Climate evolution of Venus

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[1] The processes in the atmosphere, interior, surface, and near-space environment that together maintain the climate on Venus are examined from the specific point of view of the advances that are possible with new data from Venus Express and improved evolutionary climate models. Particular difficulties, opportunities, and prospects for the next generation of missions to Venus are also discussed.

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1. Introduction

[2] A dramatically hot and dry climate is found on Venus at the present time, probably the result of the atmosphere following a divergent evolutionary path from a more Earth-like beginning. A key question is to what extent the two planets and their early inventories of gases and volatiles were physically alike, given their common origin in the same region of the young Solar System. Venus and Earth have nearly the same size and mass, and most current models suggest they have similar chemical compositions and interior structures. However, factors such as the small discrepancy in mean density (after allowing for compressional effects, see *Ringwood and Anderson* [1977]), and the absence of an internal dynamo [*Luhmann and Russell*, 1997], as well as discrepancies in the abundances of the noble gases [*Pepin*, 2006], fuel a lively debate about the extent to which the two planets can be considered to be a close match owing to essentially identical origins. The common assumption of identical origins is also clouded by the possibility of stochastic variations in late accretion history leading to unequal volatile inventories [*Morbidelli et al.*, 2000] or volatile loss and interior processing through catastrophic early impacts [*Davies*, 2008; *Zahnle*, 2006; *Alemi and Stevenson*, 2006]. Even if we understood these issues, deriving the path and time scales of Venus' divergent evolution to its present state would still present numerous challenges, not least in terms of explaining the high temperature and pressure and low water abundance at the surface.

[3] *Taylor et al.* [2007, p. 160] posed a thought experiment:

> Suppose Venus and Earth had been swapped at birth – that is, at the time when they had accumulated virtually all of their present mass but before their atmospheres were fully evolved. Venus, with its slow retrograde rotation would then be at one astronomical unit from the Sun, and Earth somewhat closer. Venus would still have any bulk compositional differences it may have acquired as a result of forming at the closer position to the center of the protosolar cloud. What would this part of the Solar System look like today?

In particular, would the atmospheres of Earth and Venus still be as dramatically different in composition, surface temperature and pressure? Would a repositioned Earth, its climate provoked by twice as much solar irradiance and its atmosphere exposed to a more aggressive solar wind, have developed a climate like that of present-day Venus? Would Venus, left more to its own devices at 1 AU from the Sun, be the planet with plate tectonics and oceans, and the one whose inhabitants were conducting our current explorations? To what extent might the chance formation of Earth's singular moon have broken any potential symmetry?

[4] In seeking to understand questions like this about the formation and initial states of the two planets, and how and by what stages their atmospheres progressed to the presently observed conditions, considerable use is made of the findings of each mission flown to Venus by spacecraft. Many of the measurements still needed (for instance, seismic determinations of the interior structure of Venus) will require substantial investment in new technologies, while other important investigations (such as the history and present activity of volcanism) can be addressed with available techniques. In this paper, we look at the current state of understanding of the atmosphere, interior, and near-space environment of Venus, and the interactions between them that produce the climate at the surface and control its evolution (Figure 1). We review actual and potential progress on these topics, particularly that beginning to be made in the light of new results from the European Venus Express mission [*Svedhem et al.*, 2009], and the important gaps that could be addressed by future planned projects.

[5] The plan of the paper is as follows. Section 2 summarizes briefly what is known about the present-day climate, implicitly defined as the state of the atmosphere, and the main processes thought to be responsible for the energy balance and stability of the system. In section 3, some major topics relevant to possible long-term changes in the stability of the atmosphere are tackled, in particular the state of the interior of Venus, its thermal evolution and consequent resurfacing rates and outgassing into the atmosphere; surface-atmosphere chemical reactions and possible equilibrium states; and the loss processes at the top of the atmosphere, in particular as they concern the history of water on Venus. These are all very uncertain and hard to understand with the current very limited measurement base,

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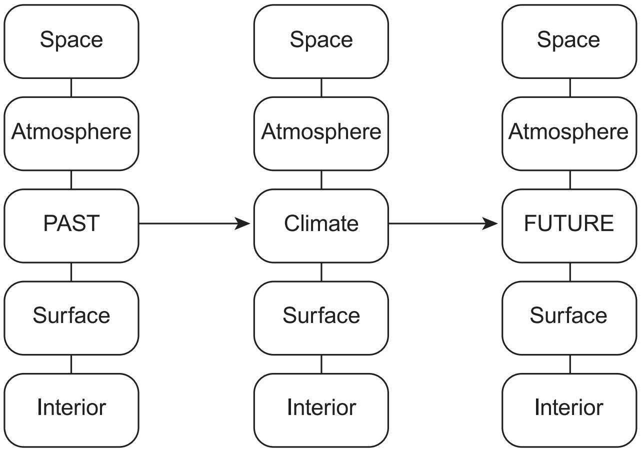

Figure 1. A conceptualization of the problem addressed in this paper and the formidable nature of its long-term goals. The properties and processes in and between the interior, surface, atmosphere, and near-space environment are all known to be important for determining the climate, in particular, the surface temperature. We want to understand these and their interrelationships not only for current conditions, but also throughout time from the formation of the planet to some future state when Venus may become more, or less, Earth-like. Each box in the diagram can be expanded into a range of different disciplines; for instance, the role of the atmosphere depends on its radiative transfer properties, on heterogeneous chemistry involving gas-liquid and gas-solid reactions, and on the circulation and dynamics. A further hidden dimension exists in the form of the same matrix for the Earth, and perhaps Mars also, and their relationship to Venus through common origins and processes.

but incremental advances are made with each successful mission, and Venus Express was developed with the goal of making a key contribution. Section 4 reviews the incorporation of key processes into evolutionary climate models, which, in principle at least, are capable of simulating the present-day climate and showing how this may have developed over the history of the Solar System to date. Such models can also be used, within their limitations, to obtain some idea of how the climate may evolve in the future. A further dimension is added by our wish to understand, within the same physical framework, the important similarities and differences between this climate system and the corresponding one for the Earth (and also Mars and Titan, although we will not consider them in depth here).

[6] The tools at our disposal for Venus climate modeling include not only the fruits of previous Venus missions and studies but also the methods that have been derived as part of the huge contemporary effort to predict the evolution of climate on the Earth. While the current emphasis in the latter is mainly on the very short term, decades to centuries, the similarities in size, composition, internal, and atmospheric processes mean that much of the same physics applies. Important contributions to the surface temperature result from an atmospheric CO_2–H_2O–aerosol driven greenhouse effect, for example, and the input of solar energy to the climate system on each planet is similar. However, the internal processes leading to critical climate elements like volcanism, global tectonics and magnetic field generation seem to be quite different, at least in outcome. New data from missions more advanced and challenging than anything attempted to date will be needed to address these; they are the subject of section 5.

2. Current Atmosphere and Climate

2.1. Historical Background

[7] Before the space age, many astronomers expected that the surface environment on Venus would resemble a more tropical version of the Earth. The Swedish Nobel Laureate Svante Arrhenius wrote nearly a century ago that the surface temperature "is calculated to be about 47°C", compared to an average of around 26°C in the Congo on Earth, and he inferred that the humidity on Venus is about six times higher than on Earth [*Arrhenius*, 1918]. Patrick Moore, in his book *The Planet Venus*, published in 1954, wrote that Venus could be a world in a "Cambrian" state, possibly complete with primitive organisms. At about the same time, however, *Urey* [1952, p. 222] noted that "the presence of carbon dioxide in the planet's atmosphere is very hard to understand unless water were originally present, and it would be impossible to understand if water were present now."

[8] Beginning in 1956 at the U.S. Naval Research Laboratory, Earth-based microwave observations of Venus showed that the planet had an equivalent blackbody temperature of about 575 K. The scientists planning the microwave radiometer to be carried on the first spacecraft mission to Venus, Mariner 2, took this to be the probable surface temperature of the planet and, weighing up all of the available observational and theoretical evidence, planned their experiment around atmospheric models in which the surface pressure ranged from 2 to 20 bars and the composition was 75% CO_2, 24% N_2, and 1% H_2O [*Barrett et al.*, 1961]. The results from the experiment confirmed a high surface temperature [*Barath et al.*, 1964] and the first direct measurements by the lander Venera 4 in 1967 delivered an improved estimate of around 675 K. Modern values for the mean surface temperature on Venus are around 730 K, which is higher than the melting point of the metals lead and tin, with excursions of more than 100 K, due primarily to topography.

[9] Much of our current knowledge of the details of the Venus atmosphere and climate system was accrued by the Pioneer Venus orbiter and entry probe missions of the late 1970s and early 1980s [*Russell*, 1992]. Four probes sounded the clouds and lower atmosphere, returning chemical, physical, and meteorological data on the Venus atmosphere. The orbiter observed the surface of Venus with a radar altimeter and sounded the atmosphere in the infrared and ultraviolet regions of the spectrum. It also provided in situ data on the upper atmosphere, ionosphere and solar wind interaction.

[10] After the Soviet Venera and VEGA missions in the early 1980s (notwithstanding the Magellan surface mapping mission which arrived at Venus in August 1990) there was a gap of 2 decades before another mission with an atmospheric focus was launched. In May 2006 Venus Express became the 28th spacecraft to arrive successfully at Venus since Mariner 2 in 1962, and the first mission to employ the near infrared spectral windows, discovered in the 1980s (see

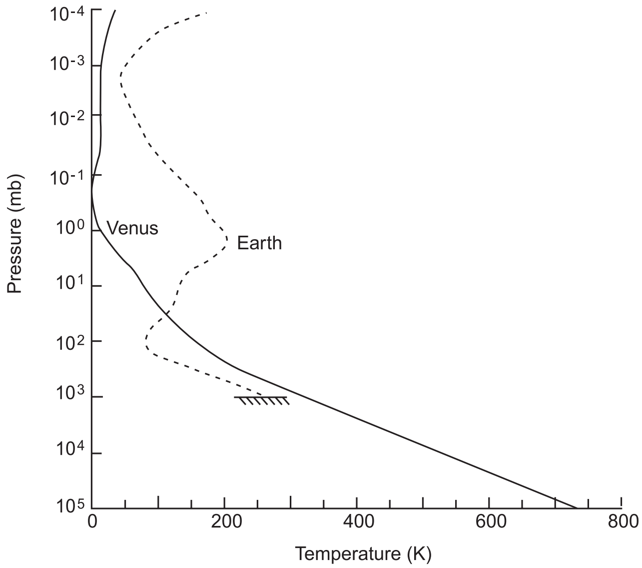

Figure 2. A comparison of measured atmosphere-temperature profiles on Earth and Venus, where the vertical scale is pressure in millibars (1000 mb equals the mean surface pressure on Earth). The solid line is derived from remote sounding measurements made by the Pioneer Venus Orbiter Infrared Radiometer [*Taylor et al.*, 1979a], extrapolated assuming a dry adiabatic lapse rate below 500 mb, and the dashed profile is derived from similar measurements by the Improved Stratospheric and Mesospheric Sounder on the Upper Atmosphere Research Satellite [*Taylor et al.*, 1993].

the review by *Taylor et al.* [1997]) from orbit to carry out systematic remote sensing observations of the Venusian atmosphere below the clouds. Potential climate-related advances and serendipitous discoveries were to be used, inter alia, as a basis for (1) producing improved greenhouse models of the energy balance in the lower atmosphere, (2) validating and improving general circulation models of the atmosphere, with improved treatment of the zonal superrotation, the meridional Hadley circulation, and the polar vortices, (3) generating new climate evolution models using simple physics and chemistry constrained by measurements, and (4) comparative studies in all three areas with the other terrestrial planets including Earth.

2.2. Atmospheric Temperature Structure

[11] The Bond albedo of Venus is around 2.5 times that of Earth (about 0.76 compared to about 0.3), so that Venus absorbs rather less radiative energy than Earth, despite its greater proximity to the Sun. The net effect of this, and the differences in atmospheric composition, is that the temperature profiles for the atmospheres of Earth and Venus are actually quite similar in the range where they overlap in pressure (Figure 2). The main difference is due to the effect of radiative heating in the Earth's ozone layer, which produces a local maximum near the 1 mb pressure level that has no equivalent on Venus.

[12] The remarkably un-Earth-like climate at Venus' surface is a consequence of the fact that the pressure, and hence the temperature, both continue to rise with depth below the 1 bar level. The profile roughly follows the hydrostatic and adiabatic formulae, as would be expected, leading to a temperature increase of about 10 K for each km of depth below the 1 bar level. This amounts to some 450 K altogether at Venus' surface pressure of 92 bars. If the Earth had such a high surface pressure, it too would be extremely hot, even without the increased proportion of greenhouse gases that is found on Venus. About 96% of this is carbon dioxide, which, along with water vapor and other minor constituents, and the net radiative effect of the ubiquitous cloud cover, drives the radiative energy balance at the surface in the direction of elevated temperatures.

