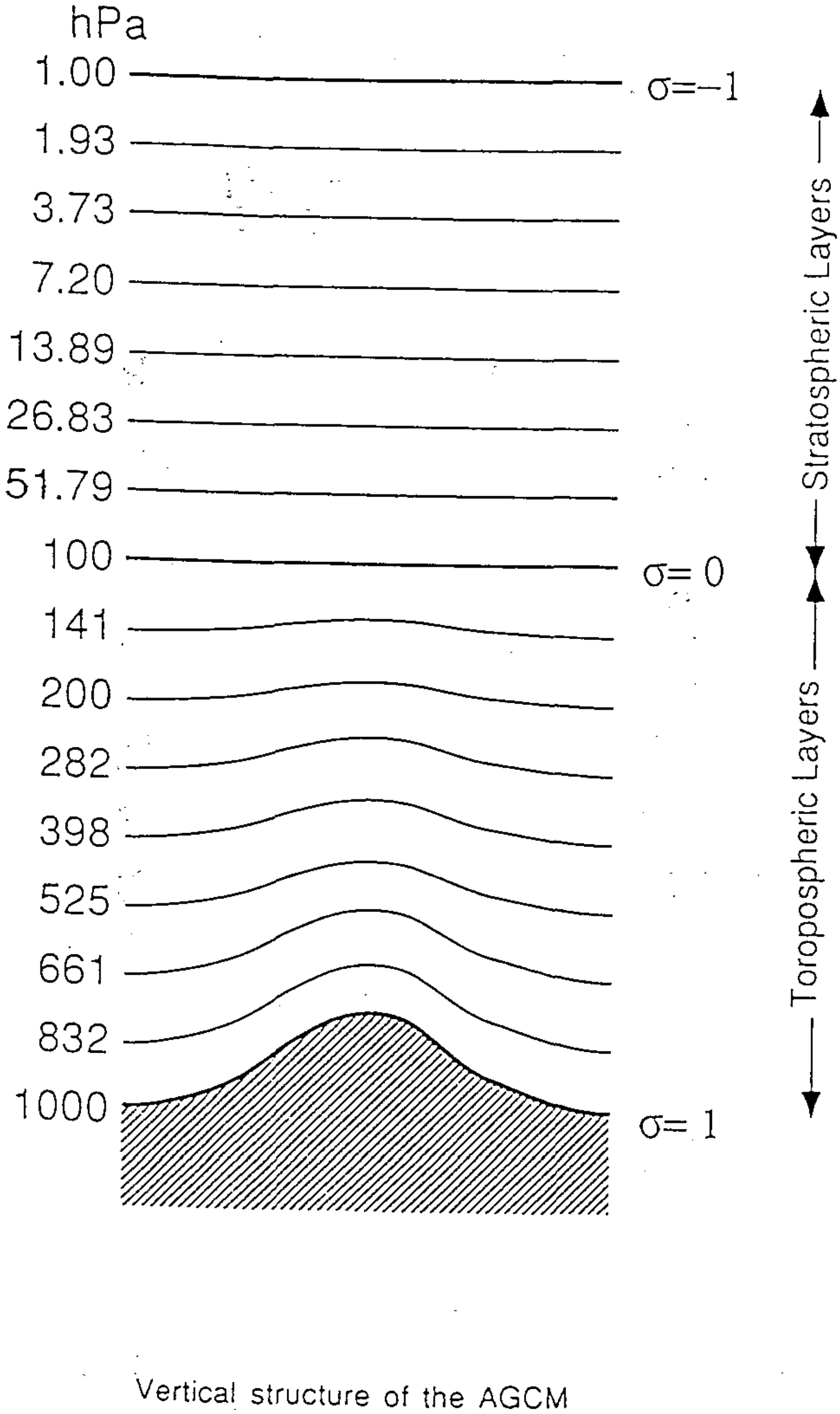

Fig. 2 The vertical structure of the AGCM.

longwave radiation were based on the multiparameter random model of Shibata and Aoki (1989) applied in four spectral regions (20-550, 550-800, 800-1200 and 1200-2200 cm^{-1}). Absorption bands of carbon dioxide, ozone and water vapor, and continuum absorption by water vapor were considered.

