The atmospheres of the inner planets

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Current knowledge of the atmospheres of Mercury, Venus, Earth and Mars is reviewed, under the headings of composition, thermal structure, clouds, dynamics, weather and climate, and aeronomy. Some recent observational or theoretical work shows common processes at work, others pose fundamental problems requiring new research including space missions. The overall problem remains to understand the origin and evolution of the planets, and the stability of their atmospheres and the surface environment or climate which they control. The latter depends on a complicated and still quite poorly-understood balance between radiative, dynamical and chemical processes.

THE inner Solar System contains a family of four planets of moderate size (compared to the asteroids and comets on one hand, and the gas giants of the outer Solar System on the other), with rocky surfaces, and interiors which contain large abundances of heavy elements such as iron and nickel. Their atmospheres are thin, but, with the exception of Mercury, they have a profound influence on the conditions prevailing at the surface.

The evolution, present state and detailed behaviour of these planets and their atmospheres are of great practical as well as scientific interest. As inhabitants of the Earth, we have reason to be extremely concerned about our ignorance of the fragile environment surrounding us, which is strongly influenced by atmospheric behaviour, which is known to be changing as a result of natural and anthropogenic perturbations, although the magnitudes and precise nature of the changes still cannot be reliably predicted. Some aspects of the problems which we face on Earth are mirrored in the powerful, 'runaway' greenhouse effect on Venus, or the deserts of Mars, which once had free water if we are interpreting the apparent geological record correctly.

Much of what is now known about the Solar System, including to some extent the Earth itself, is the result of unmanned space exploration during the last three decades, and the investigative techniques that are slowly becoming advanced enough that common processes arising from the universal physical laws can sometimes be seen at work. However, some cases are found where the planets do not seem to have shared a unified history within the early solar system, or where they do not seem to be behaving in the way one would expect when the differences in boundary conditions have been taken into account. It is fairly safe to assume that most of these mysteries are due to inadequate observations or shortcomings in our understanding of global scale atmospheric processes, rather than uniqueness of some kind in the origin or history of a particular planet, although these may occur too. In a few cases (such as the slow retrograde rotation of Venus or the ancient climate of Mars) we are led to suspect that there are things about the way our planetary neighbours, and by implication our own world, have evolved about which we know almost nothing.

Basic statistics

The inner planets orbit the sun at distances of 57.9, 108.2, 149.6, and 227.9 million kilometres respectively (Table 1). The orbits of Earth and Venus are nearly circular, those of Mercury and Mars significantly eccentric. The biggest single factor affecting surface and atmospheric conditions on any planet is the sunfall; Venus receives almost twice as much energy per unit area as Earth and nearly four times as much as Mars. However, by an interesting example of atmospheric feedback processes at work, all three planets have developed reflective cloud coverings, and in the case of the two outermost, reflective ice-covered regions, to such an extent that the solar energy actually absorbed is not very different, with Earth retaining the most and Mars second. It is intriguing to note that the surface conditions on frozen Mars and baking Venus are both sustained by roughly equal amounts of net heating, due entirely to differences in their atmospheres.

On Mercury, the intense solar heating together with the relatively low surface gravity means that even the heavier atmospheric gases can escape, and the present-day atmosphere is a very tenuous and transient affair. It appears to consist primarily of sodium (probably baked out of surface and near-surface minerals), and helium, probably of solar origin and temporarily trapped from the solar wind by the planet. The total surface pressure is estimated from ultraviolet spectrometer measurements to be less than a trillionth of that on the Earth; it does not, therefore, show any of the familiar atmospheric phenomena such as clouds or dynamical systems which are found on the other three inner planets.

The solid bodies of Venus and Earth are of nearly identical size and density and probably fairly similar in

Table 1. Physical constants for the terrestrial planets

	Mercury	Venus	Earth	Mars
Orbital and rotational data				
Mean distance from Sun (km)	$5\ 79 \times 10^{7}$	$1\ 082 \times 10^{8}$	$1\ 496 \times 10^{8}$	$2\ 279 \times 10^{8}$
Eccentricity	0 2056	0 0068	0 0167	0 0934
Obliquity (deg)	0	177	23 45	23 98
Sidereal period (days)	87 97	224.701	365 256	686 980
Rotational period (hours)	1407 5	5832 24	23 9345	24 6229
Solar day (days)	115 88	117	1	1 0287
Solar constant (kW m^{-2})	See text	2 62	1 38	0 594
Net heat input (kW m^{-2})	See text	0.367	0 842	0 499
Solid body data				
Mass (kg)	$3\ 302 \times 10^{23}$	$4\ 870 \times 10^{24}$	$5\ 976 \times 10^{24}$	$6\ 421 \times 10^{23}$
Radius (km)	2439	6051 5	6378 to 6357	3398
Surface gravity (m s^{-2})	3 70	8 60	9 78	3 72
Atmospheric data				
Composition	He, Na	See Table 2		
Mean molecular weight	–	43 44	28 98 (dry)	43 49
Mean surface temperature (K)	~ 400	730	288	220
Mean surface pressure (Nm^{-2})	$< 10^{-12}$	92	1	0 007
Mass (kg)	–	$4\ 77 \times 10^{20}$	$5\ 30 \times 10^{18}$	$\sim 10^{16}$

bulk composition. Mars is considerably smaller, with a diameter a little more than half that of the other two. Concentrating on surface features which have an important effect on the atmosphere, the principal things to note are the extreme topography on Mars with its high volcanic mountains and deep canyons, particularly in relation to its overall smaller size. Olympus Mons is more than three times as tall as Everest and more than twice as high as Maxwell, these being the highest features on Earth and Venus respectively. Parts of the Valles Marineris are nearly four times as deep as the Grand Canyon of Arizona, while the canyons in the Ishtar region of Venus are midway between the two. All four inner planet surfaces are modified by volcanism; some of the volcanoes on Earth and probably some of those on Venus are still active. Earth's surface is remarkable for its extensive coverage of liquid water; on Mars the pressures and temperatures are too low, though there is probably a lot of frozen water in the polar caps and below the surface soil at other latitudes. Venus and Mercury are too hot for liquid water but the atmosphere of Venus contains small (by terrestrial standards, if the oceans are included) amounts of water as vapour and incorporated in the clouds as sulphuric acid and possibly other hydrated material. A particular property of Mars is that the principal constituent of the atmosphere, carbon dioxide, is caused by the low temperatures to condense at the winter pole during the period of perpetual darkness. Billions of tons of the gas leave the atmosphere as snow in the winter, to evaporate when the spring comes, resulting in a large swing of nearly a third in the mean surface pressure all over the planet. This has a dramatic effect on the general circulation which is as yet little studied in the absence of the necessary comprehensive observations, some of which may be gained from Mars Observer and other new missions in the 1990s.

Next to the solar heating, and the degree of availability of large reservoirs of volatiles, the most important atmospheric boundary condition is the rotation rate of the solid planet. Mars and Venus have almost the same period, and hence the same length of day. Venus, curiously, rotates in the retrograde sense, i.e. east to west, and very slowly, only once every 243 days. This is remarkable because the planet's angular momentum vector is in the opposite sense to those of the other planets and the Sun (Uranus and Pluto are also anomalous in having their rotation axes close to the ecliptic plane), which is inconsistent with any simple theory of the origin of the Solar System. The fact that Venus rotates slowly has a profound effect on its atmospheric circulation and, through its effect, or lack of effect, on the global cloud cover, its surface climate.

The inclination of the planetary rotation axis, and the eccentricity of the orbit, give rise to the seasons. Like Mercury, Venus has nearly equal values for each parameter from which only very small sun-driven seasonal changes would be expected. Mars, at the other extreme, has a fairly large axial tilt (or 'obliquity') of 24 degrees and enough eccentricity to change the solar constant by as much as 18% during the year. Earth has almost the same obliquity as Mars and a smaller, but still significant, eccentricity of 0 0167.

Table 2. Composition of the terrestrial planet atmospheres

	Venus	Earth	Mars
Carbon dioxide	0.96	0.003	0.95
Nitrogen	0.035	0.770	0.027
Argon	0.00007	0.0093	0.016
Water vapour	~0.0001(?)	~0.01	~0.0003
Oxygen	0.21	0.0013	~0
Sulphur dioxide	0.00015	0.2 ppb	~0
Carbon monoxide	0.00004	0.12 ppm	0.0007
Neon	5 ppm	18 ppm	2.5 ppm

Values are given as fractional abundances or parts per million (ppm)

Finally, the year, or time taken to orbit the Sun once, naturally varies with heliocentric distance and is 87.97 days for Mercury, 224.7 days for Venus, 365.3 for Earth and 687.0 days for Mars. These units are Earth days; this makes little difference for Mars where the length of day is only about 37 minutes longer than Earth but the rotation period of Venus is in fact *longer* than the Venusian year. The solar day, i.e. the time for the Sun to go from noon to noon as seen from the surface of Venus, is about 117 (Earth) days. The atmosphere rotates much faster than this at some levels, for example once every four to five days near the cloud tops.

Composition

The atmospheric composition is not the same on each of the inner planets, nor should we expect it to be. Many factors are at work, of which the principal are:

(i) Gradients in the composition of the solar nebula from which the planets condensed,

(ii) Different escape rates for gases leaving the planet, as a result of the different rates of heating of the upper atmosphere, and the differences in gravitational attraction,

(iii) Physical and chemical processes which depend directly or indirectly on distance from the Sun and which govern the exchange of material between the atmosphere and the crust; life on the surface of Earth is a special case of this.

