P5.13 THE VARIABILITY OF SURFACE CLOUD RADIATIVE FORCING OVER THE US

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1. Introduction

An overall goal of this paper is to assess the effects of clouds on the radiation budget over the US in the time mean, annual, and monthly time scales. This goal will be achieved through the use of a quantity known as the surface cloud radiative forcing (Charlock and Ramanathan, 1985), which represents the radiative effects of clouds at the surface. The surface cloud radiative forcing is based on the downward and upward radiative fluxes under clear and cloudy conditions. The observed shortwave, longwave, and total surface cloud forcing are determined from a combination of satellite observations, model analyses, and radiative transfer models. The spatial and temporal patterns of the surface cloud forcing will be documented and related to cloud properties.

2. Data

This study utilizes two data sets: the International Cloud Climatology Project (ISCCP) DX data set (Rossow and Schiffer, 1999) and the surface radiation budget (SRB) data set produced by NASA (Gupta et al., 1993). The ISCCP data set contains cloud fraction (total, low, middle, high), optical depth, cloud water, cloud top temperature, cloud top pressure, and precipitable water (lower and upper tropospheric). The SRB data contains cloud shortwave, longwave, and total cloud radiative forcing (or the basic components to derive these quantities) that are based upon the cloud observations in the ISCCP DX data set. Monthly data from these data sets for the 10-year period July 1985 to June 1995 are used in this study.

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The shortwave radiative quantities in the SRB data set necessary to derive the shortwave cloud radiative forcing data were generated using the Pinker/Laszlo shortwave algorithm (Pinker and Laszlo, 1992). These parameters were derived originally at a 3-hourly temporal resolution. The 3-hourly values were first averaged into daily values, which were then averaged into monthly averages. Atmospheric water vapor is taken from a 4-D data assimilation product provided by the Data Assimilation Office at NASA GSFC and were produced with the Goddard Earth Observing System model version 1 (GEOS-1). Ozone is taken from the Total Ozone Mapping Spectrometer (TOMS), except for the December 1994 to October 1995 period, when it is taken from TIROS Operational Vertical Sounder (TOVS) data.

The longwave radiative quantities in the SRB data set necessary to derive the longwave cloud radiative forcing data were generated using the Fu et al. (1997) thermal infrared radiative transfer code that requires cloud, atmospheric profile information, and surface properties. Temperature and moisture profiles were taken from a 4-D data assimilation product provided by the Data Assimilation Office at NASA GSFC and were produced with the GEOS-1. Surface emissivities were taken from a map developed at NASA (Wilber et al., 1999).

An assessment of the quality of these monthly average fluxes was accomplished by comparisons with corresponding ground-measured fluxes over a period of four years (1992-1995) from a number of sites of the Baseline Surface Radiation Network (BSRN). From the aggregate dataset for all sites and years, mean bias (estimate-observation) was determined to be about 0.9 W m^{-2} for the shortwave and 1.7 W m^{-2} for the longwave radiative components.

3. Definitions

The cloud radiative forcing is defined as the difference between surface radiative fluxes under all-sky and clear-sky conditions. Its shortwave (SW) component may therefore be defined as:

$$CF(S)_{SW} = F(S)_{SW} - F(S)_{SW}^{cl} \qquad (1)$$

and the longwave (LW) component as:

$$CF(S)_{lw} = F(S)_{lw} - F(S)_{lw}^{cl} \qquad (2)$$

where $F(S)_{SW}$ and $F(S)_{lw}$ are the SW and LW all-sky net radiative fluxes at the surface, and $F(S)_{SW}^{cl}$ and $F(S)_{lw}^{cl}$ are the corresponding surface clear-sky quantities. The total CF at the surface can be written as the sum of the SW and LW components:

$$CF(S) = CF(S)_{SW} + CF(S)_{lw} \qquad (3)$$

4. Results

A. Time-mean surface cloud forcing

Figure 1 shows the mean total cloud fraction for the ISCCP D2 data for the 10-year period July 1985 to June 1995. In general, the cloud fractions are greater over the

