A Systems Approach to Venus Climate Modeling

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Abstract

We propose to develop a unique approach to an understanding of the various factors that have shaped Venus' climate. We plan to numerically simulate the planetary climate system by developing a set of interconnected modules, each representing one component of Venus' climate. The first modules that we will develop are numerical models for atmospheric radiative transfer, surface/atmosphere interactions, surface volatile sources, and tropospheric chemistry. These will be followed by parameterized models for exospheric escape processes, atmospheric chemistry and cloud physics, photochemistry, and global circulation. Climate feedback loops result from interconnections between modules, in the form of the parameters pressure, temperature, and atmospheric mixing ratios. The model will utilize a wide range of existing data on Venus, from laboratory and ground and spacecraft based measurements, to define the current state of the Venus climate system.

A pilot model has been completed in order to illustrate the feasibility and usefulness of such an approach. A simple atmospheric radiative transfer numerical model was developed and coupled to a number of plausible surface mineral buffering reactions. Using this approach, equilibrium climate regimes were sought. The results of the pilot model showed that under current conditions, the climate of Venus is at or near an unstable equilibrium point. Without sources, the system spontaneously evolved to a cooler, lower pressure state.

The construction of a set of interconnected computer programs to model the climate of Venus will enable us to explore several important issues regarding the evolution and stability of the Venus climate system. In particular, we will be able to calculate the possible feedback effects of surface mineral buffering of volatiles on the stability of the greenhouse effect. The climatic implications of volcanic sources of key radiatively active species such as CO_2, H_2O, and SO_2 will also be explored using the model. We will seek equilibrium climate states predicted by the model, possible steady state climates, and characteristic mechanisms and time scales for climate evolution.

Research Proposal

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Introduction

The surface temperature of Venus is about 735 K, yet it absorbs less sunlight than does the Earth. The most widely accepted explanation for its high surface temperature is the greenhouse effect (Sagan, 1960; Pollack *et al.*, 1980). The first indications that Venus' atmosphere had evolved to a temperature much higher than ours was from Earth based radio and radar observations (Barrett and Staelin, 1964; Walker and Sagan, 1966). Further confirmation of high atmospheric temperatures were provided by direct measurements from the Venera missions to Venus and from the Mariner 5 spacecraft (Kliore *et al.*, 1967). Using existing laboratory data, Sagan (1960), showed that water vapor and CO_2 absorbed in complementary parts of the thermal infrared, and together could produce a greenhouse effect sufficient to explain the high surface temperature. His simple 1-D grey radiative transfer model was the first step in modeling the greenhouse effect on Venus. The first nongrey greenhouse model of Venus' atmosphere was developed by Pollack (1969a,b), in which CO_2, H_2O, and N_2 were responsible for the infrared opacity. This 1-D radiative convective model incorporated an adiabatic temperature profile in the layer beneath optically thick water vapor clouds. Although some pressure induced bands of CO_2 were considered, the radiative properties of CO_2 at high temperatures and pressures were poorly constrained by available data. Pollack concluded that an H_2O mixing ratio of 0.5% was needed to explain the observed temperature distribution in Venus' atmosphere. Although the model was consistent with the available spacecraft data (from the Venera 4 mission) on H_2O abundances (Nature, 1964), later H_2O measurements from the Venera 11 and 12 spacecraft in 1977 and from Pioneer Venus in 1980 indicated a far lower abundance of about 100 ppm (Moroz *et al.*, 1978; Oyama *et al.*, 1979, 1980). Pollack *et al.*, (1980) published an improved radiative transfer model, utilizing improved solar flux, gaseous composition, temperature and cloud structure measurements from Pioneer Venus. SO_2, CO, and HCl were added as sources of infrared opacity, as well as several pressure induced transitions of CO_2. They were able to reproduce the observed surface temperature and lapse rate structure of Venus' atmosphere very closely with a greenhouse model that contained water vapor abundances consistent with measurements from the Pioneer gas chromatograph and Venera spectrophotometer.