It is thought that the primary atmospheres of all four planets (i.e those that formed with the solid bodies themselves) have been lost in the distant past and that the present atmospheres (Table 2) are *secondary*, that is to say produced by outgassing from the crust or by influx of cometary and meteoritic material. The commonest gases which might accrue in this way are carbon dioxide, water vapour and nitrogen. The amounts of each, and the admixture of other gases, depend on the initial composition of each planet and its subsequent evolution, particularly its thermal history. Moderately large amounts of some gases, such as argon, are produced by the decay of radioactive materials and form a significant component of the present day atmospheres of Venus, Earth and Mars. A tentative detection of small amounts of formaldehyde in the Martian atmosphere has recently been reported by investigators on the Russian Phobos mission.

It has already been noted above that its high surface temperature and relatively low gravitational field prevents Mercury from retaining more than a trace of secondary atmosphere.

A comprehensive and still up-to-date summary of present knowledge about the composition of Venus's atmosphere, plus an account of how the data were obtained, have been given by von Zahn *et al.*[1]. The abundances derive mainly from mass spectrometer and gas chromatograph measurements made on the Pioneer Venus and Venera descent probes. The corresponding source article giving the basis for our current understanding of the composition of the Martian atmosphere is that by Owen *et al.*[2]. In this case the information comes primarily from the Viking landers, which were also equipped with gas chromatographs and mass spectrometers.

The measured abundances provide a constraint for theoretical studies of the formation and evolution of planetary atmospheres (for a review, see Pollack and Yung[3]). Such studies often lead to a model of the atmospheric composition which may explain or predict the abundances of the various species by calculations based on the known or assumed history of conditions on the planet and a knowledge of the physical chemistry involved[4]. In general the models agree (or can be made to agree given some reasonable assumptions) with the observed composition of the terrestrial planet atmospheres tolerably well, and they serve to highlight difficult problems such as the low abundance of atmospheric water vapour on Venus and Mars and the anomalous distribution of rare gas isotopes among all three planetary atmospheres.

Venus has between ten and one hundred thousand times less water in its atmosphere than exists in the oceans and atmosphere of the Earth[5]. The fact that, at the same time, deuterium is about one hundred times more abundant on Venus than Earth[6] suggests that Venus had much more water initially, but that most of it has been lost since. The loss processes involve dissociation to form hydrogen and oxygen followed by escape from the planet of hydrogen, a process which depends strongly on the abundance of water in the middle atmosphere. According to Kasting *et al*[7], Venus could have lost an ocean of present-day terrestrial proportions in less than five hundred million years. These authors also suggest a reason why the D/H ratio on Venus is only greater by 100 than that on Earth. It would be much larger if all of the deuterium in the primordial Venusian ocean had been retained. However, deuterium as well as hydrogen can escape from the atmosphere when there is free water on the surface, if the UV heating of the upper atmosphere is sufficiently intense. Once the free water is all gone, the mixing ratio of vapour in the upper atmosphere falls and fractionation of the two isotopes becomes more pronounced. In Kasting *et al.*'s model, with the simplifying assumptions that all of the deuterium is lost until the last of the ocean evaporates and then none thereafter, the predicted enhancement is almost exactly that observed. These authors further point out that an extensive ocean on Venus would facilitate the disposal of the oxygen produced by water vapour dissociation. This cannot escape, and would have to be bound chemically in the crust. Most of the weathering processes by which this occurs on Earth involve liquid water.

Mars has an extremely low abundance of atmospheric water vapour, because of the temperatures which are so low that even saturated air has a low absolute humidity. Again it seems likely that this was not always the case, since many of the surface features on Mars were apparently shaped by liquid water. The low temperatures now prevailing there have locked some of the water permanently in the polar caps and, probably, much of the rest as 'permafrost' below the surface at most other latitudes. Since we cannot measure or even estimate accurately how much water exists as ice on Mars at present, it is not possible to say whether the total budget is anomalous, like that of Venus seems to be. Obtaining measurements of polar and sub-surface water on Mars remains one of the most important objectives for future planetary exploration.

The deuterium to hydrogen ratio cited above is an example of how isotopic ratios for a given chemical element can give important clues about atmospheric evolution. Another interesting case is that of the noble gases argon, krypton, neon and xenon. These are all both heavy (hence not prone to escape) and inert (hence not prone to removal by chemical reactions with the crust) and so the ratios of their abundances on different planets should be relatively easy to reconcile with models. In particular, the abundances and isotopic ratios among these elements can be expected to contain information about the early history of the solar system and the formation of the planets and their atmospheres. Ways in which this might have occurred, which have been seriously considered at times, are by capture from the solar nebula, or, later, from the solar wind, or by the collision of a number of volatile-rich bodies such as comets with the terrestrial planets during their early history. However, such measurements as exist, for example those which show that primordial argon (that which is not produced by radioactive decay, i.e. the isotopes of mass 36 and 38) and neon are orders of magnitude less abundant on Earth than on Venus, and less common on Mars than Earth by a similar large factor, suggest strongly that the present atmospheres accreted along with the planetary bodies and were later outgassed. The differences in argon abundance can then be tentatively explained in terms of differences in the density of the solar nebula at the time of formation, as can the ratios of the rare gases to carbon and nitrogen[8].

The isotopic ratios of carbon and oxygen are approximately the same on Venus, Mars, and Earth, but different for nitrogen. The ratio of ^{15}N to ^{14}N in the Martian atmosphere is about 1.7 times that on Earth. If it is assumed that the ratio was the same in all of the planets at formation and models are constructed which represent the preferential loss of the lighter isotope from the exosphere, then these require that the nitrogen was initially much more abundant on Mars than it is now. McElroy *et al.*[9] find that the partial pressure of nitrogen on Mars must have been at least 2 and perhaps as much as 30 millibars, 20 to 300 times as much as it is now. Owen *et al.*[2] independently estimated that nitrogen and carbon dioxide were at one time at least 10 and 20 times more abundant, respectively, and that the initial outgassing of water was enough to produce a layer about 10 m deep on Mars. As noted above, some or all of this may still be present as ice and permafrost.

Temperature structure

Significant amounts of solar energy reach the ground on all of the terrestrial planets, even Venus with its thick cloud cover. Enough sunlight diffuses through the cloud layers to provide about 17 watts per cm^2 of surface insolation on the average, about 12% of the total absorbed by Venus as a whole (i.e. including the atmosphere). Thus heated at and near the surface, the lower atmosphere forms a deep convective region, the troposphere. Within the troposphere none of the atmospheres cool predominantly by radiation to space, because the opacity of the overlying layers is large. The basic process whereby short-wavelength solar radiation penetrates lower atmospheres more easily than the longer thermal wavelengths is often (misleadingly) known as the greenhouse effect, and its result is to raise the surface temperature significantly above that which would apply on an airless planet. The effect is particularly extreme for Venus, where the surface temperature must rise to 730 K in order to force enough infrared cooling to balance the incoming sunlight. An airless body with the same albedo and heliocentric distance as Venus would reach equilibrium for a mean surface temperature of only about 230 K. Convection in the troposphere carries energy upwards to the base of the stratosphere, where radiative cooling to space can occur strongly. On Venus, this level (the tropopause) occurs about 40 km above the surface. The corresponding distances for Earth and Mars are 10 km and 30 km, on these planets the enhancements in surface temperature due to greenhouse warming are ~ 40 K and ~ 10 K respectively.

Above the troposphere on each terrestrial planet lies a deep layer (the middle atmosphere or mesosphere) where the temperature tends to be constant with height, because the atmosphere here is optically thin and, to a first approximation, each layer tends to find the same equilibrium temperature. This is determined by the balance between the absorption of upwelling infrared from the surface and troposphere and cooling to space, if no significant absorption of direct solar energy takes place. On Venus and Mars this simple picture holds, more or less; on Earth it is dramatically modified by the presence in the atmosphere of free oxygen, a consequence of the existence of life on the surface.

Photochemical processes involving oxygen produce ozone, which is a powerful absorber of solar ultraviolet radiation. The energy thus converted to heat by ozone produces a temperature maximum near 30 km altitude on Earth; the part of the middle atmosphere between this peak and the tropopause is called, for historical reasons, the stratosphere. Although only Earth has such an extreme example, the basically isothermal nature of the middle atmosphere is modified on all terrestrial planets by absorption of moderate amounts of solar and thermal energy in, for example, thin dust layers, and in the near infrared bands of water vapour and carbon dioxide. The temperature is, of course, also modified by dynamical effects, including wave motions, as will be discussed later. By the use of appropriate parameterizations to incorporate both radiative and dynamical effects, models of the gross thermal structures of the lower and middle atmosphere can be computed. It is necessary, however, to take account in the models of the opacities of all relevant atmosphere constituents. Early attempts to compute the temperature in a Martian pure CO_2 atmosphere failed to give the correct solution because the important contribution of airborne dust had been omitted (Figure 1). For Venus, similar calculations were a subject of controversy for nearly 20 years as increasingly sophisticated models struggled to account for the observed high surface temperature. Eventually, Pollack *et al.*[10] showed that provided all the bands of CO_2 and water vapour – not just the strongest ones – plus those of the minor constituents CO, HCl and SO_2 were included in the calculations, the correct temperatures appeared in the model. It proved to be particularly important to model the scattering and absorbing properties of the clouds correctly, and this finally became possible with the data from the Pioneer Venus probes[11].