Five types of clouds were diagnostically determined: *i.e.*, penetrative cumulus, middle level convective, planetary boundary layer stratus, large-scale condensation and cirrus anvil clouds. Partial cloudiness was allowed for the convective clouds. Parameterization of cumulus convection was based on the scheme of Arakawa and Schubert (1974). This scheme predicts mass fluxes from mutually interacting cumulus sub-ensembles which have different entrainment rates and cloud tops. The Arakawa-Schubert scheme was modified to impose an additional constraint between the minimum entrainment rate and the depth of the predicted PBL layer (Tokioka *et al.* 1988).

Effect of sub-grid-scale topography on the grid-scale flow was included as gravity-wave drag following Palmer *et al.* (1986), with quantitative adjustment as described by Yagai and Yamazaki (1988).

Thermodynamic and hydrological processes of the land surface were based on a multi-layer soil model. There are four layers with a bottom at 10 m depth. Ground temperature, soil moisture and frozen soil moisture were predicted at each level.

2.2 Sea ice model

The sea ice model predicts sea ice concentration (areal coverage ratio) as well as thickness and surface temperature. The movement of sea ice was predicted by considering advection due to oceanic currents at the first level of the ocean. The thermodynamics of sea ice was parameterized following Mellor and Kantha (1989). Energy exchanges through the surface were calculated for the sea ice area and "leads" separately and were weighted with the respective coverage ratios. The model could simulate seasonal variations in sea ice concentration and thickness realistically not only for the Arctic but also for the circum-Antarctic area. The performance of the sea ice model is described in Section 4.3 below. A detailed description of the sea ice model is given in Appendix A.

2.3 Ocean model

The oceanic component of the model (OGCM) is a global ocean general circulation model developed at MRI (see Nagai *et al.*, 1992). The model has now been extended to include a realistic ocean bottom topography and a variable resolution in the meridional direction, ranging from 0.5° at the equator to 2.0° at 12° latitude and further poleward (Fig. 3). The resolution in the longitudinal direction is 2.5°. There are 21 vertical layers, for which the thickness increases from 5.2 m at the surface to 700 m at 5000 m depth, with 11 layers located in the first 300 m (Fig. 4). The Mellor-Yamada level 2 turbulence closure scheme was included to simulate the oceanic mixed layer. The lateral eddy viscosity and diffusivity were set to 2.0×10^9 cm^2/s and 5.0×10^7 cm^2/s, respectively, for latitudes between 78°N and 78°S. The vertical eddy viscosity and diffusivity were calculated following Mellor and Yamada (1974, 1982) and Mellor and Durbin (1975). A detailed description of the ocean model is given in Appendix B.

2.4 Coupling of the component models

The AGCM and the OGCM components of the climate model used have different horizontal resolutions. Furthermore, the areal proportion of sea ice coverage in each ocean grid cell was predicted, as explained above. The surface energy fluxes in each atmospheric grid cell were calculated as the sum of the area-weighted energy fluxes between the atmosphere and the underlying surface component (which was either land, open ocean or sea ice) within that atmosphere grid cell. We allowed partial land coverage in both coastal and island grid cells.

Runoff from the land was added to the ocean by a simple runoff routing model. Surface runoff generated in the AGCM grids was assumed to instantaneously reach the outlet of each river basin. Continental and sub-continental scale river basins were determined at 5°× 4° resolution (Fig. 5) based on the drainage basin map in the *Encyclopædia Britannica World Atlas* (Walter,1957).

