A Paradigm for Testing Cloud Parameterizations

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Introduction

One of the main goals of the Atmospheric Radiation Measurement (ARM) Program is improvement of cloud and radiation parameterizations in general circulation models. This problem can be logically addressed within a three-step framework: 1) prediction of clouds from thermodynamic fields, 2) parameterization of microphysical properties of the clouds, and 3) parameterization of radiative properties of the clouds. The information derived from the parameterizations is used in a radiative transfer scheme to calculate heating rates and surface fluxes.

An important requirement for improving parameterizations is the availability of a continuous data stream. This continuous data stream is currently available from ground-based remote sensors at the Southern Great Plains (SGP) ARM site. The data stream can be used to observe and characterize cloud microphysical properties, thus enabling us to address the three steps of the parameterization problem. One example of the use of the data for retrieving cloud properties is the technique using the Millimeter Wave Cloud Radar (MMCR), the Micropulse Lidar (MPL), and the Belfort Ceilometer (BLC) for determining cloud boundaries (Clothiaux et al. 1999). Other examples are the retrieval of liquid water path (LWP) using the Microwave Radiometer (MWR) (Liljegren 1999) and indirect measurement of ice water path (IWP) using the MPL, MMCR, and Atmospheric Emittance Radiance Interferometer (AERI) (Mace et al. 1998).

Given the natural variation in cloud properties, the assumptions and complexities in the retrieval schemes, and the inherent instrument limitations and errors, the question of quality arises. Therefore, it is important to determine whether the retrievals provide any useful information for improving parameterizations. This paper discusses a paradigm that we have developed to address the data quality question. Some results from using a few months of data are also discussed to illustrate possible methods of exploiting the paradigm.

The Paradigm

The best possible validation of the retrievals is through comparisons with in situ observations although this approach has its problems. One major problem is the scarcity of in situ observations, as aircraft measurements form the bulk of this data type. Another problem is the difference in the sample volumes of the data typically used for retrievals as compared to the sample volumes of the in situ probes. Therefore, we need an alternative approach.

While developing an approach, we need to consider the necessity of a baseline for our comparison as well as a method for classification and analysis of various retrievals. A cloud-radiation impact viewpoint is our focus, and solar flux is a criteria that best fulfils our line of approach due to the major effect clouds have on it. The downwelling solar flux at the surface and upwelling solar flux at the top of the atmosphere (TOA) are two criteria that we decide on as measures for our study. Unfortunately, non-availability of continuous TOA flux data prevents its implementation for comparison purposes and we are solely dependent on the downwelling surface solar flux. As the downwelling surface solar flux is dependent on solar zenith angle in the first order, its effects are removed by normalization as represented by,

$$CF_o(t) = [F_{act,o}(t) - F_{clr,o}(t)]/F_{clr,o}(t) \tag{1}$$

for the observations, where $CF_o(t)$ is the observed cloud forcing, $F_{act,o}(t)$ the actual downwelling solar flux and $F_{clr,o}(t)$ the interpolated clear-sky solar flux (Long and Ackerman 1999). For the calculations, the cloud forcing is,

$$CF_c(t) = f \times [F_{cld,c}(t) - F_{clr,c}(t)]/F_{clr,c}(t) \tag{2}$$

where $F_{cld,c}(t)$ is the calculated flux with clouds, $F_{clr,c}(t)$ is the calculated clear-sky flux, and f is the fractional cloud cover over our retrieval domain. The fractional cover is used to weight our calculations for broken cloud cover effects on the domain. It is useful to note that f is absent for observations (Eq. [1]) as the fractionality is implicit in measurements. The values of CF(t) generally range from -1 to 0 but values greater than 0 are possible due to cloud inhomegenities. In our study we neglect observations that have values of cloud forcing greater than 0 as our procedure does not have the capability to reflect these positive values. The physical interpretation of cloud forcing implies that larger negative values and larger magnitudes are analogous to thicker clouds with higher optical depths.

Methodology for Flux Calculations

The primary data sets for our calculations are the combined MMCR, MPL, and BLC data processed to estimate cloud location and a combination of radio-sonde, thermal interferometer, surface observations and National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory's Rapid Update Cycle (RUC) model output producing atmospheric profiles of temperature and water vapor. These two processed data sets are assumed to provide an accurate summary of cloud location and thermodynamic profiles.

