Numerical experiments on the general circulation of Venus' atmosphere

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ABSTRACT

A number of numerical experiments on Venusian atmospheric circulation with a time-dependent two-layer primitive equations model was made. Both hot-house and Goody-Robinson radiation-transfer assumptions led to similar results: the major temperature differences (of the order of $n \times 10^{-1}$°C) occur between the day and night hemispheres; on the day side the air ascends and on the night side descends at a rate of $n \times 10^{0}$ cm/sec; the typical wind velocity is close to 5 m/sec; the circulation is not disturbed by large-scale eddies.

Until recently the information on Venus and its atmosphere was very scanty, since the studies of the planet with the optical telescopes have been very difficult because of dense clouds covering the visible part of the planet. The latest achievements of radioastronomy were used to determine the parameters of the planet's own rotation. The Soviet space stations "Venus-4" of 1967, and "Venus-5" and "Venus-6" of 1969 performed direct measurements of pressure, temperature, density and chemical composition of Venus' atmosphere at various altitudes. The flight of "Venus-7" in 1970 yielded data on temperature and pressure at the very surface of the planet for the first time. The radiorefraction sounding of Venus made by the American space vehicle "Mariner-5" in 1967 gave much valuable information. Thanks to all these data, we know now that Venus's atmosphere is 80 to 100 times more massive than the Earth's atmosphere and consists mainly of carbonic acid which is an intensive absorber of radiation (A. P. Vinogradov et al., 1970). For this reason dynamic and heat inertia of Venus' atmosphere should be very high. The planet's surface has been found to be 450 to 500°C hot. As the altitude increases the temperature of Venus's air decreases according to the law close to the adiabatic one (by an average of 9° per 1 km). The rotation of Venus is 243 times slower than the Earth's rotation and is in an opposite direction; the solar day on Venus is equal to 117 Earth days; the inclination of Venus' equator to the orbital plane is no more than 2°, therefore seasons are practically absent on Venus.

Only very scarce experimental data have been obtained on Venus' atmospheric wind and horizontal changes of temperature as well as of the latter in time, yet the available information suffices to raise a problem of theoretical computations of the major wind system and specific features of temperature distribution, i.e. general atmospheric circulation. Such computations were made at the P. P. Shirshov Institute of Oceanology of the USSR Academy of Sciences in 1969 and 1970.[1]

The numerical modelling of the atmospheric circulation on Venus was made with the full hydrodynamic equations on a sphere in quasistatic approximation with nondimensional pressure $\sigma = P/P_s$ as a vertical coordinate, and the equations of continuity and heat influx containing 4 independent variables, i.e. latitudinal

[1] *Atmospheric circulation on Venus was not computed previously. R. Goody and A. Robinson (1966) constructed a model of stationary circulation averaged with respect to the solar–antisolar axis; we shall see below that Venus' atmospheric circulation is not axisymmetric.*

and meridional velocity components u and v, potential temperature θ and pressure at the planet's surface P_s (temperature T, gravity potential Φ and vertical velocity analogue $\dot{\sigma}$ were determined from these variables without integrations in time). Horizontal mixing with the exchange coefficient determined according to Richardson's law at an average rate of kinetic energy dissipation equal to 0.2×10^{-4} m²/sec³ was taken into consideration. The methods of A. S. Monin and S. S. Zilitinkevich (1969) were employed to determine momentum and heat fluxes in the boundary layer and surface temperature of the planet, and to make "convective adjustment", i.e. equalization of potential temperature (with account for entropy conservation) at the appearance of hydrostatic instability in the free atmosphere.

Radiative heat influxes were computed on the hot-house model of Venus' atmosphere constructed by S. D. Gutshabash from the theoretical computations of V. V. Sobolev (1969). Dense high clouds with albedo $A = 0.76$ (coinciding with the planet's albedo) were preassigned. Some 20 % of the assimilated solar radiation flux averaging $(1-A)\, S_0/4$, where S_0 is the solar constant, were absorbed by the atmosphere. About 80 % of this flux reached the planet's surface and reradiated as longwave radiation which was absorbed completely in the lowermost atmospheric layers (the hot-house effect). Thus within the major portion of the atmospheric column, the vertical heat transport proceeded mostly through large-scale motions and convection (which occurred on the night side of the planet as well as because of cooling the atmosphere from above).

