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The manner in which a cloud scene is observed and meteorologically reported can produce varying results due to the observing system or procedures employed. As a satellite passes over a scene, the amount of reported cloud cover will be less at its zenith angle than at its limb scan angle. A ground observer will estimate the sky cover of this scene relative to an imaginary sky dome. Neither system gives an accurate estimate of earth cover, an important parameter needed to determine albedo for earth radiation balance and climate studies. New models have been developed to specify the cloud distributions that depend on the way the clouds have been observed or on the way the distributions are to be used. The Burger distribution has been found to fit well traditional sky cover, e.g. coverage of the hemispherical sky dome as viewed by a ground observer. This distribution is the result of a large number of realizations of a sawtooth weather generator which approximates a Gaussian field with a particular correlation function. Further, the parameters of the distribution -- mean sky cover and scale distance (a spatial correlation parameter) - have easily (Cont'd)

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recognized climatic meaning. A recently published atlas of these parameters, giving seasonal and diurnal worldwide coverage for cloud distributions, has been prepared. When clouds are viewed at a specific angle, i.e. from a satellite, the probability of coverage will vary. Building on the cloud-free line-of-sight modeling, by Lund and Shanklin and by Malick and Allen, we have further specified this angular dependence. Models developed by Gringorten show that coverage also depends on the size of the area viewed. In addition, spatial and temporal correlation depends on the size of area viewed as well as the smallest resolvable feature - pixel size. The cloud coverage at a given level in the atmosphere has also been modeled and can be specified using only surface observations.

THE EFFECT OF VIEWING ASPECT ON CLIMATOLOGICAL CLOUD DISTRIBUTION

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Currently there are nonhomogenious cloud observations and data bases with many types of biases. These cause minor problems with weather forecasting but for climatology the error introduced can be major. The purpose of this paper is to present an overview of methods developed to use current data bases to estimate various climatic statistics about clouds.

OBSERVATION EFFECTS

To record sky cover, a surface based observer estimates the fraction of the sky dome that is cloudy. Practical problems such as surface obscurations and thin clouds are handled in a methodical if not completely rigorous fashion. The observed coverage is subjective and is affected by various physiological factors (Neuberger, 1965). On a weather chart, sky cover is plotted at the observation location, but some clouds, e.g. high level cirrus near the horizon, may be located more than a hundred kilometers away.

When weather satellite data first became available, it was hoped that many of these shortcomings would be resolved. It soon became apparent, however, that satellite data has some of the same old problems plus some new problems: viewing angle, asynopticity with lower orbits, pixel (footprint) size, degradation of sensors, etc.

Cloud measurement problems

Here is a brief list of the problems associated with measuring clouds:

Cloud or no cloud -- On a bright day with well-formed cumulus, it is relatively easy for a surface observer or instrument (ground or space based) to identify clouds from clear areas. But there are situations - thin cirrus, sun angles, snow backgrounds (viewing from space), dawn, dusk, night time, haze, etc. - where it is difficult to say with any certainty whether there is a cloud or not. Undoubtably these problems cause biases in cloud climatology. Sometimes the magnitude of the bias can be estimated or deduced from climatic analysis.

Viewing angle -- There appears to be more cloudiness near the horizon than when a scene is viewed straight up (or down).

Field of view -- The frequency distribution of cloud amount varies with the size of the area viewed or evaluated. A small area has a very U-shaped distribution with mostly clear or overcast; as the area becomes larger the distribution approximates a normal distribution.

Pixel or footprint size -- If one looks at a cloud through binoculars, one will see many smaller clouds near the larger clouds. The same thing happens when a higher resolution sensor is used on a weather satellite. If the cloud elements are smaller than the pixel size, they may be missed completely or the whole pixel may be counted as cloudy.

Recording errors

Weather observers from many nations for several generations have kept remarkably good records. We in the atmospheric sciences should take great pride in this extraordinary feat of record archiving. Nevertheless, many types of errors have crept into the records. Fortunately, most types of random errors cancel out in climatology, but some biases remain.

