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A Comparison of "Dynamic Seedability" Prediction With Two Cloud Models During FACE - 73

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DEPARTMENT OF COMMERCE
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"Seedability" predictions of the EMB one-dimensional cumulus model are compared with those of the PSU 71 model for July 1973 during the Florida Area Cumulus Experiment (FACE) conducted by the Experimental Meteorology Laboratory. It was found that the EMB model generally predicts a higher magnitude maximum seedability and at a larger cloud radius than does the PSU 71 model. Neither cloud model showed a clear-cut superiority over the other as an aid to the decision process involved in the operation of a weather modification experiment.

1. INTRODUCTION

As a consequence of an article by Warner (1970) criticizing one-dimensional cumulus models, we have re-examined the quantitative aspects of two one-dimensional cumulus models currently in use at the Experimental Meteorology Laboratory (EML). The one model, which we will call the EMB model, is used as a decision aid during the operation of field programs in south Florida. The EMB series model has a lineage of development beginning with the Simpson et al. (1965) paper through the Simpson and Wiggert (1969, 1971) papers. The second model, which we shall call PSU 71, was developed by Cotton (1972b) mainly as a vehicle for exploring the effects of cloud microphysical processes on dynamic seedability. This model owes its lineage to the original Weinstein and Davis (1968) model developed at the Pennsylvania State University (PSU). Although both models interact with their environment by laterally entraining environmental air at the rate

$$\mu = \frac{1}{M}\frac{dM}{dz} = {}^{b}/_{R}\ , \tag{1}$$

they differ in numerical techniques and in the microphysics modeled. Several differences between the two models have been reported by Simpson (1972). In the EMB models, the entrainment calculation is first made for the thermodynamic variables only at the measured sounding points. The entrainment calculation essentially follows Stommel's graphical method, as described by Malkus (1954). Following completion of the entrainment calculation, an equation for the rise of a tower of the form

$$\frac{dw}{dt} = w \frac{dw}{dz} = \frac{g\ B}{1+\gamma} - \frac{1}{M}\frac{dM}{dz} w^2 - K_d w^2, \tag{2}$$

is integrated. The term gB is the buoyancy per unit mass, γ is the virtual mass coefficient, and K_d is a drag coefficient which is usually assumed to be zero in practice.

In the PSU 71 model, a sounding is first interpolated linearly with the logarithm of pressure for small height intervals ΔZ. Then the vertical velocity equation for a steady-state jet or the rise rate for a bubble (2), along with the thermodynamic energy equation and equations of continuity for all phases of water substance and types of condensate are simultaneously integrated vertically as a marching problem. The lapse in cloud temperature for a warm cloud, for example, is found by integrating (3)

$$\frac{dT}{dz} = \frac{-\frac{g}{cp}\left(1+\frac{q_s L}{RT}\right) + \mu(T-Tc)}{1 + \left(\frac{\varepsilon L^2 q_s}{c_p R T^2}\right)} \tag{3}$$

over each finite height step ΔZ by using a simple first-order integration scheme:

$$T_2 = T_1 + \frac{dT}{dz}\Delta Z. \tag{4}$$

As discussed in Cotton (1972b), following each finite height step the cloud is isobarically adjusted to saturation.

Simpson (1972) also noted that even when the EMB model was integrated on the PSU 71 interpolated sounding, significant differences between the liquid water profiles and temperature profiles predicted by the two models could be found. The source of discrepancy was the equation of continuity of total water substance,

$$\begin{aligned}\frac{dQ_T}{dz} &= \frac{dq_v}{dz} + \frac{dQ_c}{dz} + \frac{dQ_H}{dz} + \frac{dQ_F}{dz} + \frac{dQ_I}{dz} \\ &= -\mu(q_v - q_e) - \mu(Q_c + Q_H + Q_F + Q_I) - \text{Fallout.}\end{aligned} \tag{5}$$

As pointed out by Simpson (1972), the EMB model neglects the second term on the right side of (5), which represents the dilution of total cloud condensate by entrainment. Some condensate is affected by entrainment, however, since the entrainment of dry air as expressed by the first term on the right side of (5) requires the evaporation of condensate in order to maintain cloud saturation.

For precipitating cumuli, several other differences between the two models should be noted. The EMB series model employs an autoconversion formulation based on the work of Berry (1968). The PSU 71 model uses a time-dependent autoconversion formulation as discussed by Cotton (1972a). Both models employ a Kessler (1969) accretion formulation based on the assumption that the precipitation is distributed in a Marshall-Palmer spectrum. In the comparative experiments to be discussed in section 2, the PSU 71 model employs a precipitation fallout scheme similar to the EMB model. The only difference between the two schemes is that Simpson and Wiggert (1969) assume that the precipitation falls at the rate of the terminal velocity of a drop having the median-volume-diameter, while the PSU 71 model uses a water-content-weighted mean terminal velocity.