The major component of Venus' atmosphere is CO_2, with a mixing ratio of 0.965. Although CO_2 is a greenhouse gas on Earth, its low abundance in the atmosphere is controlled by life and the CO_2 geochemical cycle. A comparison of the total inventories of CO_2 (Wildt, 1942; Fegley and Treiman, 1991) shows that the atmosphere of Venus contains approximately the same amount of CO_2 as on Earth, including carbonates formed by sedimentation and biological processes, as well as the CO_2 in the atmosphere. At the temperatures and pressures found at Venus' surface, it is unlikely that much of the CO_2 resides in surface rocks and it may be assumed that most of its CO_2 inventory is in the atmosphere (Lewis, 1970). However, just as on the Earth and Mars, a CO_2 geochemical cycle probably exists or did exist on Venus. Evidence for volcanism, from the striking radar images of the surface sent by the Magellan spacecraft, is widespread (Head *et al.*, 1991, 1992). Volcanism represents the dominant source in both the terrestrial and martian CO_2 cycles, and it may be inferred that during periods of large scale volcanism, CO_2, SO_2, H_2O, and other volatiles were injected into Venus' atmosphere. The high temperatures and pressures (~92 bars) at the surface of Venus has led to the suggestion that surface/atmosphere interactions may play an important role in buffering CO_2 and other volatiles (Fegley and Treiman 1991). If this is the case, perturbations to the atmospheric inventory of radiatively active species, caused by volcanic eruptions, may have a significant impact on the climate of Venus, and upon the stability of the greenhouse effect. UV spectroscopic measurements (Esposito 1984) show approximately an order of magnitude decrease in cloud top SO_2 abundances from 1978 to 1988. It was suggested that this temporal variability could have been the result of a major volcanic eruption prior to Pioneer Venus and Venera missions (Esposito 1984). Heterogeneous reactions between SO_2 and the surface are likely, since the deep atmosphere abundances are 1 to 2 orders of magnitude higher than can be accounted for by equilibrium with surface minerals (Fegley and Treiman 1991). Additionally, Rasool and de Bergh (1970) have shown that the surface temperature and pressure on Venus coincide precisely with the P-T equilibrium of the calcite-wollastonite-CO_2 mineral reaction. If surface reactions are indeed buffering atmospheric SO_2 and CO_2 at the surface of Venus, and if reaction rates are significant on geologic timescales, it is of interest to assess the impact they may have on the climate of Venus.

We propose to develop a unique approach to a theoretical understanding of the various factors that have shaped Venus' climate. We plan to numerically simulate the planetary climate system by developing a set of interconnected modules, each representing one component of Venus' climate. The primary modules we will develop first are numerical models for atmospheric radiative transfer, surface/atmosphere interactions, surface volatile sources, and tropospheric chemistry. This will be followed by developing separate parameterized models for exospheric escape processes, atmospheric chemistry and cloud physics, photochemistry, and global circulation. These modules will be designed so that they may be linked with the others in the system through the boundary conditions. Climate feedback loops result from interconnections between modules, in the form of the environmental parameters pressure, temperature, and atmospheric mixing ratios.

The construction of a set of interconnected computer programs to model the climate of Venus will enable us to explore several important issues regarding the evolution and stability of the Venus climate system. In particular, we will be able to calculate the possible feedback effects of surface mineral buffering of volatiles on the stability of the greenhouse effect. The climatic implications of volcanic sources of key radiatively active species such as CO_2, H_2O, and SO_2 will also be explored using the model. Earlier epochs on Venus may have been characterized by atmospheres with different masses and compositions, and altered crustal inventories of volatiles. One goal of the project will be to seek equilibrium climate states for the model. When sources and sinks of atmospheric volatiles are considered, such as volcanism and exospheric escape, the dynamics of the climate system may be explored. We will calculate possible steady state climates that are predicted by the model, as well as time scales for climate evolution. The present state of the Venus climate system will be modeled utilizing a wide range of laboratory, ground and spacecraft-based measurements. Pioneer Venus data on the atmospheric composition, solar flux deposition, and temperature structure will be used for the radiative transfer calculations. Surface images of Venus, as provided by the Magellan spacecraft, will help to interpret the nature and magnitude of likely global volatile source terms. In addition, laboratory data on the rates and equilibrium constants for important heterogeneous reactions between the surface and atmosphere of Venus will be employed to assess the impact of volatile transport on climate change on Venus.

The Pilot Model

To test the concept of implementing Venus climate modeling as a set of interconnecting computer models, we have developed a working pilot model. The behavior of Venus' climate is modeled as interactions between radiative processes in the atmosphere and surface/atmosphere interactions. Temperature structure is calculated using a one dimensional radiative convective model. Rosseland mean absorption coefficients have been used in the grey-Eddington approximation to solve the radiative transfer equation for model atmospheres under a variety of temperatures, pressures, and atmospheric abundances. The radiative transfer module has been coupled to the surface/atmosphere interactions module through the surface boundary conditions, involving surface temperature, pressure, and atmospheric mixing ratios. Laboratory equilibrium and kinetic data for selected heterogeneous reactions are used to couple geochemical cycles to the atmospheric radiative transfer module. A schematic representation of the way the interconnections between modules is implemented is shown in Figure 1.

