Terrestrial radiation

Electromagnetic radiation emitted from the Earth and its atmosphere. Terrestrial radiation, also called thermal infrared radiation or outgoing longwave radiation, is determined by the temperature and composition of the Earth's atmosphere and surface. The atmosphere is composed of two groups of gases, one with a nearly permanent concentration, consisting principally of nitrogen (N_2) and oxygen (O_2) molecules, and another with variable concentrations of other gases. Although considered to be permanent constituents, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO) have been observed to increase in association with anthropogenic activities. One of the principal variable gases is water vapor (H_2O), the major compound that modulates the hydrological cycle involving evaporation, cloud formation, and precipitation. Water vapor concentration decreases rapidly with latitude, almost following an exponential function. Ozone (O_3) concentration also varies significantly with space and time, and occurs principally at altitudes of about 15–30 km (10–20 mi). A significant variable gas is a mixture of chlorofluorocarbons (CFCs) produced by industrial activities. *See* ATMOSPHERE; ATMOSPHERIC GENERAL CIRCULATION; HYDROLOGY; RADIATIVE TRANSFER.

The atmosphere also contains aerosol particles ranging in size from about 10^{-3} to 20 micrometers that are known to be produced by natural processes as well as by human activity. Aerosol concentrations generally decrease rapidly with height. Some aerosols are effective condensation and ice nuclei, upon which cloud particles may form. Clouds are global in nature and regularly cover more than 50% of the Earth. There are various types of clouds. Some clouds, such as high-level cirrus in the tropics and low-level stratus in the Arctic and near coastal areas, are climatologically persistent. Some clouds generate precipitation. *See* AEROSOL; CLOUD; CLOUD PHYSICS.

The temperature structure of the Earth and the atmosphere is a result of numerous physical, chemical, and dynamic processes. In a one-dimensional context, the temperature structure is determined by the balance between radiative and convective processes. From the surface to a height of about 10 km (6 mi), the temperature decreases at a typical rate of about 6.5°C (12°F) per kilometer, a region referred to as the troposphere where major weather events occur. Variability of the global temperature field is modulated by the transport of various types of energy by the winds, the radiative energy emitted from the Sun and received by the Earth, and the radiative energy emitted from the Earth and the atmosphere. *See* HEAT BALANCE, TERRESTRIAL ATMOSPHERIC; SOLAR RADIATION; SUN; TROPOSPHERE; WIND.