Using cloud location data sets, the average cloud height for periods of 10-minute intervals are determined. A simple count of the fraction of cloudy points in our averaging period gives an initial estimate of the cloud fraction. This cloud fraction is based on the assumption that temporal and spatial cloud distributions are inherently similar. As can be seen later, we use a more accurate and direct cloud fraction for our calculations. For the present scenario, a threshold value of 0.1 for f is used to differentiate between clear and cloudy scenes. Using the thermodynamic profile data set, averaged over the same 10-minute periods, cloud types are estimated based solely on a temperature criterion. For the present, we only concern ourselves with single-layer clouds. These single-layer clouds are segregated into three categories: cirrus, stratus, and altostratus. Cirrus or ice clouds are defined as clouds with base temperatures greater than –20 °C, while stratus are water clouds with top temperatures greater than -20 °C. All other clouds are assumed to have a mixed phase and classified as altostratus. Treatment of cirrus and stratus are initially considered as altostratus retrievals are not currently being done.

The next step is the radiative transfer computation to estimate $F_{cld,c}$ and $F_{clr,c}$. The radiative transfer model is a plane-parallel 2-stream model with gaseous absorption treated via k-distributions and a correlated k assumption (Kato et al. 1999). The 2% to 3% high bias relative to observations occurring in the diffuse field (Kato et al. 1997) has a negligible effect on our study. Three separate calculations, one for clear-sky, another for clouds with climatological properties, and yet another with our best estimate of cloud properties, are performed. The clear-sky calculation uses the available thermodynamic profiles and aerosol optical depths from Multi-Filter Rotating Shadowband Radiometer (MFRSR) data. An Angstrom curve is fitted to the MFRSR optical depth data, available for five wavelengths, for usage in calculations over 32 spectral bands over the solar spectrum. Ozone optical depths available from satellite (Total Ozone Mapping Experiment Spectrometer [TOMS]) data as well as fixed Rayleigh optical depths based on standard profiles are subtracted before the interpolation. The aerosol absorption calculations assume a composition of soil (Kato et al. 1997).

The next radiative transfer computation includes a cloud with climatological properties. The concept is assigning cloud microphysical properties from existing literature based on cloud type. For stratus clouds we use a lognormal distribution with mean diameter 8.2 microns and a width of 0.38. The radiative transfer calculations require another constraint and we use LWP from the MWR data. The measured LWP is used instead of climatological values of liquid water content due to uncertainties in the cloud bases as a result of insect contamination of MMCR, MPL, and BLC reflectivities. An added incentive is the examination of size sensitivities, in the presence of accurate LWP, for solar radiative transfer. The approach for cirrus is different as we use existing diagnostic parameterizations. The ice water content is from Stephens et al. (1990) while the particle sizes are from Platt (1997). These values are used in a parameterization (Fu and Liou 1993) to estimate the optical properties for our radiative transfer calculations.

The final radiative transfer computation includes a best-estimate cloud. The best-estimate cloud properties are based on retrievals. Ideally, retrievals for all the different types of clouds would allow operational use of the paradigm. Currently, MMCR reflectivities, AERI emission measurements and thermodynamic profiles are being used for cirrus retrievals of IWP and effective crystal diameters (Mace et al. 1998). These variables are used to calculate the optical properties using Fu and Liou's (1993) parameterizations. The stratus retrievals are being developed and the computation cannot be made presently.

We can now evaluate the normalized solar cloud forcing for our climatological cloud as well as our best estimate. Equation (1) is used for the calculation with a cloud fraction f estimated from the ratio of diffuse to total broadband solar radiation as devised by Long and Ackerman (1999). This estimate of cloud fraction is used instead of the estimation made from the radar counts as it is takes into account a spatial distribution more directly than the radar and so is presumably more accurate. The observed values for cloudy sky are directly available from surface radiometric measurements. The clear-sky observations are available from interpolation between clear periods (Long and Ackerman 1999). CF(t) is calculated from the observations after averaging the data to 10-minute intervals and using a value of 1 for f. A baseline for evaluation is thus obtained.

