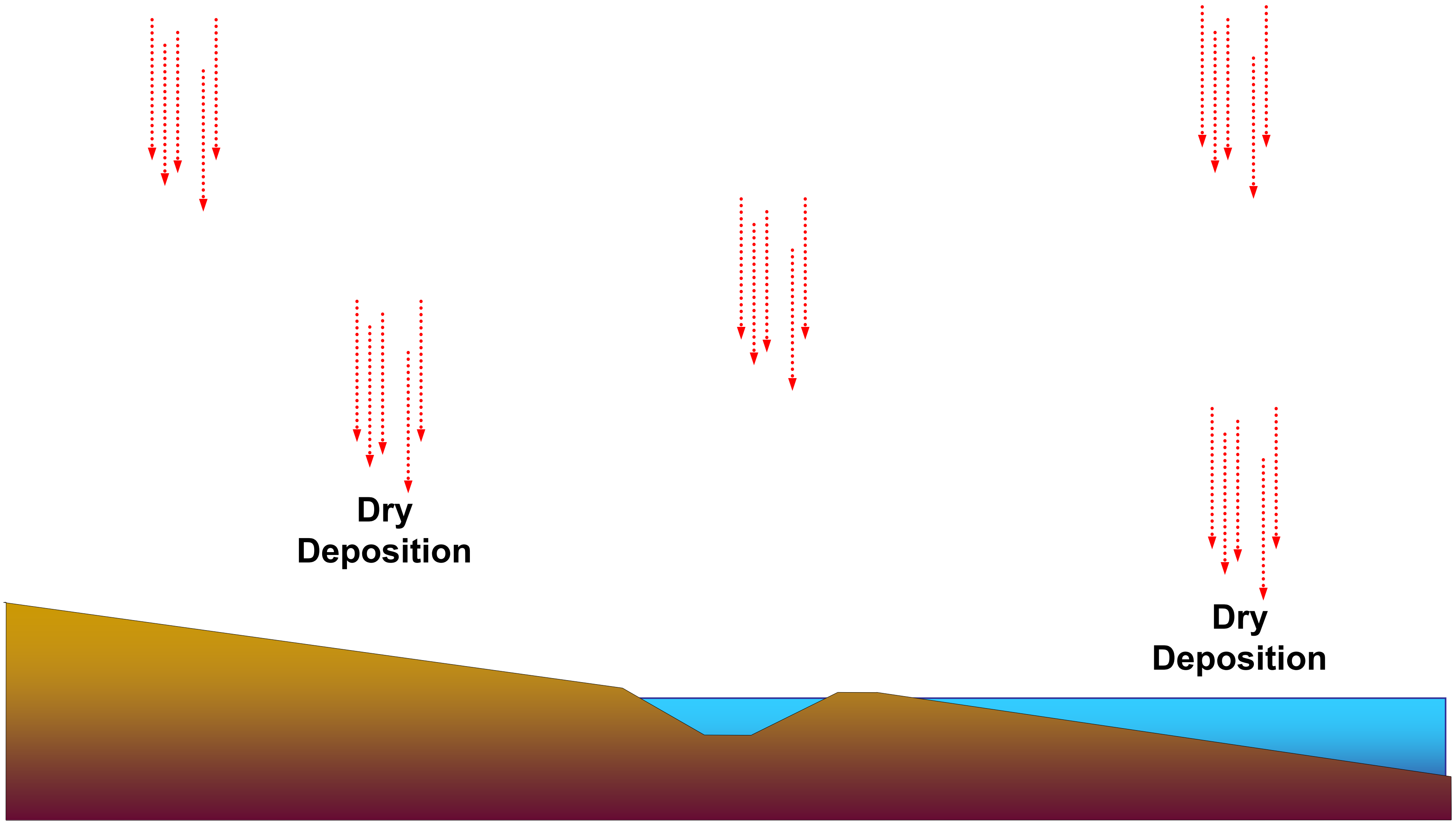
Lecture 21. Wet Deposition and General Dynamic Equation for Aerosols in the Atmosphere

Lecture 8: Dry Deposition



Review of Dry Deposition

z_o *is* the roughness length; u_* is the friction velocity.