The differential space operators were replaced by finite-difference ones on a grid with $N = 4n\ (n+1)$ points on a sphere where n is the number of latitudinal zones on a semisphere (the k-zone counting from the near-polar one contained $4k$ points, see V. G. Turikov, 1969). K. Bryan's (1966) "box-method" used for the purpose provided the adherence in the difference equations to a number of the laws of conservation (first of all, of mass) and excluding non-linear instability. Time derivatives were approximated by differences based on the method of trapezia with 3 iterations. The programme for the electronic computers was written in the ALGOL; the former admits the variation of a certain parameter including the number of points on a sphere (n parameter) and atmospheric levels.

Some numerical experiments were made on two-level models (the atmosphere is divided into two layers of similar mass) with different number of points on sphere N. The computations show that the principal features of circulation do not change as N varies over rather wide limits. In other words, the circulation of Venus' atmosphere, unlike that of the Earth, is of a global character and is not disturbed with large-scale eddies of cyclonic and anticyclonic types (these conclusions well agree with the theoretical results obtained by A.M. Obukhov (1949) according to which a planet's diameter should be a typical scale of synoptic formations on slowly rotating planets).

Most computations were made at $N = 168$ (grid spacing is ~1 500 km) for 90 Earth days and $N = 80$ (grid spacing is ~2 200 km) for 160 Earth days. The state of rest with an even distribution of pressure over the planet's surface $P_s = 80$ atm and the same potential temperature $\theta = 700$°K for the whole atmosphere was taken as initial. The average kinetic energy of unit mass E of the atmosphere grew only during the first 30 days, after which time it started varying in the vicinity of 14.5 m²/sec² which corresponds to the average wind velocity of about 5.5 m/sec (see Fig. 1 corresponding to $N = 80$). The similar

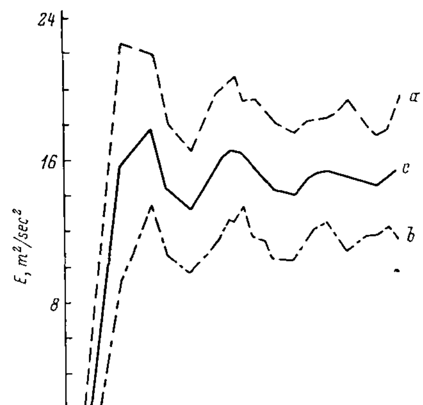

Fig. 1. Changes in time of the average kinetic energy of atmospheric unit mass E. (a) day hemisphere; (b) night hemisphere; (c) the whole planet (energy differs but slightly in the northern and southern hemispheres).

results are obtained by computations with $N = 48$ and $N = 168$ which confirms the validity of the conclusion about the global character of the major motions.

The most detailed processing was made of the results of the numerical experiments with $N = 80$ points on a sphere for 160 Earth days. Since the "fetch" of the atmosphere from rest to dynamic equilibrium (under which kinetic energy only oscillates but does not show systematic changes) requires approximately a month, this experiment made possible to overlap Venus' diurnal cycle (about 117 days) in the equilibrium regime, and the subsequent computations yielded only very little new information. As was already mentioned, there are no seasons on Venus. The computations have given data on the changes in time of the fields of horizontal wind velocity components, temperature, atmospheric pressure, vertical velocity, radiative and turbulent heat fluxes, friction stress at the planet's surface. The main results show the following. Circulation is almost symmetrical about the equator, is of a global character and develops as a result of temperature differences between the day and night hemispheres. These differences are sustained by heating of the day side by the sun and cooling of the night side through the planet's own radiation (no temperature difference was found between the equator and the poles). Circulation is not symmetric either about the rotation axis (as on the Earth) or about the solar–antisolar axis: the region of the strongest heating lags appreciably behind the sub-solar point and rather approaches the evening terminator, whereas the coldest region is found on the morning terminator (Fig. 2). The latter fact, however, is not surprising since on the Earth, too, the lowest temperature is found not at midnight but during the morning hours. Temperature difference at various points of the planet is 2.5°, and the average surface temperature on the day side is only 1° higher that that on the night side. Gravity potential fields much resemble potential temperature fields. The range of atmospheric pressure variations at the planet's surface is about 80 mb; average p_s on the day side is 28 mb lower than that on the night side (P_s field on the 140th day is presented in Fig. 5*g*). The wind system is basically as follows: in the lower atmospheric region the air flows to the most heated zone where it ascends