Skill Score Evaluation Technique

The calculation of a correlation coefficient between the observed, climatological, and best estimate normalized forcing values does not sufficiently represent the nature of variation in the data sets. Therefore, a technique used by the forecasting community is used to resolve the variances in the data sets. A skill score, which is effectively a quantitative evaluation of the performance of the retrievals, relative to the climatology, with the observations as truth, is calculated.

If we define the best estimate results as forecast (F), the climatological results as control (C), and the measured values as observed (O) the mean square error of the forecast (MSE_f), for our calculations, is,

$$MSE_f = \frac{1}{N} \sum (F_i - O_i)^2 \tag{3}$$

where N is the number of data points, and the subscripts denote the individual values of F and O. A mean square error for control can similarly be defined by replacing F with C in Eq. (3). Equation (3) can also be represented in the form,

$$MSE_f = (\overline{F} - \overline{O})^2 + (1 - R_{fo})(S_f^2 - S_o^2) + R_{fo}(S_f - S_o)^2 \tag{4}$$

where the overbars represent the respective means, S's with subscripts represent the standard deviations and R_{fo} represents the correlation coefficient of the forecast and observed data sets. The three terms in Eq. (4) represent the bias error squared (B_f), the non-systematic errors (N_f), and the variance error (V_f), respectively. These three terms provide an insight into the errors in the forecast or control data sets when compared to observations. The skill score (SS) of the forecast is,

$$SS = 1 - MSE_f / MSE_c \tag{5}$$

where the subscripts identify the data sets. A value of 0 shows no skill while positive values show better forecasting skill. The SS and MSE values are used in our analysis of the normalized cloud forcing data and are presented next.

Results

The results for cirrus are complete because of the availability of the retrievals as mentioned earlier. We would like to present the results pertaining to cirrus to provide an example of the use of the paradigm. The incomplete stratus results are also presented as they provide some interesting information.

Cirrus

The available cirrus data span 30 days between May 1997 and July 1997 and include 361 10-minute averaged data points. The time series (Figure 1) shows that both the climatological forcing values as well as the best estimates are significantly scattered about the observations. There is a significant bias (Figures 2 and 3) in the climatological values, and cirrus with larger magnitude forcings are not well represented by the climatology. The retrievals have little or no bias (Figure 3) though they have significant scatter about the observations (Figure 2). Qualitatively the retrievals seem to better represent the observations than climatology based on the parameterizations.

The mean square errors (Table 1) show that the parameterizations have a bias squared value that is around 50 times the retrieval value. The random error of the retrievals though is larger implying larger scatter. The variance error of the retrieval though is significantly smaller than the parameterizations implying a closer magnitude of variance in the retrievals when compared to observations. The mean square error of the parameterizations is approximately double that of the retrievals thereby showing that the latter better represents the observations than the former. The skill score is calculated to be 0.41 showing that retrievals significantly improve our ability to match observations. The correlation of the parameterizations to observations is 0.63 while that of retrievals to observations is 0.69 showing that the retrievals have negligibly higher correlation.