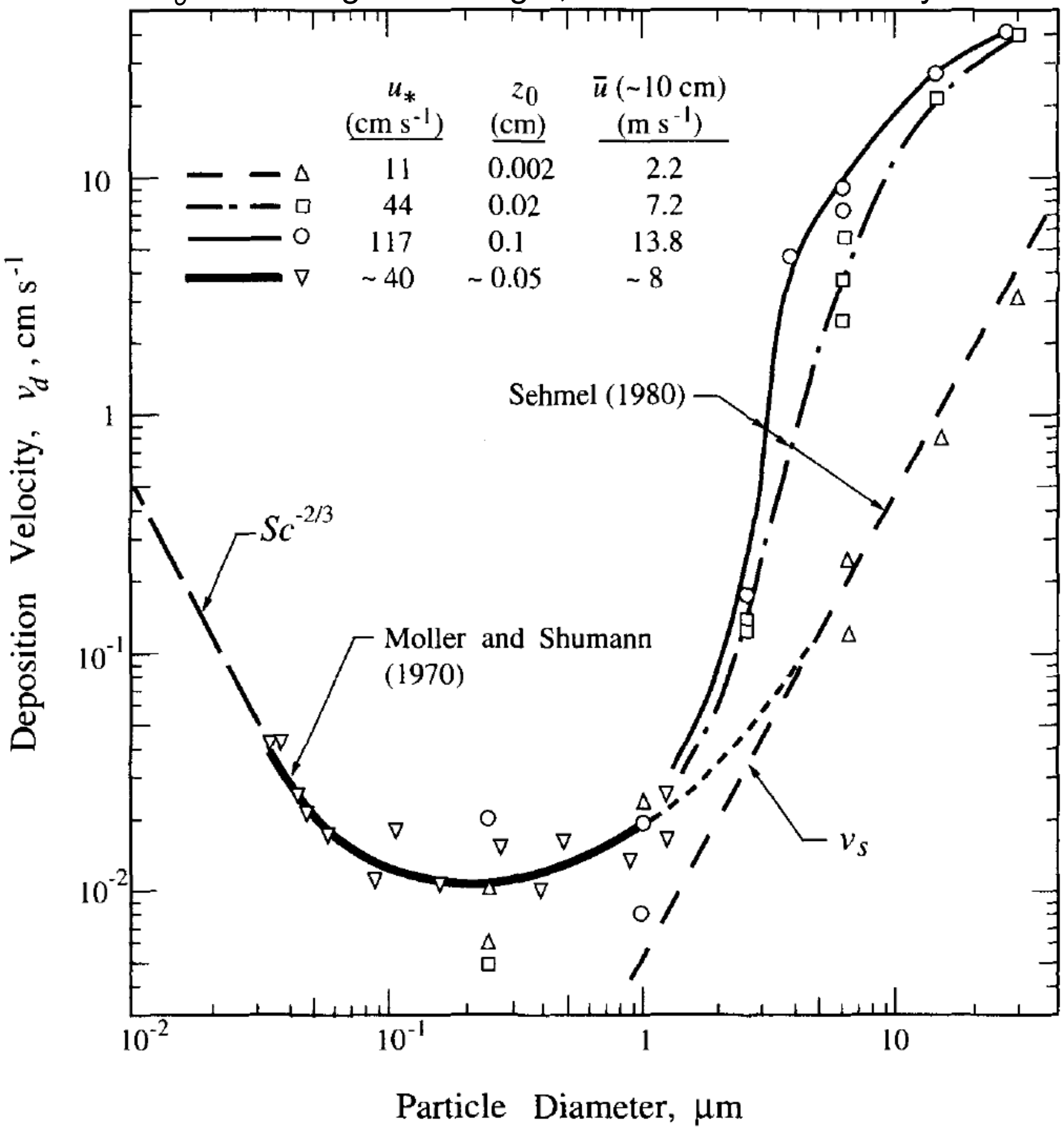
