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DYNAMICS OF PLANETARY ATMOSPHERES

NAGW-58
(Continued under grant NAGW 1956)

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July 1979 - November 1989

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I. SUMMARY

This is the final report of grant NAGW-58 under NASA's Planetary Atmospheres program. The Principal Investigator (PI) is now receiving support from the same program under grant NAGW-1956.

The overall goal is to illuminate the mechanisms that control weather and climate on the Earth and other planets. Each planet presents its own puzzling behavior - the stability of jets and vortices in Jupiter's otherwise turbulent atmosphere, the superrotation of the Venus atmosphere, the interplay of dust, polar volatiles, and climate change in Mars, the supersonic meteorology of Io, and the counterintuitive equator-to-pole temperature gradients on the outer planets. The data sets are generally those obtained from spacecraft - cloud-tracked winds, radiometrically inferred temperatures, and the results of *in situ* observations where appropriate. The approach includes both data analysis and modeling, ranging from analytic modeling to time-dependent numerical modeling of atmospheric dynamics. The latter approach involves the use of supercomputers such as the San Diego Cray. Progress is generally made when a model with a small number of free parameters either fits a data set that has a large number of independent observations or applies to several planets at once. I believe in comparative planetology, and hope to make it work.

II. ACTIVITY IN 1988-89

A. Personnel 1988-89

Andrew P. Ingersoll, P.I., part-time
Timothy E. Dowling, graduate student
Richard K. Achterberg, graduate student
Stephen S. Leroy, graduate student
M. Alex Santoso, undergrad
Allen Price, undergrad

B. Significant Accomplishments

Tim Dowling received his Ph.D. in November 1988 for his thesis entitled, "A Dynamical Study of Jupiter's Great Red Spot." The data analysis used cloud-tracked winds from Voyager images to infer the shape (topography) of constant pressure surfaces below the clouds and hence the underlying zonal velocity profile. The numerical modeling used the shallow water equations and the inferred topography to study the formation, stability, and kinetic energy budget of the large vortices and the zonal shear flow at cloud- top level. Two papers (Dowling and Ingersoll, *J. Amos. Sci*, **45**, 1380, 1988; ibid., *J. Atmos. Sci.*, **46**, 3256, 1989) published on this work.

Rich Achterberg and Ingersoll have developed a 3-dimensional numerical model of deep planetary atmospheres such as Jupiter's (Achterberg and Ingersoll, *J. Amos. Sci.*, **46**, 244, 1989). That model provides a quantitative recipe, using the vertical normal modes of the quasi-geostrophic system, for including the effects of the deep atmosphere in three-dimensional studies of motions at cloud-top levels. Alex Santoso has added small-scale forcing and viscous dissipation to the numerical model.

Allen Price has developed flow visualization techniques so that we can make motion pictures (movies) of the formation, merging and destruction of simulated vortices.

Ingersoll has developed an analytic model for the supersonic flow of SO_2 in Io's atmosphere (Ingersoll, *Icarus*, **81**, 298, 1989). The main conclusion is that each 100-km patch of surface determines its own atmospheric pressure through a combination of sublimation effects and volcanic venting. This work resolved a controversy between the P.I. (Ingersoll et al., *Icarus* **64**, 375, 1985) and Moreno, Schubert, Kivelson, et al.. (*Icarus,* 1988) who claimed that global volcanic atmospheres are possible.

Ingersoll contributed to a chapter (Michael Allison is lead author) on the "Uranus Atmospheric Dynamics and Circulation" for the book *Uranus* (J. Bergstrahl and E. Minder, Eds., 1989). Ingersoll also prepared a chapter "Atmospheres of the Giant Planets" for the Third Edition of *The New Solar System* (J.K. Beatty, et al.., 1989).

III. ACTIVITY BEFORE 1989

A. Jupiter and Saturn Studies

Ingersoll has been a major proponent of the theory that Jupiter's and Saturn's atmospheres owe their axisymmetric appearance, longevity of flow features, and multiple high-speed jets to convective motions in the fluid interior (Ingersoll and Pollard, *Icarus* **52**, 62, 1982). Figure 1 shows what might be going on beneath the visible clouds of Jupiter and Saturn. The zonal flow could decrease to zero at the base of the clouds only if the cloud layer were stably stratified. But if the cloud layer and interior were adiabatic, then the zonal motions would have to extend down as differentially rotating cylinders right through the planet (Fig. 1, right). Busse (*Icarus*, **29**, 255, 1976) suggested that convection cells, which have a columnar form (Fig. 1, left) in a rotating sphere, could maintain the differential rotation, the whole thing driven by the heat released as the planet cools.