The greatest difference between the two models appears when the cloud becomes supercooled. For the EMB model, the microphysical processes are treated by direct analogy to the warm cloud autoconversion-accretion parameterization scheme. A seeding subroutine is introduced by linearly freezing total condensate between the levels -4°C and -8°C in the model. The latent heat of fusion is released and the cloud goes from water saturation to ice saturation in this interval. Natural glaciation is simulated by releasing the latent heat of fusion linearly between -20°C and -40°C.

For the PSU 71 model, water substance is subdivided into supercooled cloud droplets, supercooled raindrops, frozen raindrops, and 21 discrete classes of ice particles. Based on observations reported by Jones (1960), the frozen raindrops are assumed to be distributed in an inverse exponential form similar to the Marshall-Palmer spectrum. The 21 discrete classes of crystals represent those crystals that have formed either by vapor-deposition nucleation or by the freezing of cloud droplets. The crystals so nucleated may take on the form of needles, columns, dendrites, hexagonal plates, graupel, or any rimed combination of these. Cloud glaciation proceeds by the specification of the concentration of crystals formed as the cloud rises. The crystals grow by vapor deposition and riming and then promote the freezing of supercooled rain drops by being collected by them. Once the cloud liquid water is depleted, the cloud is said to be glaciated and is isobarically adjusted to ice saturation. Cloud seeding may be simulated by introducing a larger number of ice crystals in a seeded cloud than in a natural cloud.

Because of the number of differences between the two models, it was decided to perform "seedability" predictions with the EMB and PSU 71 models for the FACE - 73 experimental data. The motivation was to see if the PSU 71 model, or a combination of the two, may have been a better decision aid during the FACE - 73 experiment, or will be in future experiments.

2. THE DESIGN OF THE DAILY SEEDING ROUTINE

The PSU 71 model, with modifications that are discussed below, is run on a daily basis using the same sequence of numerical experiments that was used for a decision process with the EMB model. That is, a typical seedability calculation with the EMB model involves a series of experiments with cloud radii of 0.5, 0.75, 1.00, 1.25, 1.50, 2.00, and 2.50 km. Generally, a single cloud-base height of 915 m is used for the seedability determination. The PSU 71 model was likewise run assuming a cloud base height of 915 m and for cloud radii of 0.5, 0.75, 1.00, 1.25, 1.5, and 2.0 km.

To simulate seeding, the EMB model is run for each of the above cloud radii, assuming that natural glaciation does not take place until -40°C. A "seeding subroutine" is also run in which the effects of seeding are introduced linearly between -4°C and -8°C.

For the PSU 71 model, a seeding subroutine is introduced by arbitrarily nucleating a sufficient concentration of crystals to completely glaciate the cloud as rapidly as possible. Thus, a cumulative concentration of 5.5×10^4 crystals per liter is assumed to be nucleated between -4°C and -7°C. Natural cloud glaciation is simulated by assuming that the concentration of ice crystals formed obeys the Fletcher (1962) exponential ice nuclei equation,

$$N(T_s) = N_s e^{B_s T_s} \tag{6}$$

where $N(T_s)$ represents the cumulative concentration of ice crystals nucleated at the degree of supercooling (T_s). The parameters B_s and N_s are assumed to be 0.6 and 10^{-5} per liter, respectively. An enhanced, natural, ice-crystal production model is also used. It is defined to be (6) multiplied by the ratio of the concentration of ice particles to ice nuclei as a function of temperature reported by Hobbs (1969).

In both the EMB and PSU 71 models, seedability is defined as the difference between the predicted cloud top height for a simulated seeded cloud and a simulated natural cloud. Of course, the PSU 71 model has two such seedability estimates for each cloud radius depending upon which natural model seems most appropriate.

In addition to the seedability calculation as a function of cloud radii, the parameter S-N_e as defined by Simpson and Woodley (1971) is also calculated. Here, S represents the maximum seedability for the set of prescribed cloud radii and N_e represents the number of hours during which radar echoes are detected in the target area from 1300 to 1600Z (GMT). As reported by Simpson and Woodley (1971), suitable days for experimentation were those that satisfied an objective meteorological criterion of

$$1.0 \leq S\text{-}N_e \; .$$

The maximum value of $N_e = 3$ is also introduced to bias the decision against experimentation on naturally rainy days.

3. RESULTS OF NUMERICAL EXPERIMENTATION

The EMB model was run with the 1200Z sounding and a hierarchy of cloud radii on a day-by-day basis for flight decision during a three-month period (June - August) of 1973.

The PSU model was likewise run with the previously described modifications over the same period. On 3 days, 15 June, 24 June, and 11 August, the PSU 71 model was unable to perform a complete seedability calculation. This failure was later traced to a logical oversight in the ice-phase microphysical routine hitherto not encountered by the model. This oversight has since been repaired and it is now believed that the model is thoroughly operational.