The Rosseland mean absorption coefficients were calculated by Dr. Jim Pollack at the NASA Ames Research Center from his extensive spectroscopic data base, for a wide range of CO_2, SO_2, H_2O, and CO mixing ratios. Opacity sources due to continuum, allowed transitions, and aerosols, in 68 spectral intervals, from 1.7 to 250 microns, were combined to calculate the absorption coefficients. Temperature structure calculations were performed using a grey-Eddington approximation, and employing solar flux measurements from the Pioneer Venus solar flux radiometer (Tomasko *et al.,* 1979, 1980) to solve for radiative equilibrium. The temperature profiles were then adjusted by setting the lapse rate equal to local adiabat deep in the atmosphere. Because the coefficient calculations were lengthy and performed at the NASA Ames Research Center, the active inclusion of the radiative transfer calculations in the model feedbacks was not directly possible. Instead, the data sets for a range of atmospheric mixing ratios were fit to a power law description of the Rosseland mean absorption coefficients.

For the purpose of modeling the effects of surface/atmosphere interactions on the climate of Venus, the following heterogeneous reactions were considered:

(1) $$\underset{\text{(calcite)}}{CaCO_3} + \underset{\text{(quartz)}}{Si0_2} \Leftrightarrow \underset{\text{(wollastonite)}}{CaSiO_3} + CO_2$$

(2) $$SO_2 + \underset{\text{(calcite)}}{CaCO_3} \Leftrightarrow \underset{\text{(anhydrite)}}{CaSO_4} + CO$$

(3) $$\underset{\text{(pyrite)}}{3FeS_2} + 2CO + 4CO_2 \Leftrightarrow 6COS + \underset{\text{(magnetite)}}{Fe_3O_4}$$

Reaction (1), the calcite-wollastonite-CO_2 reaction, was originally proposed by Urey (1952) as a key mechanism for buffering CO_2 on Venus. Subsequent laboratory investigations of equilibrium values of this and other possible CO_2 buffering mechanisms (Fegley and Treiman 1991), as well as improved determinations of Venus' surface conditions, have confirmed that this reaction may indeed be a very important geochemical mechanism for the regulation of CO_2 on Venus. The calcite/wollastonite reaction involving CO_2 is an important metamorphic process in the earth's crust, and is a key part of the carbonate-silicate geochemical cycle. CO_2 is liberated by this reaction, as it is dissolved in magmas which eventually find their way to the surface through volcanism. It is a remarkable fact that the equilibrium point for this reaction coincides nearly exactly with the temperature and pressure found on the surface of Venus.

The surface/atmosphere reactions calculations are coupled to the radiative transfer calculations through the conditions that exist at the boundary, namely, surface temperature, pressure, and atmospheric abundances. As the abundances of radiatively active species are modified through surface reactions the radiative equilibrium of the atmosphere is altered. Since the resulting surface parameters alter the equilibrium point of the surface mineral reactions, climate feedbacks result.

Results of the Pilot Model

In order to explore the stability characteristics of the climate as it is modeled by the two interconnected modules just described, the system is evolved statically to describe equilibrium states for both the atmosphere and surface. In general, these two equilibrium fields will not coincide. This is shown in Figure 2, for calculations involving conditions that are consistent with the present atmospheric abundances. The solid line represents the surface pressure and temperature that is achieved by allowing the three surface/atmosphere reactions to simultaneously be in equilibrium. The overall surface pressure is dominated by the calcite-wollastonite-CO_2 equilibrium with a small, but significant, contribution due to the SO_2-anhydrite buffering mechanism. The dotted line represents the surface conditions that result from radiative equilibrium that is achieved with atmospheric partial pressures that are consistent with the surface mineral buffering.

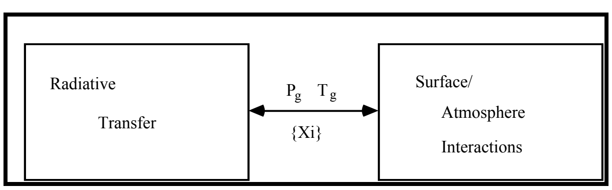

Figure 1. Pilot Climate Model Summary. Interconnections between modules simulate climate feedback loops and are accomplished by passing the environmental variables pressure, P, temperature, T, and atmospheric mixing ratios $\{X_i\}$.

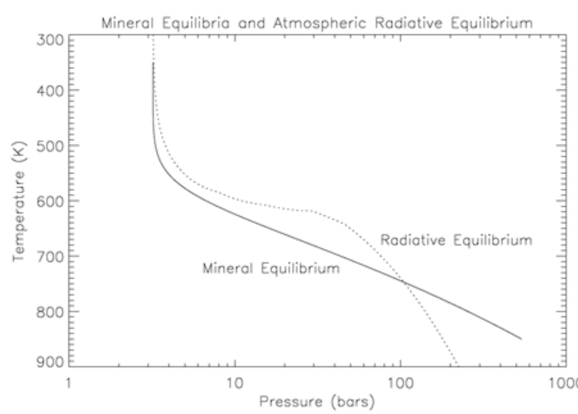

Figure 2. Mineral equilibria and radiative equilibrium curves for surface pressures and temperatures. The solid line represents atmospheric conditions for constituents in chemical equilibrium with the surface, while the dotted line shows conditions for when the atmosphere is in radiative equilibrium.