Reportable cloud cover values -- Sky cover has been recorded in hundredths (by satellite), tenths, octas, and four categories: CLR, SCT, BKN, OVC - clear, scattered, broken, and overcast. In addition, some data bases carry only the probability of below 2/8 and above 7/8. Amazingly, we have had to point out that directly calculating a mean with the courser type of data can lead to considerable error.

Interpolated cloud cover values -- If sky cover values are interpolated to a grid, they will contain too many intermediate values and the climatic distribution will be too low at the end points. Similarly, if climatic values are smoothed, the distribution will no longer be accurate. Specifically, many of the objective analysis schemes devised for use with numerical weather prediction produce very poor climatic distributions.

Asynoptic data -- Low orbiting satellites pass over at various times viewing one area at one time, another area at another time. Data is often stored at a nominal time that could be considerably different than the actual viewing time. Data stored this way causes error in the diurnal distribution, and spatial and temporal correlation. Also, it is often difficult to obtain the actual number of observations.

MODELING THE DISTRIBUTION OF SKY COVER

The distribution of sky cover (N) is bounded at 0 and 1. Although a small amount (N < .05) may be recorded as clear, completely clear or overcast does occur frequently. Karl Pearson (1898) used a Type I distribution (generalized Beta) to fit sky cover. Johnson (1949) fitted sky cover with his S_B distribution which uses the transformed variable $y=Ln[N/(1-N)]$, as a normally distributed variable similar to the more common log-normal distribution. Bean and Somerville (1981) computerized a worldwide (daytime) atlas of sky cover using the Beta distribution. Errors in these distributions are mostly in the clear and overcast categories because they do not represent truly clear and overcast probabilities. Greaves (1973) used the truncated normal distribution which has the probability for clear and overcast conditions. In addition, he described methods to account for variations in viewing area.

The Burger distribution

Burger (1985) described a new model for specifying sky cover distributions. Model distributions are shown in Figure 1 and the typical variation of its parameters in Figure 2. It is a numerical fit to the results of multiple simulations of a sawtooth simulation model (Burger and Gringorten, 1983).

The sawtooth simulation model -- This model has two parameters; the mean condition and scale distance (a parameter of spatial correlation). Briefly, the sawtooth wave model consists of sums of the heights of randomly oriented sawtooth wave formations. The height of a randomly oriented sawtooth is uniformly random, zero to one. Since the sum of uniform heights approximate a normal distribution, the summed heights approximate a multi-dimensional Gaussian process. Rather than some other waveform, e.g. cosines, sawtooths are used because: they are the fastest periodic function to calculate; the sum of their uniform heights approach normality with relatively few waves; but mostly because the resultant correlation is very similar to that found between observations of sky cover as shown in Figure 3.