[13] Measured temperature profiles for both Venus and Earth conform reasonably well to the predictions of radiative-convective model calculations like those discussed in section 4. This confirms that the processes at work are basically the same in both cases and that, unlike many aspects of the climate on Venus, there are no mysteries, at least to first order. The factor that was so surprising when it was first discovered, the high surface temperature on Venus, is largely a consequence of the large mass of the atmosphere, rather than any mysterious thermal process. As discussed below, the atmospheric bulk may not be too surprising either, provided we can account for the history of water on Venus.

[14] Conditions in the upper atmosphere are crucial for determining loss rates for atmospheric species and hence understanding the composition as a function of time, specifically issues such as the long-term water budget and the evolution of the atmospheric oxidation state and surface pressure. A number of processes are involved: dissociation, ionization, thermal and nonthermal escape, solar wind and cosmic ray erosion, meteoritic and cometary impacts. For determining the nature and extent of current losses, key measurements are temperature and composition as a function of height in the upper atmosphere, and the abundance and distribution of atoms and ions of atmospheric origin in the magnetosphere (Figure 3).

[15] Temperature profiles from 80 to 140 km altitude deduced from stellar occultations observed by the SPICAV instrument on Venus Express, combined with previous measurements, show the maximum temperature (90–100 km), increasing with the value of solar zenith angle. A sharp maximum is seen in the temperature profile near the antisolar point, corresponding to the adiabatic heating expected in the subsolar to antisolar circulation regime that occurs above the mesopause at around 90 km [*Bertaux et al.*, 2007]. Overall, the thermosphere of Venus is cooler than Earth's, because of the greater abundance of carbon dioxide, which is very efficient at radiating heat to space. Above about 150 km, the temperature is approximately constant with height on the dayside at about 300 K. The terrestrial thermosphere is the seat of rapid winds, up to 1000 m s^{-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 day-night difference of around 200 K about a mean temperature of 1000 K. On Venus however, the nighttime temperature in the thermosphere is very low, around 100 K, in contrast to 300 K on the dayside. The transition from the day to nightside values of temperature on Venus also show remarkably steep gradients [*Keating et al.*, 1979] and modelers have great difficulty

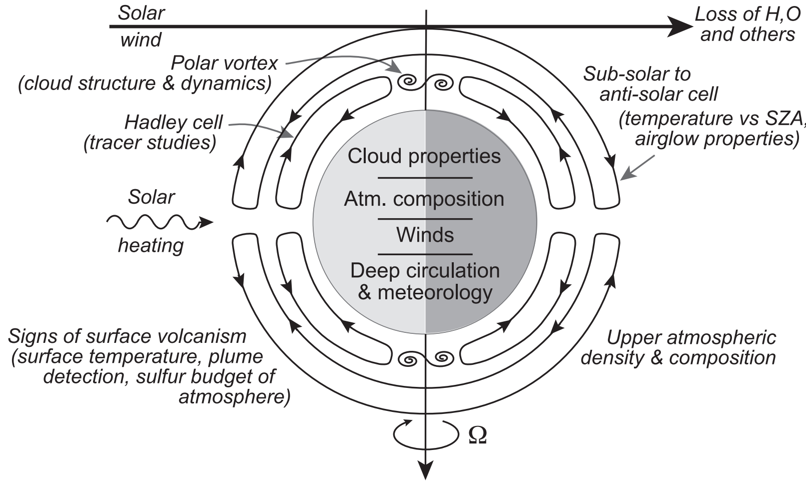

Figure 3. Thermal structure, composition, and cloud measurements have defined the main parameters of the circulation and other key features of the climate system, as illustrated schematically here and discussed in the text.

in reproducing both the minimum temperature and the short distance across the terminator with which it is attained.

2.3. Atmospheric Composition

[16] The primordial atmosphere of Venus that originally formed with the solid body, like those of the other terrestrial planets, will have been lost or radically altered in the distant past as both the young Sun and the hot, postaccretional young planets went through phases of high activity. The present atmosphere would have been produced much later by outgassing associated with volcanism, a process that may still be ongoing on Venus, as it is to some extent on Earth, augmented by the influx of unknown amounts of cometary and meteoritic material. The relative contributions of these distinct sources can, to some extent, be deduced from the data which are gradually being accrued on the composition, and in particular the isotopic ratios, in the contemporary terrestrial planet atmospheres, and in comets and meteorites.

[17] Comets are a rich source of volatile compounds such as carbon dioxide, water vapor, methane, and ammonia. If the last of these was the source of the nitrogen now present, allowing for processes such as the production of argon by the decay of radioactive potassium in the crust, the contemporary atmosphere could all be of external origin. On the other hand, the high abundance of sulfur in Venus' clouds indicates extensive volcanic activity, as discussed below. Volcanoes are also prolific sources of carbon dioxide and the other gases required to explain the present-day climate of Venus, SO_2 and H_2O in particular.

[18] Apart from carbon dioxide and water vapor, Venus' atmosphere consists primarily of inert gases, particularly nitrogen and argon (Table 1). The amount of water present as gas and bound up with sulfuric acid and other compounds in the clouds is roughly one hundred thousand times less than exists in the oceans and atmosphere of the Earth. Thus, assuming most of the primordial water is not retained in the interior, Venus is overall very dry compared to the Earth while, at the same time, deuterium is more than one hundred times more abundant on Venus than Earth. This suggests that large amounts of water have escaped and that, unless the inventory is dominated by nonprimordial sources, Venus had much more water initially [*Grinspoon*, 1993; *Donahue*, 1999]. Loss takes place by dissociation of the water in the upper atmosphere by solar ultraviolet radiation, and the subsequent escape of the hydrogen. Both deuterium and normal hydrogen escape from the atmosphere, but the heavier isotope escapes less efficiently, leading to the observed fractionation.

[19] The loss rate of the water depends strongly on its abundance in the relatively cool middle atmosphere, as well

Table 1. Composition of the Atmospheres of Venus and Earth as Fractional Abundances Except Where Parts Per Billion Is Stated[a]

Species	Venus	Earth	Climate Significance
Carbon dioxide	0.96	0.0003	Major greenhouse gas
Nitrogen	0.035	0.770	Similar total amounts
Argon	0.00007	0.0093	Evolutionary clues
Neon	0.000005	0.000018	Evolutionary clues
Water vapor	0.000030	∼.01	Volcanic, cloud, greenhouse
Sulfur dioxide	0.00015	0.2 ppb	Volcanic, cloud, greenhouse
Carbonyl sulfide	0.000004		Volcanic, cloud
Carbon monoxide	0.00004	0.00000012	Deep circulation
Atomic oxygen	trace	trace	High circulation, escape processes
Hydroxyl	trace	trace	High circulation, escape processes
Atomic hydrogen	trace	trace	Escape processes

[a]All except the noble gases argon and neon are observed by Venus Express instruments.

as the intensity of the solar ultraviolet flux. Models of the process suggest, with considerable uncertainty however, that Venus could have lost an ocean of present-day terrestrial proportions in only a few hundred million years [*Kasting et al.*, 1984]. Such potentially important processes as cloud-albedo feedback in the water-rich early atmosphere have yet to be included in models of early water loss from Venus. The oxygen produced at the same time is too massive to escape at any significant rate, according to Jeans' formula, and would remain on the planet, presumably most of it bound chemically within the crust, if thermal escape were the only process available to remove it. However, recent results from the ASPERA instrument on Venus Express show that oxygen is escaping at a rate nearly half that of the hydrogen escape flux, suggesting that large amounts of O could have escaped over time through nonthermal processes. So long as liquid water remained available, the formation of carbonates would remove atmospheric carbon dioxide efficiently, as it does on the Earth. Once the surface water was gone, the mixing ratio of water vapor in the upper atmosphere would have fallen sharply and the loss rates of both forms of hydrogen, and the take up of oxygen into minerals, would have begun declining toward the present relatively low levels. With the loss of water, the removal mechanism for CO_2 would be eliminated, and carbonate rocks on the surface would presumably eventually be subducted and lost to thermal decomposition, with the CO_2 being irreversibly returned to the atmosphere through outgassing.

[20] In the modern atmosphere of Venus, chemical cycles coupled with transport and radiative processes control the abundances of the minor constituents. The most important are the cycles involving water vapor, sulfuric acid, and their products, which maintain the cloud layers and probably also involve reactions between the atmosphere and the surface. Another is the sequence that gives rise to the observed distribution of carbon monoxide. CO is very abundant (mixing ratios on the order of a few parts per thousand by volume) in the upper atmosphere of Venus, as would be expected from the action of solar ultraviolet radiation on carbon dioxide. It is strongly depleted in the cloud layers (<1 ppmv), again not too surprisingly, since it is involved in reactions with SO_2 and the other species that make up the sulfur cycle. Below the clouds, and near the surface, however, the carbon monoxide value recovers to an average value of around 30 ppmv, but with a marked decline from pole to equator. The reason for the gradient may be that CO is transported rapidly down from the thermosphere in the polar vortices and the poleward branch of the Hadley circulation, to the troposphere where it is gradually removed by reactions in the hot lower atmosphere and at the surface.

[21] The issue of the bulk abundances of water and carbon dioxide, where Venus appears to have lost most of the former but, as a result, retained in its atmosphere much more of the latter, is of primary importance. Without liquid water, many of the weathering processes that affect, and possibly stabilize, the climate on the Earth [cf. *Walker et al.*, 1981] would not operate. The relatively small amounts of water and other hydrogen containing species that exist as vapor above, within, and below the clouds, plus an unknown quantity bound up with sulfuric acid and probably other compounds in the liquid or solid cloud particles themselves, can reveal, through their abundance and distribution, key production and loss processes, act as tracers of the dynamics, and define the cloud chemistry.

[22] Other potential, and poorly quantified reservoirs for planetary water include hydrated minerals in the crust and the interior. The indications from spectroscopic and entry probe data are that the H_2O abundance is fairly constant across the globe near the surface, but highly variable in the clouds and above [*Bezard et al.*, 2009]. The water vapor measurements prior to Venus Express above, below and within the cloud layers show a baffling disparity that is presumably, by analogy with Earth, linked to cloud formation and dissipation processes and meteorological activity in Venus' atmosphere [*Ignatiev et al.*, 1999; *Koukouli et al.*, 2005]. Systematic new measurements from the Venus Express extended mission, sounding within and below the clouds for the first time, could radically improve our understanding of these.

[23] Several of the other minor constituents in Venus's atmosphere also exhibit striking amounts of temporal and spatial variability, with hints of terrestrial analogies that can be followed up with new data. During the Galileo flyby in 1991, near infrared measurements revealed an equator-to-pole gradient in the abundance of tropospheric carbon monoxide [*Collard et al.*, 1993], which *Taylor* [1995] showed was unlikely to be volcanic in origin but could be the result of a hemispherical Hadley circulation that extended from the lower thermosphere at around 100 km all the way down to the surface. While the Galileo data had large uncertainties and limited latitude coverage, early Venus Express data [*Tsang et al.*, 2008] are confirming the equator-to-pole gradient seen by Galileo and has revealed the symmetry between hemispheres we would expect on a planet without seasons if the dynamical explanation is correct. Measurements of the seasonal CO profile on the Earth show a related similar effect, known to be due to the descent of air rich in CO from CO_2 dissociation in the mesosphere. The main differences from Venus are the generally smaller CO abundances, and the fact that enhanced values are found on Earth only over the winter pole, since the terrestrial vortex breaks up in the summer.

