EESC W4008 Homework #2 Due Mon. 10/25/04

*************** Deliver your homework directly to our TA Peng Xian ******************

1.) The Gaia hypothesis states that biological activity on Earth responds to changing climate by altering itself in such a way as to negate the climate change, i.e., life on Earth acts as a kind of thermostat that prevents atmospheric temperatures from changing too much. (As an example, imagine a planet called Daisyworld consisting of only 2 types of life, black daisies and white daisies. When the climate is cold, black daisies thrive because they absorb more sunlight than white daisies. As the black daisy population grows Daisyworld gets darker, absorbs more sunlight, and warms up, eliminating the cold climate. When the climate warms, white daisies thrive instead because they reflect sunlight better, making Daisyworld brighter and cooling it off.) Thus far only one real Gaia-type scenario has emerged (Charlson et al., 1987, *Nature* **326**, 655-661). Planktonic algae in seawater (see picture below) excrete dimethylsulfide gas (DMS), which is volatile, escapes to the atmosphere, and oxidizes to form sulfate aerosols. This may be the major component of the CCN population over remote unpolluted ocean locations. It has been suggested that DMS production and CCN concentration might increase in a warming climate (although it is not obvious why that should be the case).

a.) If the number of CCN that nucleate cloud droplets increases by a factor of 8 in response to a specified warming of the atmosphere, by what factor would the mean radius of cloud droplets in low level marine stratocumulus clouds change if the liquid water content of the clouds remains the same?

b.) The brightness (or *albedo*) of a cloud is an increasing function of the total surface area of all the cloud droplets. By what factor does the total area change? Does this make the cloud brighter or darker (i.e., more or less reflective of sunlight)? What is the effect on the climate, considering that reflection to space prevents sunlight from being absorbed and warming the Earth surface?

c.) Considering the change in mean cloud particle size, would you expect more or less rainfall in the warmer climate? Given this, should we really expect cloud liquid water content, which we had assumed in part (a) to remain the same, to really stay the same when aerosol concentration increases? If not, should it increase or decrease, and what is the resulting effect on the climate?

2.) The clouds of Venus (Rossow, 1978, *Icarus* **36**, 1-50) are a planetwide haze of 1.05 μm radius particles extending from about 50 to 80 km altitude above the hot (730 K) surface. They are composed of a concentrated solution of sulfuric acid in water and are produced by photochemical reactions rather than by cooling of lifted air. They are therefore more like terrestrial smog aerosols than terrestrial water clouds. Assume a cloud temperature of 250 K, $\rho_{acid} \sim \rho_w$, 110% acid RH, 50% sticking efficiency, a liquid acid content of 5 x 10^{-3} g m^{-3}, ambient vapor density of 3 x 10^{-8} g m^{-3}, a diffusion coefficient of 2 x 10^{-5} m^2 s^{-1}, and a viscosity of 1.5 x 10^{-5} kg m^{-1} s^{-1} for the Venus atmosphere.

a.) For what radius particle are the coagulation and coalescence rates equal?

b.) For what radius particle are the coagulation and condensation rates equal?

c.) Based on (a) and (b), which is the dominant process for forming the Venus clouds during ***most*** of the growth stage?

d.) Without calculating, give two reasons why you might guess that these clouds do or do not precipitate, based on comparison to terrestrial water clouds and/or information given above.

3.) Ice crystals in cirrus clouds tend to be larger than liquid cloud droplets in warm clouds because of the smaller concentration of efficient ice nucleating sites in the upper troposphere relative to the concentration of CCN at low altitudes. However, ice crystal fall speeds are slower than one would predict from our equation for the terminal velocity for two reasons: (1) Ice crystals are not spherical (a variety of shapes exist; see Salby p. 276), so they suffer more wind resistance; (2) Except for heavily rimed particles, ice crystals in general are not solid ice but are partly air (e.g., snowflakes), so their density is $< \rho_w$ averaged over their volume.

a.) As a very crude model, assume that ice crystals can be approximated as flat circular cylinders of radius R and height h. Also assume that the density of ice varies as $\rho_i = \rho_w(h/R)$ for crystals that aggregate enough to fall out of a cirrus cloud, i.e., the flatter the crystal, the less dense it is and the more air resistance it experiences. Derive a formula for the radius r of a sphere whose volume equals that of a cylinder of radius R and height h. Assuming that the radius of this "equivalent sphere" can be used to convert microphysics expressions for liquid into approximate expressions for ice cylinders, derive a formula for the fall speed of a cylindrical ice crystal in terms of ρ_w, h, and R.

b.) A controversial issue in climate is whether humidity will increase or decrease as climate changes. We expect evaporation from the ocean, and thus low-altitude humidity, to increase as the climate warms. But the same may not be true in the upper troposphere, far from the ocean surface, where the processes responsible for adding and subtracting water vapor are not well understood. It is thought that the subtropical upper troposphere has a lot to say about how sensitive our climate is. The subtropics are a region of infrequent deep moist convection (think deserts, resort islands, etc.), so how does water vapor enter its upper troposphere? Near the equator, where deep convection is prevalent, cumulus updrafts pump water into the upper troposphere and detrain ice crystals into the areally extensive anvil clouds we see in satellite pictures (left, below). If a significant fraction of this detrained ice can be advected (transported by the prevailing poleward winds) into the subtropical upper troposphere, it might sublime there and control the humidity of that region. That will only be true if the ice stays up there long enough to survive the trip. Assume that ice is detrained from a cumulus updraft at 5°N latitude and 12 km altitude, and it drifts poleward at 3 m/s to 25°N latitude. How small must the equivalent radius of such an ice crystal be to reach the subtropics without completely falling out of the atmosphere (neglecting any sublimation along the way for the moment)? Assume a constant h = 50 μm and a viscosity of air of $\eta = 1.5 \times 10^{-5}$ kg/(m-s). Given that most of the mass of ice clouds resides in particles of equivalent radius 25 μm – 1 mm, is detrainment and transport of ice from tropical deep convection an important water source for the subtropics?

c.) In satellite images (right, below), we often see "atmospheric rivers" of cloudiness flowing from the tropics to the midlatitudes and affecting weather in the U.S. (sometimes called the "pineapple express"). Decide which of the following hypotheses is more credible, and defend your position: (1) The cloud particles that reach the U.S. are the same ones that formed in the tropical cumulus updraft and detrained into the upper troposphere; (2) The cloud particles that formed in the tropical cumulus updraft and detrained into the upper troposphere fell out and sublimed below the cirrus cloud base long before reaching midlatitudes, but the resulting water vapor was subsequently lifted again to form new cirrus ice crystals, the process repeating itself many times until the airmass reached the U.S.