Ingersoll and Pollard (1982) showed three things about deep-sphere models: (1) the mechanical dissipation associated with differentially rotating cylinders is compatible with the internal heat source; (2) the departures from adiabaticity associated with internal convection are not so large as to be incompatible with a cylindrical velocity structure; (3) the adiabatic cylinder flow is stable when u_{yy} is less than about -3*beta.

Ingersoll and Miller, (*Icarus*, **65**, 370, 1986) extended the stability analysis to deep barotropic flows and to perturbations that have short longitudinal wavelengths. Figure 2 shows the growth rate contours for the cos(y) jet, for perturbation wavelengths ranging upward from less than the jet width to much greater than the jet width. Except in the latter extreme, the perturbation has structure in all 3 coordinates (r,θ,z), and is separable only in the azimuthal direction θ. Generating the figure required solving for the eigenvalues of a matrix N*M on a side, where N and M are the number of degrees of freedom in cylindrical radius r and axial coordinate z, respectively.

Ingersoll and Cuong (*J. Atmos. Sci.*, **38**, 2061, 1981) have a non-linear, time-dependent numerical model that produces stable isolated vortices in a Jovian-type shear flow. The vortices survive large perturbations, and grow by merging with other vortices (Figure 3). Both large and small vortices (5000 to 500 km) are stable. The essential feature of the model that allows the vortices to exist in a zonal shear flow in the deep adiabatic layer underneath the vortices. Figure 4 shows results of the time-dependent model of Dowling and Ingersoll (*J. Atmos. Sci.*, **46**, 3256, 1989).

MacLow and Ingersoll (*Icarus*, **65**, 353, 1986) studied the 58-day Jupiter movie based on Voyager 2 cylindrical projection mosaics. They found isolated vortices at all size ranges down to 500 km (major diameter) in contrast to the larger vortices described by Williams and Yamagata (*J. Atmos. Sci.* **41,** 453, 1984). The mode of interaction between two vortices is merging, in contrast to the solitary wave interaction described by Maxworthy et al. (*Icarus*, **33,** 388, 1978).

B. VENUS STUDIES

A major unsolved problem in planetary atmospheres is to identify and understand the balance of torques that maintains the Venus superrotation. The work of Pechmann and Ingersoll (*J. Atmos. Sci.*, **41**, 3290, 1984) establishes that the mean tidal heating and mean tidal accelerations are large and cannot be neglected. However the sign of the net torque due to the tidal eddy stresses and the tidally-induced mean meridional circulation is not monotonic, but changes sign with altitude at least once per scale height. This statement is based on the model that was best in fitting the Pioneer Venus data. It is not known whether perturbed models (with slightly different zonal velocity profiles, static stabilities, damping and heating profiles) would yield essentially similar results or not. Yet the question is important, for only by testing the stability of the observed zonal velocity profile with tides will one be sure that tides could maintain the Venus superrotation.

The VEGA Venus Balloon mission in June, 1985 (*Science,* **231,** 1407-1425, 1986, 7 papers) revealed a number of new facts about the atmosphere within the convective clouds at 53 to 53 kilometers altitude. Crisp and Ingersoll participated in that mission and the data analysis (see publication list). The vertical velocity of the atmosphere turned out to be large -- up to 3 m/s in bursts lasting for several hours (Linkin et al., *ibid.*, p. 1417). The horizontal temperature differences over a period of 4 days also turned out to be large -- about 6.5K (Linkin, et al., *ibid.*, p. 1420). Finally, the fluctuations in zonal velocity as revealed in Doppler radio data were large -- 60 m/s, which is comparable to the mean zonal velocity itself (Preston et al., *ibid.*, p. 1414). The Venus atmosphere is very active at these altitudes. A recent time series analysis (*Adv. Space Res.*, in press, 1987) by Ingersoll, Crisp, Grossman, and the VEGA Balloon Science Team reveals upward convective heat fluxes in the range 0 to 100 Wm^{-2}, despite the stable lapse rates (static stabilities in the range 0 to 1.0 K km^{-1}). The co-spectrum of vertical velocity and temperature has most of its power below 0.3 10^{-3} Hz. The cross-spectrum (associated with 90 phase differences between the two variables) could be associated with gravity waves, but the signal is not statistically significant.