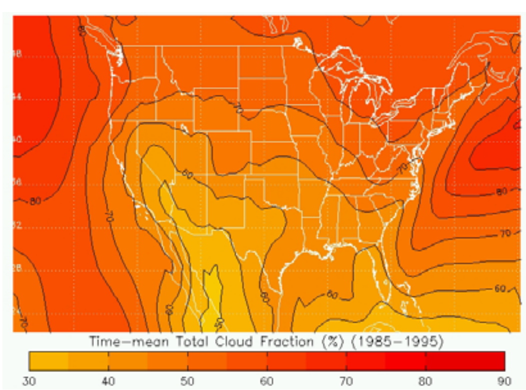

Figure 1. Time-mean cloud fraction contoured every 5%.

oceans than over the continent, with greatest values in the storm tracks off the East and West coasts. Over the land, there is a minimum in the cloud fraction over the arid region of the southwestern United States and a maximum of cloud fraction over the Northeastern US. In general, there is more cloudiness in the eastern and northern portions of the US than the southern and western portions.

Figure 2 shows the time mean SRB shortwave, longwave, and total surface cloud radiative forcing for the 10-year period July 1985 to June 1995. In all discussions of surface cloud forcing, the terms "greatest" and "smallest" refer to magnitude of the terms. From Figure 2a, the shortwave surface cloud forcing is negative everywhere, indicating that the effect of clouds in the shortwave is to cool the surface. The shortwave surface cloud forcing is greatest over the oceans, due to the lower surface albedo and higher cloud fraction in this region. Over the land, the values of the shortwave cloud forcing range from -25 W m^{-2} over the southwestern United States to -80 W m^{-2} over the northeastern United States.

The longwave surface cloud forcing (Fig. 2b) shows positive values everywhere, representing a warming effect of clouds on the surface in the longwave. The magnitude of the longwave surface cloud forcing is less than that of the shortwave forcing except over the southwestern United States where the magnitudes are comparable. The longwave forcing is greatest over the oceans in regions of persistent low stratus clouds off the west coast of the United States and in the storm tracks off the East Coast. Over the continent, the largest positive values of about +40 W m^{-2} are over the northern Great Plains, in a region of relatively large cloud fractions. Lower values of longwave surface cloud forcing exist over the southwestern United States, with values near +30 W m^{-2}.

The total surface cloud forcing (Fig. 2c), which is the sum of the shortwave and longwave surface cloud forcing, shows negative values almost everywhere over the US, indicating that the net effect of clouds is to cool the land surface. The largest negative values of near -40 W m^{-2} extend from the Gulf of Mexico northeastward to Maine, while a region of positive values of +10 W m^{-2} exists over the southern portion of California. In general, the cooling effect of the surface by clouds is greater east of the Mississippi River than west of the River.