2.4. Clouds and Radiative Balance

[24] Enough sunlight diffuses through the cloud layers on Venus to provide about 17 W per m^2 of average surface insolation, about 12% of the total absorbed by Venus as a whole when the atmosphere is included [*Crisp and Titov*, 1997; *Titov et al.*, 2007]. Most of the energy deposited at depth cannot escape as long-wave radiation but must instead be raised by convection along an approximately adiabatic temperature-pressure profile to a level near the cloud tops where it can radiate to space. An airless body with the same albedo and heliocentric distance as Venus would reach radiative equilibrium at a mean surface temperature of only about 230 K. This is close to the actual temperature at the Venusian cloud tops, as we should expect if they are the most important source of thermal infrared opacity in the tropopause region. Global measurements by the Pioneer Venus Orbiter of the net infrared emission and the total reflected solar energy [*Schofield and Taylor*, 1982] confirmed that the planet is in overall energy balance to within

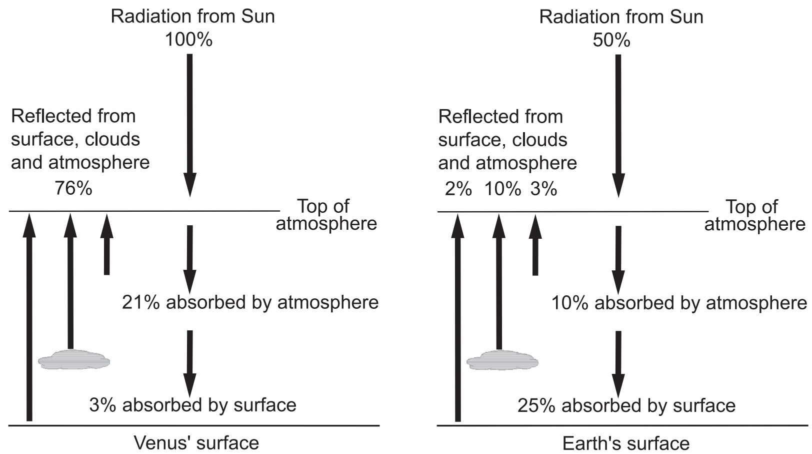

Figure 4. The different components of the radiative energy budgets of Venus and Earth are shown as planet-wide averages, taking the solar irradiance at Venus as 100% and Earth as half that. (Actually, the insolation at Earth relative to that at Venus varies between 50% and 55% when the orbital eccentricities of 0.0167 and 0.007, respectively, are taken into account.)

the accuracy of the measurements, limited by incomplete spectral and spatial coverage.

[25] On Earth, half of the radiant energy from the Sun is deposited at the surface (50%), with smaller proportions absorbed in the atmosphere (20%) or reflected back into space (30%). On Venus, however, the proportions are more like 3%, 21%, and 76% respectively, with the bulk of the energy absorbed by the planet deposited well above the surface in the principal cloud layers (Figure 4). In an energy balance calculation for the planet as a whole these values lead to an equilibrium temperature of about 230 K for Venus and 250 K for Earth, depending on the values taken for the hemispherical Bond albedo in each case, a number which is quite uncertain even for Earth. Elaborate schemes have been proposed for measuring the total energy reflected and emitted from Earth to obtain an improved value and to monitor its variability and trends as a key component of climate research. Despite the fact that this is a difficult measurement, requiring multiple spacecraft in different orbits to do it properly, a similar project for Venus would be very valuable. It could also settle the question of whether any significant part of the high surface temperature is attributable to the release of heat from the interior, in the event (thought unlikely, but not known) that this release is enormously greater for Venus than for Earth. Interior heat release cannot, in any case, be the dominant influence in surface temperature, because of the constraints placed by the energy balance measurements mentioned above.

[26] Other key differences between Venus and Earth concern the composition, microstructure and optical properties of the different types of cloud [*Esposito et al.*, 1997]. This is a major research topic for the Earth, where climate change projections depend crucially on understanding the role of different cloud types and how they may change along with temperature, circulation, and pollution loading of the atmosphere. On Venus, corresponding studies are of course at an earlier stage, but are likely to be just as crucial for understanding the climate and its evolution. It is already clear that Venus has more than one type of cloud, with the distribution depending on depth, latitude and time [e.g., *Titov et al.*, 2008; *Wilson et al.*, 2008]. The absence of major seasonal variations in the incoming radiative flux on Venus is in contrast to the Earth and another factor that needs to be taken into account.

2.5. Circulation and Dynamics

[27] As is now well known from studies of terrestrial climate change, including the most recent ice ages, variations in the circulation regimes in the atmosphere and oceans of Earth can lead to significant variations in surface temperature. Whether there is any important analog to this type of behavior on Venus is not known, but variations in cloud structure and winds are clearly seen in early Venus Express observations and their interpretation in terms of general circulation models that include the dense and in some ways ocean-like lower atmosphere, is a topic of considerable importance that is being addressed by groups in several different countries.

[28] The first-order differences between the atmospheric general circulation regimes on Venus and Earth can be explained by the differences in the rotation rates of the solid bodies and in the optical depths and masses of their atmospheres [*Rossow*, 1985; *Gierasch et al.*, 1997; *Schubert et al.*, 2007]. The relative unimportance of Coriolis forces on Venus allows a single Hadley cell to extend much closer to the pole than on Earth, apparently reaching right to the edge of the polar vortex without the intermediate Ferrell cell. Carbon monoxide measurements in the deep atmosphere by the NIMS experiment on the Galileo spacecraft [*Collard et al.*, 1993], and now by Venus Express [*Tsang et al.*, 2008], are consistent with a deep Hadley circulation on Venus that extends from well above the clouds to the surface, and from the equator to the edge of the polar vortex (Figure 5).

[29] Vortex behavior occurs in the polar region of any terrestrial planet, owing to general subsidence of cold, dense air and the propagation of zonal angular momentum in the meridional flow. On Venus, the small obliquity and the large superrotation lead to an extreme version of this effect, manifest by a sharp transition in the circulation regimes in both hemispheres at a latitude of about 65°. There, the

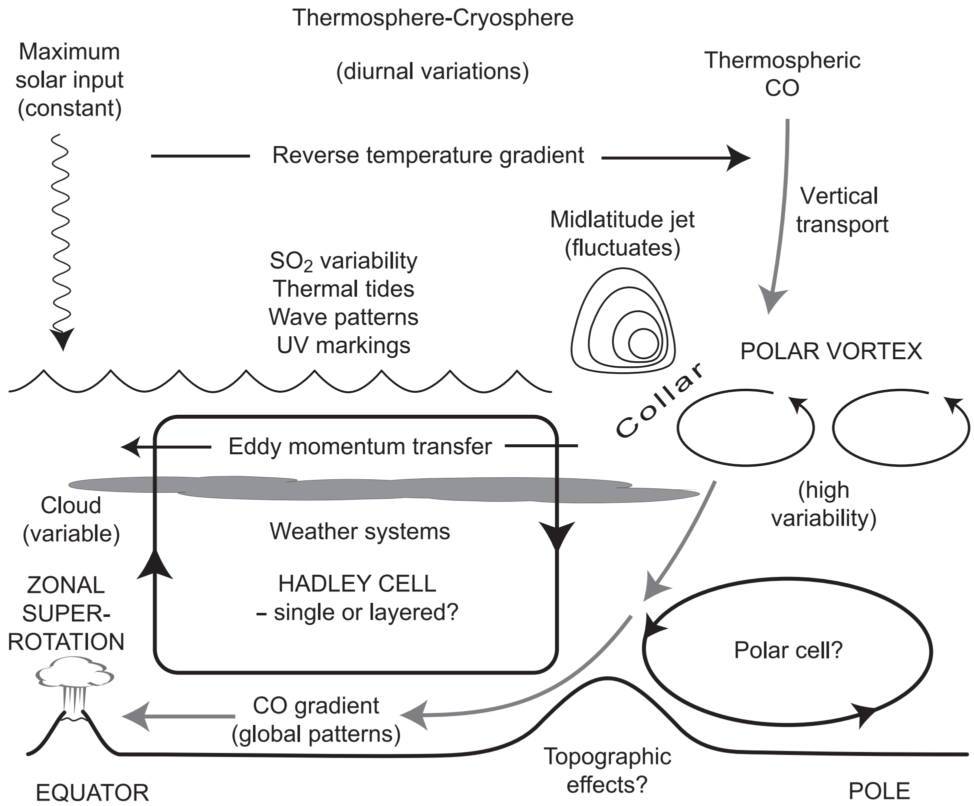

Figure 5. Some of the global-scale meteorological features observed on Venus that may be coupled to the general circulation and affect the climate.

Hadley cell stops and we find the circumpolar collar, a belt of very cold air that surrounds the pole at a radial distance of about 2500 km and has a predominantly wave number 1 structure locked to the Sun [*Taylor et al.*, 1980]. The vertical extent of the collar must be much less than its 5000 km diameter, and the indications from Pioneer Venus and early Venus Express data are that it may be only about 10 km deep, with a complex vertical structure [*Piccioni et al.*, 2007]. The temperatures that characterize the collar are about 30°C colder than at the same altitude outside, so the feature generates pressure differences that would cause it to dissipate rapidly were it not continually forced by some unknown mechanism.

[30] Inside the collar, the air at the center of the vortex must descend rapidly to conserve mass, and we expect to find a relatively cloud-free region at the pole, analogous to the eye of a terrestrial hurricane but much larger and more permanent. Interestingly, however, the ''eye'' of the Venus polar vortex is not circular but elongated, and with typically two brightness maxima (possibly corresponding to maxima in the downward flow) at either end of a quasi-linear feature connecting the two. This wave 2 characteristic gives the polar atmosphere a ''dumbbell'' appearance in infrared images that use the thermal emission from the planet as a source, and has led to the name polar dipole for the feature. A dipole was first seen at the north pole by Pioneer Venus [*Taylor et al.*, 1979b], and now a similar feature has been discovered and extensively studied at the south pole as well by Venus Express [*Piccioni et al.*, 2007]. The northern dipole was observed in successive images obtained in 1979–1980 to be rotating about the pole with a period whose dominant component, among several, was 2.7 Earth days [*Schofield and Diner*, 1983], i.e., with about twice the angular velocity of the equatorial cloud markings. If angular momentum were being conserved by a parcel of air as it migrated from equator to pole the dipole might be expected to rotate five or six times faster. In fact, the ultraviolet markings are observed to keep a roughly constant zonal velocity (solid body rotation) from the equator to at least 60° latitude, and must be accelerating poleward of this if the rotation of the dipole represents the actual speed of mass motions around the pole and not simply the phase speed of a wavelike disturbance superimposed on the polar vortex. At the time of writing, many new details of the dipole collar structure are emerging from Venus Express VIRTIS maps, soundings, and movies that must, after detailed analysis, reveal much more of its true nature. In particular, it has become clear that the ''dipole'' description is too simplistic: more complicated shapes, as well as monopoles and tripoles, also occur, with remarkably rapid (for such a large feature) morphing between them, although wave 2 does seem to dominate as some theories [e.g., *Elson*, 1982] expect.

[31] The thermal tide on Venus around the equatorial regions also has two maxima and two minima. This may not be directly connected with the polar phenomenon, since the two regions are separated by a narrow latitude band apparently free of planetary-scale waves, as well as by the predominantly wave number one collar. The Earth's atmosphere has a small wave number two component superposed

on the familiar early afternoon maximum to postmidnight minimum cycle, but this component dominates on Venus. In fact the dynamical theory of atmospheric tides, as developed for Earth, shows when applied to Venus that the observed state of affairs can be explained as primarily a consequence of the long solar day on Venus [*Fels et al.*, 1984].

[32] The tracking of meteorological features on Venus was, for many decades, limited to the transient and quasi-permanent features seen in the ultraviolet images of the cloud top region, where they revealed structures identified with Rossby and gravity wave activity [e.g., *Belton et al.*, 1976]. In the mid-1980s, this changed with the discovery of the near-infrared windows, which permitted imaging of the deep cloud structure (see the review by *Taylor et al.* [1997], and references therein). The spectral imaging instruments on Venus Express have exploited this to investigate the meteorological activity that is clearly present in the deep atmosphere of Venus, revealing chaotic convective and wave activity near the equator where most of the solar energy is deposited in the clouds, with an abrupt switch to a more laminar flow at midlatitudes, and then finally a further transition to the polar vortex complex near the poles [*Markiewicz et al.*, 2007; *Sanchez-Lavega et al.*, 2008].

3. Processes Affecting Atmospheric Evolution

3.1. Internal Structure and Thermal Evolution

[33] As already noted, Venus is generally taken to have essentially the same internal structure as the Earth. Venus certainly has a metallic core, which may however be slightly smaller than Earth's given the difference of a few percent in mean density, and may be in a different physical state. The latter could account for the apparent absence of dynamo action, as evidenced by the lack of an intrinsic magnetic field, although the details are obscure. For understanding atmospheric evolution, the key questions are (1) if Venus had a planetary magnetic field in the past, for how long, and whether it might again have one in the future, and (2) what mechanisms are primarily responsible for the removal of heat from the interior? The first of these has a key role to play in determining the rate at which atmospheric gases including, crucially, water vapor, have escaped owing to solar wind erosion. The second is related to the history of volcanic activity on Venus and the venting of gases from the interior into the atmosphere.

[34] On Venus, where lithospheric temperatures are higher than on Earth, and large excursions in surface temperature are apparently possible, the thermal evolution of the interior may even be influenced by changes in climate. If this leads to changes in the mechanisms or efficiency of heat release or outgassing, then interesting feedbacks between climate and interior evolution could potentially result [*Grinspoon*, 1997; *Solomon et al.*, 1999].

[35] *Phillips et al.* [2001] investigated climate-interior coupled evolution models for Venus by merging a partial melting/parameterized mantle convection model with a gray radiative-convective atmospheric model. They found that positive feedback can operate by the release of water to the atmosphere via mantle melting, leading to an increase in atmospheric thermal opacity and radiative temperature gradient. The amplification of the greenhouse effect raises surface and mantle temperature, leading to an increase in the partial melting rate. These very simple models demonstrate the potential for a long-term, complex interplay between the interior evolution and climate.