The Burger Areal Algorithm, BAA -- Burger's fit to the result of multiple simulations is somewhat complex although it is quite fast when programmed on computer. It is a general algorithm applicable to many weather elements. For sky cover, a small part of the algorithm is sufficient as will be shown.
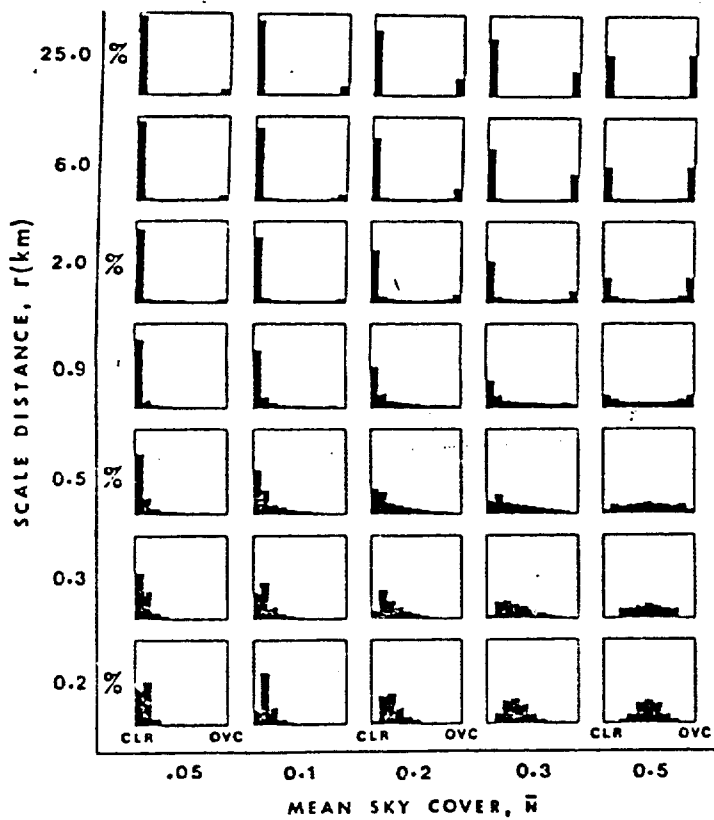
Fig. 1. Frequency distributions of sky cover categories (from clear to overcast) as produced by the BAA for various mean sky covers and scale distances.
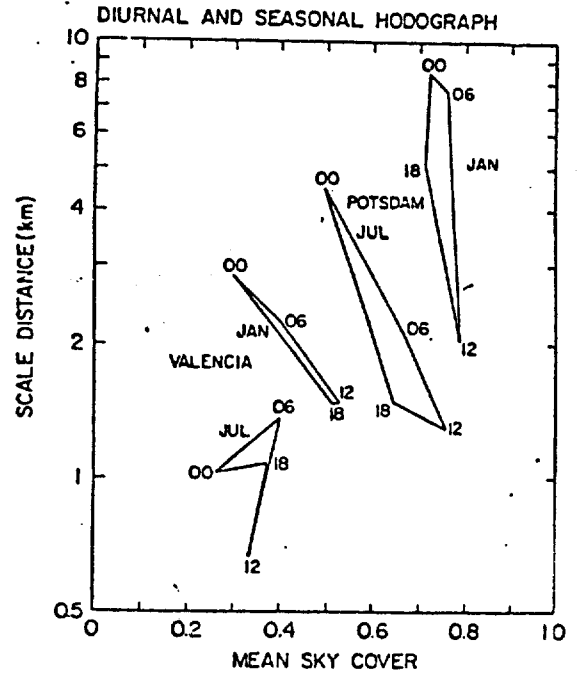

Fig. 2. Diurnal variation of mean and scale distance ofr Potsdam and Valencia in January and July. For most locations scale distances are shorter (i.e., more cumulus) in summer and afternoon.
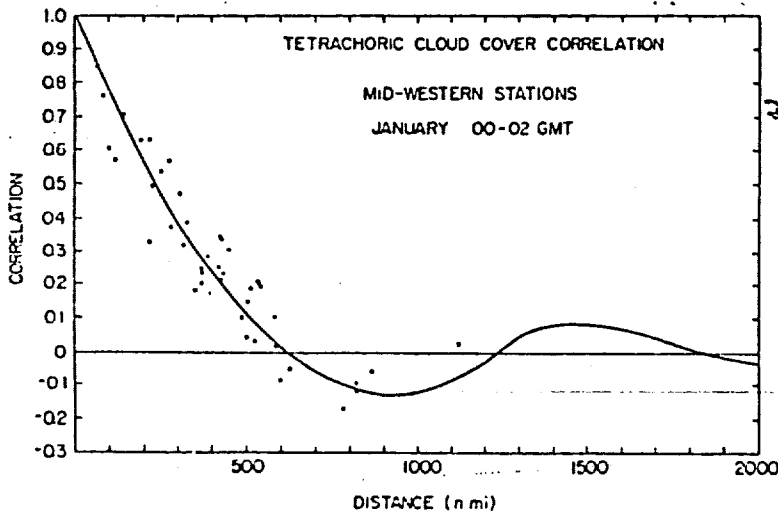

