Lecture Notes **Prepared by Prof. J. Francis Spring 2003**

Remote Sensing of Clouds Using Infrared Sensors

Primary reference: Chapter 8 of KVH

Outline

I. Cloud detection tests

II. Effective cloud fraction

III. "Cloud-clearing" for temperature sounding

IV. Cloud-top height (or cloud-top temperature) retrieval

I. Cloud detection tests

A. Cloud detection tests

In general, some use thresholds on 1 FOV, others compare adjacent FOVs (with inherent problems over inhomogeneous surfaces)

Sample tests (see p. 263 of KVH for more complete list)

1. FOV contains cloud if scene is open water (not ice) and brightness temperature (TB) < 0°C

2. Cloudy if the albedo > threshold (day only, not over snow) Need to know albedo of background to determine threshold.

3. Difference in TB between channels at 3.7 and 11 μm is larger or smaller than thresholds. This test is valuable because the 11 μm channel is more sensitive to clouds than the 3.7 μm channel. This is particularly useful for detecting clouds with optically thin tops (cirrus, clouds with glaciated tops, etc.).

4. Interchannel regression -- use microwave channels (unaffected by clouds) to simulate infrared TBs via regression, then compare simulated TBs to observed TBs. If observations are colder, assume cloudy.

5. Adjacent FOVs -- compare TBs of window channels in area with several FOVs (say, 3 x 3). Warmest pixels are clear, colder pixels are cloudy. Assumes background is homogeneous (works well over ocean most of the time) and that clouds are colder than the surface (may not be true for low clouds embedded in a surface-based temperature inversion). Consider how well this method would work in the following scene:

II. Effective cloud fraction

Some clouds are not optically thick in the IR part of the spectrum, which means that some of the radiation emitted from below the cloud passes through it and is detected by the sensor. A cloud that is not optically thick in the IR has an emissivity less than 1. A satellite sensor cannot distinguish between 2 FOVs in which one is partially covered by an opaque cloud and another that is more completely covered by a thin cloud. Thus, for remote sensing purposes, the cloud fraction in an IR FOV is called "effective cloud fraction," and is actually the product of the cloud emissivity ε and the fraction of the FOV covered by cloud N. Effective cloud fraction = εN.

$N = 0.5, \varepsilon = 1$ $N = 1, \varepsilon = 0.5$

$N\varepsilon \leq 1$ always

FOV_1 FOV_2

$N\varepsilon = 0.5$ $N\varepsilon = 0.5$

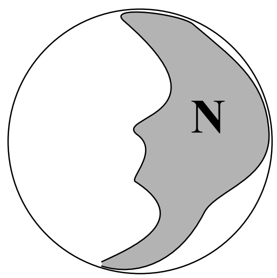
Satellite sensor cannot distinguish between these cases, but we can use this concept to perform "cloud-clearing" and retrieval of cloud-top height.

III. Cloud-clearing (mainly for temperature sounding applications)

Clouds interfere with techniques of temperature sounding from satellite-observed radiances, thus we need ways to remove their effects from observed brightness temperatures. We will discuss two methods in common use today -- the “N-star or N*” method and the Psi method.

A. N* cloud-clearing method

For this method, we assume that the radiance measured by the satellite sensor L(λ) is a linear function of the actual cloud amount in an FOV, such as this one:



FOV

$$L(\lambda) = (1-N)L_{clr}(\lambda) + N\varepsilon(L_{cld}(\lambda)) + N(1-\varepsilon)L_{clr}(\lambda) \quad 8.1$$

(a) (b) (c) (d)

N = fraction of cloud covered by cloud

ε = cloud emissivity

L_{clr} = radiance from clear surface

L_{cld} = radiance from cloud-top

Nε = effective cloud fraction

term (a) = total radiance from the FOV measured at sensor in wavelength λ

term (b) = radiance from clear portion of the FOV

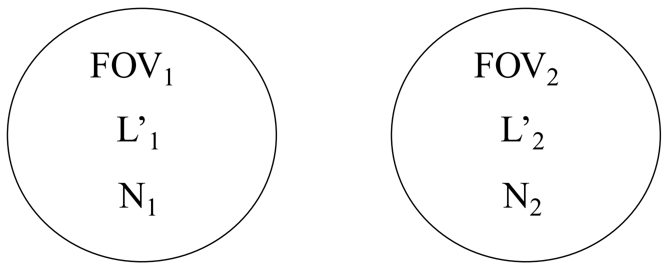
term (c) = radiance from cloud fraction of FOV

term (d) = radiance from surface that passes through the cloud

If we rearrange equation 8.1 (and shorten L(λ) to just L) we get:

$$L = N\varepsilon L_{cld} + (1 - N\varepsilon)L_{clr} \qquad 8.2$$

For the N* method use two or more FOVs:



L' = observed radiance

Assume that N is not a function of λ and

<u>Equal in the 2 FOVs</u>	<u>Not equal in the 2 FOVs</u>
cloud top and base height	cloud amount
ε	
surface temperature	
temperature profile	