[36] It is likely to be some time before we have direct measurements of the heat flow in the crust of Venus. The Pioneer Venus Orbiter measurements of the albedo and of the heat flux from the top of the atmosphere into space, over a large but incomplete range of latitude, longitude, wavelength, and solid angle, showed that the planet as a whole is in radiative balance with the Sun to within about ±15%. This is not surprising, of course, since geothermal sources on the Earth account for only about 1 part in 5000 of the energy radiated to space, and most origin and interior models show Venus and Earth containing essentially identical heat sources. The difficulty comes when trying to explain how a terrestrial-like heat flux might be transferred from the interior to the atmosphere on Venus in the absence of plate tectonics, which plays this role on the Earth. On the basis of geochemical arguments, specifically the reaction of SO_2 with calcite, $CaCO_3$, on the surface, *Fegley and Prinn* [1989] argued that the answer cannot be primarily through volcanoes since, although Venus does show very extensive signs of volcanic activity, the atmosphere would have to be even richer than it is in volcanic gases like SO_2 at present if this was the principal, steady state mechanism.

[37] Simpler calculations based on heat flow, and which do not depend on assumptions about the composition and chemical state of Venus' surface, do seem to add up, however. A long-term study of volcanic output on the Earth produced a number of 4×10^{10} W for the mean flux of energy from volcanoes, equal to about 0.1% of the total heat flux from the Earth's interior [*Pyle*, 1995]. If Venus has the same total flux but it is all accounted for by volcanoes, then we would expect 1000 times as much gas, in particular sulfur dioxide, to be released. In fact, there is approximately 100,000 times as much SO_2 in Venus' atmosphere compared to Earth's, but this could be explained by the fact that this is also the ratio of the lifetimes of the gas on the two planets when the efficient rain out mechanism that applies only on Earth is taken into account. Loss on Venus is principally by the much slower process of conversion to sulfuric acid.

[38] Clearly, the uncertainties in the above argument can only be resolved with much more data on surface composition, atmospheric chemistry, and volcanic activity on Venus. Meanwhile, the other major possibility to be considered for heat loss from the interior is one in which the rigid lithosphere below the surface on Venus is relatively thin, 45 km or less on average [*Schubert et al.*, 1997], so that conduction can transfer heat at the necessary rate, which it could not if the layer were thicker. However, Magellan observations of structures on the surface, like the massive Maxwell Montes, are inconsistent with such a thin solid crust unless there are large spatial or temporal variations in lithospheric thickness, with Maxwell and other uncompensated structures representing the areas of maximum thickness or of high plume activity.

[39] Volcanism on Venus may release a different mix of gases from Earth (where each volcano is at least slightly different from every other, in any case) and determining the amount or composition of a volcanic contribution to the atmosphere may provide clues to the internal dynamics. For

example, the idea that a resurfacing around 0.5 Ga ago was related to the transition from upper mantle convection to whole mantle convection implies the release at that time of gases that were trapped in the lower mantle 4.5 Ga ago. Models that predict the implications of such an event on Venus' atmosphere composition may be constrained by the measurements made by VIRTIS and SPICAV on Venus Express [*Svedhem et al.*, 2007].

[40] The observed abundances of atmospheric gases such as SO_2 and H_2O put some rough constraints on the resurfacing rate, although a quantitative study would require assumptions or petrologic calculations of the composition of Venusian volcanic gases, which is not known. The existence of SO_2 and H_2SO_4 in the amounts already seen requires some level of outgassing in the last 30 Ma [*Bullock and Grinspoon*, 2001], and with some reasonable assumptions for the sulfur content of volcanic gases and the volume of intrusive versus extrusive volcanism, this can lead to a specific derivation of lava flux. Thus, SO_2 and H_2O measurements, and the flux required for the maintenance of the thick global cloud deck, may provide a crude lower limit, and infrared surface maps a crude upper limit, on resurfacing rates, which can then be linked to interior models and histories.

3.2. Volcanism and Volcanic Emissions

[41] Atmospheric composition and chemistry models based on accurate data about the history and current level of volcanism on Venus are essential for understanding the current climate, and measurements that provide at least reliable estimates are being sought urgently, from Venus Express in the first instance. At the present time, the flux of volcanic gases into the atmosphere remains unknown, and could conceivably be as low as zero, although that seems very unlikely as it would require, among other adjustments, major revision in contemporary understanding of the sulfur cycle and the provenance of cloud aerosols. The evidence for volcanism on Venus is threefold: (1) the abundance of pristine volcanic structures seen on the surface; (2) the high level of volcanic gases, primarily sulfur containing, and especially SO_2; (3) constraints on overall thermal and geological evolution provided by analogy with the Earth.

[42] The global radar images obtained to date, especially from the Magellan mission, reveal thousands of volcanic features covering most of the surface of Venus. In addition to over 150 large shield volcanoes, with lava flows that often extend for hundreds of kilometers, intermediate-sized volcanic features are seen in large numbers and categorized as anemones, ticks, arachnids, etc. depending on their appearance. In many places, large numbers of small domes or vents are clustered together to form shield fields that collectively cover an area of more than 10,000 km^2. There are hundreds of these on Venus, some with extensive lava flows surrounding them, while others are located within tectonic structures. Finally, around a hundred volcanic calderas have been identified on Venus, which are apparently sources of lava flows but not associated with cones or domes [*Head et al.*, 1992].

[43] Unless they can be observed in the act of changing, the volcanoes and lava flows on the surface of Venus are difficult to date with any precision because the usual method of crater counting is unreliable, as discussed in section 3.3. The high sulfur content of the atmosphere, including the H_2SO_4 clouds, is on the other hand a powerful indicator of current, or geologically recent, activity, since gases like sulfur dioxide have a short lifetime in the atmosphere before they are removed by interaction with the surface. The latest values for the deep atmosphere abundance of SO_2 from VIRTIS on Venus Express are about ~180 ppm [*Belyaev et al.*, 2008], which is more than 2 orders of magnitude too high to be at equilibrium with the surface [*Fegley et al.*, 1997], a problem which does not exist for CO_2. The time constant for the decline of the sulfur abundance in the atmosphere if the source was removed is in the range 1–10 Ma [*Fegley and Prinn*, 1989], much shorter than the period since the hypothetical global resurfacing event 500 Ma ago, indicating that the atmospheric sulfur must be of recent origin.

[44] Pioneer Venus ultraviolet spectra from the first 5 years of operation show a decline by more than a factor of ten in sulfur dioxide abundance at the cloud tops, accompanied by a fall in the amount of submicron haze above the clouds [*Esposito*, 1984]. Venus Express SPICAV has also detected large, short-term variations in SO_2 near the 100 km altitude level [*Belyaev et al.*, 2008]. While it is not possible at present to associate these with specific eruptions on the surface, and transport effects due to local meteorology are probably a more likely cause at this great height, it is certainly true that large SO_2 variations are noted in the terrestrial upper atmosphere following large eruptions. For instance, the injection of an estimated 20 million tons of SO_2 into the stratosphere by the eruption of Mount Pinatubo in the Philippines in 1991 left localized contrasts of more than ten times the mean abundance, even 100 days after the event [*Read et al.*, 1993].

[45] The mean volcanic flux of carbonic gases, mostly CO_2, into the Earth's atmosphere is estimated to be 2.4×10^{11} kg a^{-1} [*Sigurdsson and Laj*, 1992], while the mass of sulfur compounds is 20 times less, 1.2×10^{10} kg a^{-1}. *Frankel* [1996] reports that a single large eruption like that of El Chichon in 1982 emits 6 million tonnes of SO_2 per day, adding up to around 200 million tonnes (and possibly a similar amount of chlorine) over the main phase of the event. The fluxes for Venus may be much larger, in light of the evidence of extensive volcanism revealed in the Magellan maps of the surface, the high and variable concentrations of sulfur compounds in the atmospheric gases and clouds, and the apparent absence of plate tectonics to provide an alternative means to release heat from the interior. Until more progress is made to quantify the volcanic input to the atmosphere, its role in the climate, past, present and future, remains hard to estimate.

[46] Measurements from spectroscopic instruments on orbiters like Venus Express, and by the Near-Infrared Mapping Spectrometer on the Galileo spacecraft which observed Venus during a flyby in 1990 [*Hashimoto et al.*, 2008], can help to constrain estimates of Venus' internal activity and investigate current volcanic emissions by searching for evidence of plumes from active vents containing high concentrations of sulfurous or other volcanic gases. Water vapor or carbon monoxide might be equally good tracers for this purpose. Unfortunately, the spectral plume detection objective has been made more difficult by the loss of the high-resolution Planetary Fourier

Spectrometer instrument at the outset of the mission. A different approach involves searching for hot spots on the surface that might be fresh lava fields by mapping the thermal emission in the infrared bands that see the surface. Even a negative observation can help constrain the nature of geologic activity on Venus by providing an upper limit on the current rate of volcanism. Simulations by *Hashimoto and Imamura* [2001] showed that a lava flow covering 100 km^2 or more, at a temperature of ~915 K or more, could in principle be detectable by surface mapping in the near infrared spectral windows near 1 μm, if it can be distinguished from atmospheric opacity variations (due mainly to cloud) and from surface elevation and emissivity effects.

[47] Observations have been made with the VIRTIS instrument on Venus Express through atmospheric windows at 1.02, 1.10 and 1.18 μm. While the source of most of the spatial variations seen clearly arise from topographically mediated surface temperature differences, careful declouding of the images and comparison with Magellan topography maps has begun to reveal some residual anomalies in surface emissivity which are believed to be related to composition. *Helbert et al.* [2008] found that emissivity variations observed in the Lada Terra region are correlated with surface geology, and that positive emissivity anomalies appear to be associated with relatively young lava flows, whereas negative anomalies seem to be found in more heavily fractured, and probably older, terrains. *Hashimoto et al.* [2008] also report compositional variability of surface units, with the highlands being more felsic (having a high silica content, as opposed to mafic or iron-rich minerals) than the lowlands, which they suggest implies large reservoirs of water in Venus's distant past prior to the global resurfacing event. Further observations of this type with the Venus Express extended mission may help to clarify the resurfacing history.

[48] Because the radiative balance of Venus depends sensitively on the abundances of several trace volcanic gases, including SO_2 and H_2O, and on the properties of the global cloud deck, itself a by-product of volcanogenic SO_2 and H_2O, the resurfacing history is probably linked to geologically forced climate change in Venusian history.

3.3. Resurfacing History

[49] Over the past 15 years, developments in unravelling the geological history of Venus, primarily from the cratering record as revealed by the 1989–1994 Magellan mission, have permitted quantitative assessments of the magnitude and timing of sources of volcanically derived gases to the atmosphere [e.g., *Bullock et al.*, 1993; *Bullock and Grinspoon*, 1996; *Kreslavsky and Head*, 1999]. The surface is 80% covered by various types of volcanic plains [*Basilevsky and Head*, 1998], and the cumulative crater count of approximately 1000 indicates an average surface age of 700 ± 300 My [*McKinnon et al.*, 1997]. Thus, the Magellan data set shows clearly that most of the planet has been volcanically resurfaced within the last billion years, raising the possibility that the transfer of heat, as well as of lava and atmospheric gases, is episodic rather than quasi continuous [*Turcotte et al.*, 1999]. If this is so then the climate on Venus may also have significant periodic variations driven by changes in atmospheric composition, density, and cloud properties.

[50] The spatial distribution of impact craters is indistinguishable from a random distribution, suggesting that, to first order, the plains areas of Venus are of uniform age [*Schaber et al.*, 1992; *Strom et al.*, 1994]. However, the small total number of craters and, in particular, the absence of small craters (less than 4 km across) due to atmospheric filtering of the smaller impactors makes age dating of discrete areas impossible and has led some researchers to question the conclusion of uniform age [*Campbell*, 1999]. Most of the craters are in a pristine state, with only a small percentage showing signs of tectonic (7%) or volcanic (33%) modification or embayment [*Schaber et al.*, 1992]. This supports the conclusion that the ages of the plains are highly uniform and that the global resurfacing happened on a very short time scale relative to the cratering age, with a production population of mostly unaltered craters forming after an early burst of resurfacing faded [*Bullock et al.*, 1993; *Basilevsky and Head*, 1996, 1998, 2000, 2002, 2003, 2006].