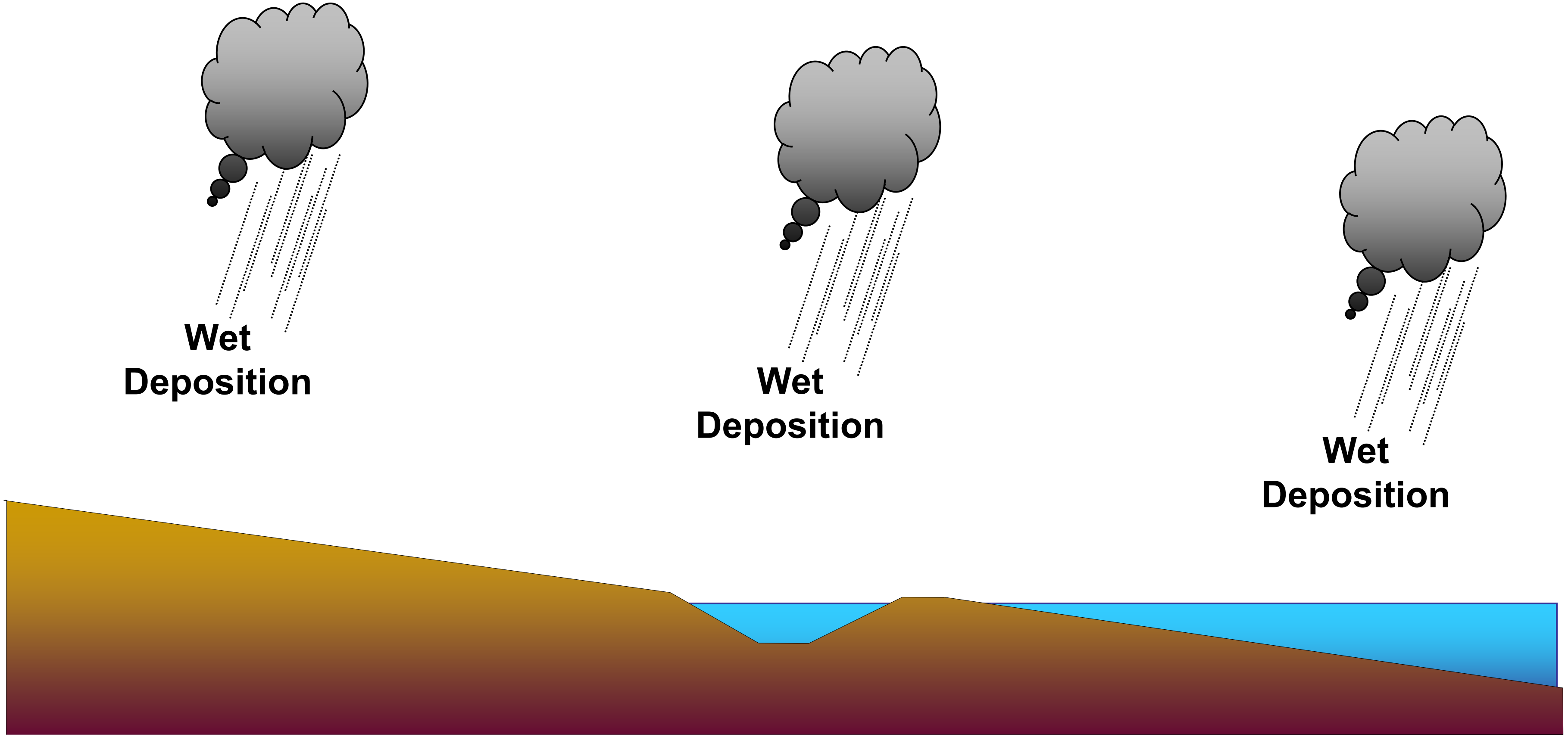


