horizontal wind field, the forcing spectrum becomes more complicated, and a spectrum of waves is generated that is not a direct reflection of the spectrum of the surface height variation. Model spatial resolution required depends on the amplitude of forcing; for very nonlinear cases considered, vertical resolution was 250 m, and horizontal resolution was slightly greater than 1 km. For smaller forcing amplitudes, spatial resolution was much coarser, being 1 km in the vertical and about 10 km in the horizontal. Background static stability and mean wind are typical of those observed in the Venus atmosphere.

Computations to date have considered a periodic sinusoidally varying surface height. Such forcing is relevant to the situation in which surface topography consists of a series of ridges extending over a region largely compared to the dimensions of each individual ridge. Because of the particular variations with altitude of static stability and mean wind in the Venus atmosphere, an evanescent region exists between about 15 km altitude and just below the cloud layer for waves having horizontal wavelengths less than about 100 km. This means waves generated at the surface having short wavelengths do not propagate to cloud levels with significant amplitude. At longer wavelengths (> 100 km), waves easily reach cloud levels and above. With surface wind speeds of several m/s and surface slopes having values in the vicinity of 0.02 (not unreasonable values in the higher mountainous regions of Venus such as Aphrodite), wave amplitudes are large enough to cause considerable nonlinear effects. From the surface to cloud levels and above, wave spatial patterns are relatively complicated and the spectra exhibit much shorter wavelengths than typical of the surface height variation, the dominant wavelength being somewhat less than 100 km for a surface height wavelength of 400 km. For this same case, maximum vertical winds at middle cloud levels associated with the waves are typical of the 2–3 m/s vertical winds observed by the VEGA balloon as it overflew the Aphrodite region. Wave horizontal wind amplitude at middle cloud levels is about 10 m/s. To date, with reasonable values of the surface forcing, we have not been able to generate waves having sufficient amplitude to cause wave breaking. Wave-induced mean winds are largest near the surface, and can become comparable to the low-altitude background wind.

N93-14396 484461 P-1

MIDDLE ATMOSPHERE OF VENUS AND ITS CLOUDS: LATITUDE AND SOLAR TIME VARIATIONS.

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The structure of the middle atmosphere of Venus and its upper clouds, derived from infrared spectrometry (from 250 to 1650 cm^{-1}) on Venera 15 [1–5] are discussed. Poleward increasing of temperature, monotonous on the average, at altitudes h >70 km changes to poleward decreasing at h <60 km. Temperature inversion at 85–95 km at low latitudes was observed as a half-day wave with two minima near 9:00 a.m. and 9:00 p.m., with a more pronounced morning feature. At high latitudes the inversion with temperature minimum near 64 km exists. There are several minima depending on solar time, but the most pronounced is one on the dayside, where the depth of inversion may reach more than 40 K (near 10:00 a.m.; we have no observations closer to noon). Another minimum is situated symmetrically on the nightside. Usually in the polar region the temperature inversion is situated deeper in the atmosphere (near 62 km). A jet at latitudes 50°–55°N divides Venus into two drastically different latitude zones: pretty homogeneous at 56–95-km zone <50° N with diffuse clouds and daily temperature variations near cloud tops about several degrees, and zone >55°N (where such dynamic structures as cold collar and hot dipole were observed) with dense low clouds (with the exceptions of the regions at 55°–80°N outside the cold collar).

We separate Venus into four latitudinal zones with approximate latitude boundaries, where the different IR-features were observed. They are characterized by different cloud scale height, H, and observed position of upper boundary of clouds (optical thickness is reached unit): h (1152) is for spectral region with maximal aerosol absorption coefficient (1152 cm^{-1}), and h (365) for the spectral region with minimal aerosol absorption coefficient (365 cm^{-1}). They are

1. l<55 – rather homogeneous, low and mid latitudes, with H_a = 3.5–4 km, and h (1152) = 67–69 km, and h (365) = 57–59 km.