Above the upper boundary to the middle atmosphere (the mesopause) begins the first component of the upper atmosphere, the thermosphere. This low-density region takes its name from the fact that temperature increases with height up to very high values, over 1000 K in the case of Earth. On each planet the thermospheric heating is caused by the absorption of

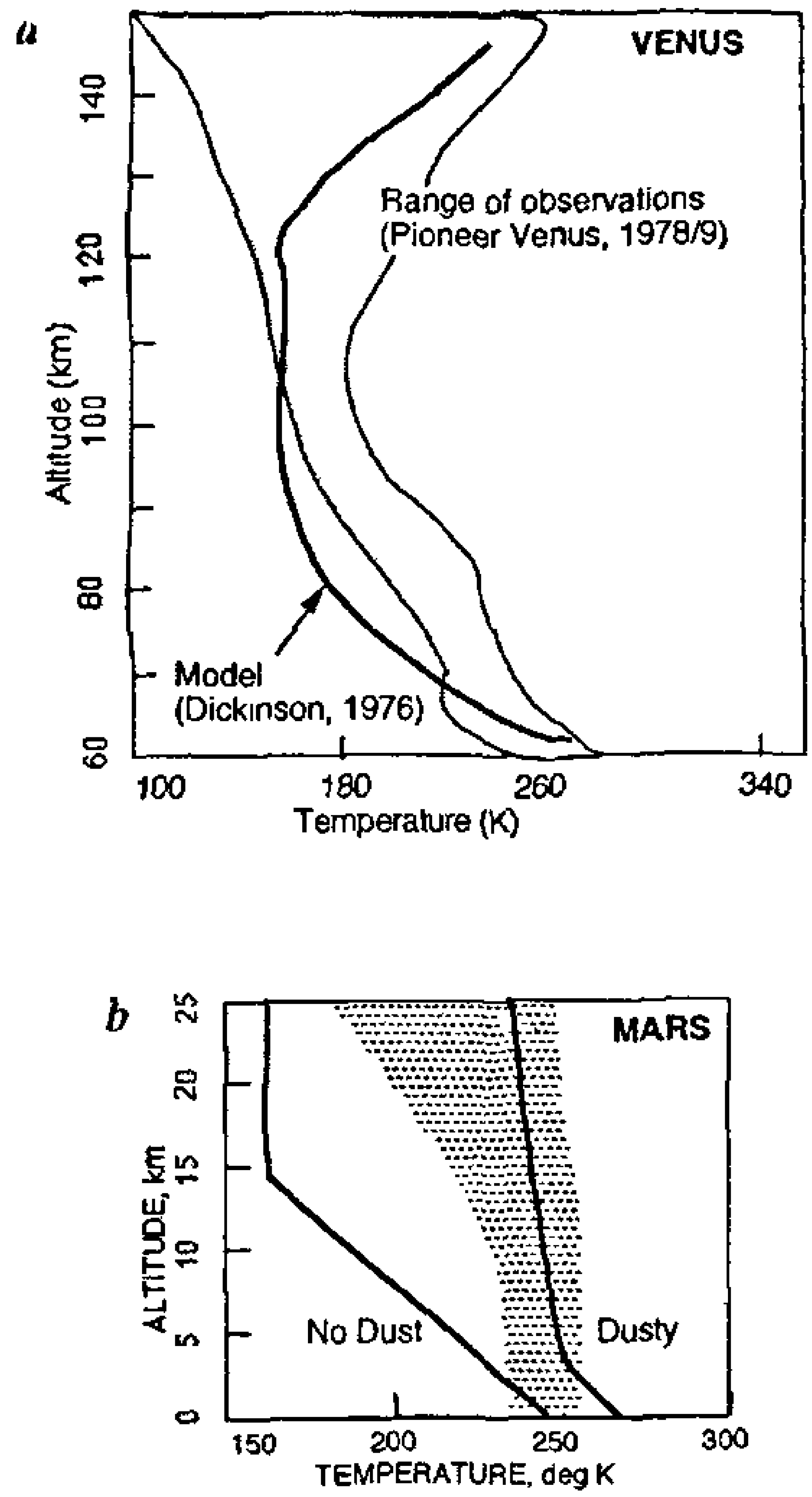

Figure 1. Comparisons between model calculations (lines) and measurements (stippled areas) for the atmospheric temperature profiles of Venus (*a*) and Mars (*b*), over similar pressure ranges. The Venusian measurements show the range measured by the Pioneer Venus Orbiter Infrared Radiometer[33,34] with a calculated profile from the model of Dickenson[35]. The Martian data (stippled area) are the envelope of Mariner 9 radio occultation measurements (Kliore *et al*[41]) and the calculations are by Gierasch and Goody[36], with and without the radiative effects of airborne dust.

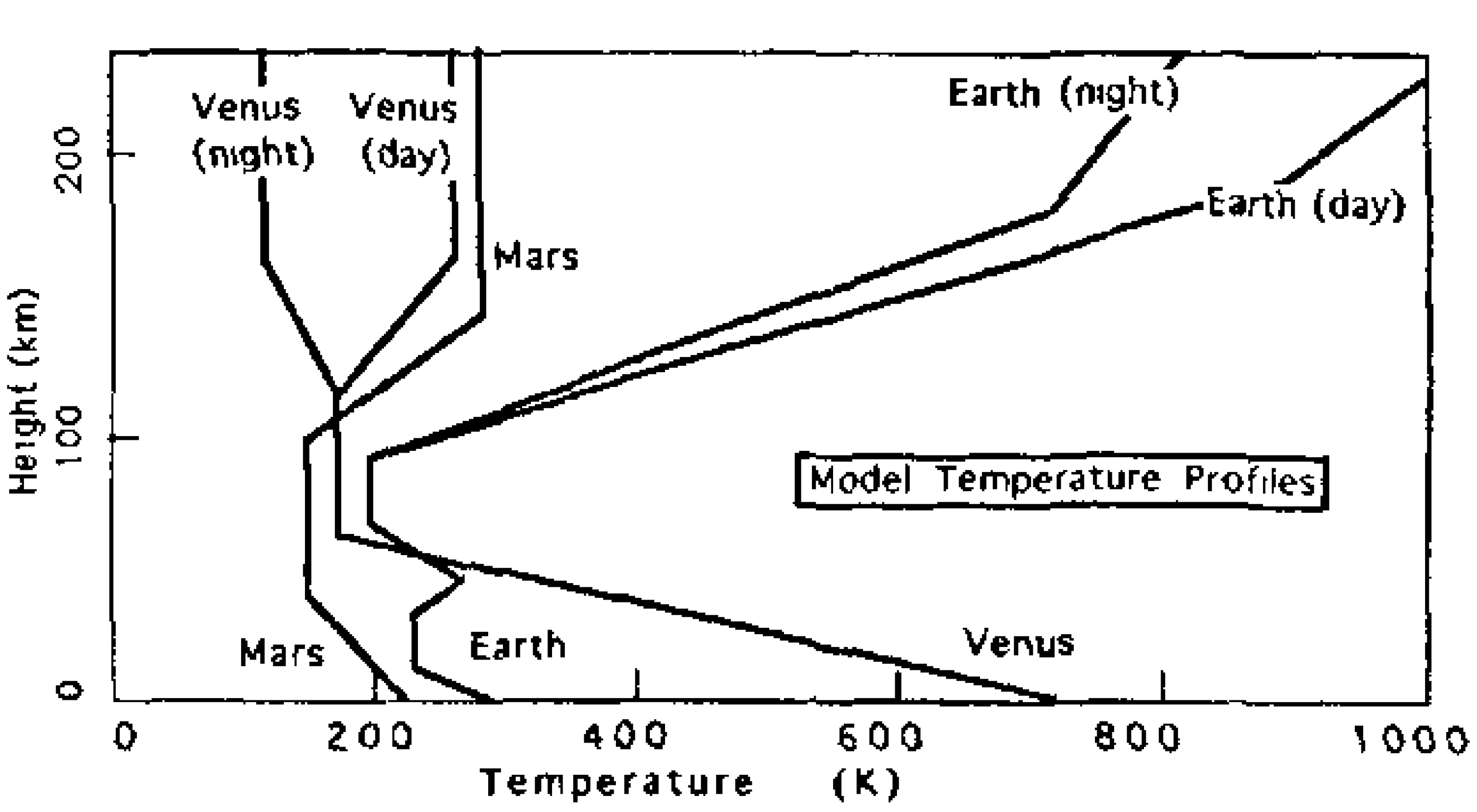

Figure 2. Model temperature profiles for the atmospheres of the terrestrial planets, after Pollack[37]. The nomenclature is that used for the Earth, on Venus and Mars there is no separate stratosphere and the term is not used. The nightside thermospheric temperature on Mars has not yet been measured.

mainly ultraviolet photons from the Sun, principally in the extreme ultraviolet portion of the spectrum. Energetic particles in the solar wind also contribute, and the actual thermospheric temperatures vary considerably with solar activity and sunspot cycle. Again using Earth as an example, the temperature at 300 km, where the composition is mostly atomic oxygen, varies from 500 K to 2000 K depending on the state of the Sun.