[51] An alternative view has been proposed in which volcanism has been random in space and time [*Guest and Stofan*, 1999; *Addington*, 2001]. Intersection relationships among sets of wrinkle ridges have been interpreted as suggesting that the regional stress domains that produced them differ significantly in age [*McGill*, 1993], in contrast to the view that much of the plains deformation was globally coherent [*Bilotti and Suppe*, 1999; *Solomon et al.*, 1999]. *Herrick and Sharpton* [2000] found on the basis of stereo-derived topography of Venusian impact craters that the number of unmodified craters may have been previously underestimated, which could lead to an underestimation of the resurfacing rate over the past several hundred My. An analysis of resurfacing rates and styles based on an assessment of 18 mapped Venusian quadrangles suggests a global resurfacing history more complex than that advocated by *Basilevsky and Head* [1996], with a wide range of volcanic styles occurring throughout a period of Venusian history with a duration that is likely to exceed 100 My [*Stofan et al.*, 2005]. The latter researchers, however, conclude that the lack of ancient impact basins implies planet-wide resurfacing by lava to depths of at least 1 km.

[52] Although individual features cannot be reliably dated, several researchers have attempted to derive relative ages of different terrain and feature types, using the fact that the cumulative area of these spatially discontinuous features is sometimes large enough for more meaningful cratering statistics. This technique relies on the extreme assumption that the formation ages of similar features are identical. However, even if this assumption is not strictly true, the technique may still detect real trends in age relationships that would otherwise be invisible to our current arsenal of observational techniques. Large shield volcanoes appear to have fewer impact craters and therefore have been interpreted to be on average younger than the plains [*Namiki and Solomon*, 1994], and the highly deformed tesserae are most likely the oldest terrain on the planet [*Ivanov and Basilevsky*, 1993]. *Price and Suppe* [1994] and *Price et al.* [1996] estimated average ages of (1.1 ± 0.1) T for the ridged and shield plains, (0.3 ± 0.2) T for large volcanoes, and (0.5 ± 0.3) T for lobate and smooth plains, where T is the average crater retention age of the entire planet's surface.

[53] Other researchers have used the state of preservation of impact craters and superposed aeolian features such as parabolic and circular halos around craters to infer chronology [*Izenberg et al.*, 1994]. Dark parabolas, often extending several tens of crater diameters, are most likely due to the dispersion of impact generated fine particles that become entrained in the superrotating winds. *Izenberg et al.* [1994] concluded that owing to either continuing aeolian activity or weathering, the dark parabolas become dark and then light halos. They inferred that dark parabolas have ages of less than 0.1 to 0.15 *T*, and that dark halos around craters are between 0.5 and 0.1 *T* in age. Craters with no halos are older that about 0.5 *T*. *Phillips and Izenberg* [1995] suggested that dark halos are removed by volcanic, and other endogenic, processes. They observed that (presumably older) areas of high crater spatial density also have high fractions of halo-free free craters. They also found more halo-free craters in some regions of low crater spatial density, especially in the Beta-Atla-Themis region, which has a relatively high fraction of modified craters, suggesting more recent geological activity. *Basilevsky and Head* [2003] have also applied the prevalence of radar-dark deposits associated with craters in some areas to the dating of relatively recent surfaces and structures.

[54] The plains of Venus are almost entirely lacking in severely embayed craters: those which are completely flooded except for the crater rim, in contrast to say, the lunar maria, where such features are common. Those severely embayed craters that do exist are shown to have been flooded by flows from discreet volcanic edifices that most likely postdate the formation of the plains. If one accepts that the majority of impact craters, while perhaps showing some minor degree of volcanic modification, do not predate the plains volcanism which resurfaced most of the planet in the last 300–1000 My, then it is clear that, regardless of the (still contentious) details, the rate of resurfacing has declined precipitously over this time period. Several of the analyses described above support the view that the resurfacing activity peaked strongly within 10 to 100 million years of the mean surface age. Clearly, further detailed observations, both orbital and in situ, are required before the history of resurfacing and volcanic outgassing on Venus can be confidently known.

3.4. Geological Constraints on Atmospheric Evolution

[55] To first order, a plausible explanation for the apparent superabundance of CO_2 on Venus relative to Earth is not particularly difficult to find. It has been estimated that the carbonate rocks on the Earth hold the equivalent of roughly 60 bars of CO_2 [*Kasting*, 1988], but since a volcanic source has clearly been active on Venus and since the conversion of atmospheric to crustal carbonate occurs much more efficiently in the presence of liquid water to dissolve the CO_2 first, the relatively water-depleted state of Venus may be responsible for so much of the gas remaining in the atmosphere. However, Venus has not always been so dry. The evidence from the D/H ratio, plus the cosmogonical argument that Venus should have accreted with similar amounts of H_2O to the Earth, both suggest that Venus, too, was once covered by oceans to a considerable depth. How long this state survived is not known; nor is the abundance of carbonates in the component of Venus' crust that is, or has been, in contact with the atmosphere and hydrosphere [*Donahue et al.*, 1997]. As noted above, some or all of any carbonate formed in the early stages could have been recycled into atmospheric CO_2 by high-temperature thermal processes during subduction of the crust.

[56] However, the crucial question of whether the current surface pressure on Venus is stable remains an interesting and important one. It is well known that the CO_2 abundance in Earth's atmosphere can vary, owing to natural and anthropogenic factors, and that it is increasing at the present time, with likely consequences for the global climate. Over time scales greater than 10^6 years, the terrestrial CO_2 abundance is regulated by the carbonate weathering cycle, and has gradually decreased over billions of years as the Sun's main sequence brightness has increased [*Walker et al.*, 1981]. If the climate on Venus is stable in the long-term then it is likely that some mechanism provides a buffer that stabilizes the atmospheric carbon dioxide content. Since *Urey* [1952] proposed the exchange between atmospheric CO_2 and common minerals in the surface, it has been shown that the reaction ($CaCO_3$ (calcite) + SiO_2 (quartz) $\leftrightarrow$ $CaSiO_3$ (wollastonite) + CO_2) reaches equilibrium at precisely the temperature and pressure found on the surface of Venus. Either this is a coincidence or the reaction proposed by Urey, augmented or dominated by other surface chemical reactions, is actively buffering the atmospheric pressure.

[57] Problems have been raised with this theory however [see, e.g., *Hashimoto and Abe*, 2005], including the question of how a sufficiently intimate contact between atmosphere and lithosphere is achieved. Any answer to the latter depends on a much better understanding of the actual mineralogical composition and physical state of the exposed material on the surface of Venus, and of weathering and possible subduction and effusion rates, than will be available without future in situ studies at the Venus surface. *Bullock and Grinspoon* [1996] showed that although the surface temperature and pressure are indeed at an equilibrium point with the calcite-wollastonite mineral reaction, it is actually an unstable equilibrium, suggesting that unknown mechanisms may be providing the stability, requiring a more complex model of surface-atmosphere interactions that are linked to the history of volcanism and the nature of the interior.

[58] In addition to any contribution to maintaining the high surface density of carbon dioxide made by coupling between the surface and the atmosphere, there must certainly be an effect on the abundance of more reactive trace species. Small changes in radiatively active atmospheric gases can change the magnitude of the Venusian greenhouse effect and shift the temperature-dependent equilibrium points of key mineral buffers, as well as the kinetics of heterogeneous reactions, resulting in climate feedbacks. Heterogeneous reactions between sulfur dioxide and the surface are seen to proceed rapidly, relative to geologic time scales, in chemical kinetics experiments performed under Venus-like conditions in the laboratory [*Fegley and Prinn*, 1989; *Fegley and Treiman*, 1992]. Since the deep atmosphere abundance of SO_2 is 1–2 orders of magnitude higher than can be accounted for by equilibrium with surface minerals [*Fegley and Treiman*, 1992], this implies active sources and sinks of sulfur. If surface reactions are indeed active in altering atmospheric SO_2, it is of interest to assess

the impact they may have on the climate of Venus using evolutionary models.

3.5. Escape Fluxes, Fractionation, and the History of Water

[59] Venus has one hundred thousand times less water in its atmosphere than exists in the oceans and atmosphere of the Earth [*Donahue and Pollack*, 1983; *Pollack et al.*, 1993]. The fact that, at the same time, deuterium is approximately 150 times more abundant than on Earth [*McElroy et al.*, 1982; *Donahue et al.*, 1982; *de Bergh et al.*, 1991] suggests that the current complement of water derives from a reservoir that has been severely depleted. This is consistent with Venus having a much higher primordial water abundance, although it could also reflect loss of water supplied more recently by exogenous or endogenous sources [*Grinspoon*, 1993; *Donahue*, 1999]. The low water abundance (about 30 ppm) suggests a water lifetime of several hundred million years, the precise value depending on the time-averaged hydrogen escape flux. This is much shorter than the lifetime of Venus' atmosphere, suggesting that water on Venus is currently in a steady state between source and loss processes [*Grinspoon*, 1987, 1993; *Donahue*, 1999]. Yet if water is indeed in a steady state, what is the source? Two obvious candidates are volcanic outgassing and cometary infall. If water is in a steady state then the escape flux also measures the time-averaged sum of these sources. If further information can be brought to bear on discriminating between these sources, for example through placing quantitative limits on the recent exogenous contribution through additional isotopic clues or other constraints on the impact flux in the inner solar system, then data on planetary escape fluxes can be used to quantify outgassing rates. Combined with geologically determined estimates of magma production rates, this can constrain magma volatile content. *Grinspoon* [1993] used such an approach in deriving a rough upper limit on average magma water content of 50 ppm by mass.

[60] 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.* [1984], Venus could have lost an ocean of present-day terrestrial proportions in less than 500 million years. These authors also suggest a reason why the D/H ratio on Venus is only greater by $\sim$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 in large amounts through nonfractionating hydrodynamic escape when there is free water on the surface, if the heating of the upper atmosphere by solar UV radiation is sufficiently intense. Once the free water is all gone, the mixing ratio of vapor in the upper atmosphere falls and the escape processes become highly fractionating between the two isotopes. In *Kasting et al.*'s [1984] model, with the simplifying assumption 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 vapor dissociation. It was thought at the time that this could not escape efficiently, an assumption that Venus Express results now challenge, and that large amounts would have to be bound chemically in the crust through weathering processes involving liquid water. *Grinspoon* [1987, 1993] and *Donahue* [1999] have pointed out that after a phase of massive water loss, evolution of the D/H ratio during the subsequent steady state phase of water evolution would likely have at least partially obscured the primordial signal, complicating efforts to derive a relationship between this observed quantity and the evolution of Venusian water.

[61] The observed high D/H ratio may be at least partly the signature of the catastrophic resurfacing and associated outgassing that apparently occurred within the past 0.5–1 billion years, presumably accompanied by a massive injection of water followed by fractionating escape [*Grinspoon*, 1993]. If this occurred recently compared to the deuterium lifetime, which is longer than the hydrogen lifetime by a factor determined by the relative escape efficiency of deuterium and hydrogen, then the enhanced D/H from this episode would be largely preserved at present. Alternatively, the interior and surface may simply have been continuously more active before that time. An extremely large comet impact, or a comet shower caused by a gravitational perturbation to the Oort cloud or the breakup of a massive, volatile rich object, could also potentially leave such a signature.

[62] The ability to discriminate between these different interpretations of the enhanced D/H ratio, with very different implications for water evolution, was long hampered by the large uncertainties in the current escape flux. Accurate evolutionary modeling also requires some knowledge of how the escape flux and deuterium fractionation efficiency have varied with time over a range of time scales. The ASPERA experiment on Venus Express has found evidence that a surprisingly large flux of oxygen ions is currently escaping from the upper atmosphere of Venus through nonthermal processes, calling into question the earlier assumption that massive hydrogen escape must necessarily have left behind large quantities of oxygen [*Barabash et al.*, 2007]. Provisional estimates by the ASPERA team suggest a planetary average column hydrogen escape flux which, if it also represents the time averaged flux, is an order of magnitude lower than those previously assumed in evolutionary models [*Donahue*, 1999]. If substantiated, the new values would imply a residence time of atmospheric water of approximately 10^9 years, roughly equal to the apparent average age of the volcanic plains that dominate the surface.

[63] Furthermore, if the water abundance is currently in steady state with outgassing from postplains volcanism, this low escape flux would imply magmas that are, in bulk, 2 orders of magnitude drier than the driest terrestrial magmas. This assumes a resurfacing rate of 0.4 $km^3\ a^{-1}$, which would be consistent with mapping of volcanic features in Magellan images [*Head et al.*, 1992; *Phillips et al.*, 1992] when combined with simulations of the observed crater population, and roughly equivalent to the current terrestrial intraplate magmatic flux [*Bullock et al.*, 1993], as described by *Grinspoon* [1993].

[64] However average escape fluxes are not so straightforward to quantify, as they cannot be specified completely by any one single instrument, which must always measure

at a single place or time. The actual total hydrogen escape flux may include the escape of neutral species, ions of lower energy than can be measured by ASPERA, and may show significant variations with solar cycle and unique solar events such as coronal mass ejections. Thus, at present the ASPERA observation must be considered to represent a lower limit on the H^+ escape flux, pending further observations. The coverage possible with the extended mission, plus more detailed analysis and modeling, should lead to a more representative value for the average in space and time.