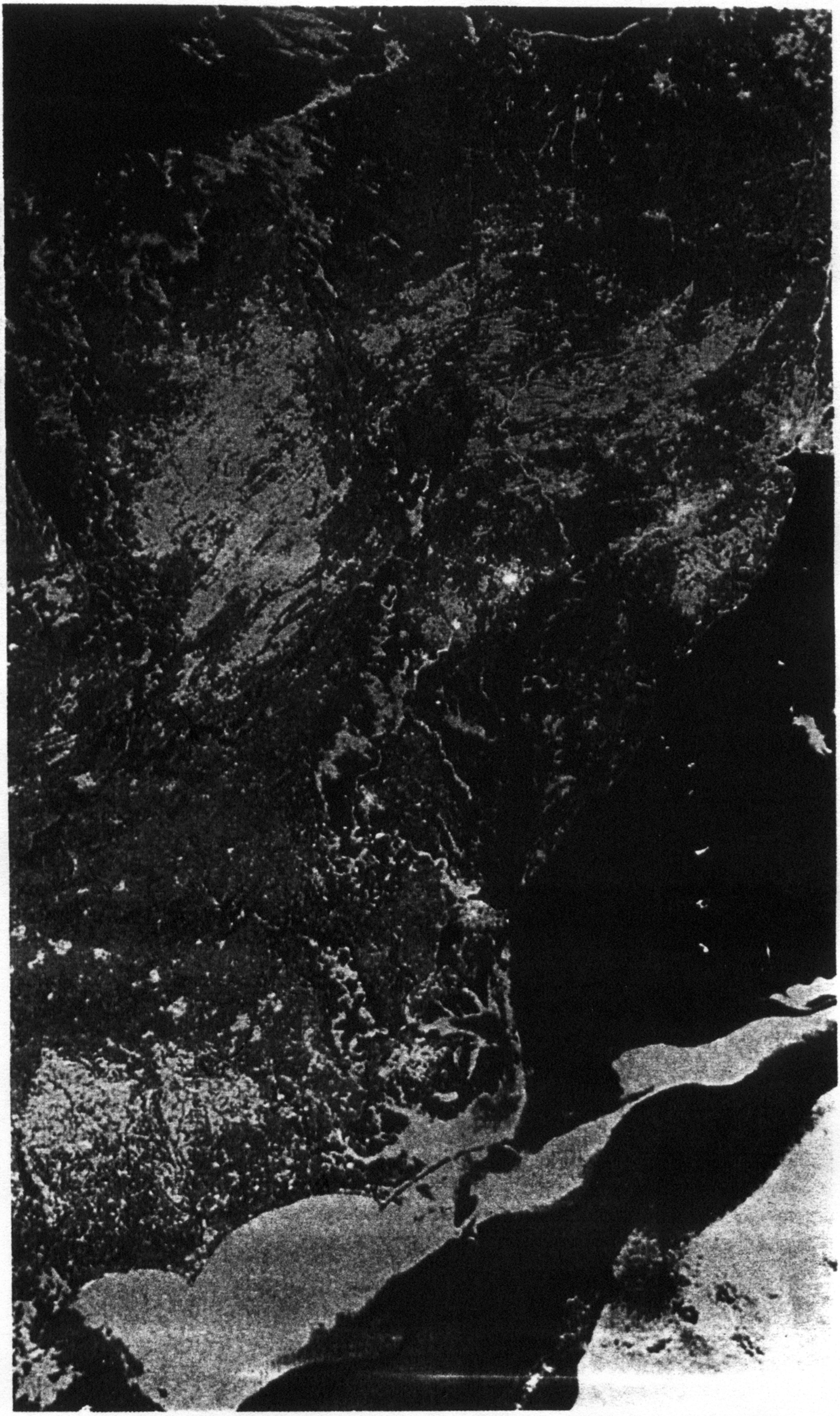
Emissivities. The Earth's surface emits electromagnetic radiation according to the laws that govern a blackbody or a gray body. A blackbody absorbs the maximum radiation and at the same time emits that same amount of radiation so that thermodynamic equilibrium is achieved as to define a uniform temperature. The rate at which emission takes place is a function of temperature and wavenumber (cm^{-1}) or wavelength (μm) according to Planck's law. A gray body is characterized by incomplete absorption and emission and is said to have emissivity less than unity. The thermal infrared emissivities from water and land surfaces are normally between 90 and 95%. It is usually assumed that the Earth's surfaces are approximately black in the analysis of infrared radiative transfer. Exceptions include snow and some sand surfaces whose emissivities are wavelength-dependent and could be less than 90%. *See* BLACKBODY; GRAYBODY; HEAT RADIATION; PLANCK'S CONSTANT.