A comparison histogram was used to make a day-by-day comparison of the predicted seedabilities of the two models. In the analysis, the days were stratified into three types of days according to the decision by the project director. These were

a. GO Days - those days which were selected for randomized seeding,

b. NO GO Days - those days which were deleted from the randomized seeding experiment due to the objective S-N_e criterion, and

c. NO Qualify Days - those days during which the objective meteorological criteria suggested it to be a GO-Day, but the project director chose not to fire the necessary 40 flares needed to qualify the day as a randomized experiment. These days did not

> qualify for a GO-Day due to such meteorological factors as the intrusion of extensive cirrus from disturbances or cloud clusters somewhat remote from the Florida peninsula, or the apparent trend of the cumulus development, suggesting the environment was synoptically disturbed.

Figure 1b illustrates a typical seedability histogram for 16 July 1973 - a GO Day. The EMB model (E) predicts a generally higher seedability with a maximum seedability of 3.3 km at 1.25 km cloud radius. The PSU 71 model predicts a somewhat lower maximum seedability of 2.70 km for the less active natural nucleation model (C_1) but at a cloud radius of 0.75 km. The sharp decay in seedability of the PSU 71 model at radii greater than the maximum seedability is characteristic of the model. The enhanced natural nucleation model (C_2) shows a similar behavior in predicted seedability, but with a consistently lower magnitude than either C_1 or E.

Most of the difference in seedability behavior between the EMB and PSU 71 models can be attributed to the differences in the glaciation theories. The typically higher seedability of the EMB model is a consequence of the neglect of natural glaciation until the cloud reaches a temperature of -40°C. For the PSU 71 model, natural glaciation begins at rather warm temperatures, at rates dependent upon the nucleation model C_1 or C_2, the amount of cloud liquid water, and the rainwater content present in the simulated cloud. Naturally, the more active the natural glaciation model, the higher will be the predicted heights of nonseeded clouds and, subsequently, the lower will be the seedability. Another factor affecting the higher seedability of the EMB model is the neglect of the dilution of total condensate by entrainment. Other factors being the same, the EMB model transports a larger quantity of supercooled water aloft than does the PSU 71 model. This water acts as a drag in the unseeded cloud and as a source of potential energy in the seeded cloud.

The rather narrow size range of clouds having significant seedability exhibited in figure 1b for the PSU 71 model is likewise a result of the natural glaciation models. That is, as a consequence of the entrainment hypothesis, larger clouds penetrate deeper into the supercooled layer and are thus more likely to activate the natural glaciation models C_1 or C_2.

A cloud radius of 1 km seems to have the best correlation in seedabilities between both models. This also lies in the size range where the PSU 71 model predicts the highest seedability.

On rare occasions the PSU 71 model with the C_1 glaciation model actually predicts higher seedability than does the EMB model. An example is 9 August 1973 as illustrated in figure 2. This is a GO Day