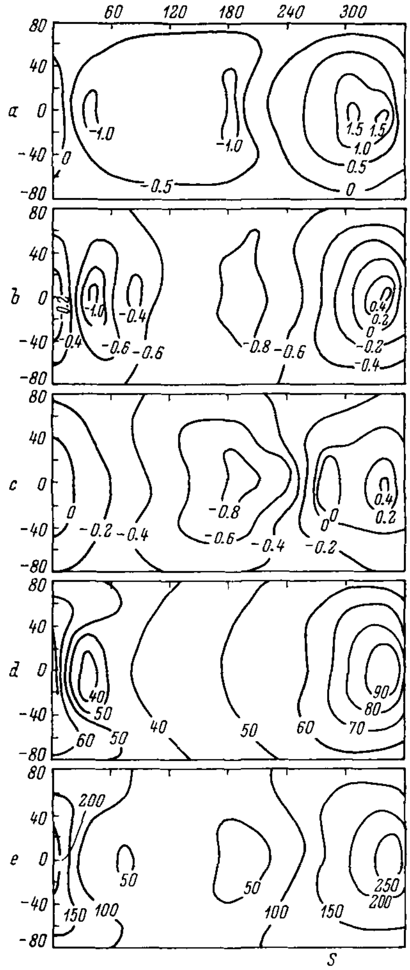

Fig. 2. Temperature and gravity potential on the 140th day of the experiment: (*a*) surface temperature T_S; (*b* and *c*) potential temperature θ on the lower ($\sigma = 0.75$) and upper ($\sigma = 0.25$) levels (numerals on the curves show deviations from 700°K); (*d* and *c*) gravity potential on level $\sigma = 0.75$ (deviation from $3.7 \times 10^4 m^2/sec^2$) and $\sigma = 0.25$ (deviation from $1.62 \times 10^5 m^2/sec^2$). Longitude is given on abscissa and latitude on ordinate. Letter *S* on bottom stands for latitude of the sub-solar point.

and spreads in the upper layer flowing to the cold region in the vicinity of which the air descends (Fig. 3). As was pointed out above, the typical wind velocity is about 5.5 m/sec (on the Earth it is about 10 m/sec, but on Venus the air is nearly 50 times denser, hence wind pressure is 10 to 15 times greater than usually on the Earth). Kinetic energy is the same in the northern and southern hemispheres, yet on the

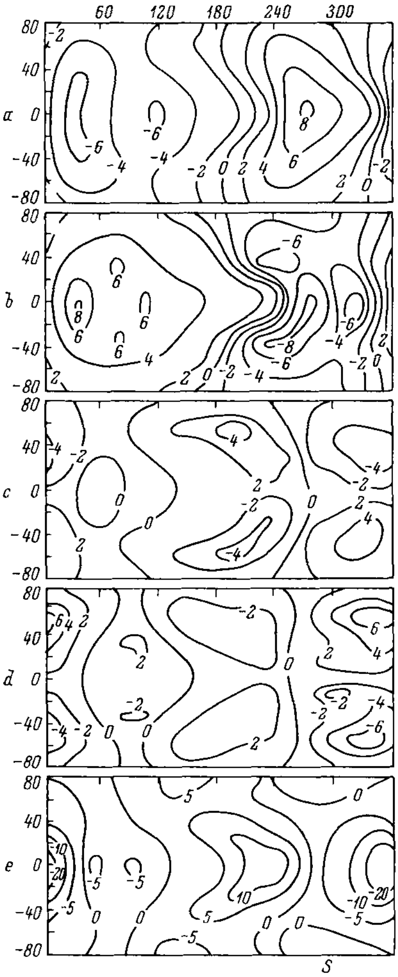

Fig. 3. Wind field on the 140th day. (*a* and *b*) latitudinal component; (*c* and *d*) meridional component in m/sec on the lower and upper levels; (c) vertical velocity analogue $\dot{\sigma}(10^7 \text{ sec}^{-1})$ on level $\sigma = 0.5$ (positive $\dot{\sigma}$ corresponds to descending motions, negative $\dot{\sigma}$ to ascending motions).