Fig. 3. Tetrachoric cloud cover correlation between pairs of 17 mid-western U.S. stations. Curve shows 3D sawtooth correlation.
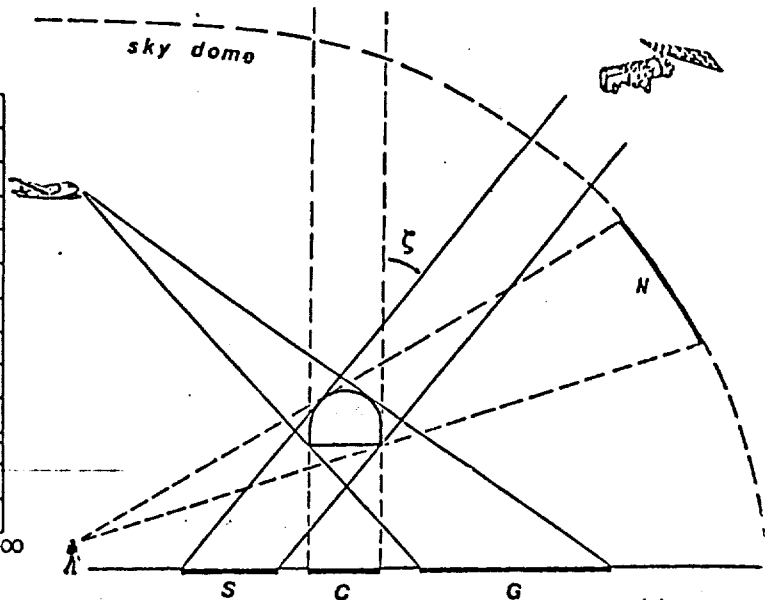

Fig. 4. Cloudiness quantifications: sky cover, N, from a ground observer; apparent cloud cover, S, from a satellite; vertical projection of cloud cover, C; and ground cover, G, from an aircraft. is view angle.

Allow the sky cover (tenths) to be N and the mean sky cover to have an equivalent normal deviate (END) of y_0. Then the END (y) of the cumulative probability for sky cover less than or equal to N is obtained as follows:

For $N < 1/2$, set $y_0' = y_0$, $N' = N$
For $N > 1/2$, set $y_0' = -y_0$, $N' = 1-N$

Find $i = 5 - INT(10N')$, where INT is the integer function, e.g. INT(4.2) = 4

Find $f = 10N' + i - 6$

Find
$$y' = y_0' \cdot G(6,z) + f \cdot G(i,z) - \sum_{j=1}^{i-1} G(j,z) \qquad (1)$$

where z is a dimensionless function:

$$z = [\ln(\sqrt{A}/r)]/\ln 2$$

where A is the area of the sky dome which we set to 2424 km², that is, a radius of 15 nm, and where r is the sky-cover scale distance (km) which varies by station, by time of day, and by time of year.

$$G(k,z) = a_k + b_k \exp(c_k z); \text{ except } G(0,z) = 0 \qquad (1a)$$

k	a	b	c
1	-.0071	.0086	.53
2	-.0205	.0097	.52
3	.0229	.0045	.64
4	-.0517	.0224	.45
5	.0260	.0087	.71
6	.9981	.0011	.89

For $N < 1/2$, set $y = y'$
For $N > 1/2$, set $y = -y$.

The algorithm given in Eq. (1) is satisfactory for sky cover. Specifically, it is limited to $1 < z < 7$, .385 km $< r <$ 24.6 km, and a mean between .0062 and .9999. See Burger (1985) for the more general algorithm.

Obtaining the mean and scale distance from data -- Scale distance was originally defined as the separation distance at which correlation is 0.99. As new models were developed, we needed to use scale distances found with older models, but it was important that they resembled each other over the entire range of correlation. We chose Gringorten's (1979) Model B as the standard. Thus, in the 3D sawtooth the scale distance has a correlation of 0.988, but closely resembles Model B over the range of correlation 1. to 0.1.

Burger developed an algorithm to derive scale distance given the distribution of sky cover:

$$r(km) = \sqrt{2424}/2^z, \text{ where } z = a + b \ln(\Delta y + c) \qquad (2)$$

FOR DATA IN OCTAS

choose if:	Δy	a	b	c
CLR & OVC frequent	$y_{7/8} - y_{0/8}$	4.44437	1.78645	0.75
Prob. OVC near 0	$y_{4/8} - y_{0/8}$	5.49416	1.80228	0.43
Prob. CLR near 0	$y_{7/8} - y_{4/8}$	5.88697	1.78077	0.34

FOR DATA IN AIRWAYS - CLR, SCT, BKN, OVC

choose if:	Δy	a	b	c
CLR & BKN frequent	$y_{BKN} - y_{CLR}$	4.35802	1.75995	0.67
Prob. OVC near 0	$y_{SCT} - y_{CLR}$	5.57793	1.75995	.335
Prob. CLR near 0	$y_{BKN} - y_{SCT}$	5.57793	1.75995	.335

y_q is the equivalent normal deviate of the cumulative probability up to and including q.