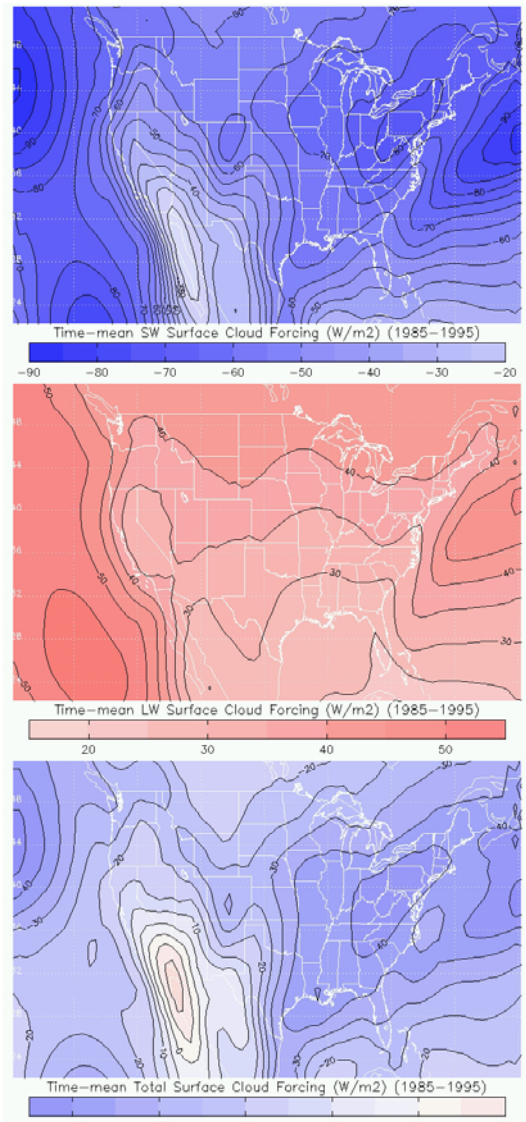

Figure 2. Time-mean surface a) shortwave, b) longwave, and c) total cloud forcing (W m^{-2}) for the 10-year period 1985 to 1995. Values are contoured every 5 W m^{-2}.

B. The variability of cloud forcing

Figure 3a shows the standard deviation of total surface cloud forcing for all months in the 10-year period. The variability of the total surface cloud radiative forcing ranges from 15 W m^{-2} over the extreme southwestern US to 45 W m^{-2} over the extreme northeastern US. This variability is due to contributions on the interannual, annual, seasonal, and monthly time scales.

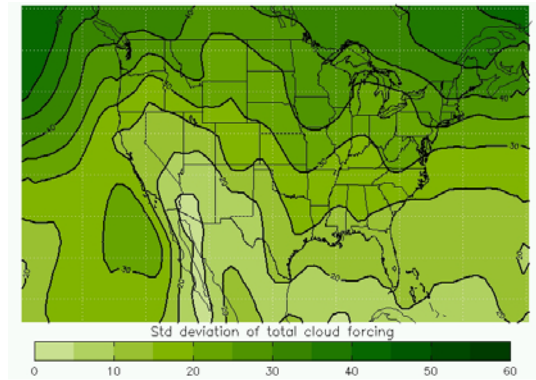

Figure 3a. Standard deviation of total surface cloud forcing. Every 5 W m^{-2} is contoured.

The contribution of the annual cycle to the variability of cloud forcing is illustrated using harmonic analysis. Figure 3b shows the first harmonic of total surface cloud forcing in NASA SRB data. Higher harmonics were calculated, but contained little amplitude, and so are not discussed. The tendency for the equatorward-directed vectors across the domain indicates that the surface cloud forcing has its largest negative values in June over almost the entire US. June is the time of largest insolation, so the contrast

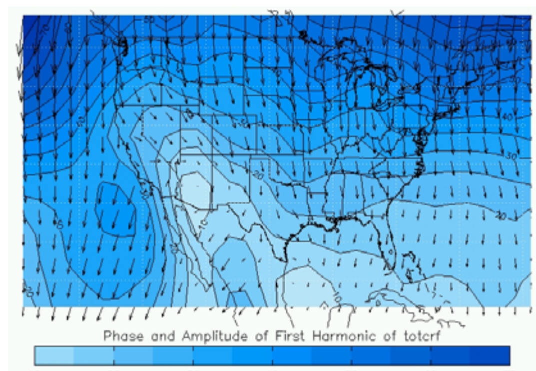

Figure 3b. Phase and amplitude of the first harmonic of total surface cloud radiative forcing based on monthly-mean data from the NASA SRB data set. Amplitudes are contoured every 5 W m^{-2}. The length of the arrow is scaled to the amplitude, and the orientation of arrow indicates the month during which the first harmonic has the largest negative value. An arrow with a 12 o'clock orientation indicates a January with largest negative value, and orientation rotates through the calendar months in a clockwise fashion.

between radiation reaching the surface under cloudy and clear conditions is greatest. This amplitude of the surface cloud forcing increases in a poleward direction, from about 10 W m^{-2} in the southern US to 60 W m^{-2} in the northeastern US, and this is a result of the larger annual variability in solar zenith angle in the northern latitudes. The patterns shown in the amplitude correspond well with those of the variance over all months shown in Figure 3a, indicating the annual cycle is responsible for a large portion of the total variance in the dataset.