Absorption and emission of radiation by atmospheric molecules are more complex and require a fundamental understanding of quantum mechanics. A molecule, composed of atoms, can rotate, or revolve, about an axis through its center of gravity and, therefore, has rotational energy. The atoms of the molecule are bounded by certain forces like springs in which the individual atoms can vibrate about their equilibrium positions relative to one another. The molecule, therefore, also has vibrational energy. It is also possible for the energy of a molecule to change due to a change in the energy state of the electrons of which it is composed. Thus, the molecule has electronic energy. These three forms of energy are said to be quantized, and assume only discrete values. Absorption and emission of radiation take place when the molecules undergo transitions from one energy state to another, and these transitions are generally governed by selection rules in quantum mechanics. Rotational energy changes are relatively small, and many of the rotational energy levels are populated at terrestrial temperatures. Changes in vibrational energy are much larger than the minimum changes in rotational energy. Thus, vibrational transitions never occur alone but are coupled with simultaneous rotational transitions, producing a group of absorption lines known as the vibrational-rotational band in the thermal infrared spectrum of the Earth's atmosphere associated with atmospheric gases. These lines have finite widths and overlap one another. The line shape is determined by molecular collision in the lower atmosphere and by random thermal motion in the upper atmosphere. For collisions the width of the line is primarily dependent upon pressure but is also affected by temperature. *See* INFRARED SPECTROSCOPY; MOLECULE; QUANTUM MECHANICS; SELECTION RULES (PHYSICS).

The water molecule is composed of two hydrogen atoms and one oxygen atom that form an isosceles triangle that is obtuse, referred to as an asymmetric top configuration. This configuration produces the pure water vapor rotational band ranging from 0 to 1000 cm^{-1}, which is important in the generation of tropospheric cooling. The band located at 1594.78 cm^{-1} (6.25 μm) is the vibrational-rotational band of water vapor that has been used for remote sensing of its concentration from satellites. Water vapor also exhibits less selective absorption in the region from 800 to 1200 cm^{-1}, the so-called thermal infrared window. Carbon dioxide has a linear symmetrical configuration, with the carbon atom in the middle and oxygen atoms on each side. The perpendicular vibration of oxygen atoms coupled with rotational transitions produces the 15-μm CO_2 band, known for causing greenhouse warming. Ozone has an asymmetric top configuration similar to water vapor and exhibits absorption in the 9.6-μm region. Methane and nitrous oxide also show strong absorption bands in the 7–8-μm region. Other gases with absorption bands in the thermal infrared region are sulfur dioxide, ammonia, and chlorofluorocarbons. The above gases are referred to as greenhouse gases because of their ability to absorb or trap the radiation emitted by the Earth and the atmosphere. *See* CARBON DIOXIDE; GREENHOUSE EFFECT; METHANE; WATER.

Clouds are global in nature and can interact with terrestrial radiation. Clouds are composed of water droplets or ice crystals and can both reflect and transmit the radiation emitted from the surface and the atmosphere while emitting infrared radiation according to the temperature structure within themselves. If the cloud as a whole is a blackbody, it will behave just like the Earth's surface. In this case, radiation from below and above the cloud would not be able to penetrate the cloud. The emitted radiance at the cloud top or bottom is governed by Planck's law. Most clouds that are composed of water droplets are black clouds because of high number concentrations and small droplet sizes. However, clouds that are composed of ice crystals with sizes ranging from a few micrometers to 1000 μm, such as cirrus clouds, are generally nonblack. Determination of the radiative properties of cirrus clouds in conjunction with remote sensing and climate studies is a subject of contemporary research.

Radiation measurement. **Figure 1** illustrates the radiant energy emitted from a number of temperatures covering the Earth and the atmosphere as a function of wavenumber and wavelength. This energy is called Planck intensity (or radiance), and the units that are commonly used are denoted as watt per square meter per solid angle per wavenumber ($W/m^2 \cdot sr \cdot cm^{-1}$). Also shown is an atmospheric emission spectrum measured from the Infrared



Infrared radiation image from an altitude of 620 km, covering approximately 700 km, and ranging from south of Cape Hatteras, NC, to Lake Ontario. Temperature values from cold to hot are represented by the color sequence purple, blue, green, brown, yellow, orange, red, gray, and white. (*NASA*)