C. SATURN, URANUS, AND NEPTUNE STUDIES

Ingersoll and Porco (*Icarus*, **35**, 27, 1978) published a time dependent thermal model showing how the interior adjusts its radial and meridional heat fluxes and temperatures in response to surface solar heating and infrared cooling. Results for a non-oblique planet (Jupiter) were presented. Two modifications were necessary for comparison with Saturn and Uranus. first, seasonal effects had to be incorporated, in effect by making the model time-dependent. Second, horizontal heat transfer in the sunlit atmosphere had to be included. The latter modification allows us to treat planets like Uranus, whose internal heat source is insufficient to make up for the radiative imbalances at the top of the atmosphere.

Friedson and Ingersoll (*Icarus*, **69**, 135, 1987) recently published the results of this study, for comparison with the pole-to-pole temperature profile observed by Voyager IRIS at Uranus. The general lack of thermal contrast (~1.5K) in the model agrees with observation, but details of the observed profile (e.g. the mid-latitude temperature minima in north and south hemispheres) could not be explained. Ingersoll participated in the Uranus encounter as chairman of the Voyager Atmospheres Working Group and member of the Imaging Science Team (Smith et al., *Science*, **233**, 43, 1986; see also Ingersoll, *Sci. American*, **255**, 38, Jan. 1987).

D. Io STUDIES

Ingersoll, Summers and Schlipf (*Icarus*, **64**, 375, 1985) have a hydrodynamic model of very thin planetary atmospheres. In the model, a volatile surface frost (SO_2) sublimates on the sunlit side, flows toward the terminator at supersonic speed, and turns into a free molecular flow as the molecules stick to the cold surface on the dark side. Thus an atmosphere only exists on the sunlit side. This a natural extension of atmospheric behavior at pressures below that on Mars, where condensation affects atmospheric mass on a seasonal time scale but not on a daily time scale.

The dynamics of this supersonic flow is novel, since it takes place in a compressible gas that is hydrostatically supported by a solid surface. Thus any discontinuity is part hydraulic jump and part compressional shock wave. Besides its intrinsic interest (a supersonic general circulation is new in atmospheric science), the model calculations should provide good estimates of the relation of SO_2 migration, frost temperatures, and global resurfacing rates. Definite predictions for SO_2 column densities at the time of Galileo can be made.

To date the model has been run only for the axisymmetric case, in which the surface is covered by an SO_2 frost with prescribed temperature that falls off smoothly from the subsolar point. Atmospheric density, pressure, and mass transport are proportional to the frost vapor pressure, which is a sensitive function of temperature. More complicated two-dimensional cases that include the measured distribution of SO_2 frost and frost temperature over the surface (McEwen et al., submitted to *Icarus*, Nov. 1987) have not been run. Nor has the subsurface cold trapping model (Matson and Nash, *J.G.R.*, **88**, 4771-4783, 1983) been included as a lower boundary condition. Finally, the photochemistry and spatial distribution of species in a supersonic atmosphere have not been considered. These are the nest steps in any effort to model the meteorology of Io.

E. MARS STUDIES

Paige has been using Viking Infrared Thermal Mapper (IRTM) data (1) to study the heat balance of the Martian poles and the implied mass balance of the CO_2 frost throughout the year, (2) to deduce the albedo of the frost at the surface from radiation data, (3) to understand the north-south asymmetry (permanent CO_2 frost only at the south pole), (4) to estimate the advective heat transport to the poles by the atmosphere.

Understanding the current behavior of the CO_2 caps is essential if one is going to model past climate change on Mars and polar layered terrain. Paige received his Ph.D. on this work. A paper, "Heat Budget of the Martian Polar Regions", by Paige and Ingersoll has been published (*Science*, **228**, 1160-1168, 1985).

