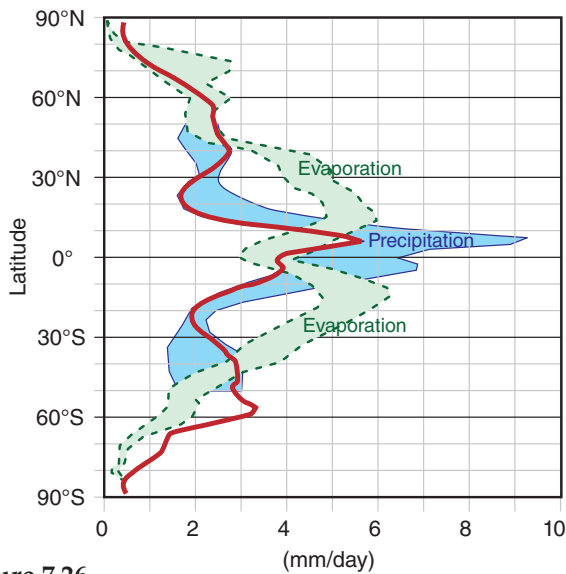


**Figure 7.25**  
 Annual mean precipitation during years 1979 to 2000. [Adapted from image courtesy of US Climate Prediction Center (NOAA/ National Weather Service, National Centers for Environmental Prediction). <http://www.cpc.ncep.noaa.gov/products/precip/CWlink/wayne/annual.precip.html>]



**Figure 7.26**  
 Zonally averaged rates of evaporation (light grey with dotted outline) and precipitation (dark grey with solid black outline). Estimated from a combination of satellite observations, numerical simulations, and surface observations. Spread of the grey areas indicates uncertainty (disagreement among the different methods). Data courtesy of NASA GSFC and the Global Precipitation Climatology Project (plotted as the thick black line).

glacier snow). The weight of additional snow on top can further compact deeper older snow.

**Piste** is the name for a ski run where the snow has been compacted by grooming machines. Density and strength can be increased by mechanically chopping and compacting the snow, by adding liquid water (that later freezes), and by adding chemicals such as nitrate fertilizers or urea.

### 7.7.4. Precipitation Distribution

Combining rain-gauge data over land with satellite observations over oceans gives the annual precipitation distribution shown in Fig. 7.25. The heaviest rain is in the tropics, where the warm sea surface causes copious amounts of evaporation (Fig. 7.26), where the warm air can hold a large amount of precipitable water, and where the general circulation contains updrafts. Rain is suppressed at 30° north and south due to extensive regions of downdraft in the Hadley-cell circulation. This circulation is discussed in the General Circulation chapter.

## 7.8. PRECIPITATION MEASUREMENT

The simplest precipitation instrument is a **rain gauge**, which is a cylindrical bucket into which the rain falls. By using a measuring stick to manually read the water depth in the bucket at successive times such as every hour, you can determine rainfall rate. For greater sensitivity, a funnel can be placed over the bucket to collect rain faster, but the depth of water in the bucket must be reduced by the ratio of the horizontal cross-section areas of the bucket to the funnel opening. To get the **liquid-water equivalent** of the snowfall, some rain gauges are heated to melt snow, and others are painted black to passively melt snow by absorbing sunlight. Some gauges are surrounded by a segmented **wind shield** to reduce errors due to blowing precipitation.

Automated rain gauges exist. **Weighing rain gauges** weigh the rain-filled bucket over successive intervals, inferring rain accumulation by weight increase, knowing the density of liquid water.

**Tipping-bucket rain gauges** direct the captured rain into a tiny bucket on one side of a lever. When the bucket gets full, it tips the lever like a seesaw (teeter-totter), emptying that bucket while simultaneously moving under the funnel an empty bucket from the other end of the lever. Each tip can be counted digitally, and the frequency of tips during an hour gives the rainfall rate.

**Drip rain gauges** funnel rainwater into a small orifice, under which individual drips of water form

by surface tension. As each drip separates from the funnel orifice, it touches two conductors as it falls toward a drain, allowing each drip to be counted.