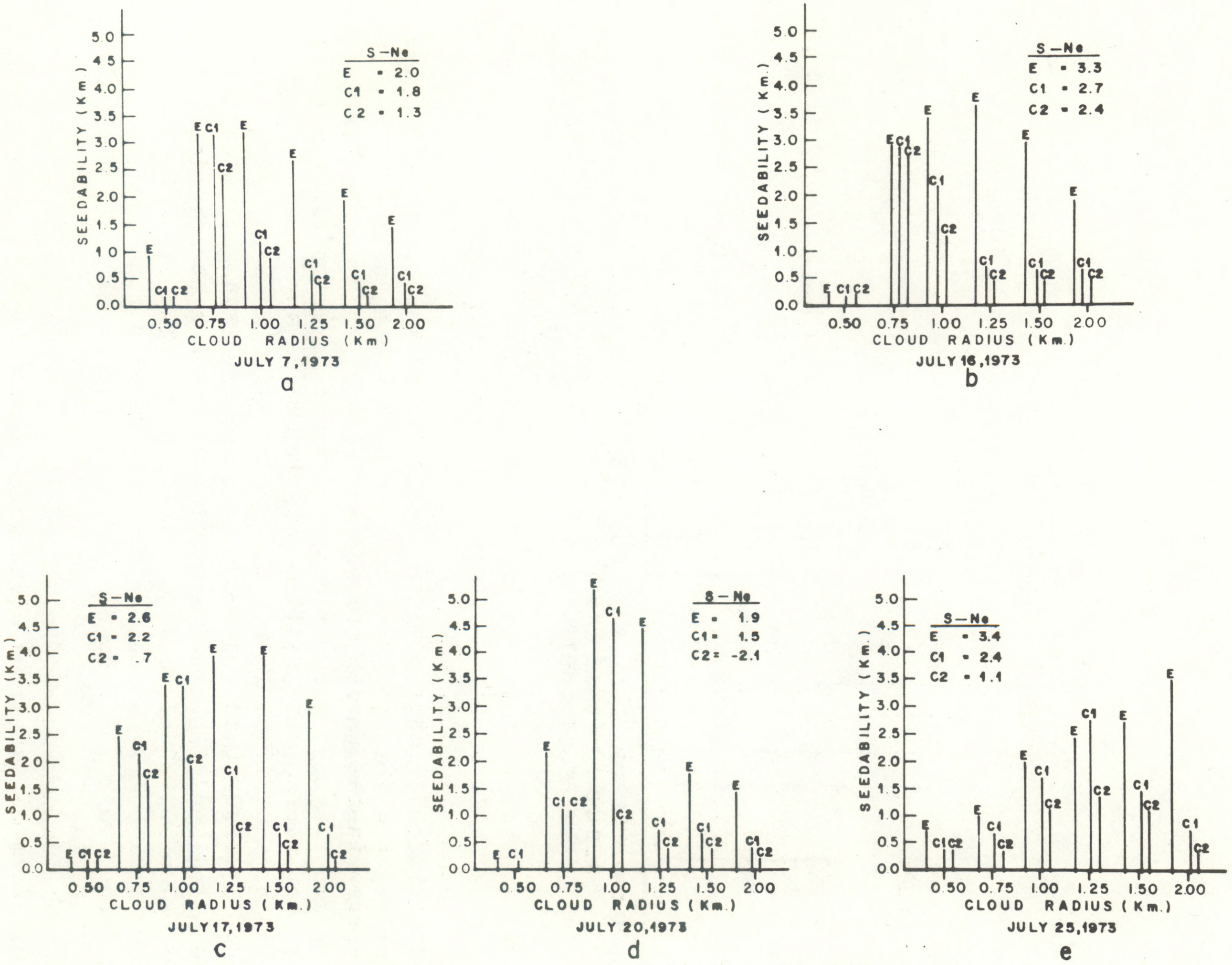


Figure 1. Seedability predictions for July 1973 on GO Days with the EMB model (E) and the PSU 71 model employing low amplitude natural glaciation (C_1) and enhanced natural glaciation (C_2).

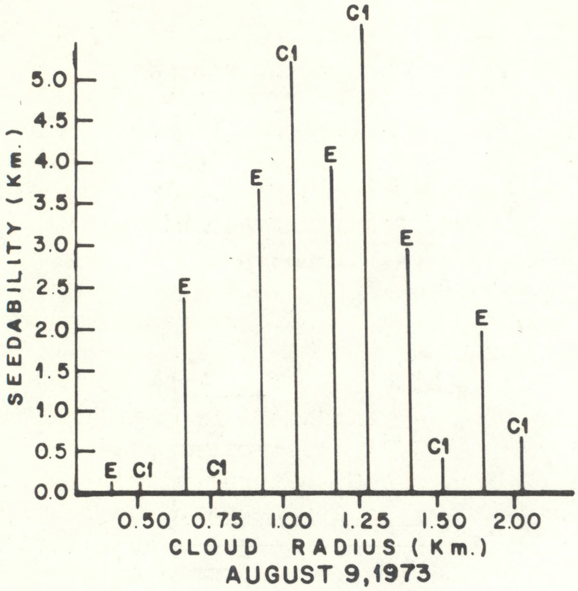


Figure 2. An example of higher seedability prediction with the PSU 71 model (C_1) than with the EMB model (E).

and, as illustrated in figure 2, the predicted seedabilities are quite large. The reasons for such behavior are by no means obvious. Perhaps other differences between the two models, such as the sounding interpolation scheme and the warm cloud microphysics may have contributed to this reversal in behavior of seedability prediction.

To see if the PSU 71 model may have any advantages as a decision aid in the actual seeding experiment, let us compare the predicted seedabilities on GO, NO GO, and NO QUALIFY Days. The days that were used as "Radar Control" days during the analysis were not included in the data, since the project director could not subjectively define the day as a NO QUALIFY Day.

Figure 1 (a-e) illustrates the seedability comparison histograms for July 1973 on GO Days. In general, the EMB model predicts a larger magnitude seedability and at a larger radius than the PSU 71 model. This can be seen in the seedability spectra for natural glaciation models C_1 and C_2 as well as the $S-N_e$ criterion. Based on the analysis of GO Days, if we were to use the PSU 71 model as a regular decision aid, the threshold magnitude of seedability and $S-N_e$ acceptable for a GO decision should be adjusted downward from the acceptable range for the EMB model.

Figure 3 (a-e) illustrates the seedability comparison histograms for the July 1973 on NO QUALIFY Days. The behavior of the two models on the NO QUALIFY Days studied is generally the same as on GO Days. Again, the PSU 71 model exhibits a lower magnitude seedability at smaller cloud radii than does the EMB model. Both models developed a somewhat peculiar spectrum on 30 July 1973, as illustrated in figure 3e. The predicted seedabilities were negligible, except for clouds of radius 1.25 km and greater, at which point the predicted seedabilities exceeded 5 km.