The key difference between the north and south is the higher reflectivity of the southern cap in spring compared to the reflectivity of the northern cap in spring. this difference might be due to greater amounts of dust on the northern cap, but the remarkable reproducibility of the seasonal pressure curves from dusty years to clear years suggests a more fundamental mechanism. Paige's data analysis suggests that the intensity of sunlight (the south has a shorter, more intense spring and summer) leads to annealing of the frost and a higher albedo. This idea has profound implications for the climate of Mars by reducing the sensitivity to orbital forcing.

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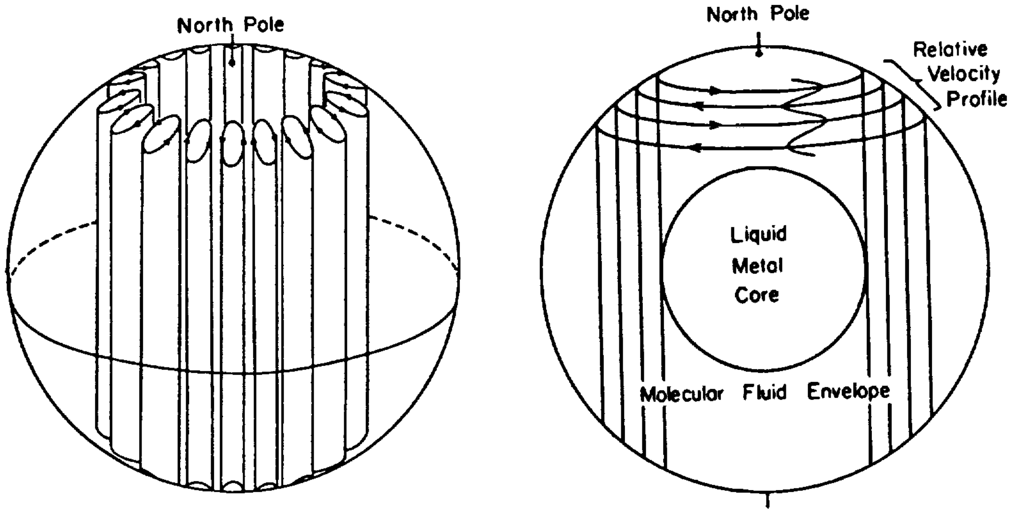

FIG. 1. Columnar convection cells (left) and cylindrical zonal flow (right). As shown by Busse (1976), the columnar mode is the preferred form of convective instability in a uniformly rotating, viscous, conducting fluid. The cylindrical mode is the most general form of steady zonal motion in an inviscid, adiabatic fluid. The interaction of these two modes is analogous to the behavior of transverse convective disturbances in a sheared horizontal layer described by Lipps (1971).

Fig. 1

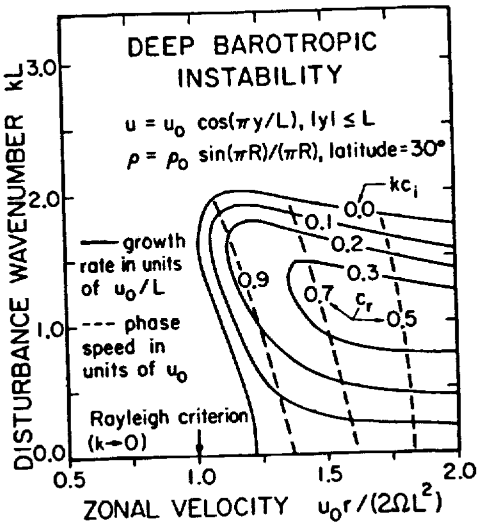

FIG. 2. Growth rates and phase speeds of disturbances on the cosine jet. Here y is distance inward from the cylinder of radius r_0. The cylinder meets the surface of the sphere at latitude 30°. Density ρ depends on the spherical radius R, with $R = 1$ and $\rho = 0$ at the planet's surface. The eastward wavenumber of the disturbance is k, and the half-width of the jet is L. The arrow labeled Rayleigh criterion indicates the onset of deep barotropic instability when sidewall effects are unimportant and $kL \rightarrow 0$; this criterion was originally derived by Ingersoll and Pollard (1982) for deep spheres.