FIGURE 19.2 Particle dry deposition velocity data for deposition on a water surface in a wind tunnel (Slinn et al. 1978).

$$v_d = \frac{1}{r_t} = \frac{1}{r_a + r_b + r_a r_b v_s} + v_s$$

Wet Deposition



Wet deposition refers to the natural processes by which material is scavenged by atmospheric hydrometeors (cloud and fog drops, rain, snow) and is consequently delivered to the Earth's surface. A number of different terms are used: precipitation scavenging, wet removal, washout, and rainout. *Rainout* usually refers to in-cloud scavenging and *washout,* to below-cloud scavenging by falling rain, snow, and so on.

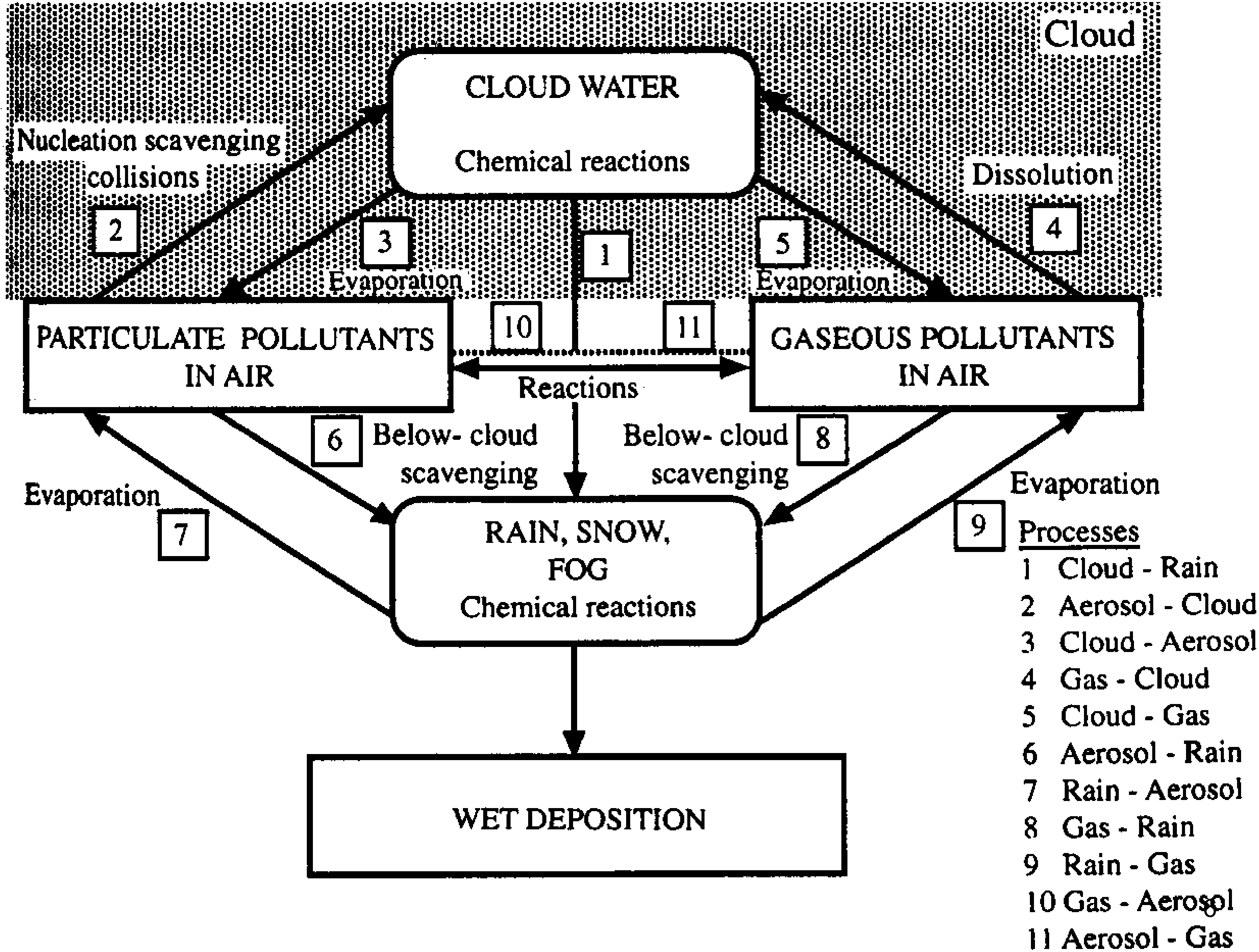
1. Precipitation scavenging, that is, the removal of species by a raining cloud

2. Cloud interception, the impaction of cloud droplets on the terrain usually at the top of tall mountains

3. Fog deposition, that is, the removal of material by settling fog droplets

4. Snow deposition, removal of material during a snowstorm

In all of these processes three steps are necessary for wet removal of a material. Specifically, the species (gas or aerosol) must first be brought into the presence of condensed water. Then, the species must be scavenged by the hydrometeors, and finally it needs to be delivered to the Earth's surface. Furthermore, the compound may undergo chemical transformations during each one of the above steps.


