Analysis of the Temperature Dependence of Low Cloud Optical Thickness Using ARM Data and the GISS GCM

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One of the larger uncertainties in global climate model estimates of sensitivity to external perturbations is the projected climate change of cloud optical thickness. Conventional wisdom suggests that since an adiabatically lifted parcel condenses more water if its temperature is higher, its optical thickness should increase with warming. For low and middle-level clouds, whose albedo effect dominates their cloud forcing, such a change would represent a negative feedback. However, optical thickness depends on cloud physical thickness and droplet effective radius as well, and deviations of cloud liquid water from adiabatic behavior are possible.

Satellite optical thickness retrievals from the International Satellite Cloud Convergence Project (ISCCP) (Tselioudis and Rossow 1994) in fact show the expected temperature dependence of optical thickness for low clouds only at cold temperatures in the current climate; in warm climates, optical thickness actually decreases with temperature instead. Atmospheric Radiation Measurement (ARM) data from the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site can be used to understand this behavior and to determine the possible relevance of the current climate variability to the cloud optics feedback to be expected in a decadal-to-century scale anthropogenic climate change.

To perform the analysis, we use four data sources from the SGP Central Facility:

- The Microwave Radiometer (MWR) estimates cloud liquid water path (LWP).
- The Belfort Laser Ceilometer (BLC) measures cloud base height
- The Geostationary Operational Environmental Satellite (GOES) infrared satellite brightness temperatures identify scenes with only low clouds at the SGP Central Facility and estimate the cloud top temperature of these clouds (if their optical thickness is sufficient for the brightness temperature to be representative of the cloud top temperature)
- The Balloon Borne Sounding System (BBSS) translates cloud top temperature into cloud top height, defines a mean cloud temperature, and provides ancillary information such as relative humidity, wind, and pressure for characterizing the thermodynamic and synoptic conditions.

MWR data with LWP < .04 mm are excluded based on the accuracy of the instrument and retrieval algorithm; this restricts us to optical thicknesses greater than about 5. Comparisons of higher LWP amounts with Minnis' optical thickness retrievals from GOES show good consistency up to optical thicknesses of about 30, above which the GOES algorithm saturates.

From these basic parameters, we derive cloud physical thickness as the difference between cloud top and base heights, and liquid water content (LWC) from the ratio of LWP to cloud physical thickness. Unfortunately, at the present time, ARM does not produce a cloud droplet effective radius product. We study two time periods: A "cold month" ensemble including all data from December 1994, January 1995, February 1995, and March 1996, and a "warm month" ensemble including all data from June, July, August, and September of 1996. These months were chosen as representative of times of year when ISCCP shows (slightly) increasing vs. decreasing low cloud optical thickness with temperature over land at the SGP latitude. The particular months chosen were based on availability of data from all four instruments and adequate samples of isolated low clouds.

In the cold months, LWP correlates well with LWC, but does not monotonically increase with cloud physical thickness. In warm months, just the opposite is true: LWC is a poor predictor of LWP variations, especially for thicker clouds, but LWP is positively correlated with cloud physical thickness.

The seasonal difference in behavior applies to the temperature dependence of cloud properties as well. In the cold months, LWP shows no clear temperature dependence for T > 270 K (Figure 1a); it is systematically lower at colder temperatures, but these may be an artifact of the insensitivity of MWR to ice, i.e., LWP may be a small fraction of the total cloud water path at these temperatures. In the warm months, LWP clearly decreases with cloud temperature (Figure 1b). The seasonal difference in behavior is consistent with the ISCCP optical thickness inference for midlatitude land in general, suggesting that ARM data might provide relevant information about the causes of the ISCCP result.

We find that in both the winter and summer seasons, cloud physical thickness decreases with cloud temperature (and with surface temperature, which is unbiased by changes in cloud top and base altitude; Figure 2a). In the warm months, LWC decreases with increasing cloud temperature (Figure 2b), just the opposite of what one would expect if liquid water behaved adiabatically. In the cold months, LWC is fairly independent of temperature, also non-adiabatic in its behavior but not to the extent that is observed in summer. It is thus the combination of clouds physically thinning and liquid water being removed with warming that accounts for the ISCCP result.