Fig. 2

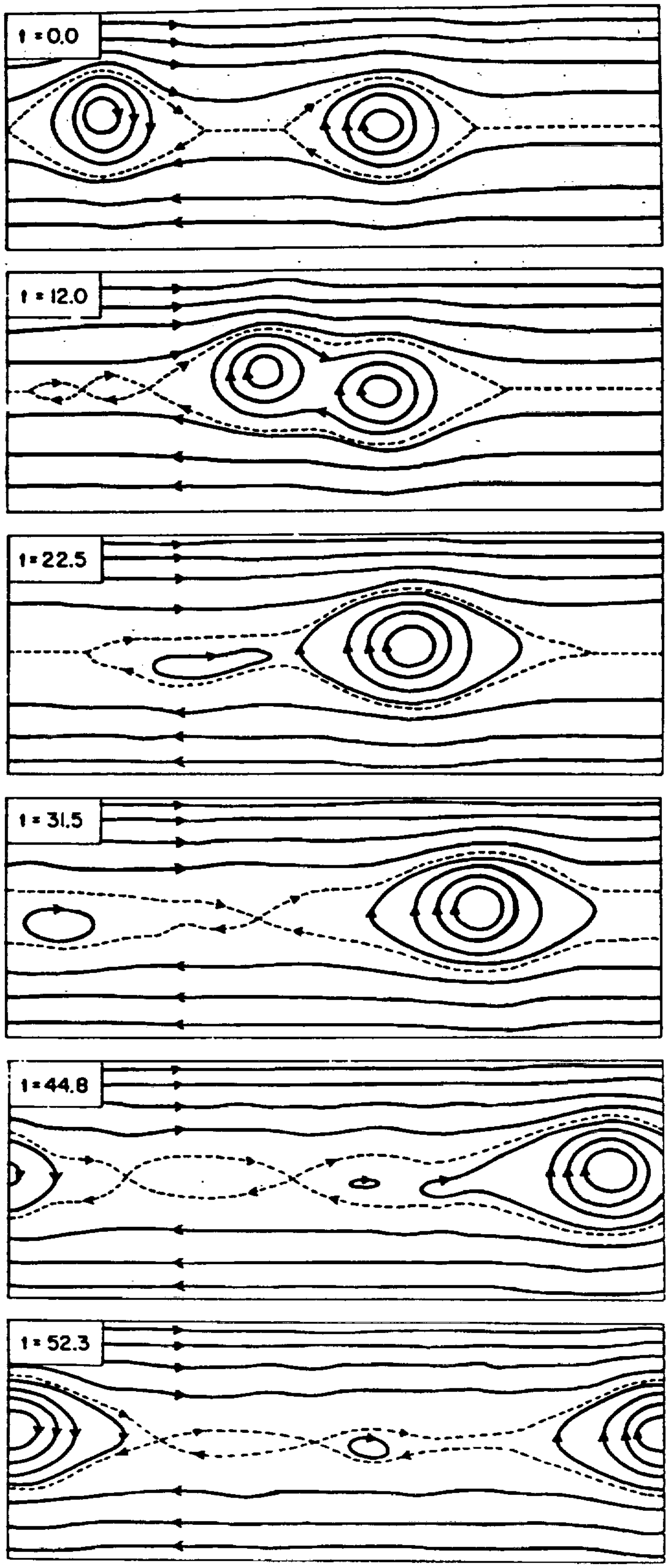

Fig. 3

FIG. 7. Interaction of vortices for $k^2 = 10$. Because the solution is periodic in x, the two vortices that appear to be moving apart at $t = 22.5$ and $t = 31.5$ then collide, causing a smaller vortex to form at $t = 44.8$. Eventually, the large vortex sweeps up all the smaller vortices and the flow is steady.