With the feedback loops that are considered in this model, it can be seen that these two curves intersect at only two points. At about 95 bars of surface pressure and 735 K, equilibrium between the surface mineral buffers and radiative processes is achieved. The intersection at the lower right of the P-T diagram corresponds roughly to the surface temperature and pressure that exists on Venus today. Another equilibrium point exists at an atmospheric state where most radiatively active species have returned to surface reservoirs, and only water and inert gases (i.e. N_2) remain. An extremely important point here, and one that is robust to many of the details of the model, is that the current equilibrium point is unstable. This is due chiefly to the relative slopes of the radiative and mineral equilibria curves. Small perturbations in the climate system, such as an injection of radiatively active volatiles through volcanism, or the removal of a constituent through buffering, will precipitate a catastrophic change in climate to a much hotter or much cooler state. A good candidate for initiating a cooling trend, for example, would be the uptake of SO_2 though the SO_2-anhydrite buffer, since Venus' lower atmosphere currently contains 10 to 100 times as much SO_2 as can be accounted for by equilibrium with surface rocks (Volkov 1986, Fegley and Treiman 1991).

Nominal values for the thermodynamic constants of the three surface/atmosphere reactions considered here place Venus' present atmosphere on the cooler side of the mineral equilibrium curve. However, uncertainty in these data could place Venus' current conditions on either side of this unstable equilibrium. Recent Magellan images have shown that Venus has an extensive, and most likely recent, history of volcanism. Rates of volcanism, as determined by the modeling efforts of Bullock *et al.*, (1993) show that a flux of about 0.4 km^3/yr is consistent with the observed impact cratering record. Although volatile abundances of Venus magmas are poorly constrained, estimates of water abundances (Grinspoon *et al.*, 1993) and the observed temporal variability of SO_2 (Esposito 1984), show that significant sources of radiatively active gases may be currently active. It is possible, therefore, that the nominal cooling trend that is demonstrated in the model is offset by sources that are presently active. If this is true, Venus' climate may be in a kind of steady state, with volcanism providing sources of infrared opacity to the atmosphere, and geochemical sinks removing them.

If, on the other hand, the Venus surface/atmosphere system were on the other side of the separatrix, a rapid escalation of temperature and pressure would ensue due to a strong positive feedback between the surface buffering reactions and radiative equilibrium. The viability of such a runaway situation is predicated on the assumption that both sulfur and carbon reservoirs are capable of continuously supplying volatiles to the atmosphere. This is probably not the case for CO_2, since the current atmospheric inventory of CO_2 on Venus is nearly the same as the combined oceanic-crustal-atmospheric inventory on earth. At some point in this runaway scenario, therefore, one or more of the surface buffers must switch off, and the climate of Venus would be "pegged" at a high temperature and pressure state, with all surface reservoirs depleted.

Conclusions

The purpose of the pilot project has been to illustrate how a systems approach may be developed to model interactions between elements in a planetary climate system. Although the atmospheric evolution and geochemical cycles in a planetary system are naturally extremely complex, by modeling the behavior of key elements of the climate and its feedbacks, it is possible to deduce some general stability properties that a given climate system may possess. This systems approach has been applied to the climate of Venus to show the possible nature of its climate stability. Understanding Venus' climate must necessarily involve a great number of factors that can be progressively introduced into the kind of systems approach discussed here. In the simple implementation described here, the radiative transfer calculations were performed by interpolating between a discrete number of model atmospheres, because the calculation of Rosseland mean opacities is lengthy. As a result, the feedback between the two modules is rather a rough approximation of the actual behavior of the system. A full implementation of the model will involve the active inclusion of the absorption coefficient calculations in the entire climate feedback system, resulting in a more accurate and detailed analysis of the climate feedbacks. As far as the effects of chemical and radiative equilibrium are concerned, one of the most important feedbacks on climate may be the effect of changes in bolometric albedo. For the fully developed model, we will place a heavy emphasis on the evolutionary chemical and physical cloud model, and on the potentially significant climate feedbacks that might occur. Additional modules, involving exospheric escape processes, atmospheric chemistry and cloud physics, photochemistry, and global circulation, will also developed and connected to the existing modules to provide a much richer set of feedback loops than exist in the pilot model. The results so far generated have illustrated that this 'systems' approach to modeling the climate of Venus is feasible. Interesting implications for the climate stability have been demonstrated, and we believe that a full implementation of this project will yield important new insights on the evolution and stability of the climate of Venus.

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