These are statistical inferences only; a significant scatter is associated with instantaneous weather-related variability. This creates an interpretation problem—if the observed temperature dependence of LWP is simply dynamics-driven, it may not be relevant to the question of cloud optics feedback in a decadal climate change. As a first attempt to separate weather- and climate-related components of variability, we have removed the seasonal and diurnal cycles from each ensemble and calculated the instantaneous temperature deviation (T') to define whether the observation occurred in the warm or cold sector of a given synoptic pattern. We have then used the deviation from the lower troposphere mean meridional wind (v') and the associated T' to sort the data. The resulting crude synoptic classification has four categories:

- v'>0, T'>0: typical of flow in the warm sector south of synoptic low pressure
- v'>0, T'<0: associated with pre-warm frontal passage east of the low and wraparound flow north of the low

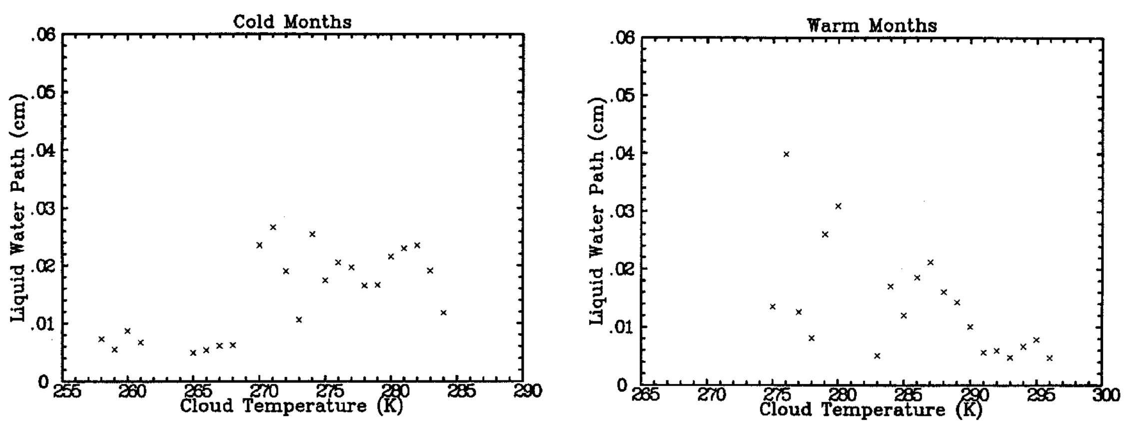

Figure 1. Temperature dependence of MWR low cloud LWP for (a) cold months, (b) warm months.

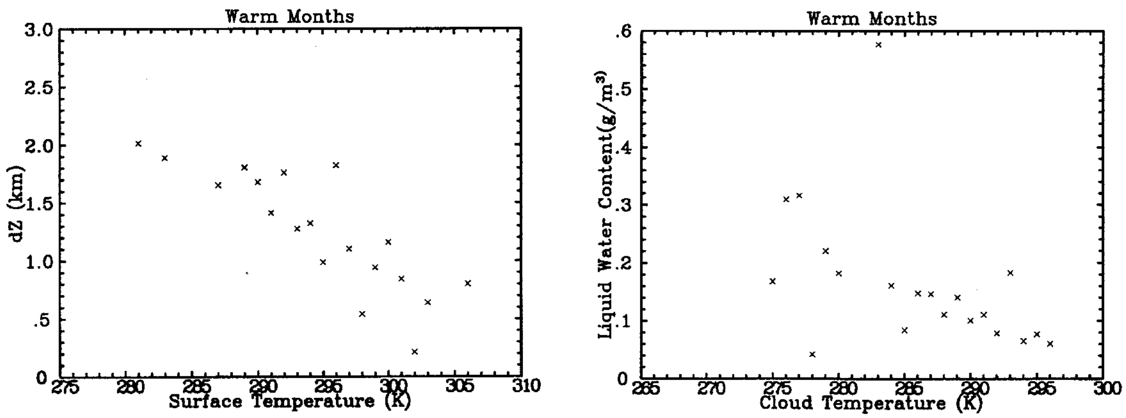

Figure 2. Warm month temperature dependence of low cloud (a) physical thickness, (b) LWC.