The atmospheric model provided the ocean-surface fluxes of momentum, heat and freshwater, the conductive heat flux through the sea ice and the momentum flux at the sea ice surface to the ocean and sea ice models. All components of the ocean-surface heat flux were assumed to be absorbed in the top layer of the ocean with the exception of shortwave radiation, a portion of which penetrates

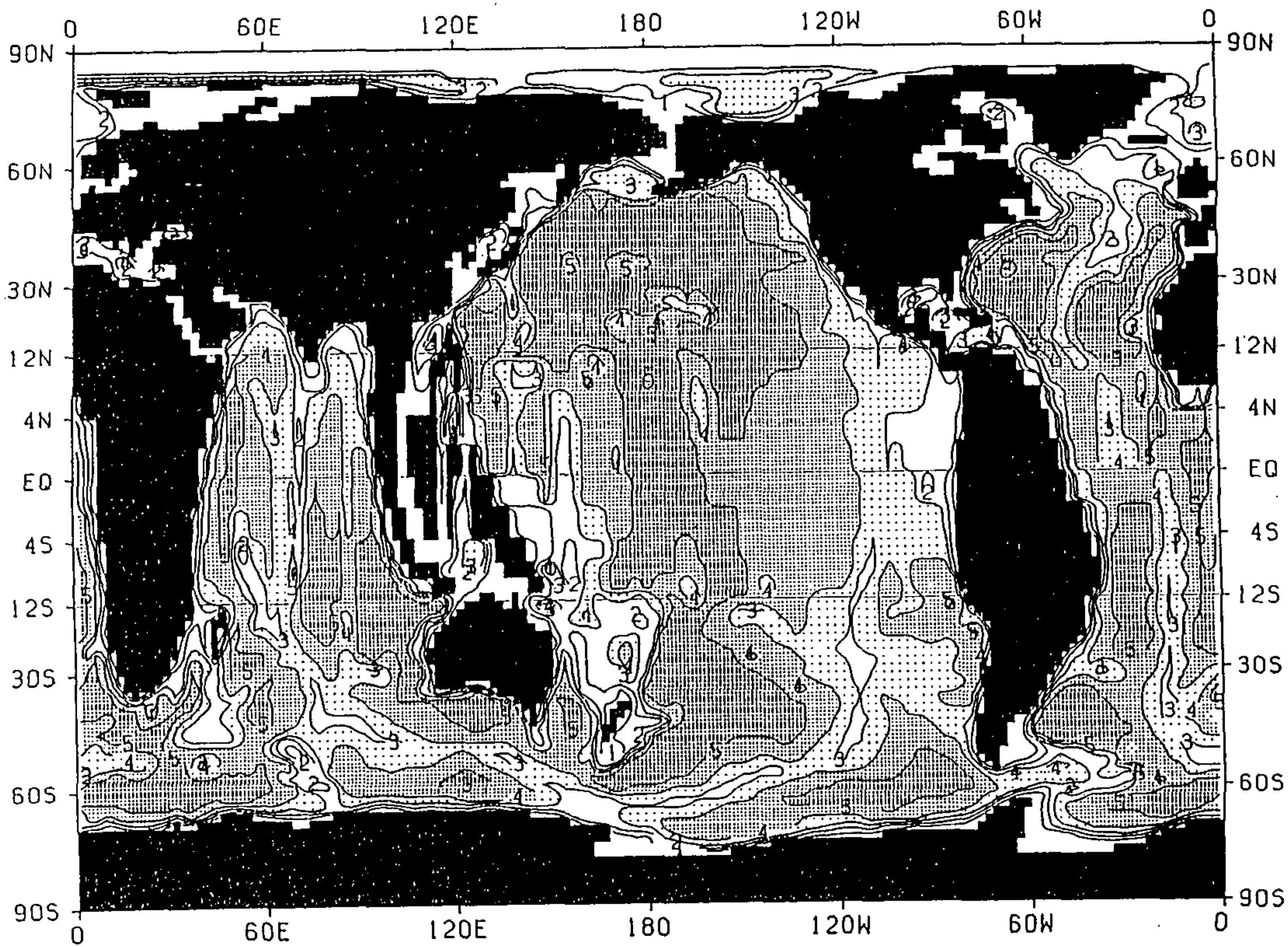

Fig. 3 The horizontal resolution and topography of the OGCM. Variable resolution is used in the meridional direction, ranging from 0.5° at the equator to 2.0° at 12° latitude and further poleward. Contour interval is 1000 m.