day side it is almost twice as large as on the night side (18 against 11 m^2/sec^2); the latitudinal motions contain almost two-fold higher energy than the meridional motions, The average zonal circulation is very weak—its energy is three orders lower than the energy of non-zonal motions. Intensive vertical motions are a peculiar feature of Venus' atmosphere. On the day side, the air, on the average, ascends, whereas on the night side it descends ($\dot{\sigma} \pm 10^{-7}$ sec^{-1}). Vertical velocity w has the maximum values of several centimetres per second. On the day side, the lower atmosphere is heated at a rate of 5.3×10^{-7} grad/sec by turbulence and at an order lower rate by radiation, whereas the upper atmosphere is cooled by radiation at a rate of 2.4×10^{-7} grad/sec. On the night side, local heat influxes are absent in the lower layer, and the upper layer is cooled at a rate of 3.4×10^{-7} grad/sec. All Venus' atmosphere is in a state of convective mixing: on the day side, this is caused by heating from below, and on the night side by cooling from above. Fig. 4 shows the zonal profiles of P_s, T_s, $\dot{\sigma}$ and E of both north–south orientation (solid lines, north is in top) and solar–antisolar orientation (dashed lines, the sun is on top). Symmetry about the equator is clear-cut with T_s and E (and also θ and Φ at both levels) maxima at the equator and their minima in high latitudes, and with $\dot{\sigma}$ maxima and minima of the reverse location. Fig. 5 presents a succession of atmospheric pressure P_s charts for the near-ground region of the planet at different moments of the Venus' day. On all the charts, pressure distribution with respect to the terminator is basically constant. The centre of the high pressure region is in the vicinity of the morning terminator; whereas the low pressure centre lies between the sub-solar point and the evening terminator (this shift is attributed to high heat inertia of the atmosphere). Some of the charts reveal weaker secondary centres east of the basic pressure extrema. As the planet rotates these secondary centres gradually increase and become to act as the basic extrema (the former extrema become weaker and disappear altogether). A typical period of such evolution lasts nearly 50 Earth days.

Apart from the described computations, a numerical experiment was also made at $N = 80$ points on a sphere with a two-level model in which all short-wave radiation was absorbed in the upper layer and no hot-house effect was observed (if not to speak of the vertical resolution, radiation fluxes in a two-dimensional model of R. Goody and A. Robinson (1966) were computed in such a way). The fetch of the atmosphere lasted there approximately the same period, and kinetic energy came to somewhat lower equilibrium level of 11 m^2/sec^2 with an opposite but lesser difference between the day and the night sides of the planet (10 against 12 m^2/sec^2). The average surface temperature T_s on the day side was 0.4° lower than on the night side, however

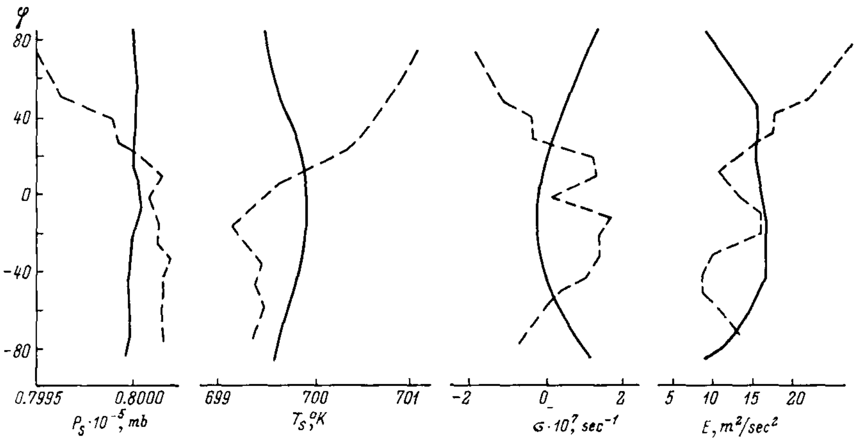

Fig. 4. Zonal profiles of pressure P and temperatures T_s at Venus' surface, vertical velocity $\dot{\sigma}$ and kinetic energy E. Solid lines: north–south; dashed lines: day–night.

the entire atmosphere on the day side was 0.1° warmer. The air ascent on the day side and its descent on the night side were, on the average, the same as those in the hot-house model. Equatorial extrema are also found here in the zonal profiles of P_s, T_s and $\dot{\sigma}$. The meteorological maps were not symmetrical with respect to the solar–antisolar axis (though the disturbances of