- v'<0, T'<0: northerly flow behind a surface cold front and west of the low
- v'<0, T'>0: most likely during the transition from high to low pressure.

These general synoptic impressions are confirmed by the synoptic composites of ISCCP cloud types compiled by Lau and Crane (1995).

Within a given synoptic category, differences between the cold month and warm month ensembles may be a good proxy for long-term climate change, since both the seasonal and decadal changes are characterized by rising temperature and decreasing meridional temperature gradient. Within a seasonal ensemble, dynamical effects can be isolated as cold vs. warm sector differences for a given flow direction. The results are presented in Table 1.

Table 1. Mean SGP low cloud parameters grouped by synoptic category for cold month/warm month ensembles.

Category	# Observations BBSS (MWR)	LWP (mm)	LWC (g/m^3)	dz (km)	ztop (km)	zbot (km)
v'>0, T'<0	6(101) / 14(267)	0.14/0.21	0.07/0.13	1.97/1.52	2.76/2.40	0.79/0.87
v'<0, T'<0	7(99) / 20(284)	0.15/0.14	0.10/0.14	1.89/1.30	2.84/2.44	0.95/1.14
v'>0, T'>0	17(315)/ 8(100)	0.21/0.12	0.15/0.11	1.59/1.28	2.32/2.59	0.73/1.31
v'<0, T'>0	9(144) / 9(149)	0.20/0.12	0.16/0.10	1.37/1.46	2.42/2.34	1.04/0.88
T'<0	13(200)/35(557)	0.15/0.17	0.09 0/.14	1.93/1.40	2.80/2.43	0.87/1.03
T'>0	26(459)/17(249)	0.21/0 12	0.15/0.11	1.52/1.39	2.35/2.44	0.83/1.05
All	39(659)/52(806)	0.19/ 0.15	0.13/0.13	1.65/1.39	2.49/2.43	0.84/1.04

Several conclusions can be drawn from this table:

- LWP decreases from winter to summer, primarily because of low clouds in the warm sector; pre-frontal/wraparound cold sector clouds exhibit the opposite behavior.
- Isolated low clouds occur preferentially in the warm sector in winter and in the cold sector in summer; this reduces the net effect of seasonal LWP differences.

- Cloud physical thickness decreases from winter to summer, more so in the cold sector; lowering cloud top and rising cloud base both contribute to the seasonal difference.

- LWC decreases/increases from winter to summer in the warm/cold sector; seasonal changes of LWC and thickness thus work together in the warm sector and against each other in the cold sector to explain the seasonal LWP changes.

This suggests that, barring unusual cloud droplet radius effects, we might expect a positive decadal low cloud optical thickness feedback in midlatitude land climate regimes, but of magnitude somewhat smaller than the current climate temperature sensitivity. The feedback is due to low cloud sensitivity in the warm sector of baroclinic wave systems. The decrease of LWC with warming does not appear to be due to precipitation; evaporation due to increasing turbulent entrainment of drier air with warming appears to be a better candidate, based on the observed thermodynamic stability of the cloud-top interface.

The Goddard Institute for Space Studies (GISS) general circulation model (GCM) (Del Genio et al. 1996) qualitatively reproduces the ISCCP observation of increasing cloud optical thickness with temperature at high latitudes and decreasing at low latitudes, although the GCM overestimates the magnitude of this dependence over tropical and subtropical oceans. In equilibrium doubled CO_2 simulations, the GCM's feedback is consistent with its current climate temperature dependence, but with smaller magnitude. In the GCM, much of the tendency for optical thickness to decrease with temperature at low latitudes is due to cloud physical thickness changes. The GCM allows for vertically subgrid-scale cloud physical thickness, based on stability. Reductions in both the mean number of layers occupied by low cloud and the thickness of cloud within a given layer contribute to this tendency at most latitudes, although layer 1 clouds get thicker with warming near the equator. In layer 1, where the majority of low clouds occur, LWC generally decreases with temperature at low latitudes as well. LWC in the GCM is strongly negatively correlated with parameterized entrainment and weakly correlated with precipitation in the tropics, but to a certain extent, this behavior is built into the prognostic cloud water parameterizations.

References

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