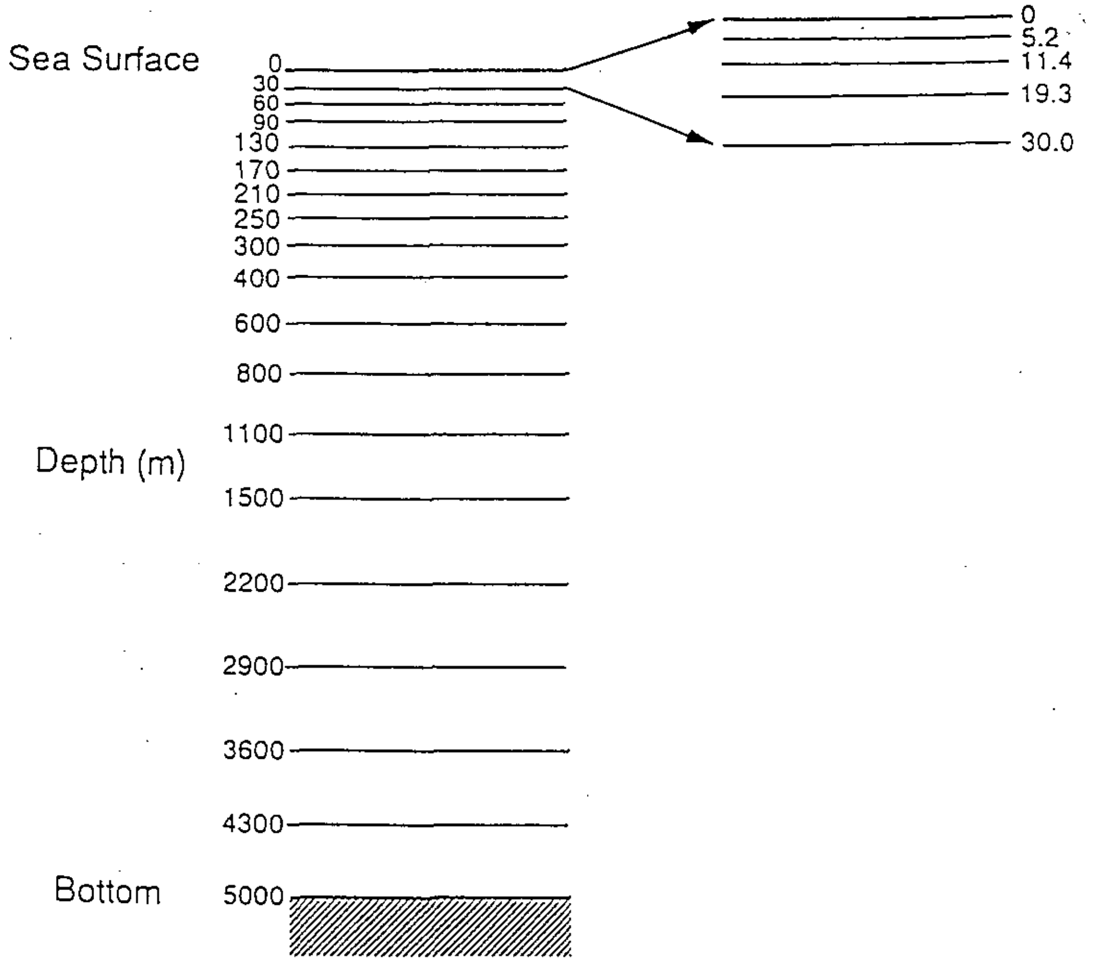

Fig. 4 The vertical structure of the OGCM.