Unfortunately, the greater number of days during July 1973 fell into the NO GO category. Figure 4(a-o) shows the comparison histograms for the NO GO category during July. The comparative behavior of the models is generally the same as on GO and NO QUALIFY Days. That is, the EMB model again shows a characteristically higher magnitude maximum seedability and at a larger radius than the PSU 71 model.

Both models generally predict a lower magnitude $S-N_e$ in the NO GO category than in the GO category. The PSU 71 model often predicts negative values of $S-N_e$, especially with the C_2 natural glaciation model. The only major distinction between the two models occurred on 8 July 1973 (fig. 4c), and 27 July 1973 (fig. 4m) where significant seedabilities were predicted by the EMB model, yet the PSU 71 model predicted consistently small seedabilities.

4. SUMMARY AND CONCLUSIONS

The seedability predictions by the EMB model and the PSU 71 model have been compared. It was found that the EMB model generally predicts a higher magnitude maximum seedability and at a larger cloud radius than does the PSU 71 model. Thus, if the PSU 71 model is to be used as a regular decision aid, the magnitude of seedability and $S-N_e$ acceptable for a GO decision should be adjusted downward from the acceptable range for the EMB model.

The actual magnitude of the difference in seedability predicted by the two models is strongly dependent upon the choice of natural glaciation model (C_1 or C_2) for the PSU 71 model. The enhanced natural ice particle production model (C_2) results in a generally lower magnitude seedability than C_1 or the EMB model. Because of the uncertainty in the nature of the natural ice particle production process, it is recommended that a single glaciation model, namely C_1, be used when the PSU 71 model is used as a regular decision aid.