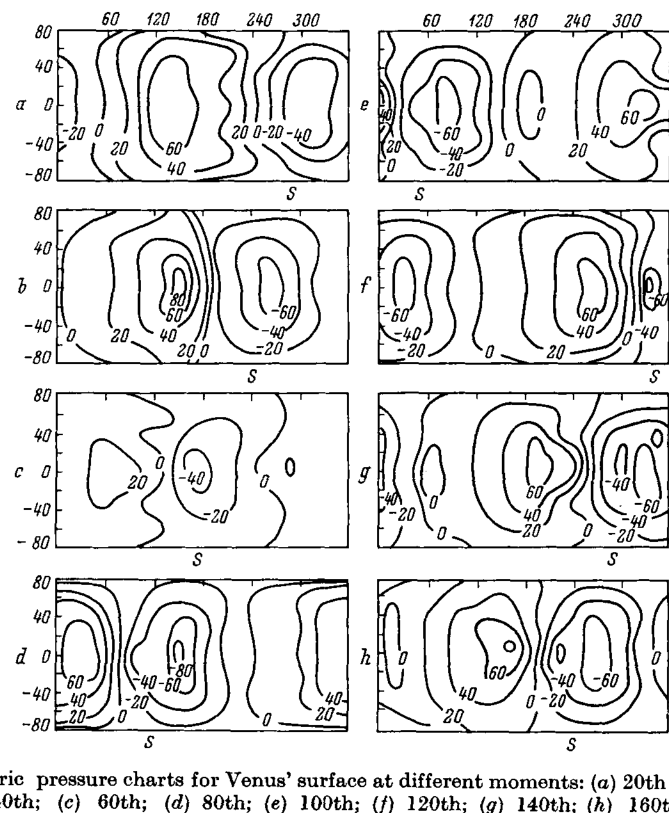

Fig. 5. Atmospheric pressure charts for Venus' surface at different moments: (*a*) 20th day of the numerical experiment; (*b*) 40th; (*c*) 60th; (*d*) 80th; (*e*) 100th; (*f*) 120th; (*g*) 140th; (*h*) 160th. Numerals on the curves show P_s deviations from 80 000 mb.

symmetry were somewhat smaller than in the hot-house model).

It is interesting to compare the obtained results with the similarity theory developed by G. S. Golitsyn (1970) for large-scale motions of planetary atmospheres. The so-called "coefficient of use" whose value for Venus' atmosphere is unknown appears in this theory. If this coefficient is assumed to be as that for the Earth's atmosphere, estimates by G. S. Golitsyn's equations yield typical wind velocity of about 1.5 m/sec and typical temperature difference on the planet's surface of nearly 2°. Thus even without special selection of the coefficient of use, predictions of the similarity theory are in rather good agreement with the results of the numerical experiments.

The general conclusions can be summarized as follows. *According to the computations of Venus' atmosphere, the major temperature differences do not occur between the equator and the poles but between the day and the night hemispheres (a result of the slow rotation of the planet). However the heat inertia of the atmosphere is very large, and the average temperature on the day side is only several tenths of a degree higher than on the night side. Temperature range at the planet's surface is several degrees. On the day side, the air for the most part ascends and on the night side it descends at a rate of several centimetres per second. The typical wind velocity is close to 5 m/sec. Circulation is almost symmetrical about the equator, however it has no axial symmetry. Unlike the Earth's atmosphere, Venus' circulation is of a global character, i.e. it is not disturbed by atmospheric eddies of the types of cyclones and anticyclones.* The above-mentioned general features are evident in both radiation models; these features may be considered reliably established. Smaller details depend, of course, on the peculiar distribution of radiation heat influxes. The hot-house radiation model can probably be considered more realistic.

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ЧИСЛЕННЫЕ ЭКСПЕРИМЕНТЫ ПО ОБЩЕЙ ЦИРКУЛЯЦИИ АТМОСФЕРЫ ВЕНЕРЫ

На основе примитивных уравнений (двуслойная модель) проведён ряд численных экспериментов по общей циркуляции атмосферы Венеры. Парниковая модель радиационного режима, так же как и модель Гуди и Робинсона дают сходные результаты: главные температурные различия (порядка 1°C) имеют место между дневным и ночным полушариями, на дневной стороне воздух поднимается, на ночной — опускается со скоростью порядка нескольких сантиметров в секунду, типичная скорость ветра близка к 5 м/сек, циркуляция не затушёвана крупномасштабными вихрями.