There is considerable error when the mean sky cover is calculated with the standard formula using the broad categories of CLR, SCT, BKN, OVC. There is measurable error even for the narrower categories of octas. Burger developed the following equation to minimize error. Given z from the algorithm above:

$$y_o = (y_{CLR} + y_{BKN})/(1.9962 + .0022e^{.89z}) \tag{3}$$

The Burger distribution as a function of area size

Above we used the Burger distribution for sky cover of the sky dome which we took to be 2424 km^2. However, the distribution is more general. In the equation for z, we can change the size of the area by replacing the value 2424 by the desired area in km^2. As the area becomes small, the distribution becomes very U shaped and in the limit becomes only probabilities at clear and overcast. As the area becomes very large, the distribution tends toward a normal distribution centered at mean cloud cover. The figure showing the Burger distribution for sky cover assumes a 2424 km^2 area, but this figure could be used for other sizes by use of a false scale distance (r'):

$$r' = r(2424/A)^{1/2} \qquad \text{where A is the area in km}^2 \tag{4}$$

The Burger Areal Algorithm can also give directly the distribution for a different size area. The limited version given above can be used as long as the z which is a function of area remains within stated limits.

Cloud coverage in layers given ceiling distributions

Gringorten (1982) developed some useful procedures for estimating cloud coverage in layers above the surface. The development of the new algorithms by Burger makes these procedure very attractive. Here we limit our discussion to one straightfoward application.

A ceilng is the lowest cloud deck that covers 6/10 or more of the sky. Climatological summaries of the frequency of ceilings as a function of height above the surface have been made for many locations. Rearranging the Burger algorithm given above, the equivalent normal deviate (y_o) of the mean sky cover from the surface to the level H is:

$$y_o(H) = [y(H) + G(1,z)]/G(6,z) \tag{5}$$

where y(H) is the equivalent normal deviate of the cumulative probability of ceilings up to height H. The function G and z are calculated as above.

The mean sky cover is associated with one or more clouds (possibly overlapping) between the surface and the height H. To obtain the probability of clouds in a layer of thickness h the correlation between levels must be taken into account. This was modeled (Gringorten, 1982) with the following algorithm:

$$\overline{P}_h = (\overline{P}_{H+h} - \overline{P}_H)/[(1 - \overline{P}_H) \cdot (1 - e^{h/(1.69 - 1.94\sqrt{H} - 0.475h)})] \tag{6}$$

where $\overline{P}_h$ is the mean cloud cover in the layer with bottom at H km and top at H+h km. P_H and P_{H+h} are the mean sky cover up to H and H+h respectively and are given by the cumulative probability associated with the equivalent normal deviates $Y_o(H)$ and $y_o(H+h)$. The root mean square error of the above estimate of the mean cloud cover in a layer using the systematic aircraft data collected in Germany (deBary and Holler, 1963) was 0.032 (3.2%).

CLOUD COVER AS A FUNCTION OF VIEWING ANGLE

Figure 4 depicts various methods used in assessing cloud cover from three platforms. Cloud cover, C, is defined as the vertical projection of clouds onto the earth. Cloud amount quantification from a ground observer, aircraft, and satellite are shown as N, G, and S, respectively.

PCFLOS as a function of zenith angle

A major application of cloud climatologies is to specify the probability of clouds along a line-of-sight (PCFLOS). Based on whole sky cloud photos at Columbia, Missouri, Lund and Shanklin (1973) developed a matrix model to estimate PCFLOS as a function of sky cover and elevation angle. Malick, Allen, and Zakanycz (1979) improved this model by ensuring that the PCFLOS values integrated over the total sky dome equalled one minus the total sky cover. The curves produced by this model (called the SRI model since it was developed at Stanford Research Institute) can be easily calculated:

$$PCFLOS = [1 - N(1 + 3N)/4][1 + (.55 - N/2) \tan Z] \tag{7}$$

where N is sky cover as observed from the ground and Z is the zenith angle.