Then Eq. 8.2 becomes:

$$L'_1 = (1 - N_1\varepsilon)L_{clr} + N_1\varepsilon L_{cld}$$

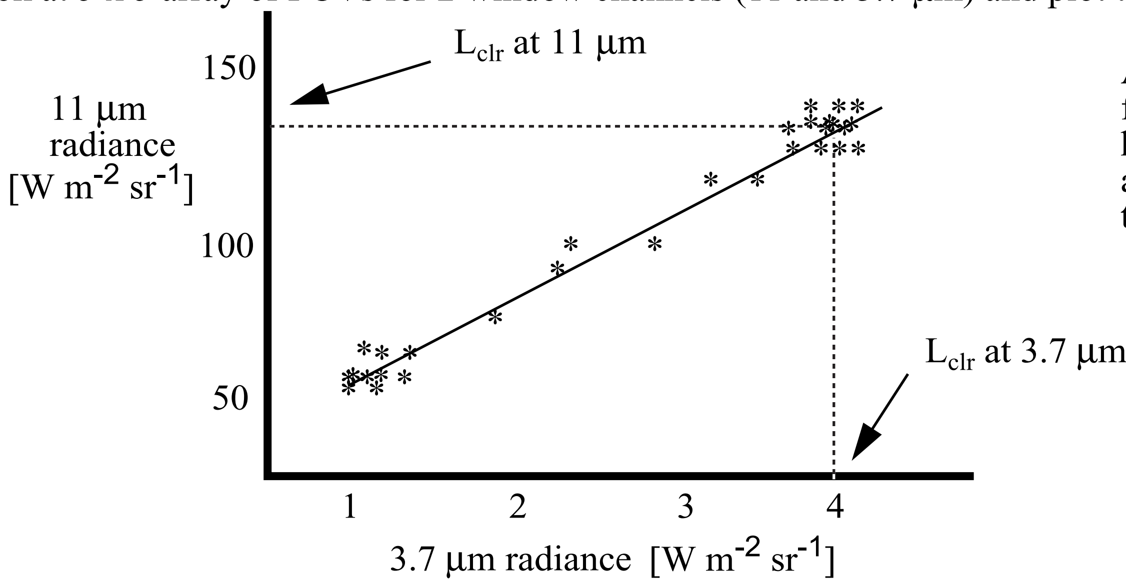
$$L'_2 = (1 - N_2\varepsilon)L_{clr} + N_2\varepsilon L_{cld}$$

Solve for ε and set equations equal to each other:

$$N^x = \frac{N_1\varepsilon}{N_2\varepsilon} = \frac{L'_1 - L_{clr}}{L'_2 - L_{clr}} \qquad 8.3$$

Measure L'_1 and L'_2 with the satellite, but how do you measure L_{clr}?

Look at 5 x 5 array of FOVs for 2 window channels (11 and 3.7 µm) and plot the values like this:



Assumed L is linear function of N, as shown here, so points spread along line are due only to variations in N

So, if you pick off the clear-sky value (warmest cluster) for either channel (say, 140 $Wm^{-2}sr^{-1}$ for 11 µm), you can use that in Eq. 8.3 to calculate N*. Then, because we assume N* is the same for all IR wavelengths, can use N* to calculate L_{clr} for other channels, such as for sounding channels (which are not window channels) to produce cloud-cleared radiances for those channels.

Advantages of the N* method: simple, fast, widely used

Disadvantages: does not work well over inhomogeneous surfaces, when clouds are thin, when cloud-top temperature is close to the surface temperature. Sometimes the assumptions it depends on are not true.

B. Psi cloud-clearing method

Concept: IR channels are affected by clouds while microwave channels are not. Choose pairs of IR/microwave sounding channels with similar weighting functions. Use microwave radiances to simulate clear-sky IR radiances using regression relationships.

Advantages: Uses only 1 FOV so inhomogeneous surfaces are not a problem, fast

Disadvantages: Need enough microwave channels to simulate IR radiances, technique not as widely used

IV. Cloud-top Pressure (or cloud-top temperature) Retrieval

Most common technique is called "CO_2 Slicing," which is based on the Radiance Ratio Method, explained below. This method is similar to the N* method described previously, but instead of using two different FOVs it uses pairs of wavelengths.

$$L'(\lambda_1) = (1 - N\varepsilon)L_{clr}(\lambda_1) + N\varepsilon L_{cld}(\lambda_1)$$

$$L'(\lambda_2) = (1 - N\varepsilon)L_{clr}(\lambda_2) + N\varepsilon L_{cld}(\lambda_2)$$

$$N\varepsilon(\lambda_1) = N\varepsilon(\lambda_2) \quad \text{[assume } \varepsilon \text{ same for } \lambda_1 \text{ and } \lambda_2\text{]}$$

rearranging:

$$\underset{\text{(a)}}{\frac{L'(\lambda_1) - L_{clr}(\lambda_1)}{L'(\lambda_2) - L_{clr}(\lambda_2)}} = \underset{\text{(b)}}{\frac{L_{cld}(\lambda_1, p_c) - L_{clr}(\lambda_1)}{L_{cld}(\lambda_2, p_c) - L_{clr}(\lambda_2)}} = f(\lambda_1, \lambda_2, p_c)$$

Compute (a) using observed radiances in λ_1 and λ_2. L_{clr} for each wavelength is calculated with a radiative transfer model and observed temperature/moisture sounding.

Compute (b) by varying cloud-top pressure p_c in a radiative transfer model until (b) is as close to (a) as possible. The value of p_c that gives closest agreement is the retrieved cloud-top pressure.

Once cloud-top pressure is known, the cloud-top temperature can be determined using the observed temperature profile.