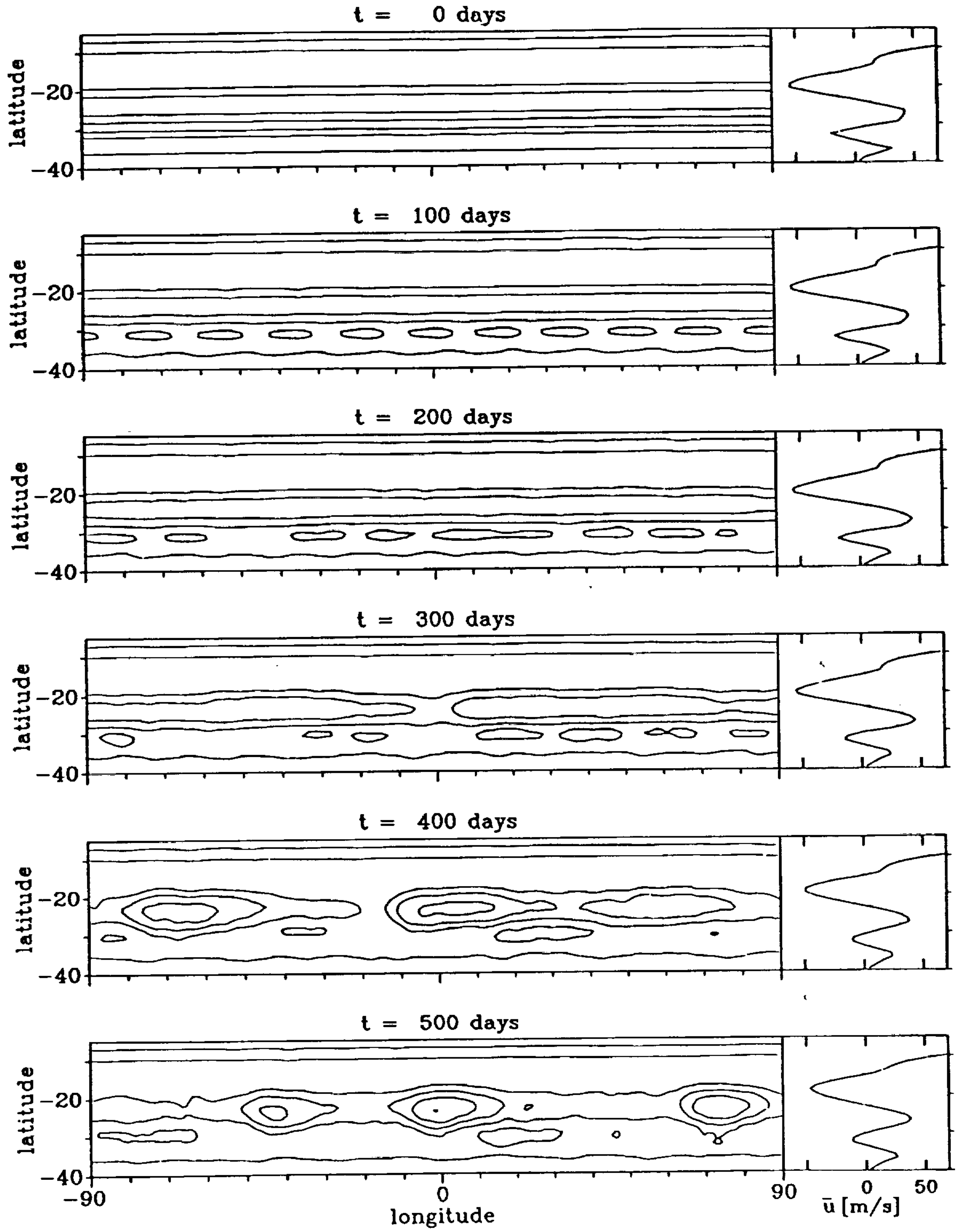

FIG. 17. Genesis experiment. The initial state is constructed by adding a small sinusoidal perturbation of ten wavelengths, in a $\mathrm{sech}^2(\phi/90°)\ \sin^{1/2}(-\pi(\lambda + 5°)/35°)$ envelope, to the free-surface height $g(h + h_2)$ calculated from the cloud-top zonal wind profile (Fig. 4). This envelope brings the perturbation of the northward velocity v to zero at the northern and southern boundaries ($\lambda = -5°, -40°$), and adds a slight longitudinal height difference to the initial ten waves. The specified parameter q_0 is -1.40×10^{-9} s m^{-2} for the GRS. The zonal wind is forced with $\tau = 400$ d. The peak initial perturbation velocity is 1.6 m s^{-1}, compared to the 54 m s^{-1} peak initial zonal wind. By $t = 500$ days, there are three large, distinct vortices in the GRS's shear flow. By $t = 750$ days, two of these vortices have merged, and by $t = 1600$ days, only one large vortex remains. This vortex is run through $t = 2000$ days. Even though the initial conditions are vastly different for the run shown here and the run shown in Fig. 16, the final forms are quite similar.