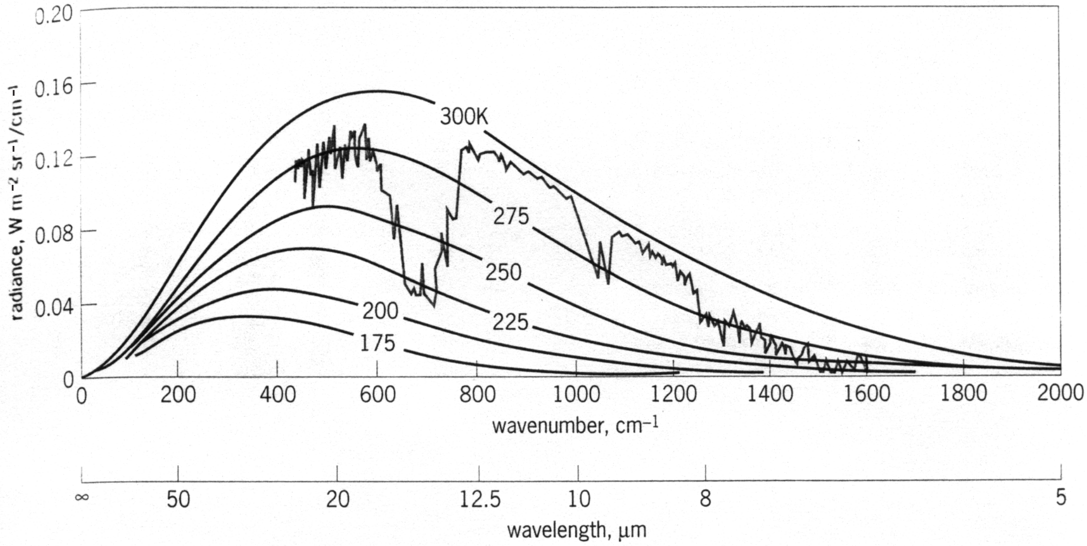


Fig. 1. **Theoretical Planck radiance curves for a number of the Earth's atmospheric temperatures as a function of wavenumber and wavelength. Also shown in color is a thermal infrared emission spectrum observed from the *Nimbus 4* satellite using an infrared interferometer spectrometer.**

Interferometer Spectrometer on board the *Nimbus 4* satellite launched in April 1970. This spectrum demonstrates that certain portions of the terrestrial radiation are trapped by water, carbon dioxide, ozone, and other minor gases, the regions of which have been noted above. The Infrared Interferometer Spectrometer can be employed to measure the absorption lines. With the advance of high technology, high spectral resolution infrared spectrometry has been developed for atmospheric measurements from space, particularly for applications to the remote sensing of minor gaseous concentrations from satellites. *See* RADIANCE; RADIOMETRY.

Meteorological satellites. Terrestrial radiation originating from the Earth-atmosphere-ocean system, as well as solar radiation reflected and scattered back to space, is measured on a daily basis by meteorological satellites. Instruments on meteorological satellites measure visible, ultraviolet, infrared, and microwave radiation. *See* ABSORPTION OF ELECTROMAGNETIC RADIATION; ELECTROMAGNETIC RADIATION; METEOROLOGICAL SATELLITES; REFLECTION OF ELECTROMAGNETIC RADIATION; SCATTERING OF ELECTROMAGNETIC RADIATION.

Each spectral region provides meteorologists and other Earth system scientists with information about atmospheric ozone, water vapor, temperature, aerosols, clouds, precipitation, lightning, and many other parameters. Measuring atmospheric radiation allows the detection of sea and land temperature,