The thermospheres of Venus and Mars are cooler than Earth's, because of the greater abundance of carbon dioxide which is very efficient at radiating heat to space (Figure 2). Above about 150 km, the temperature on these two planets is approximately constant with height on the dayside, at about 300 K. The terrestrial thermosphere is the seat of rapid winds, up to 1000 ms^{-1} or more, and this tends to redistribute energy originally absorbed from the Sun over the dark as well as the sunlit hemisphere. The result is a modest day-night difference of around 200 K about a mean temperature of 1000 K. On Venus, however, the night-time temperature in the thermosphere is very low, around 100 K. The same measurement for Mars has yet to be made, but is likely to show temperatures somewhat lower still. The transition from the day to nightside values of temperature on Venus also shows surprisingly steep gradients[12] and modellers have great difficulty in reproducing both the minimum temperature and the short distance across the terminator with which it is attained. The implication is that the dynamics of Venus's thermosphere is such that the flow of air in response to the temperature gradient is inhibited, perhaps by large-scale eddies. Models of such effects may also apply, suitably modified, to Mars, and measurements of thermospheric temperatures on Mars are perhaps one key to the puzzle. It is already clear that in temperature structure, as well as aeronomy (see below), the thermospheric region is one where the terrestrial planets are radically different.

Clouds

Convective activity in the tropospheres of the planets raises moist air from near the warm surfaces to cooler upper levels, where the volatile content can condense to form clouds. On the terrestrial planets water is the most important volatile, although on Venus the only positively identified cloud constituent is a strong aqueous solution of sulphuric acid and on Mars, clouds of solid CO_2 form as well as clouds of water ice. The detailed structure of the clouds depends on the atmospheric dynamics and will be discussed below.

Venus is completely enshrouded by cloud in a layer over 20 km deep. The main deck extends from about 45 to about 65 km above the surface with haze layers above and below. Within this gross structure, detailed layering occurs and particles of different sizes congregate at different height levels. The particles range in diameter from less than 1 to over 30 microns and tend to a trimodal size distribution, with the commonest diameters falling towards the ends of the overall range and in the 2–3 micron region. It is these intermediate size or 'mode 2' droplets which are visible from outside Venus and for which spectroscopic, polarimetric and other evidence yields a composition of 75% H_2SO_4 and 25% H_2O. The composition of the smaller, 'mode 1' drops is unknown; these form an aerosol haze extending throughout the cloud layer. Most of the mass of the clouds is in the big 'mode 3' drops; these may be crystalline sulphur or, alternatively, be more evolved sulphuric acid drops constituting a tail to the mode 2 distribution curve, rather than a mode of their own.

In spite of their depth, the clouds of Venus are not completely opaque at all wavelengths, because they are quite efficient scatterers at visible and near-infrared wavelengths. It is noted elsewhere that a significant fraction of the incident sunlight diffuses down to the surface; a corollary of this is that the hot surface and lower atmosphere of Venus, which emit strongly in the infrared, can be seen from outside the atmosphere through the clouds at wavelengths outside regions of strong CO_2 or H_2O absorption. The best observations of this recently-discovered phenomenon were made by the Near Infrared Mapping Spectrometer on Galileo. Maps of Venus by this instrument show large horizontal variations in the thickness of the main cloud deck in considerable detail[13].

The Venusian sulphuric acid droplets may be formed when H_2O and SO_2 (the latter possibly of volcanic origin) combine photochemically near the cloud top level. It is difficult to explain the details of the size distribution, particularly to explain the existence of particular modes, and their multiplicity. Compositional contrasts and dynamical effects may be at work but at present the observations which would elucidate these are in short supply.

Another feature of the Venusian clouds which has been hotly debated is the question of whether or not lightning is present. On theoretical grounds, this was thought rather unlikely, because the clouds are too tenuous, although localized storms and clouds of volcanic ejecta could provide the right conditions. The Galileo observations from February 1990[14] provided the hardest experimental evidence to date by detecting impulsive radio signals in the 100 kHz to 5.6 MHz frequency range, for which lightning is the only known source. Lightning was not detected optically, however, in spite of a search by the Galileo imaging experiment[15].

Most terrestrial clouds are of relatively pure water, as liquid or solid, and typically have much higher number densities than those on Venus. The Venusian clouds are really very extensive hazes, within even the thickest part of which, visibilities of many kilometres would be possible. A counterpart to the Venusian clouds is found

Table 3. Properties of clouds and dust in the terrestrial planet atmospheres

	Venus	Earth	Mars
Fractional coverage	1 00	0 40	0 05 (cloud) 0–1 0 (dust)
Typical optical depth	25–40	5–7	0 2–6 (dust)
Composition	$H_2SO_4 \cdot H_2O$	H_2O	Magnetite etc. (dust), H_2O, CO_2
Number density (cm^{-3})			
– liquid	50–300	100–1000	0
– solid	10–50	0 1–50	30–1000
Typical mass loading ($g\ m^{-3}$)	0 01–0 1	0 1–10	0 0002–0 1
Main production process	Chemistry	Condensation	Windblown (dust)
Equivalent depth (mm)	0.1–0 2	0 03–0 05	1–100
Effective radius (μm)	2–4	10	0 4–2 5 (dust)
Main forms	Stratiform	Stratiform cumulus	Stratiform, mixed (dust)
Temporal variability	Slight (haze) High (deep)	High	High

The equivalent depth is the estimated thickness of the cloud material if it were deposited on the surface The effective radius is the radius of the spherical particles having most nearly the same scattering properties as the cloud at visible wavelengths After Esposito *et al* [11] with changes and additions

in the terrestrial stratosphere, where the so-called Junge layer is found at about 20 km altitude. This contains sulphuric acid droplets, but is much thinner (average optical depth in the visible about 0.001, compared to 20 to 35 on Venus) and consists of particles with modal diameter about 0.15 microns. The Junge layer is considerably enhanced by major volcanic events, and may also be undergoing a slow secular increase due to anthropogenic (man-made) sources of acidic gases. The properties of the more conventional terrestrial (water) clouds are summarized in Table 3 along with comparative properties for Venusian and Martian clouds.

Terrestrial cloud types are normally either convective (formed in warm, buoyant air parcels), layer type (formed by the forced lifting of stable air) or orographic (produced by the motion of moist air over topographical features). Nearly half of the surface is covered by one or other of these cloud types at any given time. On Mars, clouds occur much less frequently and the mean cover is only a few per cent. Nevertheless, analogues to all the common terrestrial types occur on occasion. Martian convective clouds tend to occur near local noon over high ground, where the surface is strongly heated. The atmosphere, heated from below, can become unstable; the resulting clouds have been observed at heights from 4 to 6 km above the surface.

Hazes of ice crystals are seen over the Martian poles in autumn and spring. The autumn 'polar hood' in the North is particularly pervasive and extends as far South as 50°N. It clears in early winter as the crystals precipitate out of the atmosphere. Orographic clouds form both as extensive layers over large-scale topography and as lee clouds behind tall features such as the giant volcanoes. The latter frequently show the structure of buoyancy waves caused initially by the cooling of the air mass as it rises to cross the obstacle; it then falls on the other side, warms by adiabatic compression, and begins to rise again. Moisture tends to condense at the highest excursions; the train of clouds thus formed can extend for hundreds of kilometres.

Low-level hazes of condensed water vapour are common on Mars, especially at dawn and dusk and over low areas. These are produced by the rapid cooling of the surface as the solar heating drops off towards nightfall; they can persist all night and several hours into the morning before dispersing, often accompanied by a light surface frost.

Although most of the clouds on Mars are composed of water, at times CO_2 crystals are also present. It is not always possible to say unambiguously whether a cloud is H_2O, CO_2 or both, at times or places where the local conditions are cold enough to permit CO_2 condensation. The high hazes (up to 50 km altitude) which can be seen in many photographs of the limb of Mars, and certain other wispy clouds which apparently form at high altitudes at night, vanishing quickly after daybreak, are most probably CO_2. The detection of what was probably a CO_2 cloud on Venus at high altitudes over the dawn terminator was reported by the Pioneer Venus orbiter infrared radiometer team in 1979[16].

In energy balance and hence climatological terms, it is not clouds which are most important on Mars – unlike Venus and Earth – but rather airborne dust. The atmosphere appears always to contain a considerable load of dust, mixed through the lower 20 or 30 km. The lowest value of the vertical optical depth observed by either of the Viking landers during their first year of operation was 0.18 at one site and 0.36 at the other[17]. This amount of dust is enough to modify themosphere temperature profile substantially, and hence to affect the dynamics. Under certain circumstances, these modifications can be such that the resultant winds raise more dust, leading eventually to a dust storm which can blanket the entire planet. Major storms tend to occur annually, when Mars is close to perihelion, and to originate in approximately the same part of the southern hemisphere. A model for their formation has been proposed by Leovy and Zurek[18].

The general circulation

The first-order effect of solar heating on the global-scale motions of a planetary atmosphere is through its dependence on latitude, which causes the insolation to be greater at low and middle latitudes than at high. If the planet did not rotate at all, then the air at the sub-solar point would tend to rise convectively and that at the anti-solar point would tend to fall; air would migrate from one to the other in a pattern symmetric about the planet-Sun line. Even very slow rotation, however, like that of Venus, tends to distribute the heating around bands of constant latitude faster than typical radiative and dynamical time constants, so that the rotational poles define the main axis of symmetry. In the upper atmosphere of Venus, there is some evidence that both equator-to-pole and subsolar-to-antisolar regimes are present together. In the deep Venusian atmosphere, the time constant for radiative cooling (i.e. the characteristic time in which the atmosphere would cool down if the Sun were removed) is several thousand times the length of even the long Venusian day, so that the Sun appears to the atmosphere to move rapidly overhead and the predominant gradients are equator-to-pole. This is the case also on Earth and Mars, where the time constants are shorter but so also is the length of the day.