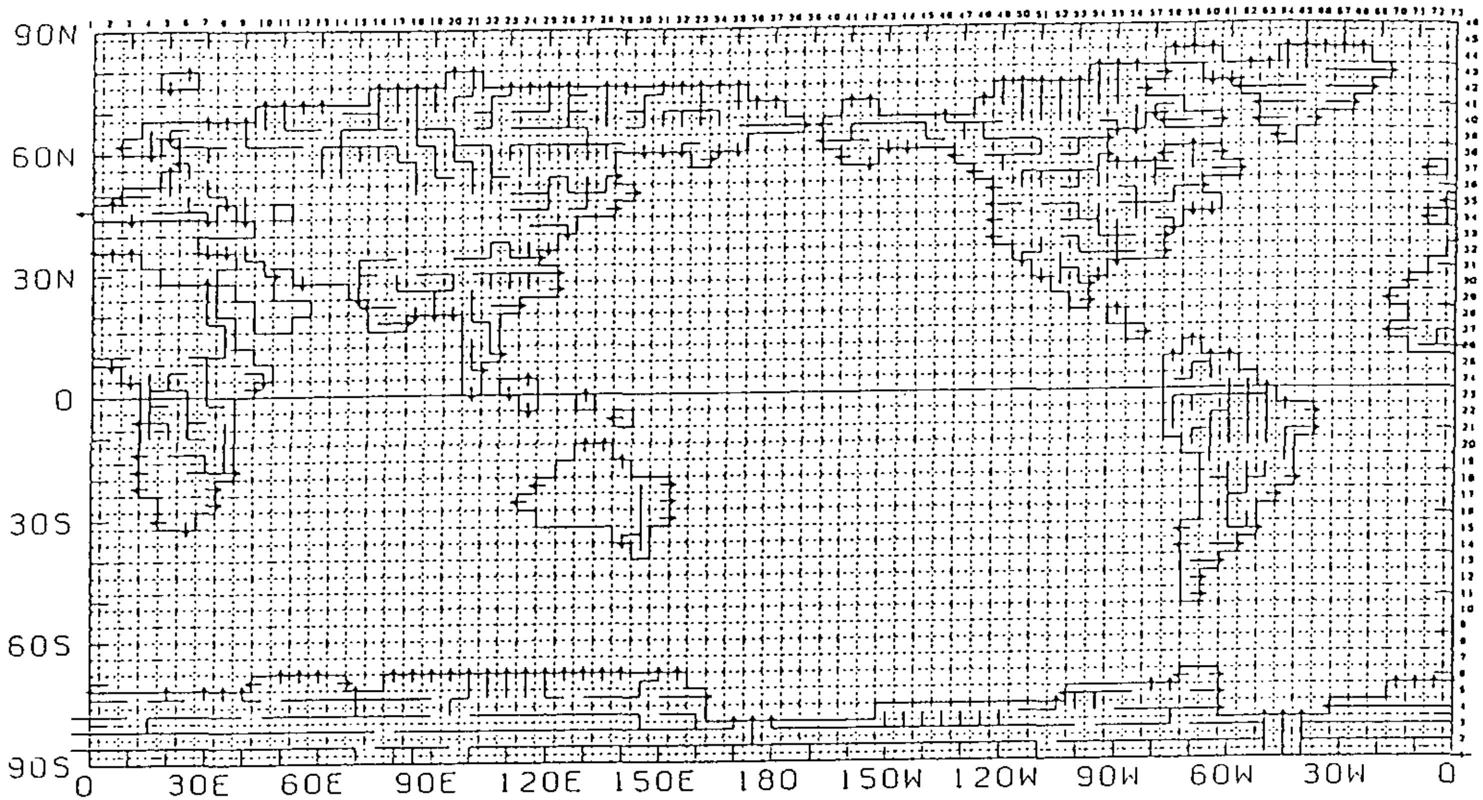

Fig. 5 Drainage basins and river directions.