Cloud
CLOUD WATER
Chemical reactions
Nucleation scavenging
collisions
2
3
Evaporation
1
5
Evaporation
Dissolution
4
PARTICULATE POLLUTANTS
IN AIR
10
11
GASEOUS POLLUTANTS
IN AIR
Reactions
6
Below- cloud
scavenging
Below- cloud
scavenging
8
Evaporation
7
Evaporation
9
RAIN, SNOW,
FOG
Chemical reactions
WET DEPOSITION
Processes
1 Cloud - Rain
2 Aerosol - Cloud
3 Cloud - Aerosol
4 Gas - Cloud
5 Cloud - Gas
6 Aerosol - Rain
7 Rain - Aerosol
8 Gas - Rain
9 Rain - Gas
10 Gas - Aerosol
11 Aerosol - Gas

PRECIPITATION SCAVENGING OF PARTICLES

The below-cloud scavenging (washout) rate of aerosol particles of diameter d_p can be written as

$$\frac{dn_M(d_p)}{dt} = -\Lambda(d_p) n_M(d_p)$$

where the scavenging coefficient $\Lambda(d_p)$ is given by

$$\Lambda(d_p) = \int_0^\infty \frac{\pi}{4} D_p^2 U_t(D_p) E(D_p, d_p) N(D_p) dD_p$$

Calculation therefore of the aerosol scavenging rate, for a given aerosol diameter d_p, requires knowledge of the droplet size distribution $N(D_p)$ and the scavenging efficiency $E(D_p, d_p)$.

The collision efficiency $E(D_p, d_p)$ is by definition equal to the ratio of the total number of collisions occurring between droplets and particles to the total number of particles in an area equal to the droplet's effective cross-sectional area. A value of $E = 1$ implies that all particles in the geometric volume swept out by a falling drop will be collected.

Slinn (1983) proposed the following correlation for *E* that fits experimental data:

$$E = \frac{4}{\mathrm{Re\,Sc}}\left[1 + 0.4\,\mathrm{Re}^{1/2}\mathrm{Sc}^{1/3} + 0.16\,\mathrm{Re}^{1/2}\mathrm{Sc}^{1/2}\right] + 4\phi\left[\omega^{-1} + (1 + 2\,\mathrm{Re}^{1/2})\phi\right] + \left(\frac{\mathrm{St} - S^*}{\mathrm{St} - S^* + \frac{2}{3}}\right)^{3/2}$$

$$S^* = \frac{1.2 + \frac{1}{12}\ln(1 + \mathrm{Re})}{1 + \ln(1 + \mathrm{Re})}$$

$\mathrm{Re} = D_p U_t \rho_a / 2\mu_a$	(Reynolds number of raindrop based on its radius)
$\mathrm{Sc} = \mu_a / \rho_a D$	(Schmidt number of collected particle)
$\mathrm{St} = 2\tau(U_t - u_t)/D_p$	(Stokes number of collected particle, where τ is its characteristic relaxation time)
$\phi = d_p / D_p$	(ratio of diameters)
$\omega = \mu_w / \mu_a$	(viscosity ratio)

