high quality images of cloud systems both day and night.

Problem 6.19: An IR imager observes a cloud layer with $T_B = 240\ K$. The cloud radiates as a blackbody and the surface air temperature near that location is known to be 15°C.
(a) Assuming a standard atmospheric lapse rate of $\Gamma = 6.5$ K/km, estimate the height of the cloud layer top.
(b) Assuming the cloud top is a blackbody over the entire LW band, compute the upward flux of longwave radiation (OLR) that would be observed by an aircraft flying directly over the cloud.

If you view a movie loop of GOES IR imagery covering a full day or longer, you can see not only the evolution of cloud patterns associated with extratropical cyclones, thunderstorms, etc., but also the evolution in surface temperature. It is not uncommon to see the land surface temperature vary sharply between day and night, while ocean surfaces remain at relatively constant temperature over long periods.

Problem 6.20: Examine Fig. 6.9 for clues as to the most likely season and/or time of day when the image was taken. Explain your reasoning.

IR imagery is currently the primary basis for mapping global sea surface temperatures (SSTs) at high precision (approaching 0.1 K), allowing the depiction of the Gulf Stream and other features of importance for climate and weather forecasting, as well as for fisheries and for physical oceanographic studies. In particular, the well-known El Niño phenomenon, which dramatically influences large-scale weather patterns around much of the world, is manifested in the form of a dramatic warming of SSTs over the Eastern Tropical Pacific ocean. *In situ* measurements of SST by buoys and ships are rather sparse in this region, so IR imagery is the principal method today for monitoring the onset and evolution of El Niño.

Keep in mind, however, that accurate IR observations of surface temperature are only possible in cloud-free areas and with careful attention to the correction of minor atmospheric effects, mostly due to water vapor. One way to isolate, and correct, contamination due to water vapor is to utilize two channels at nearby wavelengths but with differing sensitivity to absorption by water vapor. The difference in brightness temperature between the two images is then an indicator of how much water vapor is present. In fact, one common form of this so-called *split window* technique entails the simultaneous retrieval of both SST and total column water vapor, also known as *precipitable water.* Both variables are of great interest to meteorologists, though for different reasons.

When even thin or broken clouds are present, which is true a majority of the time at many locations around the globe, IR imagers can no longer accurately measure surface properties. When surface measurements are required in the presence of clouds, we turn to the microwave band.

6.4.7 Microwave Imaging from Space

Passive microwave remote sensing is in many respects similar to IR remote sensing, in that a satellite sensor views naturally emitted radiation from the earth and atmosphere.[3] Especially at wavelengths greater than 3 cm (frequencies less than 10 GHz), atmospheric effects are fairly small, and the primary variable observed in this case is thermal emission from the earth's surface. There are several important differences from IR imagery that are worth briefly noting.

For one thing, it takes a rather heavy cloud to seriously interfere with a microwave imager's ability to observe the surface, in contrast to IR imagers, which are foiled by even thin clouds. In fact, at low microwave frequencies, only a cloud that is actually producing rainfall presents a serious obstacle.

Also, in contrast to the IR band, the microwave emissivities of natural surfaces are often considerably less than unity and may in fact vary wildly from one scene to the next. In particular, ocean surface emissivities may be as small as 0.25–0.7, whereas land surface emissivities are typically in the range 0.8–0.95. This variation in

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[3] *Active* remote sensing is also employed in the microwave band but entails the measurement of backscattered radiation from an artificial source. Radar is the best-known example.

surface emissivity makes it much more difficult (though not impossible) to use microwave imagery for accurately estimating surface temperature, but greatly facilitates the determination of other surface properties.

A particularly convenient property of the microwave band is the validity of the Rayleigh-Jeans approximation introduced in Section 6.1.4. Because of the accurate proportionality between blackbody radiance and temperature in the microwave band, the slightly cumbersome relationship between T, ε, and T_B represented by (6.46) simplifies down to just

$$T_B = \varepsilon T \; . \tag{6.47}$$

Elsewhere in this book, we tend to neglect the polarization properties of radiation. But polarization cannot be ignored for microwave remote sensing. In particular, the ocean surface emissivity is markedly higher for vertical polarization than for horizontal polarization when the ocean is viewed at an oblique angle. In fact, if the water surface is perfectly smooth, the reflectivity r, and thus the emissivity $\varepsilon = 1 - r$, is given by the Fresnel relations discussed in Chapter 4. Fig. 4.5b showed the Fresnel reflectivity of water for a microwave frequency of 37 GHz. For a satellite sensor viewing a water surface at a typical angle from vertical (i.e. *nadir angle*) of $\sim 50^\circ$, the horizontally polarized emissivity $\varepsilon_h \approx 0.35$ while the vertically polarized emissivity $\varepsilon_v \approx 0.65$. Thus, for the same physical temperature of $T = 283$ K, the brightness temperature of emission from the ocean surface is approximately 100 K for horizontal polarization and close to 185 K for vertical polarization, an 85 K difference.

Things get even more interesting when you consider that the microwave emissivity of the ocean surface is not a constant at any given frequency but depends (albeit fairly weakly) on the sea surface temperature T_s (via changes in the complex index of refraction N of seawater) and on the degree of roughening and foam coverage associated with a given near-surface wind speed U. Thus, the observed brightness temperature can be represented as

$$T_{B,p} \approx \varepsilon_p(T_s, U) T_s + \Delta_{\text{atmos}} \; , \tag{6.48}$$

where p represents the polarization (V or H) and Δ_{atmos} represents an atmospheric correction, which is usually small ($<$10 K) at low