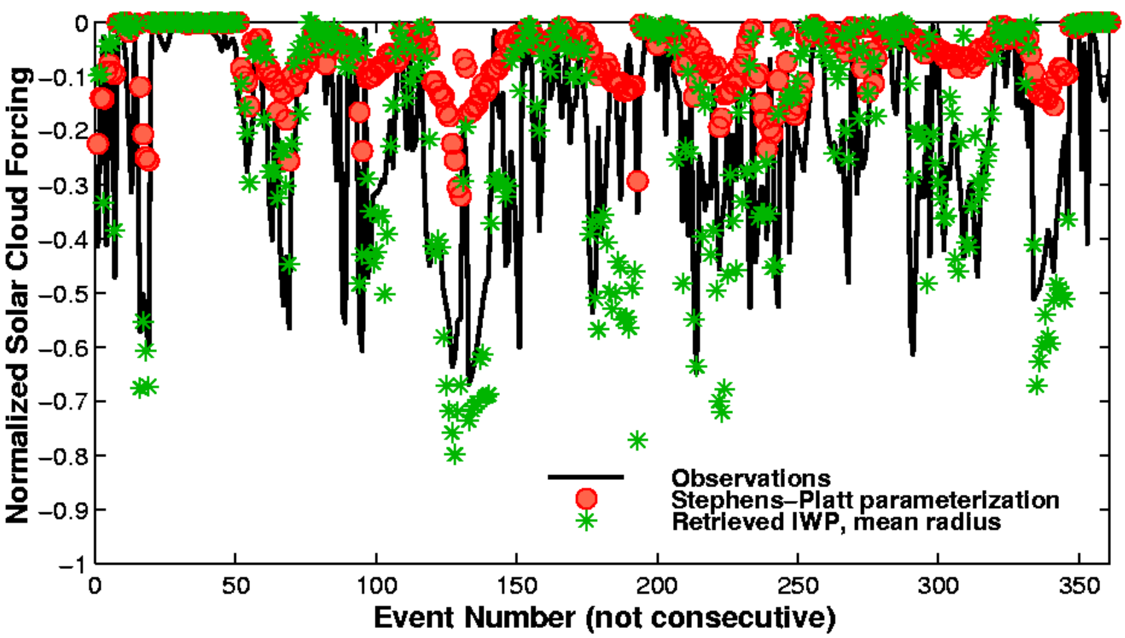

Figure 1. The time series of the cirrus data is shown here. The horizontal axis represents a series of points that are ascending in time but not necessarily consecutive. The vertical axis represents normalized solar cloud forcings. The black lines are observations, red-filled circles are climatological values, and green stars are the best estimates.

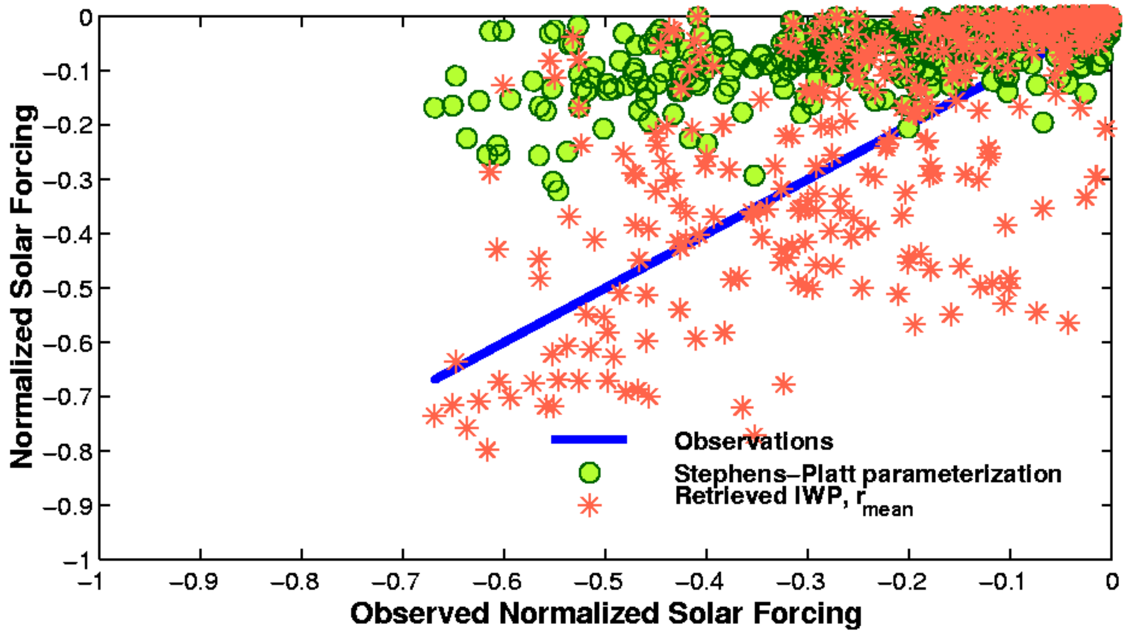

Figure 2. The cirrus scatter plot of the climatological data (green circles) and best estimates (red stars) against the observed values of normalized solar cloud forcings are shown here.