The net effect of the basic gradients of temperature with latitude and height expected on each of the terrestrial planets is to tend to force an hemispherical convection cell with rising air at low latitudes moving polewards and falling air at high latitudes moving equatorwards. The rotation of the planet will tilt the wind vectors at an angle to the equator, as observed for example in the prevailing trade winds on Earth or in the migration of cloud patterns on Venus. This basic pattern was inferred by Hadley in the 18th century and is named after him. In fact, in the atmospheres of the terrestrial planets Hadley's circulation is unstable, and multiple cells are formed instead. Within individual cells, the motions are on average smooth flows but at any given time have a variety of wave and chaotic motions superimposed on them.

Because atmospheric motions are so complex, it is difficult to give more than a very superficial account of the parallels or contrasts which can be drawn between the different terrestrial planets. Circulation studies are now, to a large extent, the province of the modeller with large computers upon which the various processes can be parameterized and the time-dependent fluid dynamical equations solved. These in turn depend on measurements, primarily of the temperature fields (Figure 3), to initialize and constrain the model as far as possible. Sophisticated models of all three terrestrial planets have been generated, for example by Young and

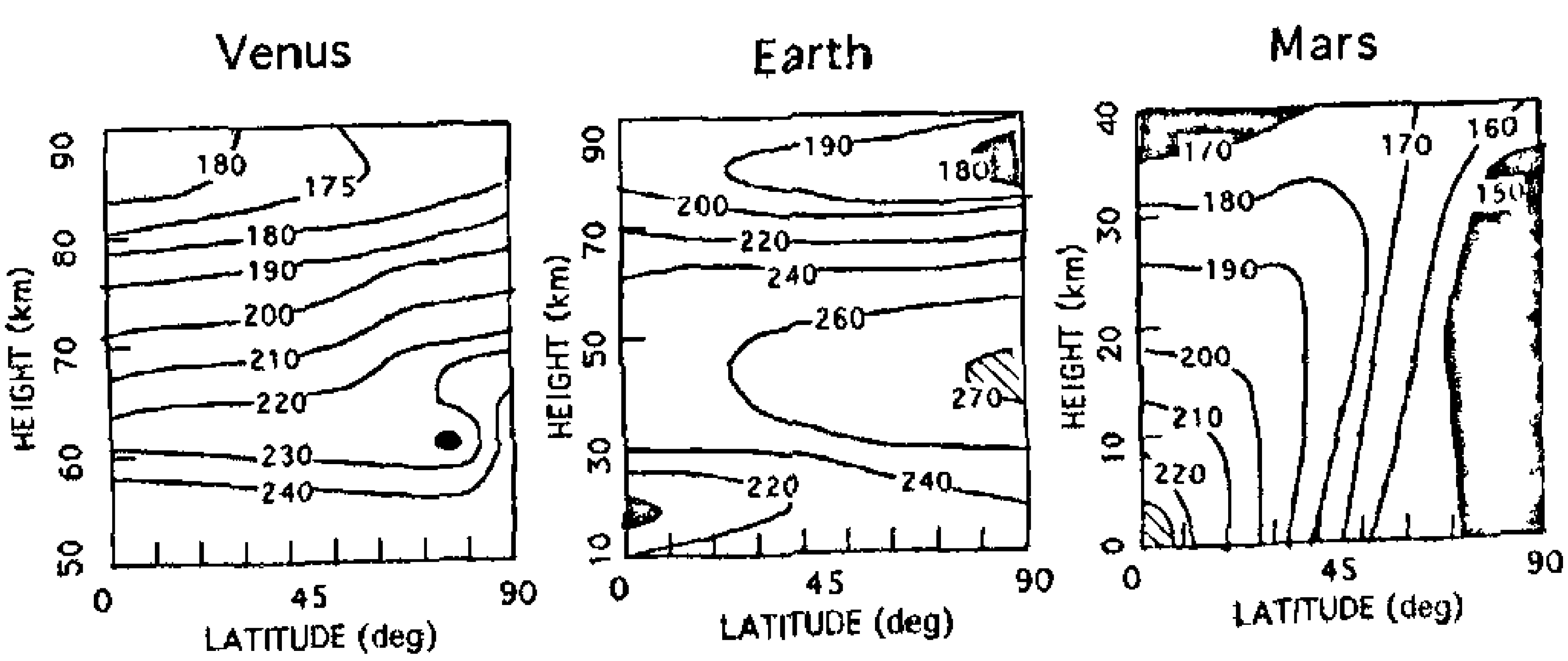

Figure 3. Meridional temperature cross-sections for the atmospheres of the terrestrial planets. For details and original data, see (i) *Pioneer Venus Orbiter Infrared Radiometer measurements*[11], (ii) Nimbus 7 Stratospheric and Mesospheric Sounder data[18] and (iii) Mariner 9 Infrared Interferometer Spectrometer data[19]

Pollack[19] for Venus, by many groups for Earth (see the review by Simmons and Bengtsson[20] for a discussion and for references), and by Leovy and Mintz[21] for Mars. None of these models is complete or detailed enough to give an entirely satisfactory representation of any of the three atmospheres, and approximations and parameterizations, which differ with the conditions and uncertainties for each planet, are always used. The ideal general circulation model, which would be completely physics-based and would represent any atmosphere with appropriate initialization and boundary conditions, is still some time away.

For Venus a major question is the origin and maintenance of the global superrotation, which manifests itself in cloud structure which moves rapidly around the planet in the zonal direction (i.e. parallel to the equator). The cloud markings, which appear with high contrast through an ultraviolet filter, have their origin at heights 50 or 60 km above the surface (where the pressure is of the order of 100 mb) and travel around the equator in 4 to 5 days, corresponding to speeds near 100 ms^{-1}. This is more than 50 times faster than the rotation rate of the surface below. Measurements of the winds below the clouds, and calculations (from temperature data) of the winds above the cloud tops, show that the zonal wind speed declines at higher and lower levels, reaching values near zero at about 100 km and near the surface respectively.

Attempts have been made to explain the high zonal wind speeds on Venus by several mechanisms, all of which fall into one of three main categories:

(i) The gravitational interaction of the Sun with the atmospheric tides.
(ii) The overhead motion of the Sun in the sky.
(iii) The upward transport of momentum from the surface.

The original work on each of these has been reviewed by Schubert[22]. Rather than provide a conclusive or convincing model, these studies demonstrate that there is no simple explanation for rates of superrotation as high as those observed on Venus. Currently prevailing opinion favours a version of mechanism (iii), in which momentum from the solid planet is transported by waves whose interaction with the main flow is complex and in which the mean meridional circulation plays an important role. With suitable parameterizations, Young and Pollack[19] were able to produce large zonal velocities in their three-dimensional spectral model of Venus's atmosphere. Superrotation also occurs in the Earth's atmosphere, but only at much higher levels than on Venus, where the densities are very small. The corresponding situation on Mars at altitudes well above the surface is unknown.

The cloud motions which trace the zonal winds also reveal the pattern of the meridional circulation on Venus[13, 15]. The Hadley cell in each hemisphere extends

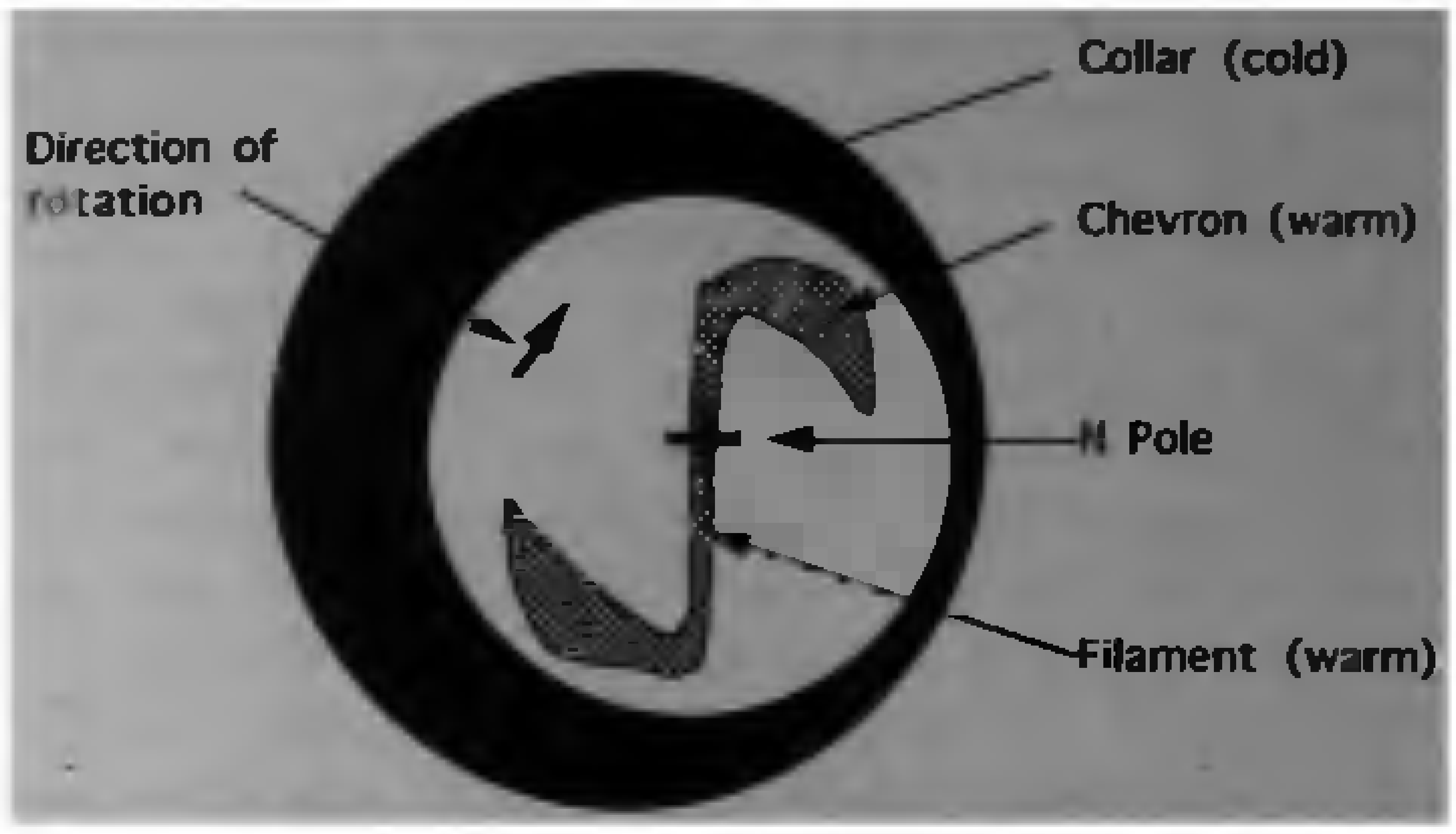

Figure 4. Sketch illustrating the general appearance of the polar dipole/collar features at cloud-top level on Venus[40].