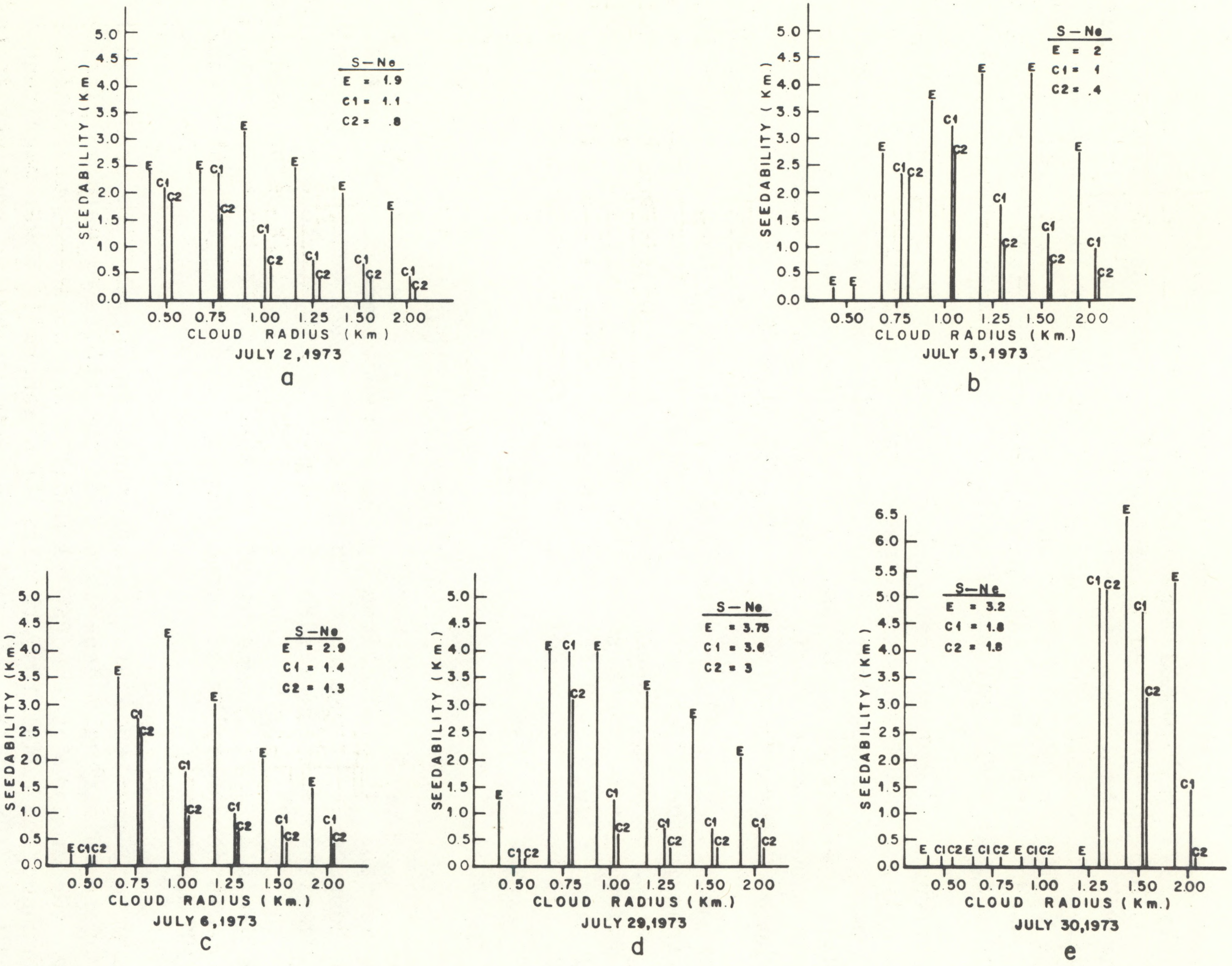


Figure 3. Seedability predictions for July 1973 on NO QUALIFY Days with the EMB model (E) and the PSU 71 model employing