Exceptions to the June maximum in negative cloud forcing occur over California, where there is a tendency for the largest negative cloud forcing to occur in the spring, and over western Mexico, where there is a tendency for the largest negative cloud forcing to occur in the late summer. These patterns are likely a reflection of more abundant cloudiness during the rainy seasons in these regions that occurs during a part of the year with relatively large solar insolation.

To show the month-to-month variability of total cloud forcing, Figure 4 displays the standard deviation of the monthly total cloud radiative forcing in the 10-year period where the annual cycle has been removed from the data prior to this calculation. This variability is 12-18 W m^{-2} across the U.S., with a swath of relatively higher variability from the Gulf Coast to the Northern Plains. The lowest variability is found over the southwestern U.S., in a region of minimum cloud fractions in the time-mean.

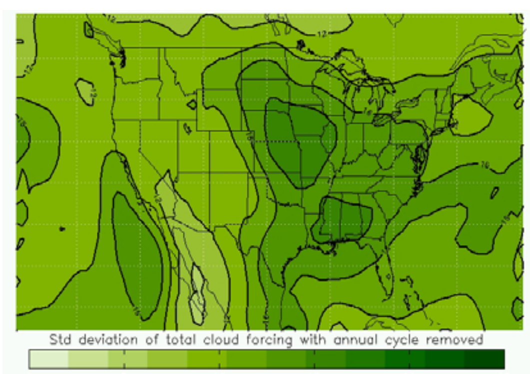

Figure 4. Standard deviation of total surface cloud forcing with the annual cycle removed. Values every 2 W m^{-2} are contoured.

In an attempt to explain the pattern of month-to-month variability shown in Figure 4, we correlated various cloud properties with the total cloud forcing. Table 1 shows the correlation between cloud properties and the total cloud radiative forcing for all US land-only points with the annual cycle removed. (The ISCCP landmask was used to determine land-only points). The highest correlation occurs with cloud water, where months with high cloud water lead to large negative values of surface cloud forcing over the U.S. Total cloud fraction has a slightly lower correlation with surface cloud forcing, where months with more abundant cloudiness result in months with large

Cloud Property	Correlation
Cloud Water	-0.62
Total Cloud Fraction	-0.54
Optical Depth	-0.50
Cloud Top Pressure	-0.37
Cloud Top Temp	-0.34

Table 1. Correlation of cloud properties with total surface cloud forcing for land points over US with the annual cycle removed.

negative surface cloud forcing. Optical thickness also shows a negative correlation with surface cloud forcing. Optically-thick clouds attenuate the downwelling solar radiation, and therefore months with optically-thicker clouds tend to have large negative values of surface cloud forcing. The cloud top pressure and cloud top temperature indicate that months that have clouds with lower tops (higher pressure and temperature) tend to have larger negative values of cloud forcing. This result reflects the tendency for low clouds to be optically-thicker than high clouds.

Figure 5a shows a spatial map of the correlation between cloud optical depth and surface cloud forcing with the annual cycle removed. Correlations are highest in a swath of values near -0.7 that extends from the southern US to the Great Lakes region across the US, in the region of high variability shown in Figure 3a. Since optical depth is strongly related to cloud water path, the map of correlation with cloud water is similar, and is not shown.