to higher latitudes than on Earth, in part a consequence of the slower zonal rotation speeds. Near the poles on Venus, a complex instability develops, resulting in dramatic and apparently long-lived wave structures. The *polar collar* takes the form of a ribbon of very cold air, some 10 km deep and a thousand km in radius, centered on the pole. Inside the collar, temperatures are some 40 K cooler than outside the feature. Poleward of the inner edge of the collar lies the *polar dipole*, a wave-number 2 feature consisting of two curiously-shaped warm regions circulating around the pole (Figure 4). Both the dipole and the collar have so far resisted attempts to model them as normal modes of the atmosphere[23].

The Hadley cell near the surface on the more rapidly rotating Earth extends only to mid-latitudes, with other cells polewards. In the stratosphere, recent evidence from satellite experiments which observe the transport of long-lived minor constituents such as CH_4 and N_2O, suggests that distinct Hadley-type cells extend over a wider range of latitudes and grow and decline in intensity with the seasons[24]. Zonal winds in the stratosphere can exceed 100 ms^{-1} at times but on average do not achieve the Venusian values; they also are seasonal. Waves on many spatial and time scales abound and are intimately connected with the mean flow.

Although data on the Martian circulation are even more sparse than for Venus (one reason being the relative absence of clouds to be tracked as they follow the winds), wave motions are especially important here because the topography is so extreme. Mountains up to 25 km tall and valleys down to 7 km deep are found on the small, rapidly rotating planet where the atmospheric scale height (a characteristic depth, defined as the altitude range over which the pressure falls by 1/e) is about 8 km. Topography affects the circulation in two main ways: firstly by interfering mechanically with the flow and secondly, by enhancing the temperature contrasts at the base of the atmosphere which drives the winds in the first place. The global distribution of

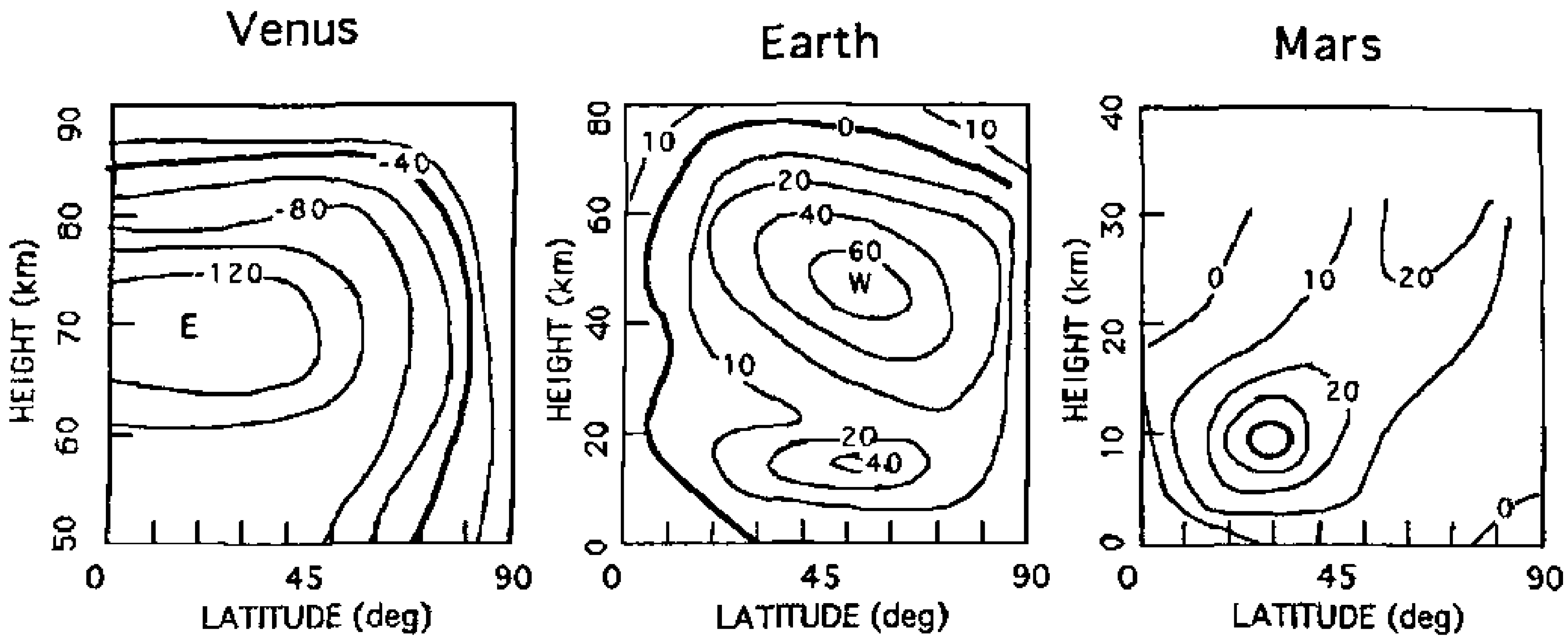

Figure 5. Mean zonal winds (in ms^{-1}, with the 40 ms^{-1} contour in bold) on the terrestrial planets *a*, The middle atmosphere of Venus, from a model used by Fels *et al*[42] to match the observed tidal structure in the meridional temperature field (see text), *b*, Earth, after Holton[43], *c*, Mars, using model results from Leovy and Mintz[21].

topography and albedo differences determine which periodicities will be driven in addition to the natural wave modes of the atmosphere[25]. Topographical effects, like those caused by the flow of the atmosphere over structure on the surface, are important on Earth also, though not as important as on Mars. On Venus, they may be negligible as far as the general circulation is concerned.

A particularly important form of wave motion is that induced by the daily motion of the Sun overhead, the solar tide. This contains a range of Fourier components, because the forcing is non-sinusoidal; the actual atmospheric response depends on the mean wind and the interference between the various components. The classical tidal theory of Chapman and Lindzen[26] produces reasonable agreement with the main known features of the tidal behaviour of all three terrestrial planets. For example, the solar tide on Venus as measured by the Pioneer Venus orbiter has been analysed by Fels *et al.* who find that experiment and theory can be reconciled provided that a realistic representation of the zonal wind is incorporated. Their model zonal wind profile is shown in Figure 5 *a*; this quite closely resembles that deduced independently from calculations assuming cyclostrophic balance (i.e. a balance between the pressure gradient acting on a parcel of air and the centrifugal force due to its zonal motion) and is probably, therefore, a good approximation to the mean conditions on Venus. Plots of the corresponding wind structure on Earth and Mars appear in Figures 5 *b* and 5 *c*.

Overall, the circulation regimes of Venus, Earth and Mars appear fairly dissimilar, due primarily to the vast differences in optical thickness and in solid body rotation rate, and also to the different roles of volatiles and topography. Underlying these differences are some basic similarities in the forces attempting to drive hemispherical Hadley-type cells, and tides and other wave motions. Once, a more detailed survey of the Martian circulation has been obtained by future orbiters, and comparative studies of all three atmospheres can be conducted in more depth, it may be possible for the similarities and differences to be better understood in terms of the boundary conditions on each planet

Weather and climate

Reference has already been made to time-dependent phenomena in planetary atmospheres, such as seasonal convection cells in the stratosphere of Earth and dust storms on Mars. Fluctuations in the steady state are commonly termed weather when relatively short term, apparently chaotic changes are being considered. These certainly occur on Mars and Venus although we have little detailed information. On the Earth, processes with periods of seconds are sometimes important (in thunderstorms, for example), ranging up to oscillations in the ocean circulation which might have periods of decades or longer.

The climate is the long-term mean state of the atmospheres and secular changes in this have occurred in the past on the Earth and Mars and, presumably, Venus, although there is no hard evidence for the latter as yet[27]. Palaeoclimatic studies seek to understand ancient events like the terrestrial ice ages or the flooding of the surface of Mars (as evidenced in the geological record on the surface) by invoking either cyclic astronomical effects or catastrophies, and sometimes both. The former include very long term changes in the orbital parameters (inclination, oblateness and obliquity) and in solar output. The latter include collisions with comets and asteroids, which are unusual but not very rare events, and serious anthropogenic pollution of the atmosphere with chemically or radiatively active gases like carbon dioxide and the oxides of nitrogen

Venus with its deep atmosphere of nearly pure CO_2 and extensive cover of sulphur-bearing clouds is in some respects an extrapolation of the current trend on Earth. We have already remarked about how the special properties of the H_2SO_4 clouds on Venus contribute very significantly to the high surface temperatures, by scattering conservatively at short (solar) wavelengths while strongly absorbing long wavelength (planetary) radiation. Changes in the optical properties or depth of the cloud layers on time scales of years or longer will affect climatic variables such as surface temperature and general circulation regime. At present the radiative, dynamical and chemical processes appear to be in balance but the stability of the currently observed state is debatable.