2. 55 <l <75 – the most inhomogeneous latitudes as for aerosol, and for temperature. Two types of areas are found here: (1) cold collar, with $H_a \le 1$ km, h (1152) = 60–62 km, and h (365) = 58–60 km, and (2) inhomogeneous areas outside cold collar with $H_a \ge 4$–5 km, h (1152) = 70–72 km, and h (365) = 56–60 km.

3. 75 <l <85 – the hot dipole. The temperature is only several degrees higher in hot dipole than outside it near the upper boundary of the clouds at the same levels in the atmosphere. The clouds are situated lower and have larger scale height. For the hot dipole H_a = 1–1.5 km, h (1152) = 59–63 km, and h (365) = 56–58 km, and outside it, $H_a \le 1$ km, h (1152) = 63–64 km, and h (365) = 61–63 km.

4. l>85 – usually the clouds here have a very sharp upper boundary, with $H_a \le 0.5$ km, h (1152) = 62–64 km, and h (365) = 62–64 km.

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N93-14397 716239 P-2

SO_2 IN THE MIDDLE ATMOSPHERE OF VENUS: IR MEASUREMENTS FROM VENERA 15 AND COMPARISON TO UV.

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Two sets of measurements of SO_2 bands in the Venus spectra are presented and compared: IR spectra obtained on the USSR Venera 15 orbiter [1–3] and UV spectra from the American Pioneer Venus orbiter and sounding rockets [4–6]. The 40-mbar level was chosen as a reference level for comparison. The UV data are referred to this level. There are three SO_2 bands in the infrared spectrum: at 519 cm^{-1}, 1150 cm^{-1}, and 1360 cm^{-1}. The levels of their formation in the atmosphere may differ significantly, more than 10 km. In principal, it allows us to obtain the vertical profile of SO_2 from 58 to 72 km, in the best case. So the IR data are sensitive to the 40-mbar level (maybe with exception of the cold collar). For low and mid latitudes, both data give a mixing ratio, f, of several tens of ppb and SO_2 scale height (H) of 1.5–2.5 km, which is in a good agreement with the photochemically predicted values [7]. This confirms that the photochemical processes dominate in the upper clouds at low and mid latitudes. Both data show an increase of abundance to several hundreds of ppb at high latitudes, but there are differences in scale-height latitudinal behavior. Decreases to 1 km are seen according to UV, but according to the IR the high latitudes of Venus are seen to be strongly inhomogeneous. Dynamic features with low position of clouds seeing in the IR, such as cold collar, hot dipole, and polar cap, are not observed in UV. The IR data show H = 3–5 km on the average for high latitudes outside the cold collar, and the mixing ratio varies from 100–200 ppb in hot dipole to 1000 ppb in inhomogeneous regions with retrieved high diffuse clouds. We find inside the cold collar f ~ 1–10 ppb and H ~ 1 km. The comparison of IR and UV data shows that the vertical profile of SO_2 may be more complex than our two-parametric model, and H decreases with height at h > 69 km. In this case the differences in H are explained by viewing angle differences between the observations and the differential opacity at UV and IR. Temporal variations may also contribute.

Latitudinal averaged column density at 62 km (near observed upper boundary of clouds at high latitudes) obtained from the IR is about 10^{19} cm^{-2} at low latitudes and it increases to 10^{20} cm^{-2} at high latitudes.

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N93-14398 P-3

OUTGASSING HISTORY OF VENUS AND THE ABSENCE OF WATER ON VENUS.

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Similarities in the size and mean density of Earth and Venus encourage the use of Earth-analogue models for the evolution of Venus. However, the amount of water in the present Venus atmosphere is miniscule compared to Earth's oceans [e.g., 1–3]. The "missing" water is thus one of the most significant problems related to the origin and evolution of Venus and has been discussed extensively [e.g., 2–14]. Lewis [4] proposed that Venus accreted with less water, but this has been challenged [10,13]. The high D/H ratio in Venus' atmosphere is consistent with an earlier water mass more than 100 times higher than at present conditions and is often cited to support a "wet" Venus, but this amounts to only 0.01 to 0.1% of the water in terrestrial oceans [5,12,15, and Table 1] and the high D/H ratio on Venus could easily reflect cometary injection [14]. Nevertheless, many authors begin with the premise that Venus once had an oceanlike water mass on its surface, and investigate the many possible mechanisms that might account for its loss [e.g., 2,6–12]. In this paper we propose that Venus degassed to a lower degree than the Earth and never had an oceanlike surface water mass.