[65] With SPICAV/SOIR's very high spectral resolution it is possible to study the ratio of HDO and H_2O, which may shed light on the escape of H and D. In particular, by measuring simultaneous vertical profiles of H_2O and HDO above the clouds, SPICAV is examining D/H fractionation. *Bertaux et al.* [2007] show several measured profiles of H_2O and HDO from 70 to 95 km altitude in which the averaged HDO/H_2O ratio equals a factor of 240 ± 25 times the ratio in Earth's ocean, or nearly a factor of 2 times the bulk atmospheric value measured in the lower atmosphere. This surprising result could be due to some combination of (1) preferential destruction of H_2 relative to HD, perhaps from photolysis induced isotopic fractionation [*Liang and Yung*, 2009]; (2) preferential escape of H relative to D, leaving a residue of enhanced HDO at these altitudes; or (3) selective condensation, a process that has recently been found to be important for fractionating D and H on Mars, and also on Earth [*Bertaux and Montmessin*, 2001]. Solving this problem will depend on obtaining a better understanding of both global dynamics and photochemistry in the upper atmosphere. At present the observations are limited to latitudes from 70 to 86°N. Venus Express extended mission observations that sample a wider range of latitudes will help to distinguish between these two fractionation mechanisms, and allow a clearer understanding of the potential of the D/H results to resolve more definitively between competing models for the history of water on Venus.

[66] Observations over a significant fraction of a solar cycle will also be important for deriving a time averaged escape flux for recent epochs and for understanding the relative importance of several escape mechanisms. This will allow improved modeling of the variation of escape rate and fractionation efficiency with changing atmospheric composition, structure and solar inputs, which will be necessary for improved reconstructions of water evolution. Eventually, direct observations of surface materials may be able to find evidence for an early period of Venus history when surface water was stable and abundant. As noted above, the possibility that the highlands on Venus are more felsic than the lowlands, inferred by *Hashimoto et al.* [2008] using Galileo spectroscopic data, may support the existence of large reservoirs of water in Venus's distant past, since aqueous processes are involved in the formation of felsic provinces on Earth.

4. Climate Models and Parameterizations

4.1. General Circulation Models

[67] The overall goal for Venus climate modeling must be the development of fully three-dimensional, time-dependent general circulation models in which all of the relevant sources and sinks, and all radiative, dynamical, and chemical processes, are included with high precision and resolution. This is a goal which is being approached, although so far not attained, for terrestrial climate models, which of course are much better tested and constrained by data. Nevertheless, modified, and where necessary simplified, terrestrial GCMs are being used to model the dynamical component of the current climate of Venus, and to help understand common processes with the Earth [*Yamamoto and Takahashi*, 2003; *Lebonnois et al.*, 2005; *Lee et al.*, 2007].

[68] Experiments with these models show that global superrotation tends to develop in optically thick atmospheres on slowly rotating planets as different as Venus and Titan. However, the present state of model development, including the details of energy deposition profiles required in the model specification, is deficient in that the predicted wind speeds are too slow, by a factor of 2 or more. The features seen in ultraviolet images of Venus rotate around the planet in a period of only 4 to 5 days, corresponding to wind velocities of more than 100 m s^{-1} at the cloud tops, while the solid surface of Venus rotates at only about 2 m s^{-1}, or once every 243 days. More information about cloud variability and wave modes in the atmosphere below the visible cloud tops, from repeated UV and IR mapping, should permit progress in understanding issues such as the role of the surface topography in maintaining or opposing the superrotation and the role of waves or eddies in the transport of angular momentum.

4.2. Evolutionary Models

[69] Eventually, helped by the massive effort being applied to model the changing climate of the Earth, Venus GCMs will incorporate the relationships between dynamics, volcanism, exospheric escape, surface-atmosphere reactions, composition, clouds and radiative balance. For the time being, however, our attempts to trace the origins and evolution of Venus' atmosphere depend on simplified one-dimensional evolutionary climate models that incorporate the global-scale processes and their interrelations in one (altitude) rather than three spatial dimensions, neglecting or simplifying dynamics so they can model the complex set of time-dependent feedbacks that control the planetary climate.

[70] The current state of the art with 1-D evolutionary models is represented by that of *Bullock and Grinspoon* [2001]. In this, a radiative transfer code calculates the radiative-convective equilibrium temperature structure as a function of atmospheric composition, and is coupled to a chemical/microphysical model of Venus' clouds, models of volcanic outgassing, models of heterogeneous reactions of atmospheric gases with surface minerals, and a model of the escape of hydrogen from the exosphere. Figure 6 shows the various modules and their coupling in the model. An atmospheric radiative transfer code is used to describe the transport and balance of energy within the atmosphere, calculating thermal infrared fluxes, heating rates, and temperature profiles that are tested for consistency with spacecraft and ground-based observations. The code must be flexible and fast enough to predict these quantities with respect to variations in solar flux and atmospheric composition as they change over time, which involves making some simplifying parameterizations. Bullock and Grinspoon used a one dimensional, two-stream model of infrared

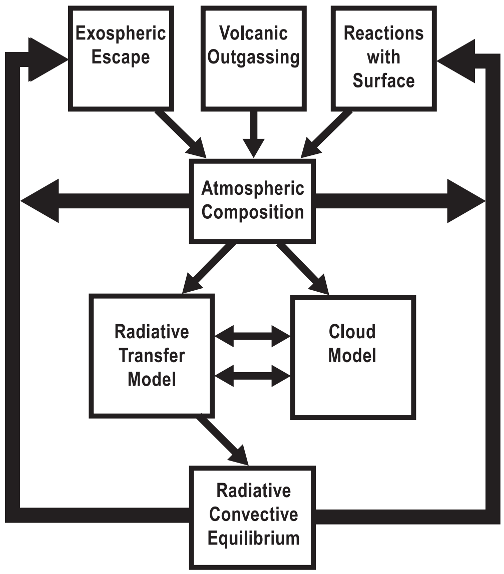

Figure 6. A block diagram of the Venus climate evolution model of *Bullock and Grinspoon* [2001]. At each time step the atmospheric composition is adjusted for the effects of volcanic exospheric loss, volcanic outgassing, and by reactions with the surface, then the coupled cloud and radiative-convective models are allowed to reach equilibrium.

radiative transfer employing correlated-k gaseous absorption coefficients to describe the spectral properties of nine molecular species found in Venus' atmosphere: CO_2, H_2O, SO_2, CO, OCS, HDO, H_2S, HCl, and HF. Net infrared fluxes were then calculated using the hemispheric mean approximation appropriate to an emitting, highly absorbing and scattering atmosphere, balanced using an iterative variational method against the observed solar net flux profile from the radiometer on the Pioneer Venus entry probes.

[71] The resulting radiative equilibrium profile of temperature as a function of altitude calculated by this model matches the Venus International Reference Atmosphere [*Kliore et al.*, 1986], which is based on measured temperature profiles, very well everywhere except above 70 km (Figure 7). To some extent this may be fortuitous, since the model makes a large number of simplifying assumptions, and each of these modules can be developed, and the overall scheme refined, using new data and mission findings. Previous models have obvious limitations, including those in the following list, and should be reexamined, using the new data and improved computational techniques now available:

[72] 1. Convection was assumed to reduce the lapse rate in the radiative equilibrium temperature profile to the adiabatic value wherever it tended to be larger.

[73] 2. *Tomasko et al.* [1980], and others, have shown that an extra source of opacity above the cloud tops has to be arbitrarily introduced in models before they will accurately predict the upper atmosphere temperature structure.

[74] 3. Energy deposited in the atmosphere by absorption of UV radiation, mostly above 70 km, was not accounted for, since the net solar fluxes from Pioneer Venus have a cutoff at 0.4 μm [*Tomasko et al.*, 1980].

[75] 4. The arbitrary addition of large "mode 3" cloud particles above 65 km, with a scale height of 4 km, was necessary to achieve agreement between the radiative transfer model and the VIRA temperature structure.

[76] 5. The direct reactions of atmospheric CO_2 with surface silicates were neglected, though *Bullock and Grinspoon* [2001] noted that such reactions are possible, even likely. The kinetics of such reactions are poorly known, making it difficult to include them; future laboratory experiments to determine these rate constants would allow potentially important improvements to the model.

[77] 6. The number of spectral and vertical increments in the model had fairly low maximum values of 68 and 20, respectively, and simple spectral and hemispherical integration schemes were used.

[78] Further tests of a model with these and other improvements can be made through comprehensive comparisons to the radio occultation temperature profiles already available from Magellan and Venus Express orbiters [*Jenkins et al.*, 1994; *Häusler et al.*, 2006].

4.3. Cloud Models

[79] Cloud properties, including the vertical and horizontal distribution, composition, microphysics, and variability, are notoriously difficult to model in terrestrial climate models, since they depend simultaneously on temperature, composition (including the number and composition of condensation nuclei), and dynamics. However, the difficulties must be faced because, on Venus as on Earth, changes in the thickness of clouds have two important effects on climate. They alter the visual albedo of the planet, changing the input of solar energy, and they alter the thermal infrared opacity of the mid atmosphere, affecting the temperature in the atmosphere and at the surface.

[80] For their evolutionary calculations, *Bullock and Grinspoon* [2001] combined a thermochemical model of Venus' cloud aerosols by *Krasnopolsky and Pollack* [1994] with a simple microphysical model, to predict the number

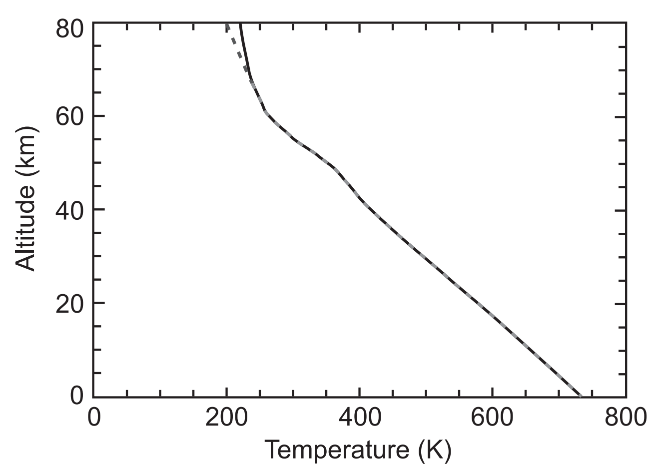

Figure 7. Temperature (solid line) calculated with the radiative transfer model of *Bullock and Grinspoon* [2001]. For comparison, the Venus International Reference Atmosphere [*Kliore et al.*, 1986] is plotted with a dashed line.

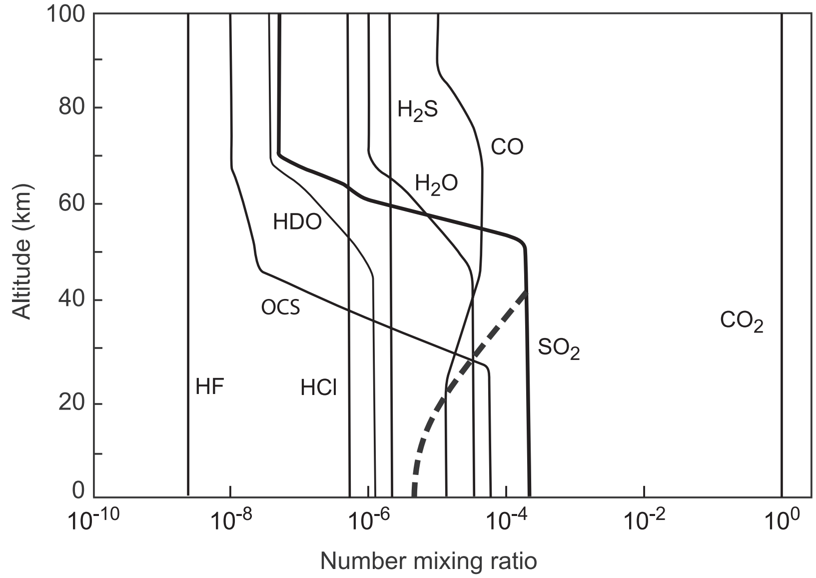

Figure 8. Mixing ratios assumed in the baseline models of *Bullock and Grinspoon* [2001] shown as a function of altitude. The points are the SO_2 mixing ratio as a function of altitude derived by *Bertaux et al.* [1996] from VEGA 1 and 2 entry probe data.

density profile with altitude of aerosol particles as a function of the atmospheric abundances of H_2O and SO_2. Then, changes in cloud structure, infrared opacity, and albedo could be incorporated into the radiative transfer model using optical constants for H_2SO_4/H_2O from *Palmer and Williams* [1975] and Mie scattering calculations. In addition to the large uncertainties in the thermochemistry and microphysics of the Venusian clouds, improved simulations would add the large-scale global variations in cloud structure and optical thickness that are apparent in the VIRTIS and VMC maps from Venus Express [*Titov et al.*, 2008]. These need to be analyzed statistically, and their overall affect on radiative balance quantified, before they are incorporated in a new generation of 1-D climate models. Eventually, the realistic inclusion of these spatially and temporally variable elements will require the development of 3-D models combining the dynamical code of a GCM with full climate physics.