The surface and atmospheric conditions on Earth are maintained by mechanisms similar to those at work on Venus. Although the amplitudes of the feedback processes are less, the balance is better studied for Earth because of the much more complete data base which is available, including a valuable if incomplete historical record extending back thousands of years. A comprehensive discussion of the global climate of Earth, its maintenance and factors causing it to change, may be found in Houghton[28]. The main factors which need to be taken into account appear schematically in Figure 6. Of particular interest at the present time is the effect of the build-up of minor constituents, especially carbon dioxide, due to anthropogenic activities, the role of the global ocean circulation[29], especially in inducing short-term changes[30], and the interaction of cloud with both the solar and planetary thermal radiation[31]. It has been shown, for example, using a model with the feedback processes of known importance included, that surface temperatures, particularly at high latitudes, may increase by several degrees in response to a doubling of atmospheric CO_2[32]. At present, CO_2 is increasing at a rate which would result in doubling in less than a century.

Long-term changes in the Martian climate are driven by the large values of planet's orbital eccentricity and obliquity. Pollack[27] reviews how resonances in these could give rise to an epoch of high atmospheric pressure, with free surface water, at a time when Mars may have had permanent polar caps of frozen CO_2. Much of the CO_2 has since been absorbed into the surface layers of the planets, probably by the formation of carbonates, an irreversible process. Nevertheless, Mars probably still undergoes large changes in climate on a range of time scales, typically of the order of millions of years, in which the mean surface pressure might vary between one to twenty or thirty millibars (the current value is about seven and a half millibars) with corresponding mean temperature extremes. The latter are estimated to span polar cap temperatures ranging from values low enough to re-establish permanent CO_2 polar caps, to values above the melting point of water. Major changes in all aspects of the Martian environment, including its meteorology, will take place along with these.

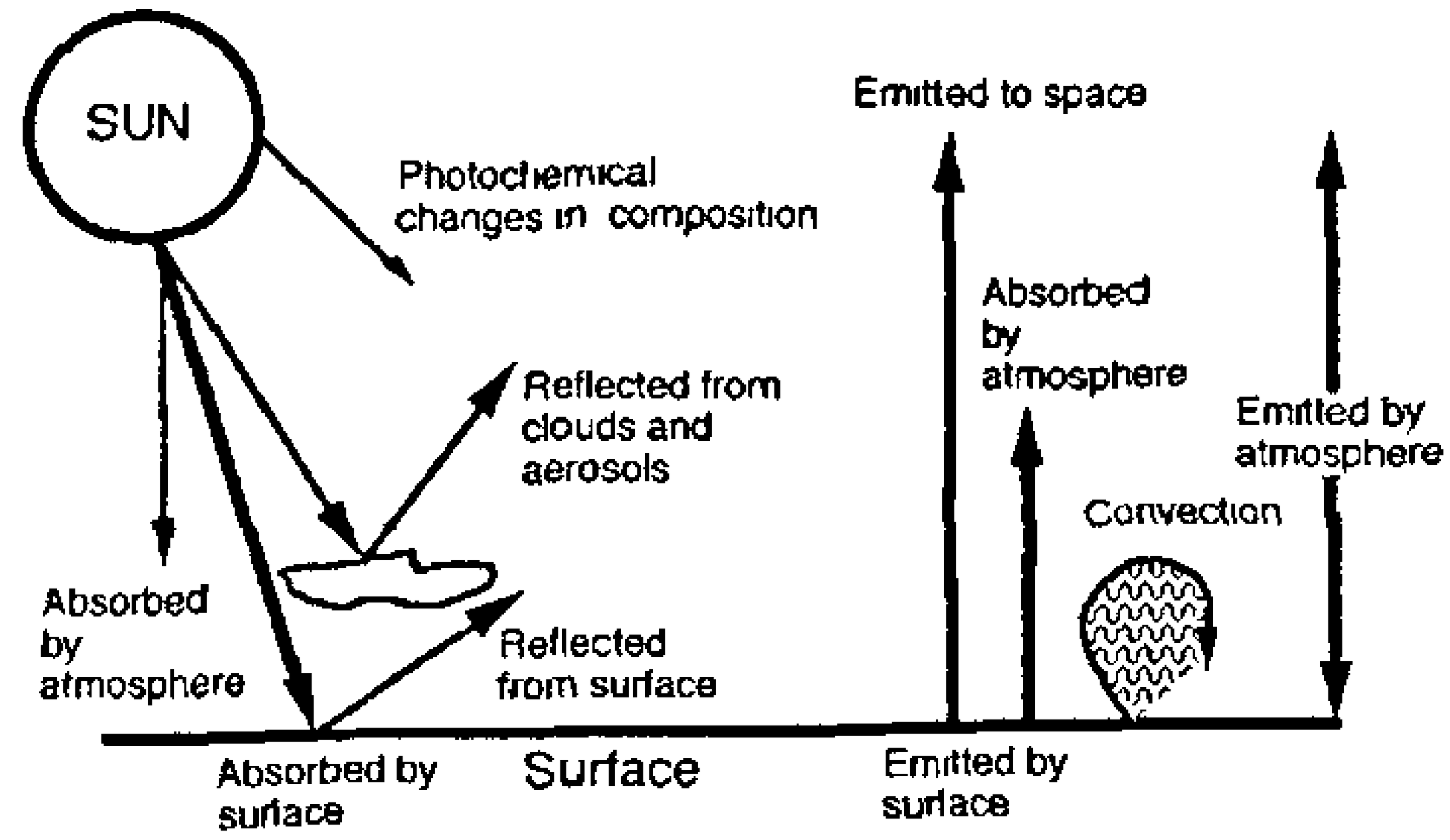

Figure 6. Schematic illustration of the radiative components of the terrestrial climate system. Composition, energy and momentum balances are affected by surface interactions also, for example with the oceans on Earth and the cryospheres on Earth and Mars. The deep atmosphere on Venus behaves like an ocean in some important respects

Aeronomy

Aeronomy refers to the study of non-equilibrium processes which occur most prominently at low atmospheric densities. These can be grouped under three main headings:

(i) Processes related to the physical separation and escape of atmospheric constituents.
(ii) Non-LTE radiative transfer processes (LTE stands for local thermodynamic equilibrium, the condition which applies in general when the populations of molecular energy levels are determined by collisions rather than radiative exchange).
(iii) Dissociation, ionization, and photochemistry.

The most intensively studied photochemical problem currently is the question of the production, maintenance and stability of the ozone layer on Earth. For many years, the simple scheme proposed by Chapman in 1930 was felt to give an adequate account of the production and destruction of ozone by reactions involving only oxygen, viz.

$$O_2 + h\nu \rightarrow O + O$$

$$O_2 + O \rightarrow O_3$$

balanced by

$$O_3 + h\nu \rightarrow O_2 + O$$

$$O_3 + O \rightarrow 2O_2.$$

However, it is now realized that catalytic reactions involving highly reactive species such as the oxides of nitrogen, especially NO and NO_2, can have a vital role in spite of their low abundances. In recent years, the importance of further chemical cycles involving halogen-containing compounds has been recognized, and the part played by radicals such as hydroxyl (OH) and chloroxyl (ClO) is slowly being understood. The scene is now so complicated, involving not only these so-called NO_x, ClO_x and HO_x chemical cycles, but also complex interplay between chemistry, radiation and dynamics, that progress can be made only with the help of increasingly sophisticated measurements and computer models. The key reactants are often extremely difficult to measure, so that the acquisition of data to initialize and test the models is complicated and demanding. Large programmes which interlink measurements and theory, such as NASA's *Upper Atmosphere Research Satellite* programme, represent the next major step forward.

On Venus, the key questions have to do mostly with the processes which form and maintain the sulphuric acid cloud layers, and which give rise to a non-uniform distribution of associated species such as SO_2 and elemental sulphur, and hence to the ultraviolet markings on the visible face of Venus. Other key questions are the possible roles of chemical cycles like those which determine the abundances of minor constituents in Earth's atmosphere, and the abundances and inter-relationships of minor constituents, for example the halogen-containing species, of which so far HCl and HF have been observed.

The peculiar thermal structure of the thermospheric region on Venus has already been discussed. This highlights how imperfect our understanding is of heating and cooling rates on Venus, and non-LTE radiative transfer and the molecular transport of heat across the terminator in particular. We have also discussed the unexpected value of the deuterium to hydrogen ratio on Venus, which depends on measurements still to be confirmed, and on reliable calculations of the escape rate of hydrogen over very long spans of time, a process whose importance extends to the other planets, including Earth.

Finally, in considering crucial questions such as the chemical interaction between the surface of Venus and the atmosphere, we find that, for example, it is still not known whether there are significant amounts of molecular oxygen in Venus's atmosphere; without such fundamental information as this it seems clear that further measurements must have the highest priority.