An **evaporative rain gauge** has two metal plates, one above the other, each oriented horizontally (one facing up, and the other facing down). Each plate is heated electrically to maintain the same specified temperature warmer than ambient air. Precipitation falling on the hot top plate evaporates quickly, thereby removing heat from that plate. By measuring the amount of extra electricity needed to keep the top plate at the same temperature as the bottom, and knowing the latent heat of vaporization, the rainfall rate can be determined.

**Attenuation rain gauges** have a light beam that shines horizontally across an open air path exposed to precipitation. The attenuation of the light beam is related to precipitation intensity, but errors can be due to air pollution, fog, and different absorption cross-sections of liquid vs. solid precipitation.

A **disdrometer** measures size distribution of rain drops via the momentum imparted to a horizontal plate by each falling drop. Another method is a particle imager that sends light from an array of light-emitting diodes to an array of tiny photodetectors. Each hydrometeor casts a shadow that can be detected, where the size and the shape of the shadows are used together to estimate precipitation rate, hydrometeor type and size. A **Knollenberg probe** uses this imaging method, and can be mounted on aircraft flying through clouds and precipitation.

A **liquid-water content (LWC) probe** consists of an electrically heated wire. When mounted on an aircraft flying through a cloud, the rain and cloud droplets evaporate upon hitting the hot wire. By measuring the electrical power needed to maintain a constant wire temperature against the evaporative cooling, the LWC can be inferred.

Snow amount on the ground can be measured by placing a liquid antifreeze-filled thin-skin metal **snow pillow** on the ground before the winter snow season. As snow accumulates during the season, the weight of the snow squeezes the pillow and displaces some of the fluid. Pressure sensors measure the weight of the displaced fluid to infer snow weight.

Downward-pointing **ultrasonic snow-depth sensors** mounted on a tall pole measure the travel time for an emitted pulse of sound to reach the ground and echo back to the sensor on the pole. This gives the distance between the top of the snow and the sensor, which can be subtracted from the sensor height above bare ground to give the snow depth. Similar sensors use travel time for IR or visible light pulses.

Remote sensors (see the Satellites & Radar chapter) can also be used to measure rain rate or accumu-

lation. Ground-based **weather radar** actively emits microwaves, and can estimate rainfall rate from the echo intensity and polarization characteristics of the microwave signal that is scattered back to the radar from the precipitation particles. **Passive microwave sensors** on some weather satellites can measure the **brightness temperature** of the minute amounts of microwaves emitted from the Earth's surface and atmosphere. With this info one can infer the atmospheric total water content in a column of the atmosphere (used to estimate **tropical rainfall** over the oceans), and can infer snow depth on the ground (over high-latitude regions).



## 7.9. REVIEW

Cloud droplets that form on cloud condensation nuclei (CCN) overcome a formation barrier caused by the surface tension of the curved surface. However, because there are so many CCN between which the available water is partitioned, the result is a large number of very small droplets. These drops grow slowly by diffusion, and develop a monodisperse droplet-size distribution. Such a distribution reduces droplet collisions, and does not favor droplet growth into precipitation hydrometeors. Hence, we get pretty clouds, but no rain.

Warm-cloud ( $T > 0^{\circ}\text{C}$ ) rain can happen in the tropics, particularly over oceans where there are fewer CCN allow formation of a smaller number of larger drops. Several other processes can cause the droplet sizes to have more diversity, resulting in different terminal velocities for different drops. This encourages collision and coalescence to merge smaller droplets into ones that are large enough to precipitate out.

In clouds colder than  $0^{\circ}\text{C}$ , ice nuclei trigger ice crystals to grow. Ice crystals can exist in the air along with supercooled liquid drops. Because of the difference between liquid and ice saturation humidities, the ice can grow at the expense of evaporating liquid droplets. If the ratio of water to ice hydrometeors is about a million to one, then most of the water will be transferred to ice crystals, which are then heavy enough to fall as precipitation.

As larger ice particles fall and hit smaller supercooled liquid droplets, the droplets can freeze as rime onto the ice crystals, causing the hydrometeors to grow even faster. This process can create graupel and hail. Also, ice crystals can aggregate (collide and stick together) to make larger clumps of snow. Most rain at midlatitudes results from melted snow that form from this "cold cloud" process.