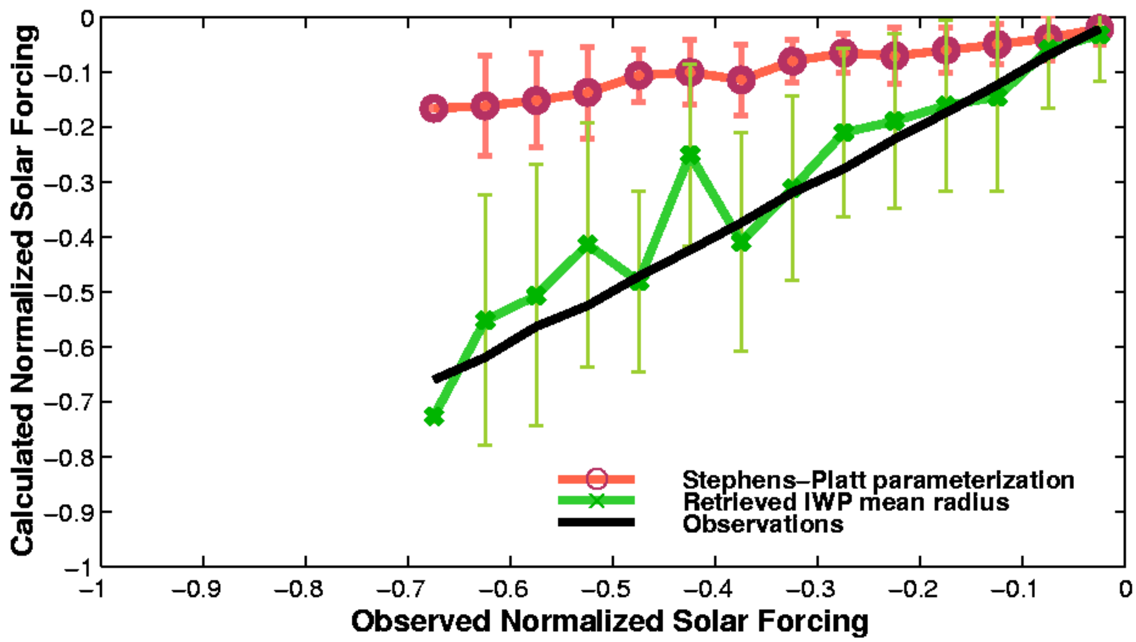

Figure 3. A plot of cirrus observations and their corresponding climatological and best estimate forcing values averaged respectively over 0.05 units wide bins. The black line represents the observations, magenta line the climatology, and the green line the retrievals. Error bars represent one standard deviation of the variation in data.

Table 1. The mean square errors between the parameterizations and observations and the retrievals and observations are shown in the columns. The rows represent the individual error components.

	MSE_c Mean Square Error of Parameterizations	MSE_f Mean Square Error of Retrievals
B Bias squared	0.023	0.0004
N Random errors	0.013	0.0244
V Variance errors	0.008	0.001
Total	0.044	0.026

Stratus

The stratus data for climatological cloud are available from January 1997 to January 1998. There are 1179 10-minute averaged data points. Notwithstanding the availability of best estimates we compared the climatology calculations with observations. The scatter plot (Figure 4) and Figure 5 show that fixed microphysics calculations have low bias compared to the observations. This may be interpreted as insensitivity of radiation to microphysics especially in the thicker cloud regime with forcing values greater than 0.4. We feel that accurate LWPs are more important in radiation calculations, and sensitivity due to MWR measurement error may be higher than due to size and width of particles. The full import of these results needs to be interpreted.

