Earth’s albedo
Earth’s annual-mean albedo at the top of atmosphere. (a) Total albedo, obtained as the ratio of total upward to downward solar radiative energy flux at the top of the atmosphere. (b) Clear-sky component of the albedo, obtained as the ratio of upward solar radiative energy flux from cloudless regions to total downward flux. All radiative energy fluxes were measured by NASA’s space-based Clouds and Earth’s Radiant Energy System (CERES) instruments. They were averaged over the 13 years from March 2000 through February 2013 prior to the computation of the albedos. The right panels show the zonal means of the left panels. The dashed red line in the upper right panel is the fit from the heuristic model in the box on p. 103.
Figure 4.3: Scattering by optically thin clouds. Path length depends on angle of incidence.

Arises because water not only reflects light but also refracts it, transmitting radiative energy below the surface where much of it is eventually absorbed (if it is not scattered back out of the water, e.g., by phytoplankton in the water). At more oblique incidence, more of the incoming sunlight is reflected and less is refracted—a result from geometric optics that for smooth surfaces is encapsulated in what are known as Fresnel's reflection formulas. Fresnel's reflection formulas also apply locally to the face of a water wave, because the face is much larger than the wavelength of sunlight. When a ray of sunlight strikes the mean ocean surface at an oblique angle, its incidence on a steep wave face can be close to normal. Fresnel's reflection formulas imply that more light is refracted into the wave than would be the case for oblique incidence on a flat ocean surface; the albedo is locally reduced. Thus, at oblique angles of incidence on the mean ocean surface, waviness reduces the albedo. Conversely and for analogous reasons, at closer to normal incidence on the mean ocean surface, waviness increases the albedo. But it remains true also for a wavy ocean surface that its albedo increases the more oblique the incidence of the sunlight. This dependence on the angle of incidence is consistent with a common experience: more sunlight is reflected from a water surface at sunrise or sunset than at...
Figure 4.4: Scattering by optically thick clouds. Stronger scattering for lower angles of incidence because of forward scattering.

Because the sun on average is lower in the sky in high latitudes than in low latitudes, the average angle of incidence of sunlight is more oblique in high latitudes. Consequently, the mean albedo of the ocean surface increases with latitude. Its global-mean value is about 10%.

For clouds, the albedo similarly depends on the angle of incidence of sunlight and properties such as the cloud water path, the typical size of droplets, and the shape of any ice crystals that may be present. For example, the albedo generally is higher for smaller droplets or a larger cloud water path. Each, holding the other fixed, increases the total cross-sectional area of scatterers that intercept rays of sunlight, increasing the albedo. The albedo of clouds generally is also greater for more oblique incidence of sunlight. Here the dependence on the angle of incidence can arise for two reasons. First, for optically thin (i.e., almost transparent) and plane clouds, a ray of sunlight that strikes a cloud at an oblique angle has a longer path through the cloud and therefore a greater chance of being intercepted by a cloud particle than a ray incident normal to the cloud plane. This increases the albedo for oblique incidence on thin clouds. Second, particles that are greater than the wavelength of light, such as cloud
Figure 4.5: Earth’s annual-mean albedo at the top of atmosphere. (a) Total albedo, obtained as the ratio of total upward to downward solar radiative energy flux at the top of the atmosphere. (b) Clear-sky component of the albedo, obtained as the ratio of upward solar radiative energy flux from cloudless regions to total downward flux. All radiative energy fluxes were measured by NASA’s space-based Clouds and Earth’s Radiant Energy System (CERES) instruments. They were averaged over the 13 years from March 2000 through February 2013 prior to the computation of the albedos. The right panels show the zonal means of the left panels. The dashed red line in the upper right panel is the fit from the heuristic model in the box on p. 103.
CHAPTER 4

4.6: Clouds over the Amazon Delta as viewed from the International Space Station. Openings between the clouds are clearly visible in the foreground, at a nearly normal viewing angle. Toward the horizon, at more oblique viewing angles, openings are masked by vertical cloud protrusions, and the cloud field appears more uniform. (Image credit: NASA)

Notes

1. See Cox and Munk (1955) for an early theoretical calculation of the ocean albedo given its wave spectrum and Payne (1972) and Jin et al. (2004) for measurements.

2. See Loeb et al. (2009) and Stephens et al. (2012) for a description of the data on which Fig. 4.5 is based.

As a simple model illustrating how vertical protrusions can modulate the albedo of cloud fields, consider a cloud field consisting of \( n \) hemispheric clouds, each with a radius \( r \). Assume the clouds are so-called Lambertian (completely diffuse) scatterers, which scatter the solar radiative energy flux they intercept isotropically, with an albedo \( \alpha_c \). Underneath the clouds is ground with albedo \( \alpha_g \). We ignore absorption of sunlight by the atmosphere, multiple scattering between the clouds and the ground, and clouds shadowing one another. Because of symmetry, we can confine our considerations to a two-dimensional section:

A solar radiative energy flux incident at an elevation angle \( \theta \) is intercepted by each cloud with an arc length (length of shadow in a plane normal to the incident ray)

\[
r \int_0^{\theta+\pi/2} \cos(\theta - \phi) \, d\phi = r(1 + \sin \theta).
\]

Therefore, of the solar radiative energy \( \propto L \sin \hat{\theta} \) incident on a length segment \( L \), the fraction \( \alpha_c f_c (1 + \sin \hat{\theta})/\sin \hat{\theta} \) is reflected, where \( f_c = nr/L \) is the cloud fraction. The length of the ground segment not shadowed by clouds is \( L - nr(1 + \sin \hat{\theta})/\sin \hat{\theta} \), so the fraction reflected by the ground is \( \alpha_g (1 - f_c (1 + \sin \theta)/\sin \hat{\theta}) \). This gives for the overall albedo of the cloud field

\[
\alpha = \alpha_g + f_c (\alpha_c - \alpha_g) \frac{1 + \sin \hat{\theta}}{\sin \hat{\theta}}.
\]

If clouds shadow one another so that no sunlight penetrates the holes between them (i.e., \( 1 - f_c (1 + \sin \theta)/\sin \hat{\theta} < 0 \)), all incident solar energy is scattered by clouds and none by the ground. So the overall albedo simply is the cloud albedo \( \alpha_c \).