Lower degree of outgassing for Venus and its consequences:

1. ^{40}Ar in the atmosphere of Venus and Earth. ^{40}Ar in Venus' atmosphere is ~1/4 of that in Earth's atmosphere, when normalized by planetary mass and ignoring ^{40}Ar stored in Earth's continental crust [2,16]. Since K/U and Th/U ratios and K contents in venusian crustal rocks are similar to those in terrestrial rocks [17,18], less ^{40}Ar in Venus' atmosphere implies a lower degree of outgassing for ^{40}Ar [16]. ^{40}Ar in Earth's atmosphere represents 62% degassing of the time-integrated ^{40}Ar budget of DM (degassed mantle), but ^{40}Ar in Venus' atmosphere represents only 15% degassing of its DM, if the relative masses of DM in Venus and Earth are similar.

2. Comparison of N_2, CO_2, and H_2O on Earth and Venus. Previous workers noted that the CO_2/N_2 ratio of surface reservoirs on Venus and Earth are nearly identical when CO_2 stored in Earth's continental crust is included [2,9]. However, such comparisons did not take into account the effect of recycling CO_2 back to Earth's DM, which may be a significant part of the Earth's CO_2 budget [19]. The present venusian crust is hot (surface temperature 740 K) and the formation of carbonates requires liquid water, at least on the Earth, hence the venusian crust is probably a poor repository of volatiles. Most of the outgassed volatiles from Venus' DM are, therefore, likely to reside in the atmosphere. Hence, subduction on Venus, if it occurs, should have little effect on surface CO_2 budget, analogous to the case for N_2 on Earth. In this context, the atmospheric composition of Venus can be used to estimate total outgassing from the interior.

Table 1 compares the volatile inventory of Earth, which is corrected for recycling, with that of Venus. Although the atmosphere of Venus has twice as much N_2 as the AC* of Earth, it has only about half as much CO_2, and orders of magnitude less water. This sequence is the inverse of the solubilities of these volatile components in basaltic melts (Table 1). In the context of a solubility-controlled degassing model, the relative difference in N_2, CO_2, and H_2O on Earth and Venus can perhaps be explained by a lower degree of outgassing of Venus compared to Earth.

For solubility-controlled equilibrium outgassing we can write the following equation [20]

$$c_i M + \frac{P_i V_g}{RT_m} = c_i^0 M_0, \Rightarrow \frac{c_i^0}{c_i} = 1 + \frac{V_g}{K_i RT_m M}, \Rightarrow$$

$$K_i\left(\frac{1}{1-F_i} - 1\right) = K_j\left(\frac{1}{1-F_j} - 1\right)$$

where c_i^0 and c_i are the initial and final concentrations of gas species i in the magma, M_0 and M are the intial and final mass of the magma

TABLE 1. Comparison of volatile inventory of Earth and Venus.

	H_2O	CO_2	N_2
Solubility (in mol g^{-1} bar^{-1})	1.8×10^{-6}	1.8×10^{-8}	$\sim 3.6 \times 10^{-9}$
AC* of Earth (in moles)	8×10^{22}	$(2.4^{+0.9}_{-0.6}) \times 10^{22}$	$(2.0 \pm 0.2) \times 10^{20}$
Atm of Venus (in moles)	10^{16} to 10^{17}	$(1.1 \pm 0.1) \times 10^{22}$	$(4.3 \pm 0.5) \times 10^{20}$

Solubility data are those in basaltic magma at 1 kbar partial vapor pressure and 1200°C. Source of data: water [21]; CO_2 [22,23]; and N_2 [24], atm of Venus [1–3]. AC* (atm + crust) plus a correction for recycling (recycling of water is ignored since the comparison is not affected by augmenting water on Earth's surface).