Figure 5b shows the correlation between total cloud fraction and total surface cloud forcing. In the southern portion of the US, correlations are near -0.6, although not quite as high as those with optical depth and cloud forcing. These correlations decrease to -0.3 as one moves poleward, indicating that over the Northern Great Plains, there is less of a relationship between total cloud fraction and surface cloud forcing than over the Gulf Coast.

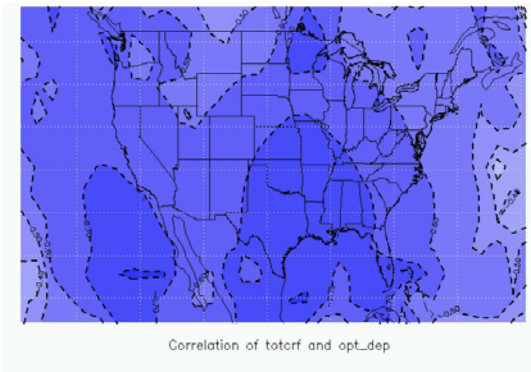

Figure 5a. Correlation of monthly cloud optical depth with total surface cloud forcing (annual cycle removed). Values every 0.10 are contoured, negative values are dashed.

Over the Gulf Coast and Southern Great Plains, cloud fraction and cloud optical thickness appear to be important to the total surface cloud forcing. Over the Northern Great Plains, however, cloud fraction plays less of a role, and the optically thickness of the clouds is more important than cloud fraction to the surface cloud forcing.

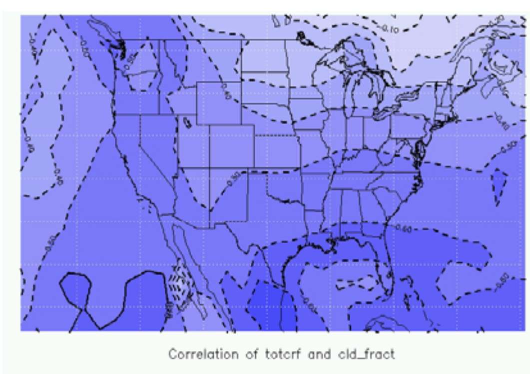

Figure 5b. Correlation of monthly total cloud fraction with total surface cloud forcing (annual cycle removed). Values every 0.10 are contoured, negative values are dashed.

5. Summary

This study used calculations of surface cloud radiative forcing contained in the NASA SRB dataset. The monthly cloud forcing data were accessed for the 10-year period 1985 to 1995. The shortwave component is negative everywhere over the US, and is larger in magnitude than the longwave component, which is everywhere positive. The time-mean total surface cloud forcing, which is the sum of the shortwave and longwave cloud forcing components, largely reflects the shortwave component, and ranges from +10 W m^{-2} in the southwestern US to -40 W m^{-2} over the northeastern US. The net effect of clouds in the time-mean is to cool the surface almost everywhere over the US.

The variability of the total cloud forcing varies from 15 W m^{-2} over the southwestern US to 45 W m^{-2} over the extreme northeastern US. The majority of this variability is due to the annual cycle of solar insolation, which results in large values of negative cloud forcing in June. Two exceptions to the June maximum in cloud forcing magnitude are western Mexico and California, where the surface cloud forcing has maximum negative values in August and April, respectively.

The month-to-month variability of total surface cloud forcing was investigated by removing the annual cycle form the monthly data. This variability is 12-18 W m^{-2} across the U.S., with a swath of relatively higher variability extending from the Gulf Coast to the Northern Plains. The lowest variability is found over the southwestern U.S. The monthly values of total surface cloud forcing were correlated with several cloud properties in an attempt to explain this pattern of variability. In the region of high variability extending from the Gulf Coast to the Northern Plains, cloud fraction and cloud optical thickness are important to the total surface radiative forcing in the Gulf region. As one moves poleward to the Northern Great Plains, cloud optical thickness more directly affects cloud forcing at the surface than does cloud fraction.

Acknowledgements

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