For Mars, the most crucial question at present in the area of atmospheric photochemistry is one of the stability of the carbon dioxide atmosphere itself, against dissociation of the CO_2 by solar ultraviolet radiation. In defiance of calculations based on the best available measurements and theory, the dissociation products CO and O_2 appear to be present only in extremely small amounts and it is necessary to postulate some unidentified, but extremely efficient, recombination mechanism for CO_2. Very rapid vertical mixing, and/or an accelerated recombination rate enhanced by catalysis involving hydrogen peroxide, are possible mechanisms which have been proposed. Measurements, as yet unavailable, of the vertical distributions of water vapour and ozone on Mars may provide the key.

Summary

The primary goal of planetary science is to understand how the solar system, and in particular the Earth-like planets, originated and how they evolved to their present state. We are also, of course, deeply interested in how it might evolve further in the future. In the process of attaining this overall goal, we would also expect to learn exactly what are the mechanisms which are at work, and which through their complex interaction and balance determine the mean state (the climate) at any given time, and the seasonal cycles and random fluctuations (the weather), which we can observe.

It should be clear from what has been said above that this process of understanding is not very far advanced. We have really very little idea of how the climate of the Earth, for example, is going to evolve in the next few centuries, even though many models predict that changes large enough to affect the global habitability seriously are possible, even likely. Fortunately, the problem is recognized, at least in the United States, to the degree that model development, and advanced measurement programmes employing remote sounding from satellites, are in hand, which will contribute much new knowledge in the next decade. Probably, the most important major improvement which can be expected in terrestrial atmospheric science is the resolution of the question of the stability of the ozone layer against pollution-induced secular changes, and of the surface temperature field against this and related changes. The prime example of the latter is the steady and essentially irreversible increase in atmospheric carbon dioxide and its feedback into the climate through the 'greenhouse' effect.

For Venus and Mars, measurement programmes of comparable sophistication to the terrestrial ones are needed. The details of the general circulation and the photochemistry of the clouds on Venus are likely to be a long time coming. In the meantime, important new observations of the surface morphology, designed to reveal the processes which shaped it (including the role, if any, of plate tectonics, a process of great significance on Venus' near twin, the Earth) are being made by the Magellan orbiter. A key breakthrough will come with any clarification of the scale of volcanism on Venus. Volcanoes may be important for maintaining the cloud layers and hence the extreme climate of Venus.

Evidence preserved in the surface relief is beginning to shed some light on the question of whether or not Venus, Earth and Mars all had oceans.

For Mars the key questions are the detailed dynamical behaviour of the atmosphere, with the seasonal condensation of CO_2 and the strong radiative and topographical forcing; the water and dust budgets and their seasonal change; and the long-term climate and its changes. Fortunately, for Mars solutions are actively being sought with new missions of exploration, such as Mars Observer and Mars-96. Fundamental data on the structure and composition of the atmosphere and its variations are to be gathered, which should advance our understanding of the basic state of the atmosphere of Mars beyond that which exists for Venus, leading to further productive comparisons with each other and with the Earth.

1 von Zahn, U., Kumar, S., Niemann, H. and Prinn, R., in *Venus* (eds Hunten, D. M., Colin, L., Donahue, T. M. and Moroz, V. I.), U. Arizona Press, 1983, pp. 299–430
2 Owen, T., Biemann, K., Rushneck, D. R., Biller, J. E., Howarth, D. W. and LaFleur, A. L., *J. Geophys. Res.*, 1977, **82**, 4635–4639
3 Pollack, J. B. and Yung, Y. L., *Annu. Rev. Earth Planet. Sci.*, 1980, **8**, 425–487
4 Wayne, R. P., *Chemistry of Atmospheres*, Oxford University Press, Oxford, 1985
5 Donahue, T. M. and Pollack, J. B., in *Venus* (eds Hunten, D. M., Colin, L., Donahue, T. M. and Moroz, V. I.), U. Arizona Press, 1983, pp. 1003–1036
6 Donahue, T. M., Hoffman, J. H., Hodges, R. R. Jr and Watson, A. J., *Science*, 1982, **216**, 630–633
7 Kasting, J. F., Pollack, J. B. and Ackerman, T., *Icarus*, 1984, **57**, 335–354
8 Pollack, J. B. and Black, D. C., *Science*, 1979, **205**, 56–59
9 McElroy, M. B., Kong, T. Y. and Yung, Y. L., *J. Geophys. Res.*, 1977, **82**, 4379–4388.
10 Pollack, J. B., Toon, O. B. and Boese, R., *J. Geophys. Res.*, 1980, **85**, 8223–8231
11 Esposito, L. W., Knollenberg, R. G., Marov, M. Ya., Toon, O. B. and Turco, R. P., in *Venus* (eds Hunten, D. M., Colin, L., Donahue, T. M. and Moroz, V. I.), U. Arizona Press, 1983, pp. 484–564
12 Keating, G. M., Taylor, F. W., Nicholson, J. Y. and Hinson, E. W., *Science*, 1979, **205**, 62–64
13 Carlson, R. W., Baines, K. H., Encrenaz, T., Taylor, F. W., Drossart, P., Kamp, L. W., Pollack, J. B., Lellouch, E., Collard, A. D., Calcutt, S. B., Grinspoon, D., Weisman, P. R., Smythe, W. D., Ocampo, A. C., Danielson, G. E., Fanale, F. P., Johnson, T. V., Keiffer, H. B., Matson, D. L., McCord, T. B. and Soderblom, L. A., *Science*, 1991, **253**, 1541–1548
14 Gurnett, D. A., Kurth, W. S., Roux, Gendrin, R., Kennel, C. F. and Bolton, S. J., *Science*, 1991, **253**, 1522–1525
15 Belton, M. J. S., *et al.*, *Science*, 1991, **253**, 1531–1536
16 Taylor, F. W., Beer, R., Chahine, M. T., Diner, D. J., Elson, L. S., Haskins, R. D., McCleese, D. J., Martonchik, J. V., Reichley, P. E., Bradley, S. P., Delderfield, J., Schofield, J. T., Farmer, C. B., Froidevaux, L., Leung, J., Coffey, M. T. and Gille, J., *J. Geophys. Res.*, 1980, **85**, 7963–8006
17. Pollack, J. B., Colburn, D. S., Flaser, M., Kahn, R., Carlston, C. E. and Pidek, D., *J. Geophys. Res.*, 1979, **84**, 2929–2945
18. Leovy, C. B. and Zurek, R. W., *J. Geophys. Res.*, 1979 **84**, 2956–2968
19 Young, R. E. and Pollack, J. B., *J. Atmos. Sci.*, 1977, **34**, 1315–1351
20 Simmons, A. J. and Bengtsson, L., in *The Global Climate* (ed. Houghton, J. T.), Cambridge University Press, 1984
21 Leovy, C. B. and Mintz, Y., *J. Atmos. Sci.*, 1969, **26** 1167–1190
22. Schubert, G., in *Venus* (eds Hunten, D. M., Colin, L., Donahue, T. M. and Moroz, V. I.), U. Arizona Press, 1983, pp. 681–765
23. Valdes, P., D. Phil. Thesis, University of Oxford, 1985.
24 Taylor, F. W. and Dudhia, A., *Philos. Trans. R. Soc. London*, 1987, **A323**, 567–576.
25 Webster, P. J., *Icarus*, 1977, **30**, 629–649
26 Chapman, S. and Lindzen, R. S., *Atmospheric Tides*, Reidel, Dordrecht, 1970
27 Pollack, J. B., *Icarus*, 1991, **91**, 173–198
28 Houghton, J. T. (ed.), *The Global Climate*, Cambridge Unversity Press, 1984
29 Kondratiev, K. Ya. and Moskalenko, N. I., in *The Global Climate* (ed. Houghton, J. T.), Cambridge University Press 1984, pp. 225–232
30 Wunsch, C., in *The Global Climate* (ed. Houghton, J. T.), Cambridge University Press, 1984, pp. 189–200
31 Webster, P. J. and Stevens, G. L. in *The Global Climate* (ed. Houghton, J. T.), Cambridge University Press, 1984, pp. 63–67
32. Houghton, J. T., Jenkins, G. J. and Ephraums, J. J. (eds.) *Climate Change*, The IPCC Scientific Assessment. Cambridge University P\ress, 1990, pp. 365
33 Taylor, F. W., Schofield, J. T. and Bradley, S. P., *Philos. Trans. R. Soc. London*, 1981, **A303**, 215–223
34 Taylor, F. W., Hunten, D. M. and Ksanfomality, L. V., in *Venus* (eds Hunten, D. M., Colin, L., Donahue, T. M. and Moroz, V. I.), U. Arizona Press, 1983, pp. 299–430
35 Dickinson, R. E., *Icarus*, 1976, **27**, 479–493
36. Gierasch, P. and Goody, R. M., *J. Atmos. Sci.*, 1972, **29**, 400–402.
37. Pollack, J. B., in *The New Solar System*, Cambridge University Press, 1981, pp. 57–70
38 Taylor, F. W., *Surv. Geophys.*, 1987, **9**, 123–148
39 Conrath, B. J., *Icarus*, 1981, **48**, 246–255
40 Taylor, F. W., in *Middle Atmosphere of Venus* (eds Schaefer, K. and Spankuch, D.), Academie-Verlag, Berlin, 1990, vol. 18, pp. 93–97
41 Kliore, A. J., Cain, D. L., Seidel, B. L. and Fjelbo, G., *Icarus*, 1970, **12**, 90–92
42 Fels, S. B., Schofield, J. J. and Crisp, D., *Nature*, 1984, **312**, 431–434
43 Holton, J. R., *An Introduction to Dynamical Meteorology*, Academic Press, New York, 1979