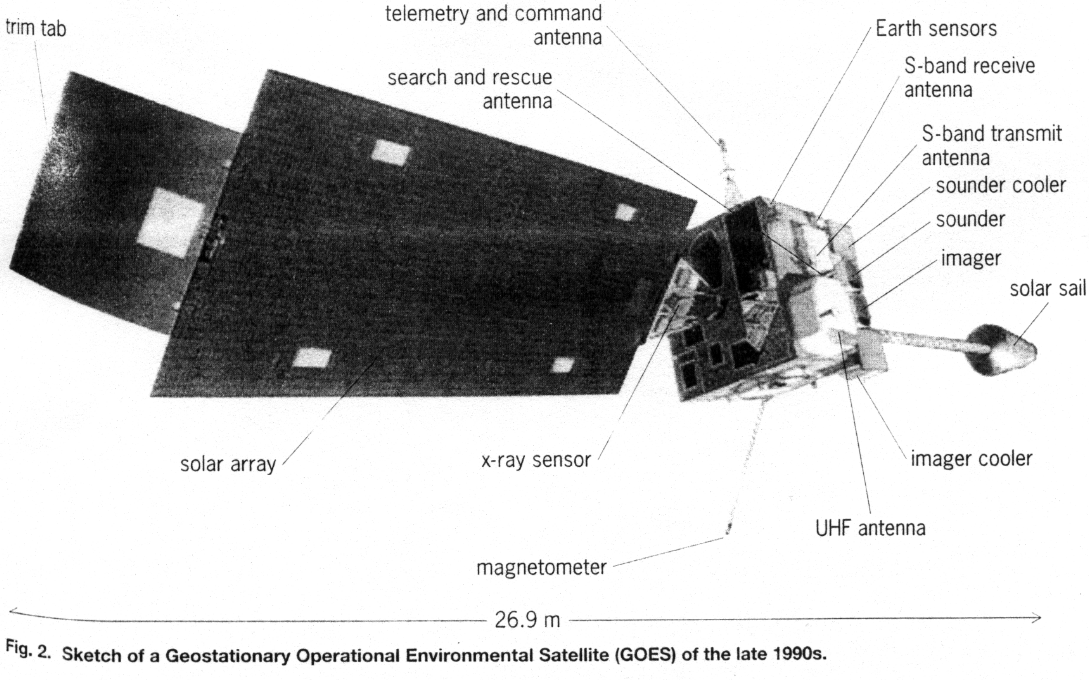


Fig. 2. **Sketch of a Geostationary Operational Environmental Satellite (GOES) of the late 1990s.**

snow and ice cover, and winds at the surface of the ocean. By tracking the movement of clouds and other atmospheric features, such as aerosols and water vapor, it is possible to obtain estimates of winds above the surface. *See* SATELLITE METEOROLOGY.

Scientists use physically based algorithms to process the satellite-observed spectral radiation into either images of atmospheric and surface features or desired estimates of weather parameters. For example, the physical relationship between the absorption and reemission of infrared radiation is used to estimate atmospheric temperature profiles over vast reaches of ocean areas. *See* REMOTE SENSING.

Orbits of meteorological satellites are generally selected as one of two types. Geostationary (geosynchronous) orbits are in the equatorial plane and have the advantage of obtaining continuous, time-lapse observations of a portion of Earth as large as the Americas (**Fig. 2**). Other, near-polar orbits are Sun-synchronous and are designed to measure all areas of Earth at nearly the same local times each day.

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Since meteorological satellites were first flown by NASA in the 1960s, a system of research and operational weather forecast-related satellites has been developed in the United States by the National Oceanic and Atmospheric Administration, and by the weather services of Japan, India, Russia, and the European Union. Today, worldwide weather satellite coverage is providing input to computer forecast models and to National Weather Service and television weather forecasters on an hourly basis. *See* WEATHER FORECASTING AND PREDICTION.

The scientific discoveries in weather and climate credited to observations from satellites include: (1) measurement of the energy output from the Sun and the radiation budget of the Earth—warmer and darker than was believed before satellite observations; (2) the organization of tropical weather systems and waves; (3) the existence of mesoscale convective clusters—major precipitation-producing weather systems over midlatitude continents; (4) development and growth of severe thunderstorms on "gust fronts" outflowing from other storms; and (5) variation of the warm core inner structure of tropical storms and associated spiral bands.

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