4.4. Interior/Surface/Atmosphere Interactions

[81] *Bullock and Grinspoon* [1996, 2001] included the reaction of sulfur dioxide with surface calcite ($CaCO_3$ + SO_2 $\leftrightarrow$ $CaSO_4$ (anhydrite) + CO) using kinetic data measured by *Fegley and Prinn* [1989], who showed that this reaction proceeds rapidly under Venus surface conditions. However, the actual bulk reaction rate will depend not only on chemical kinetics but also on the ability of the gas to diffuse to new reaction sites on buried grains once the easily available surface has reacted. To solve this problem, Bullock and Grinspoon used a diffusion/reaction formalism which takes into account the temperature-dependent lifetime for SO_2 reaction with surface carbonate, τ, as well as the time required for the diffusion of SO_2 (with temperature and porosity-dependent diffusion coefficient, D) into the planetary surface. In this formalism, the abundance n of SO_2 is determined by

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial z^2} - \frac{n}{\tau}$$

The choice of diffusion coefficient requires assumptions about soil porosity and the effectiveness with which forming $CaSO_4$ rinds will reduce pore space. These can be tested by future surface missions and further laboratory experiments. The above equation reveals that the effect of the SO_2-anhydrite buffering mechanism is temperature-dependent, through both the reaction rate and the diffusion coefficient.

[82] There is another set of possibilities tied to some uncertainties and controversies about the current sulfur abundance in the lower atmosphere and the stability of sulfur-bearing minerals at the surface. *Bullock and Grinspoon* [2001] assumed the lower atmosphere mixing ratios of reactive gases shown in Figure 8. Here, the lower mixing ratio of SO_2 is assumed to be constant below the clouds at a value of 180 ppm, as measured by Pioneer Venus, and SO_2 at the surface is more than two orders more abundant than required for equilibrium with calcite, but it is close to equilibrium with pyrite and magnetite. *Hashimoto and Abe* [2005] have suggested that the SO_2 abundance may in fact be controlled by a pyrite buffer, in which case near equilibrium may exist. However, for either of these reactions to be in equilibrium the reactants must exist at the surface. While there are no unequivocal data for the existence of either of these phases, $CaCO_3$ is a possible interpretation of the Venera X-ray fluorescence data. FeS_2 has been shown in laboratory experiments to have a lifetime of $\sim$100 days at Venus surface conditions [*Fegley et al.*, 1995], so it is unlikely to exist for geologically relevant time scales.

[83] By contrast, *Bertaux et al.* [1996] reporting results from VEGA 1 and 2, found a steep decline in SO_2 toward the surface. If the SO_2 abundance in the lowest part of the atmosphere in contact with the surface is actually only 30 ppm, as the VEGA team reported, rather than 180 ppm, then it is conceivable that SO_2 is not very far out of equilibrium from the calcite-anhydrite buffer. However, the steep lower atmosphere gradient of SO_2 inferred by

Bertaux et al. [1996] would have to be maintained by some unknown dynamical or chemical process.

[84] Preliminary results by *Marcq et al.* [2008], using VIRTIS on Venus Express, have pointed toward sulfur abundances just below the clouds more consistent with the Pioneer Venus, constant mixing ratio profile. Although the loss of the Planetary Fourier Spectrometer makes such determinations of lower atmosphere abundances more challenging, further results from VIRTIS on Venus Express could help to resolve between these two different pictures of lower atmosphere SO_2, with important consequences for the nature of the sulfur cycle and surface/atmosphere interactions.

4.5. Exospheric Escape

[85] *Bullock and Grinspoon* [2001] utilized the diffusion limit approximation [*Chamberlain and Hunten*, 1987] to calculate the loss of H and D from the top of the atmosphere. The current escape flux of H from Venus is due to two mechanisms: an electric field-driven flow of ions in the nightside hydrogen bulge, and charge exchange. Each of these processes has a different solar cycle average loss rate. Prior to the Venus Express mission, estimates of the average escape flux over time were 1.6×10^{7} cm^{-2} s^{-1} [*Donahue et al.*, 1997; *Donahue*, 1999] for H, and about a tenth of this for D. For diffusion-limited escape, where the loss rate is limited by the ability of H and D to diffuse to the exobase, these amount to H and D lifetimes in the atmosphere of 170 million years and 1.7 billion years, respectively. As discussed in section 3.5, these values will eventually need to be revised in the light of Venus Express observations.

4.6. Model Experiments

[86] Their Venus climate evolution model was used by *Bullock and Grinspoon* [2001] to predict how surface temperatures and cloud structure responded to large-scale volcanic injections of radiatively active gases. They found that for volcanic outgassing associated with the emplacement of the largest plains units on Venus, surface temperature excursions of 100 K were possible. Outgassing was modeled as a sudden pulse of water and sulfur dioxide to the atmosphere, declining exponentially with a time constant of 100 million years, and assuming that the total amount of lava erupted onto the surface is equal to a global layer 1 km in thickness. The water content of the lava was assumed to be 50 ppm by weight and the sulfur dioxide content to be 0.2%, typical for terrestrial Ocean Island basalts and large igneous provinces, which *Bullock and Grinspoon* [2001] argue are likely to be the best terrestrial compositional analogs to plains magmas on Venus. Atmospheric sulfur dioxide is lost rapidly to temperature-dependent reactions with surface carbonates, while atmospheric water is lost more slowly owing to its dissociation by solar UV and the exospheric escape of H. At 735 K, the residence time for sulfur dioxide is approximately 30 million years; the residence time for atmospheric water was assumed to be 160 million years. Both atmospheric constituents decline in abundance more slowly than this owing to the continued but exponentially declining outgassing rate. The initial conditions for the model included an abundance for atmospheric water at the surface of 30 ppmv (today's value for Venus), and an atmospheric sulfur dioxide abundance, in thermochemical equilibrium with the surface, of 18 ppmv (1/100 of today's value for Venus).

[87] These initial conditions yield a starting surface temperature of 780 K, but subsequent evolution of surface temperatures are fairly independent of the starting conditions. The surface temperature initially declines from 780 K to 750 K owing to the formation of thick clouds and increased albedo. However, after about 150 million years, the thinning clouds lower the planetary albedo, increasing surface temperatures to between 800 K and 850 K for about 400 million years. A further drop in surface temperatures after 600 million years is due to the loss of clouds and their infrared scattering, which helps to maintain warmer surface temperatures.

[88] Several groups have investigated whether surface temperature changes of this magnitude could have significant effects on surface geology and geophysics. Diverse puzzling aspects of the surface geology of Venus can potentially be explained by such extreme climate changes. Climate-driven variations in thermal stress are consistent with the formation of wrinkle ridges on the most widespread volcanic plains units due to the propagation of a climate-induced thermal pulse that deformed the surface within 100 My of their formation [*Solomon et al.*, 1999]. Others include (1) the origin of "ribbon terrain" in ancient crustal plateaus, which may indicate large changes in the depth of the brittle-ductile transition [*Phillips and Hansen*, 1998; *Brown and Grimm*, 1999], (2) the origin of extensive canali thousands of kilometers in length which could have been carved by carbonatite flows that would be stable in a somewhat warmer climate regime [*Kargel et al.*, 1994], (3) widespread and apparently coherent formation of polygonal and gridded terrains [*Anderson and Smrekar*, 1999; *Smrekar et al.*, 2002; *Moreels and Smrekar*, 2003], and (4) steep-sided dome morphology which could be consistent with rhyolitic composition (a volcanic rock resembling granite) only if surface temperatures were high enough to inhibit crust formation during extrusion [*Stofan et al.*, 2005].

[89] Taken collectively these independent suggestions of possible climate influence on geology provide strong motivation for further investigation of the links between outgassing, climate, and surface records of climate change.

[90] Such coupling between climate change and thermal stress provides an avenue for testing models of outgassing history against the geological record of deformation. In this way the geologic history of the planet becomes an additional tool for exploring how the physics of planetary-wide feedbacks have driven Venus' climate evolution, perhaps occasionally driven its tectonic evolution, and led to the present atmospheric state.

[91] The range of temperatures found by *Bullock and Grinspoon*'s [2001] experiment are indicated on Figure 9, which also shows two simple radiative-convective models from *Taylor* [2006], and a measured temperature profile for the middle atmosphere of Venus from the Magellan radio occultation experiment [*Jenkins et al.*, 1994]. The simple models have a stratosphere in radiative equilibrium with the Sun, overlying a deep atmosphere in which the profile follows a dry adiabat. The solid line is such a model calculated assuming present-day conditions; the dashed line is an imaginary scenario in which the surface pressure on

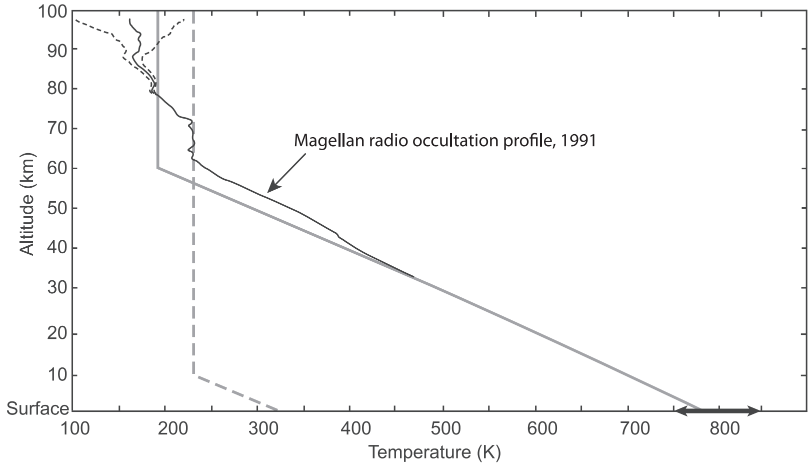

Figure 9. Two simple models for the temperature profile in Venus' atmosphere: one calculated for the present-day (solid line) and the other (dashed line) for a hypothetical scenario in which the surface pressure and the CO_2 mixing ratio both relax to Earth-like values. The heavy double-headed arrow at the surface shows the range of temperatures that appeared in model experiments by *Bullock and Grinspoon* [2001] in which enhanced amounts of volcanic gases were injected into the atmosphere. A middle-atmosphere temperature profile from the Magellan radio occultation experiment [*Jenkins et al.*, 1994] is shown for comparison with all of these.

Venus falls to 1 bar and the planetary albedo falls to 0.52, that is, to a less cloud-reflective state, perhaps as the result of continued exospheric loss and chemical erosion of the atmosphere following a cessation of the volcanic source at some distant point in the future. This is roughly the scenario imagined by Arrhenius a century ago, and gives rise to a surface temperature of 320 K, precisely his assessment (What Arrhenius actually wrote was, "assuming the sun constant to two calories per cubic centimeter (0.061 cu. in.) per minute." Verifying that this corresponds to an albedo of 0.52 is left as an exercise for the reader).

[92] As a final example of the use of climate models, and the motivation for improving them to obtain accurate results, we show in Table 2 the effect on the surface temperature of removing various key atmospheric constituents from the model of *Bullock and Grinspoon* [2001]. The leading role of carbon dioxide in maintaining the greenhouse is not surprising, although its predominance perhaps is, while the cloud number is very model-dependent and may be variable, as no doubt are the smaller contributions from trace species. The larger effect of water vapor relative to the others comes from its very rich infrared spectrum (which makes it the principal greenhouse gas on Earth), which compensates for its low mixing ratio on Venus. In contrast, notwithstanding its key role in cloud formation, sulfur dioxide makes a relatively small spectral contribution on both planets, even on Venus where its abundance is relatively high, because it has few infrared bands. *Bullock and Grinspoon* [1996] found that if all of the CO_2 were removed from the atmosphere, leaving only N_2, water vapor and other trace constituents, the surface temperature would be roughly 400 K.