Fig. 4(1)

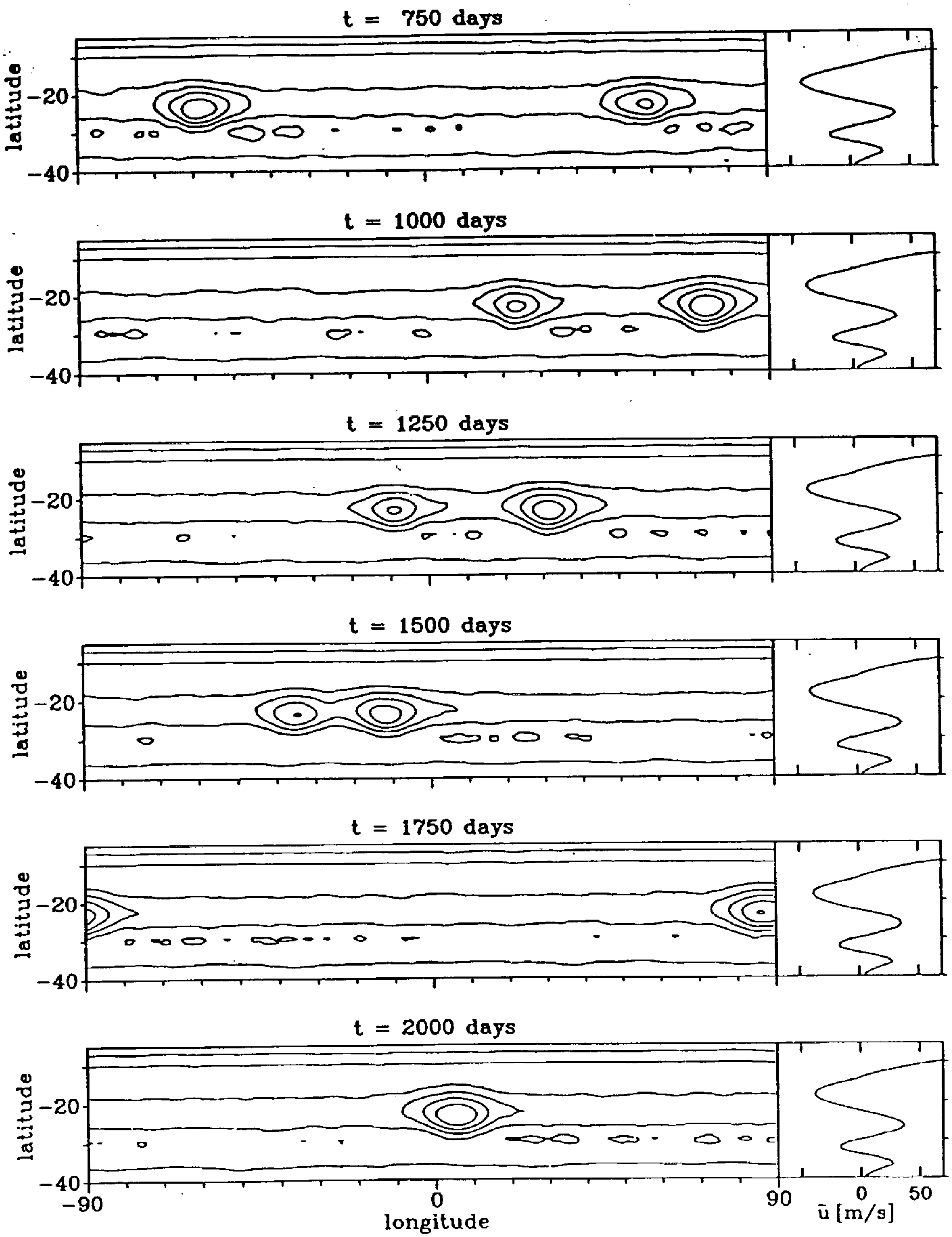

FIG. 17. (*Continued*)

Fig. 4(2)