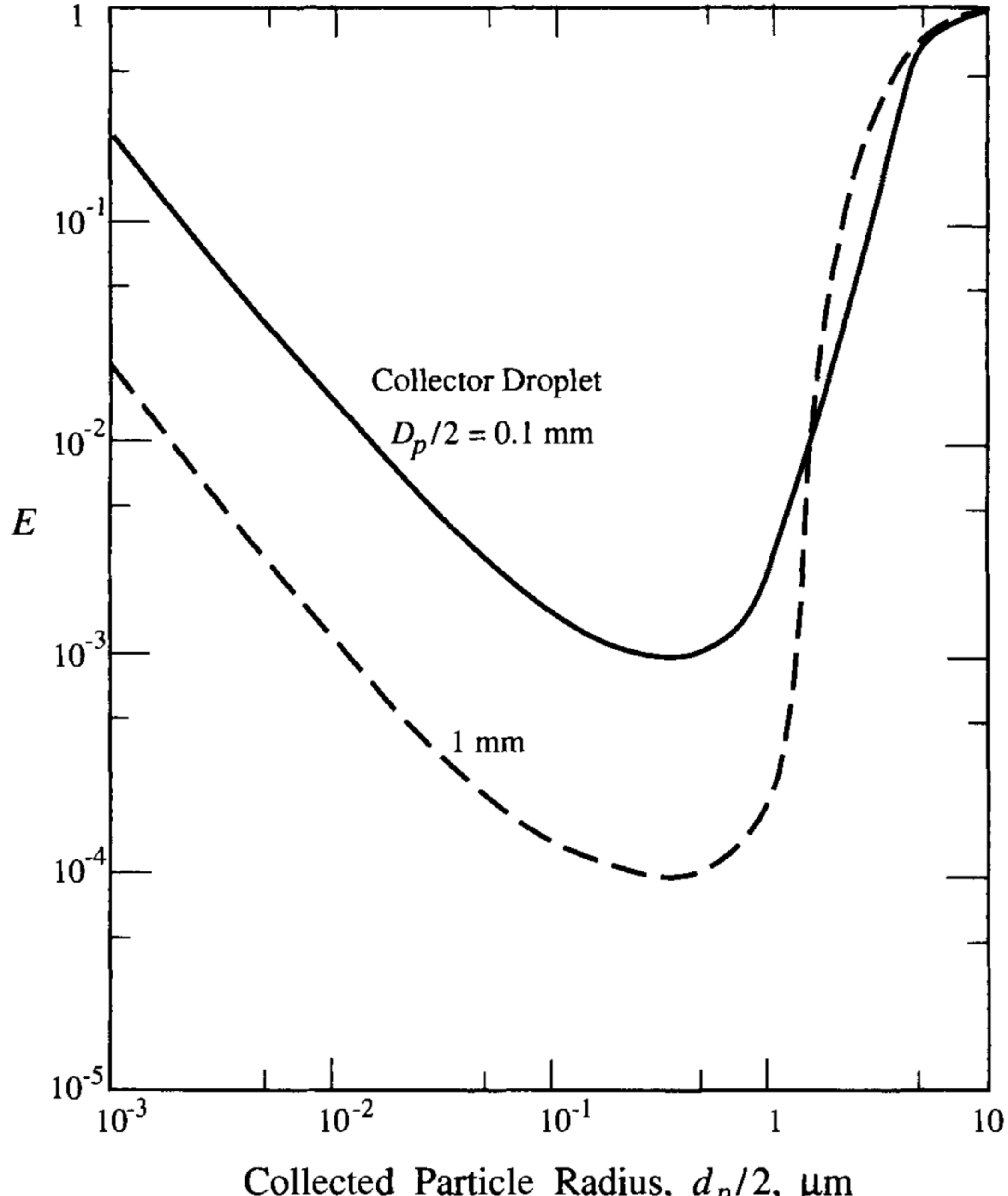


FIGURE 20.6 Semiempirical correlation for the collection efficiency E of two drops (Slinn 1983) as a function of the collected particle size. The collected particle is assumed to have unit density.

For monodisperse aerosols and raindrops, the scavenging coefficient can be calculated as

$$\Lambda(d_p) = \frac{3}{2}\frac{E(D_p, d_p)p_0}{D_p}$$

Where $p_0 = \frac{\pi}{6} D_p^3 U_t(D_p) N_D$ is the rainfall intensity (mm/hr)