low amplitude natural glaciation (C_1) and enhanced natural glaciation (C_2).

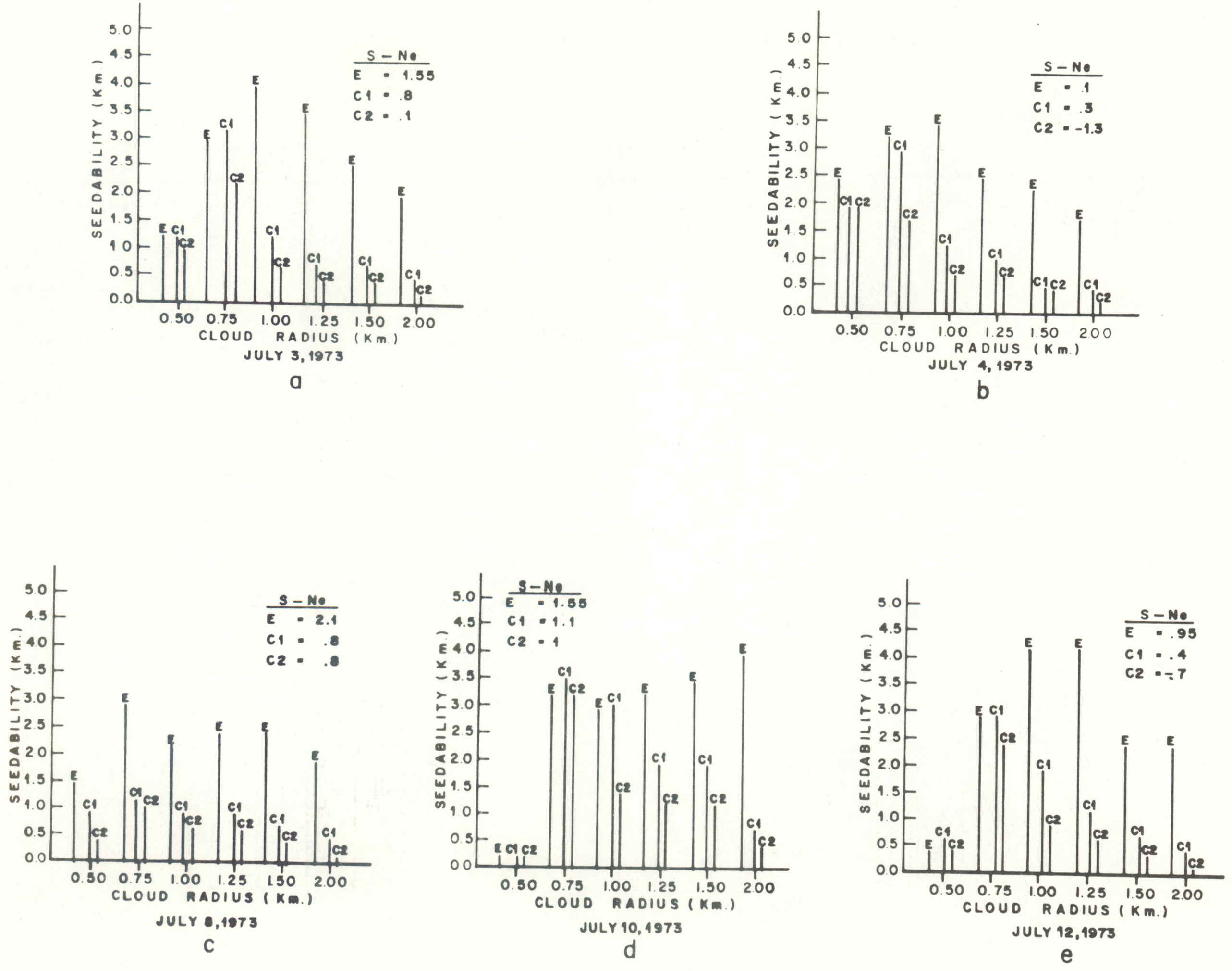
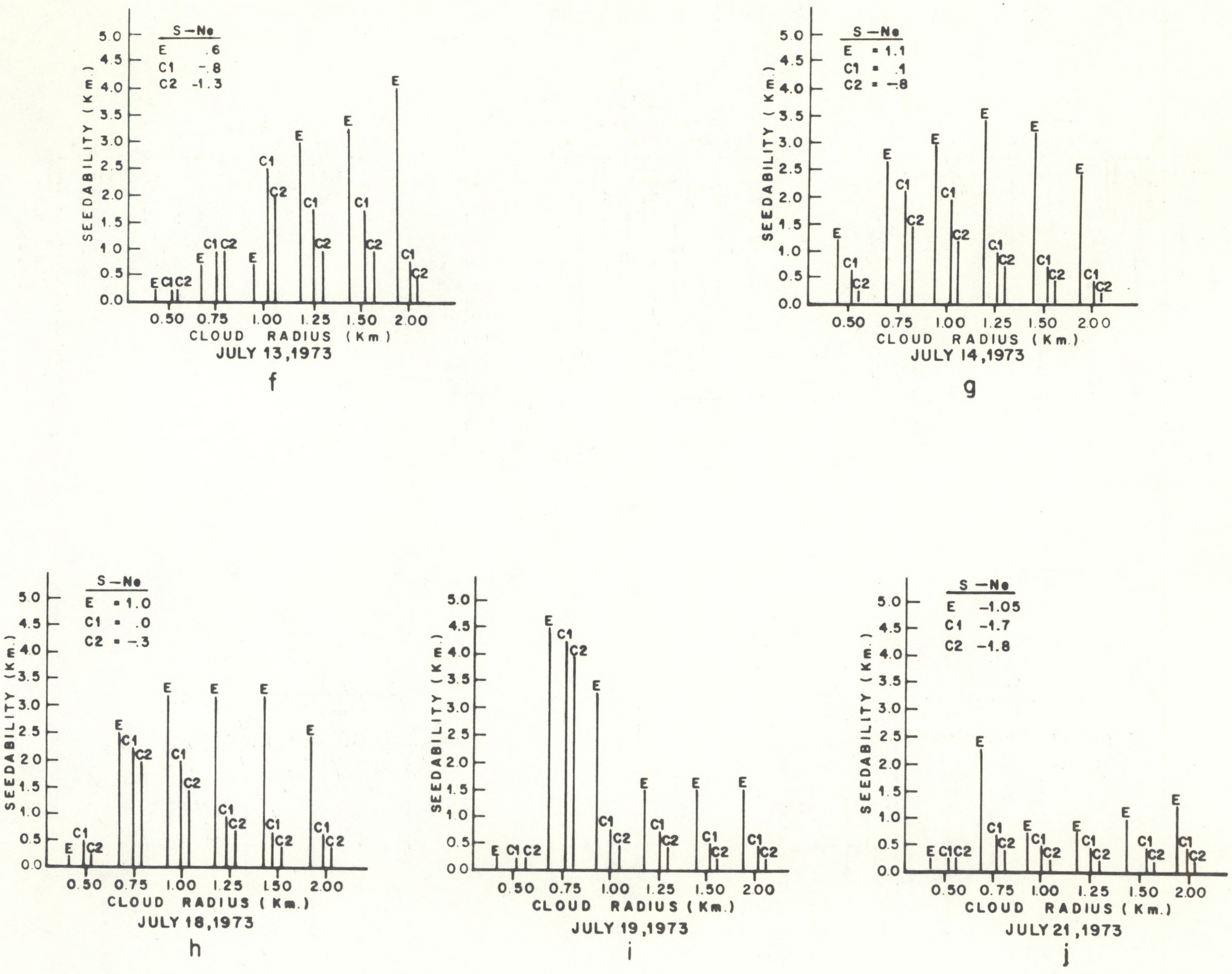