Lund had realized that the matrix model overestimated PCFLOS and stated to the authors that the SRI adjustment was an improvement (Lund, 1985).

In addition to the Columbia whole sky photos, we compared the SRI model to three additional sets of data: (1) data collected in the AFGL CFLOS program – a large data base consisting of aircraft observation of CFLOS (Bertoni, 1967, 1977), (2) whole-sky photography data in Estonia and the Canary Islands that were published, along with a theory, in Feigelson (1984), (3) the SRI model using several series of high resolution space shuttle photos looking at the same location from various angles (Snow et al., 1985 & 1986). We concluded that for elevation angles above 30° there was very good agreement – differences being only a few percent.

For angles within about 10° above the horizon, we incorporated the influence of earth curvature and cloud height by calculating the angle (α_c) that the line-of-sight intercepts the cloud:

$$\cos(\alpha_c = \cos(\alpha_g) R/(R + H) \tag{8}$$

where α is the elevation angle measured at ground level

    R is the radius of the Earth
    H is the height of the cloud above the ground.

The climatological probability of CFLOS

Given the probability of a cloud-free line-of-sight (CFLOS) for a given zenith angle (Z) and for a given sky cover, the climatological probability of CFLOS can be calculated by summing this probability over each sky cover category weighted by its climatological frequency of occurrence. This probability is still a function of zenith angle. The calculation of the climatological probability of CFLOS for non-geostationary satellites involves many zenith angles and can become time consuming. Burger found the climatological probability nearly independent of scale distance and so developed a more direct method of calculating the climatological probability of cloud-free line-of-sight (CPCFLOS):

$$CPCFLOS(Z) = 1 - aP_o + (a - 1)P_o^2 \qquad (0 < Z < 80°) \tag{9}$$

where P_o = PCFLOS as given in Eq. 7 and $a = (c_1 + c_2 r + c_3 r^2) + (c_4 + c_5 r + c_6 r^2)Z + (c_7 + c_8 r + c_9 r^2)Z^2$.

n	c_n for $Z > 30°$	c_n for $Z < 30°$
1	.9137	1.2958
2	.06032	-.2339
3	-.0191	.1001
4	4.7423×10^4	-1.2255×20^{-2}
5	-3.2087×10^{-4}	9.4255×10^{-3}
6	9.0008×10^{-5}	-3.812×10^{-3}
7	8.2725×10^{-6}	1.1425×10^{-4}
8	-5.8336×10^{-6}	-8.6538×10^{-5}
9	1.8496×10^{-6}	3.3768×10^{-5}

Cloud coverage as seen by satellite

The detection of clouds by satellite sensors is plagued by the overestimation of loud amount at viewing angles other than zero. Figure 5 illustrates the problem. The raction of the scene assessed as cloudy, increases as the viewing angle increases ecause the sides as well as the tops are detected. This problem is greatest for geotationary satellites and viewing high latitudes and for orbiting satellites scanning imb angles. The dashed curve in Figure 6 shows this effect for 10 passes of a polar rbiter over the Atlantic Ocean. The bottom four curves in Figure 6 presents the result f four sequences of space shuttle photos as described and modeled by Snow, et al, (1985 1986). The function SCC (ζ) is seen to be smooth and remarkably repeatable.

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Fig. 5. Cloud cover and satellite cloud cover *S* as seen from the space shuttle orbiter at viewing angles of 50°, 30° and 0°. Surface area is displaced for clarity. The cloud field is invariant in the third dimension, that is, each cloud indicates an entire cloud row. Heavy lines represent the portion of area assessed from the satellite as cloudy. *S* is a function of cloud depth, viewing angle, and *C*. The illustration is for a cloud depth to width ratio of 0.866.

Fig. 6. Satellite cloud cover versus viewing angle ζ. Open circles indicate Kyushu Island data; solid circles show Dominican Republic data. The dashed curve is Average oceanic cloud cover as measured by meteorological satellite sensors operating in the visible wavelengths.