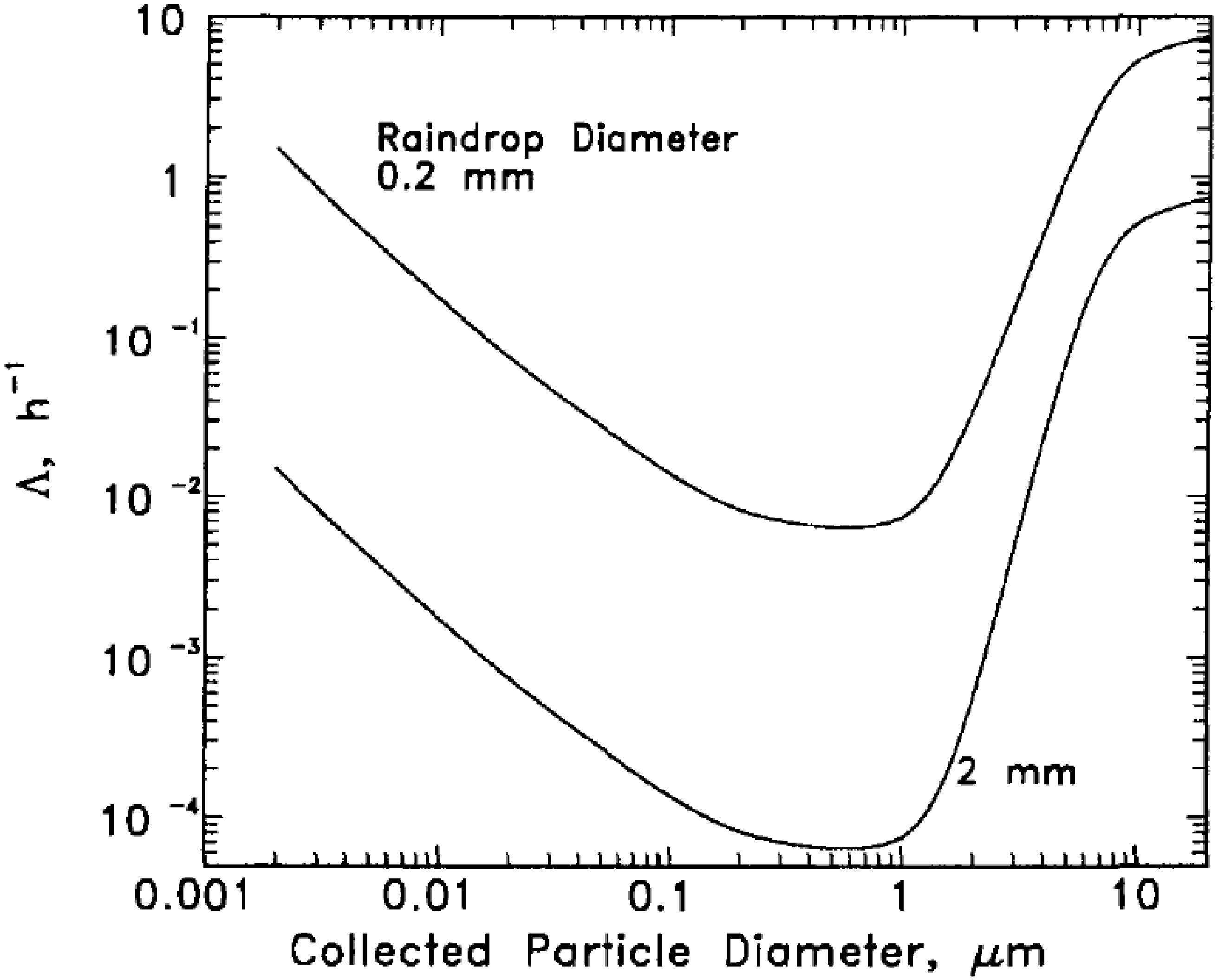


FIGURE 20.7 Scavenging coefficient for monodisperse particles as a function of their diameter collected by monodisperse raindrops with diameters 0.2 and 2 mm assuming a rainfall intensity of 1 mm h^{-1}.

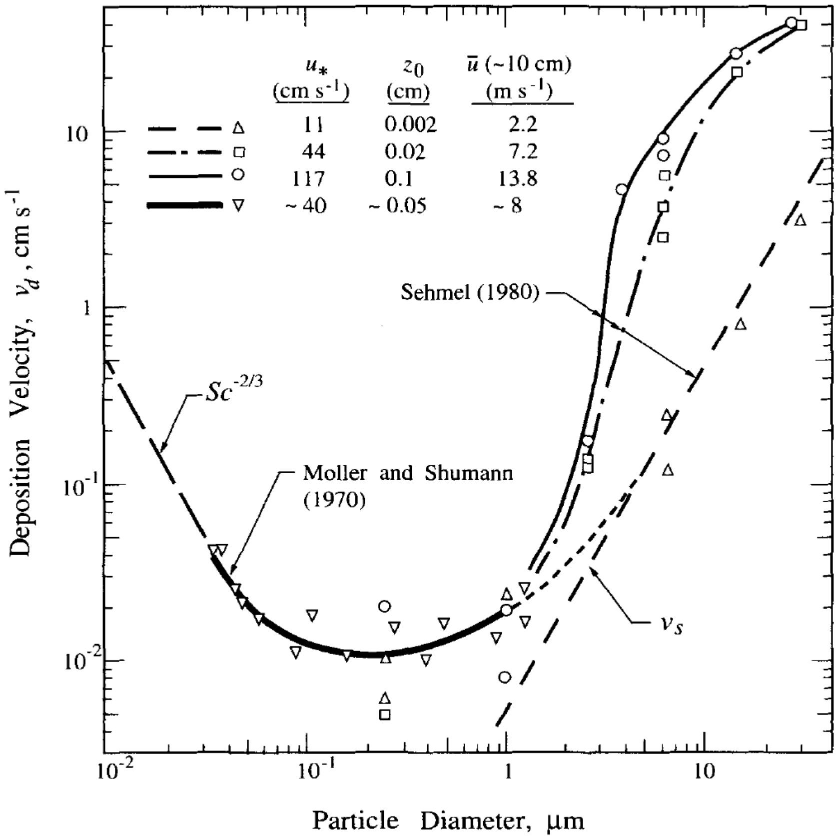


Fig. 1. Particle dry deposition velocity as a function of particle sizes.