Figure 4. Seedability predictions for July 1973 NO GO Days with the EMB model (E) and the PSU 71 model employing low amplitude natural glaciation (C_1) and enhanced natural glaciation (C_2).



CLOUD RADIUS (Km)
JULY 13,1973
f

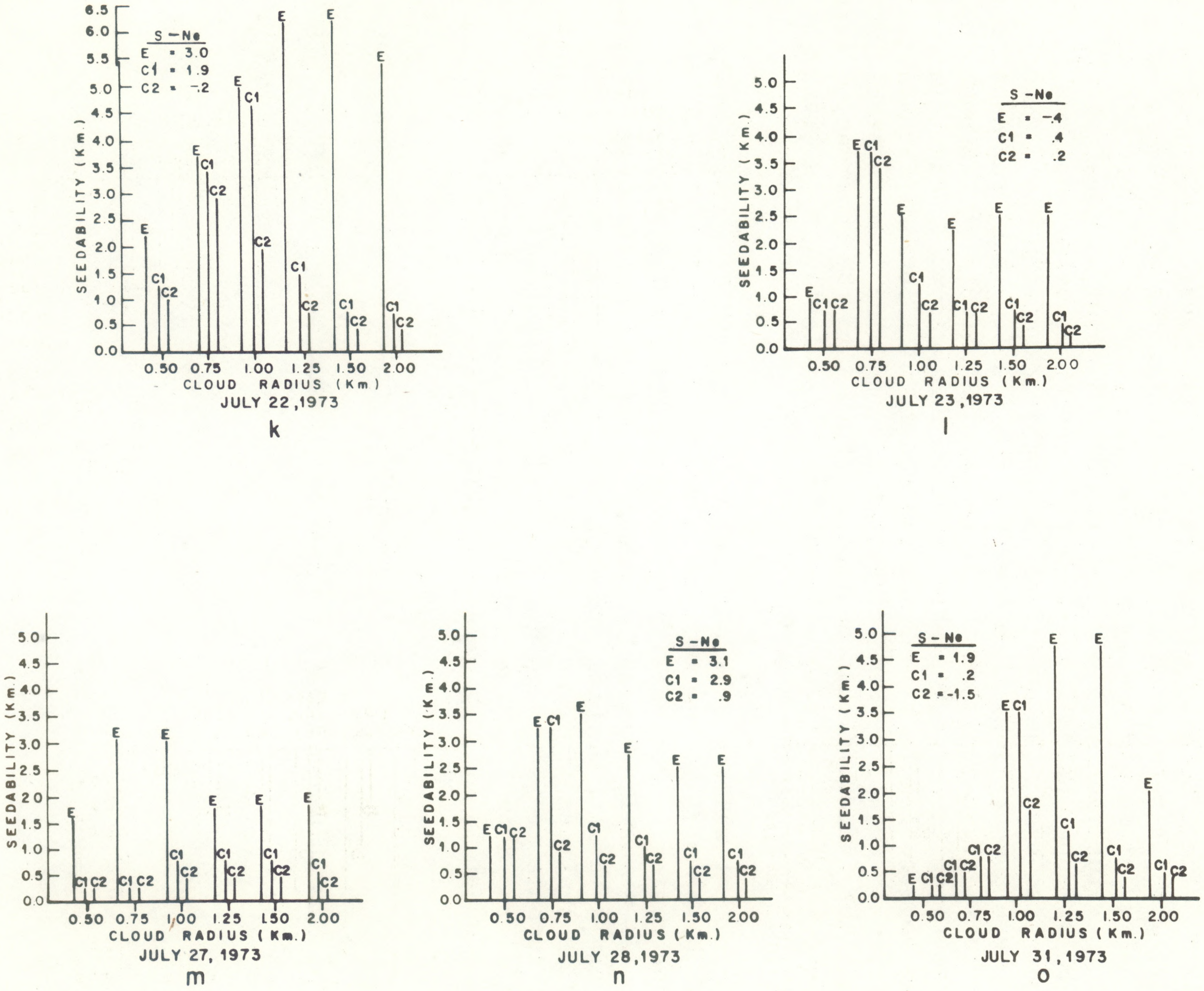
CLOUD RADIUS (Km.)
JULY 14,1973
g

CLOUD RADIUS (Km.)
JULY 18,1973
h

CLOUD RADIUS (Km.)
JULY 19,1973
i

CLOUD RADIUS (Km.)
JULY 21,1973
j

Figure 4. (continued)



JULY 22, 1973
k

JULY 23, 1973
l

JULY 27, 1973
m

JULY 28, 1973
n

JULY 31, 1973
o

Figure 4. (continued)

Overall, neither cloud model showed a clear-cut superiority over the other as an aid to the decision process involved in the operation of a weather modification experiment. The PSU 71 model has several advantages related to its greater generality, flexibility, and numerical accuracy. In addition, these advantages are not gained at the expense of computer time. Because the EMB requires two vertical scans of a sounding, plus iterations to adjust to saturation at each level, while the PSU 71 model requires only a single scan through a sounding and adjusts to saturation analytically, the PSU 71 model is considerably faster below supercooled levels. Within the supercooled portions of the atmosphere, however, the additional microphysics of the PSU 71 model require more computations than does the EMB model. Thus, the speed ratio of the two models depends on the degree of instability of the sounding. If the sounding is quite unstable, then most clouds will penetrate deep into the supercooled layer and the two models will perform a seedability calculation in about the same time. If the sounding is more stable, such that only the largest clouds penetrate deeply into the supercooled layers, the PSU 71 model may perform a seedability calculation in as little as one-half the time of the EMB model.

Note that while models such as the EMB or PSU 71 models may be considered the work-horses of cumulus modeling, they nonetheless have many shortcomings. Our ability to simulate the glaciation process, for example, is severely limited by uncertainties in the production rate of ice crystals in both natural and modified clouds. In addition, the neglect of nonlinear interactions of cloud parcels and the representation of turbulence as a simple 1/R entrainment hypothesis are simplifications of the dynamic structure of a cumulus cloud, which certainly limit the generaly utility of such models.

5. ACKNOWLEDGMENT

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