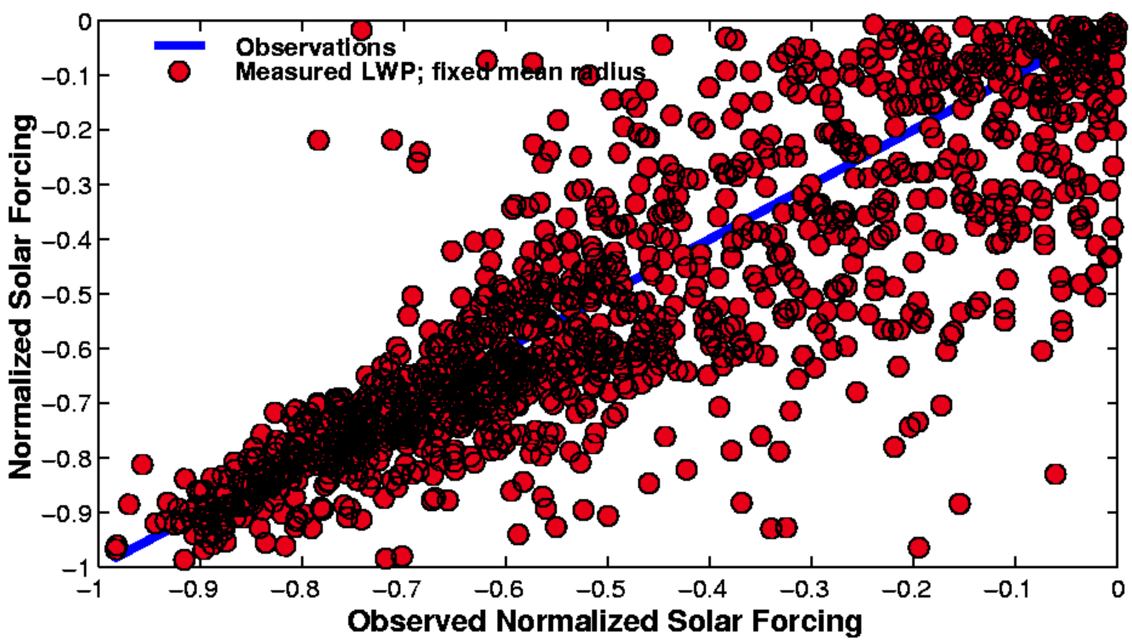

Figure 4. A scatter plot of 1179 stratus climatological normalized cloud forcing data points (maroon circles) plotted against the observed data (black line).

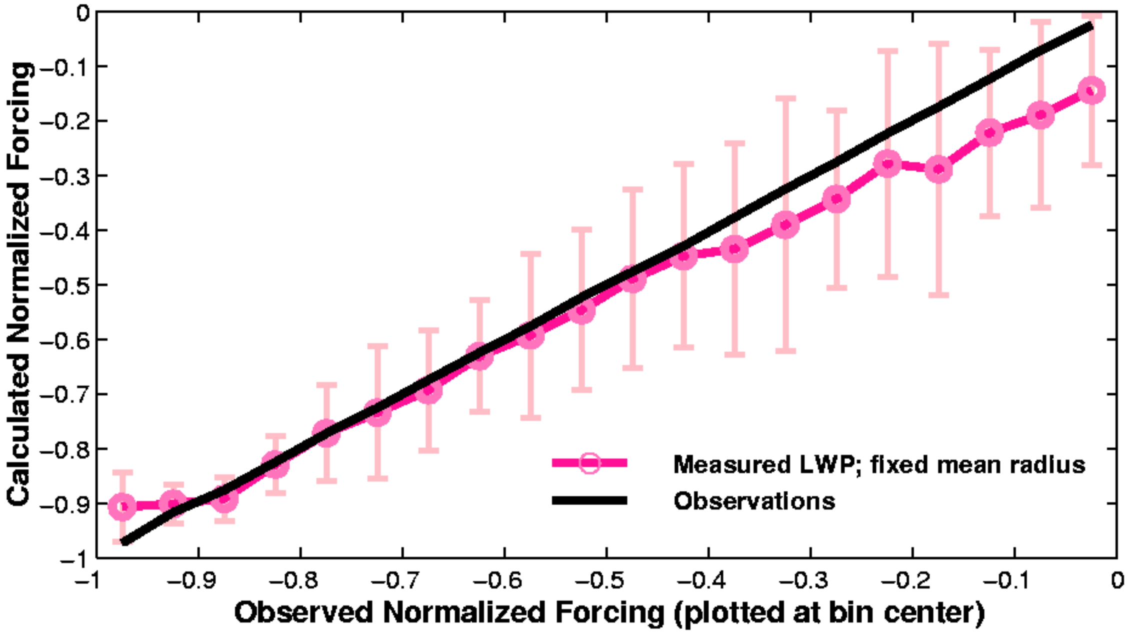

Figure 5. A plot of stratus observations and their corresponding climatological and best estimate forcing values averaged respectively over 0.05 units wide bins. The black line represents the observations and the magenta line the climatology. Error bars represent one standard deviation of variation in the data.

Conclusions and Future Work

It is clear that the paradigm, we set out to develop, does provide us with a framework for assessing performances of existing parameterizations and comparing them with retrievals. What this paradigm provides is not only a method for testing the retrievals but also a technique that evaluates their performance against an existing parameterization. Having developed this scheme, our next work would be to apply it to different locations and as many cloud types as possible.

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