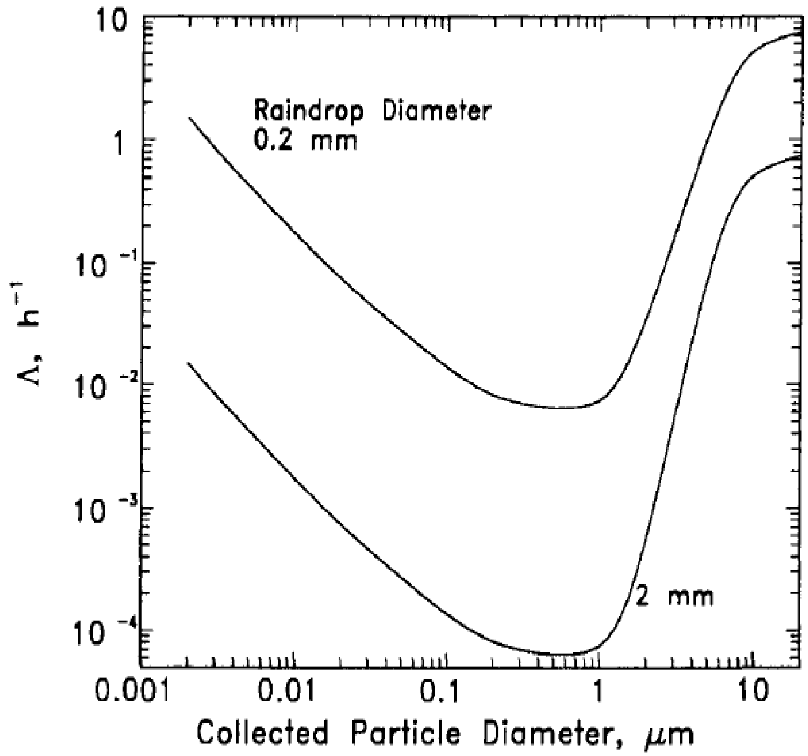


Fig. 2. Scavenging coefficient for monodisperse particles as a function of their diameter collected by monodisperse raindrops with diameters 0.2 and 2 mm assuming a rainfall intensity of 1 mm h^{-1}.

Calculate the lifetimes of particles with diameters of 0.01, 0.3, and 10 μm in the surface layer with depth of 100 m due to (a) dry deposition (using Sehmel curve for larger particles and assuming particles are welled mixed with in the layer), and (b) wet scavenging by rain (assuming droplet diameter of 0.2 mm and rainfall intensity of 1 mm/h).

General Dynamic Equation for Aerosols in the Atmosphere

THE DISCRETE GENERAL DYNAMIC EQUATION

In reality, there is a minimum number of monomers in a stable nucleus g^*, and generally $g^* > 2$. In the presence of a supersaturated vapor, stable clusters of size g^* will form continuously at a rate given by the theory of homogeneous nucleation.

$$\frac{dN_k}{dt} = \frac{1}{2}\sum_{j=g^*}^{k-g^*} K_{j,k-j}N_jN_{k-j} - N_k\sum_{j=g^*}^{\infty} K_{k,j}N_j + p_{k-1}N_{k-1}$$
$$- (p_k + \gamma_k)N_k + \gamma_{k+1}N_{k+1} + J_0(t)\delta_{g^*,k} + S_k - R_k$$
$$k = g^*, g^* + 1, \ldots$$

where S_k is the emission rate of k-mers by sources and R_k is their removal rate.

THE CONTINUOUS GENERAL DYNAMIC EQUATION

$$\frac{\partial n(v,t)}{\partial t} = \frac{1}{2}\int_0^v K(v-q,q)n(v-q,t)n(q,t)\,dq - n(v,t)\int_0^\infty K(q,v)n(q,t)\,dq - \frac{\partial}{\partial v}[I(v)n(v,t)] + J_0(v)\delta(v-v_0) + S(v) - R(v)$$

TABLE 13.4 Properties of Coagulation, Condensation, and Nucleation

Process	Number Concentration	Volume Concentration
Coagulation	Decreases	No change
Condensation	No change	Increases
Nucleation	Increases	Increases
Coagulation and condensation	Decreases	Increases