5. Future Observations and Evolutionary Analyses

[93] The discussions in the previous sections confirm the expectation that understanding the climate system on Venus is a vast and complex undertaking that will proceed gradually in tandem with the similar undertaking for the Earth, but with an especial need for much more data. The data will come mainly from planetary missions, including the current Venus Express, the Japanese Climate Orbiter now under construction, and those future missions still under discussion that eventually fly. The latter must in time include landed and buoyant probes of long duration, which can make very precise measurements of atmospheric composition, surface and cloud properties. Further off, but essential, are the missions that will sample the geochemistry of the surface and probe the deep interior using seismic and other measurements. It is profoundly to be hoped that progress toward these goals will be faster during the next few decades than it has been in the last two, when Venus Express ended a long period of benign neglect of a nearby, Earth-like world that is uniquely instructive for so many of our crucial environmental issues.

5.1. Venus Express Extended Mission and Venus Climate Orbiter

[94] A strong case has been put forward for extending the Venus Express mission beyond its original span of 500 days, about 2 Venus years, to 1000 and then to about 2000 days,

Table 2. Evolution of Surface Temperature With Composition in the *Bullock and Grinspoon* [2001] Model[a]

Species Removed	Change in Surface Temperature (K)
HCl	1.5
CO	3.3
SO_2	2.5
Clouds	142.8
H_2O	68.8
OCS	12
CO_2	422.7

[a]The temperature decreases listed assume that the indicated species is removed entirely from the atmospheric greenhouse calculation, while the albedo of the planet remains unchanged (even when clouds are removed).

ending in December 2012 [*Svedhem et al.*, 2009]. It is worth considering how this long extension will help to meet the original goals of the mission in terms of a new picture of the climate on Venus.

[95] The goal of Venus Express as originally stated was the acquisition and dissemination of new knowledge about the Venusian climate and its place in our understanding of the climate regimes on all of the terrestrial planets (including Earth, Mars, and, for some purposes, Titan), specifically in the following key areas and objectives: (1) Detection of volcanic activity and better quantification of the volcanic gas inventory in the atmosphere; (2) improved knowledge of vertical cloud structure, microphysics, and variability; (3) updated inventories of minor constituent abundances; (4) atmospheric temperature fields above, in, and below the clouds; (5) new observational constraints from mapping on the general circulation and dynamical phenomena like the polar vortices and deep atmosphere "weather"; (6) improved estimates of atmospheric loss rates for O, C, H, and D; (7) interaction with the solar wind and escape processes; and (8) detection of any interannual and interhemispheric asymmetries and trends in all of the above.

[96] Another 4 years of operation should lead to further advances in all of these areas, particularly where time-dependent phenomena are involved. Meteorological activity takes place on all time scales, and studies of the long-term behavior of the polar vortices and of the global circulation, in particular, require long-term observations. Wind information over more latitudes, time of day, longitudes, and times are needed to ascertain the time and spatial variability and periodicities in the dynamics. Separation of standing versus traveling wave phenomena, the study of the stability of the superrotation, and fluctuations in wind profiles will need long temporal sequences to establish what periodicities are present. Rare dynamical events such as volcanic eruptions and bright cloud surges like that seen in January 2007 [*Titov et al.*, 2008], but observed only once, require dedicated periods of continuous mapping to either detect volcanism or give a reliable upper limit for the current volcanic activity of Venus.

[97] Completely new data will result from upper atmosphere in situ measurements and joint operations with the Japanese Venus Climate Orbiter [*Nakamura et al.*, 2007]. The VCO, also known in Japan as Planet-C, is due to launch in the first half of 2010 and to arrive in December of the same year, with a payload of atmospheric sounding instruments. These are designed to obtain an understanding of the atmospheric circulation and meteorology on Venus, in particular the driving force behind the zonal superrotation. VCO has an equatorial orbit while Venus Express (VEX) has a polar orbit, and these will be synchronized for studies of the dynamics of the cloud motions. VCO can obtain much longer uninterrupted observations of a particular area than VEX, while VIRTIS and SPICAV have spectral capabilities that VCO lacks, so global contextual information from VCO, coupled with local spectral information and vertical profiles of temperature and density from stellar and radio occultations by VEX will enable improved studies of the motions and evolution of structure in the cloud features, and consequent advances in understanding of cloud formation and destruction mechanisms, including radiative dynamic feedbacks in the middle and lower clouds.

[98] The controversial question of lightning on Venus has implications for the climate through its effect on atmospheric chemistry and composition. Current VEX magnetometer observations include signals attributed to lightning, possibly cloud-to-cloud rather than cloud-to-ground, but the phenomenon has not yet been detected optically. VCO has a high-speed lightning observation camera and simultaneous observations of optical flashes by VCO and whistlers by VEX would present an irrefutable detection of lightning, as well as further clues as to the source regions and mechanisms.

[99] The other climate-related investigations by Venus Express that are enabled by an extended mission include observations of the plasma environment and atmosphere-solar wind interaction as the Sun moves toward solar maximum conditions. The upper atmosphere dynamical regime has been monitored in a period of very low solar activity; extension of the observations will allow the intensity and morphology of the O_2 and OH airglow features, in particular, to be correlated with solar activity [cf. *Stewart et al.*, 1980].

[100] There is also the opportunity, considered too risky for the main mission, to reduce the pericenter altitude to dip into the upper atmosphere. This will extend the measurements of local magnetic fields and plasma parameters to relatively low altitudes and high densities in the region where the atmosphere is impacted by the solar wind. Atmospheric drag measurements from orbit perturbations and the onboard accelerometer will provide unique information on density and temperature in the range 150–200 km, which is not accessible by other means.

[101] Venus Express and Venus Climate Orbiter will not address, let alone resolve, every one of the key questions about Venus that have accumulated as a result of exploration by the Venera, VEGA, Pioneer and Magellan missions. The knowledge gaps that will remain, that can be predicted in advance, are mostly in the area of atmospheric evolution (addressable by accurate measurements of noble gas isotopic ratios, for instance) and composition (a full understanding of surface-atmosphere interactions, cloud composition and chemistry will require in situ trace constituent abundance measurements, especially at the surface and in the clouds). Other areas that will be largely untouched by Venus Express are surface geology, geochemistry, and interior structure, and surface-atmosphere and surface-interior interactions. For these investigations, high-pressure balloons, landed missions and sample return may be the optimum way forward.

5.2. Entry Probes and Floating Stations

[102] ESA recently turned down a proposal for a Venus Entry Probe mission [*Chassefiere et al.*, 2007] in favor of in-depth studies of a new Outer Planets mission to follow Galileo and Cassini. The best prospect now for obtaining essential data on, for instance, the cloud chemistry and the isotopic composition of noble gases, rests with NASA, where the most recent decadal survey called for a Venus In Situ Explorer mission, which will seek to (1) understand the physics and chemistry of Venus' atmosphere through measurement of its composition, especially the abundances of its trace gases, sulfur, light stable isotopes, and noble gas isotopes, below the clouds and all the way down to the

surface with more detail than is possible using remote sensing; (2) constrain the coupling of thermochemical, photochemical, and dynamical processes in Venus' atmosphere and between the surface and atmosphere to understand radiative balance, climate, and dynamics, and to characterize the chemical cycles involving clouds, surface and atmospheric gases; (3) understand the physics and chemistry of Venus' crust through analysis of near-IR descent images from below the clouds to the surface and through measurements of elemental abundances and mineralogy from a surface sample; (4) understand the properties of Venus' atmosphere down to the surface through meteorological measurements and improve our understanding of Venus' zonal cloud level winds through temporal measurements over several Earth days; (5) understand the weathering environment of the crust of Venus in the context of the dynamics of the atmosphere of Venus and the composition and texture of its surface materials; and (6) map the mineralogy and chemical composition of Venus' surface on the planetary scale for evidence of past hydrological cycles, oceans, and life and constraints on the evolution of Venus' atmosphere.

[103] Much of what we now know about the history of Earth's atmosphere has been inferred from measurements of abundances and isotopic ratios for the noble gases. Not only are these chemically inert, which greatly simplifies the range of potential sources and sinks for any given isotope, but also some are produced at well-defined rates by the radioactive decay of parent molecules with a range of half-lives that spans most of the history of the planet. The wide range of atomic masses (from ^{2}He to ^{130}Xe) among the commonest of these gases, and the convenient mass scale (for instance, ^{20}Ne/^{21}Ne/^{22}Ne) across measurable abundances of the same element, make them a convenient yardstick for determining mantle degassing and atmospheric loss rates over time.

[104] It follows that measurements of noble gases in the atmosphere of Venus are a powerful tool for tracing Venus' evolution in the same way. Direct comparisons of the relative abundances of neon, krypton, xenon, argon and helium and their isotopes between the two planets highlight differences in their histories, and tell us something about the nature and timing of the events that produced them. For instance, the Pioneer Venus probes discovered that Venus is rich in neon and nonradiogenic argon compared to Earth and Mars, prompting speculation that they may have been brought in during the collision with Venus of a very large comet from the cold outer reaches of the solar system, where substantial quantities of these species can be trapped in water ice as clathrates. More isotopic ratio measurements, especially if they are more accurate than the 10% or so achieved by Pioneer Venus, will refine this theory and distinguish it from rival explanations.

[105] As another example, *Watson et al.* [2007] argue that argon compatibility with rock forming minerals has interesting implications for interpretation of argon ratios on Venus versus Earth. What has long been interpreted as implying a difference in total cumulative outgassing may actually say more about the history of the crust and weathering. Many other instances can be cited where accurate measurements of trace gas abundances will improve our understanding of Venus' atmosphere and climate [see, e.g., *Baines et al.*, 2007]. They will also make it much clearer which events are common between Venus and Earth and which may be unique, like the massive cometary impact described above, to one or the other. However, the data required can only be obtained in situ, using Venus entry probes, buoyant stations, and landers, and not by orbiters like the current generation of missions from Europe and Japan.

5.3. Surface Missions and Sample Return

[106] The hostile conditions on the surface of Venus, particularly the high temperature, have in the past limited the lifetime of landed missions to about 1 h on the surface. This is the time it takes for a well-insulated payload to rise in temperature to the point where electronics and other systems fail. Advanced technology that can overcome this problem and permit a long-lived lander on Venus is under development, but still some considerable distance away in practical terms. Ten years ago, when the European Space Agency decided to study a mission to land on Venus, drill a core sample, and return it to Earth, the conclusion was that the only realistic option was to carry out the surface phase quickly enough that conventional electronics, packed with thermally insulating phase change material, could be used [*Coradini et al.*, 1998]. Numerous NASA studies over a 40-year period reached similar conclusions, and the Venus In Situ Explorer, currently the most likely mission to fly to Venus after the Japanese Climate Orbiter, follows the same path to obtain surface samples which are carried to a platform floating at an altitude where a more comfortable temperature for analysis can be found. NASA has recently commissioned a Science and Technology Definition Team to study a possible Flagship Mission to Venus to be launched in the 2025 time frame. Such an ambitious mission would likely include a large orbiter equipped with a radar interferometer, and multiple landers and floating stations.

[107] Taking the ESA sample return study as an example, two launches using the most powerful version of the Ariane vehicle would be required, one to carry an orbiter and Earth return vehicle, and the other to insert a lander directly into the Venusian atmosphere. The latter, with a landed mass of 4 tons, would acquire three 100-g samples from on and below the surface, and a bottle of near-surface atmosphere, before ascending by balloon to the 1 bar level near the cloud tops. A double-balloon arrangement might be employed, using a metal bellows filled with helium to traverse the lowest 12 km and then a more conventional Teflon-coated Kapton balloon for the rest of the ascent. From the float level around 55 to 60 km above the surface, a rocket would carry the samples into orbit where they would rendezvous with the return vehicle and be transferred for the flight back to Earth and a landing by parachute. The rendezvous, in particular, is a slow affair and the total elapsed time for the mission, from takeoff to retrieval of the samples, was estimated to be 6 years.

[108] This brief summary is enough to illustrate the complexities of a sample return mission and to make clear why there are no plans to implement one soon. Still, it is essential that the technological challenges are systematically studied so that eventually samples can be analyzed in terrestrial laboratories and key issues related to the climate and its evolution answered. The variety of analyses that can

be conducted in a laboratory, as opposed to on Venus, and their greater accuracy and precision, will make it possible to determine the ages of Venusian surface units, a vital area of information. The analysis of atmospheric samples would provide much improved data on rare gas isotopic ratios, and with several samples spaced vertically in altitude by about 10 km we could address the key questions of water vapor abundance, cloud chemistry, and the role of currently active volcanism. In situ correlative gas chromatography and mass spectroscopy will be needed for the more reactive species that are expected to be present, especially near the surface.

[109] Returning a core of the surface to Earth would enable a determination of the amount of weathering that occurs and also would allow analysis to be done on Venusian rock samples from below the surface that were unaffected by the atmosphere. This would provide the composition and structure of the near-surface material and help us to understand the differences in bulk density, atmospheric constituents and absolute abundances and water contents of the terrestrial planets. The importance to the climate history of Venus of understanding the original abundance of water has already been discussed, and is also relevant to the even more profound question of whether life developed on Venus under more benign conditions in the past.

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