5C/1111

FINAL REPORT

Principal Investigator: Yuk L. Yung
CALIFORNIA INSTITUTION OF TECHNOLOGY
Division of Geological and Planetary Sciences, MC 150-21
Pasadena, CA 91125
Phone: (626) 395-6940
Fax: (626) 585-1917
Email: yly@gps.caltech.edu

Title:	Variability of Clouds Over a Solar Cycle
Grant Number:	NAG5-7680
Period of Performance:	**10/01/98 – 12/31/01**

A. OBJECTIVES

One of the most controversial aspects of climate studies is *the debate over the natural and anthropogenic causes of climate change* (IPCC, 1990, 1996). Historical data strongly suggest that the Little Ice Age (from 1550 to 1850 AD when the mean temperature was colder by about 1 °C) was most likely caused by variability of the sun and not greenhouse molecules (*e.g.* CO_2). However, the known variability in solar irradiance and modulation of cosmic rays provides too little energy, by many orders of magnitude, to lead to climate changes in the troposphere. The conjecture is that there is a *"trigger mechanism"*. This idea may now be subjected to a quantitative test using recent global datasets.

Using the best available modern cloud data from International Satellite Cloud Climatology Project (ISCCP), Svensmark and Friis-Christensen (1997) found a correlation of a large variation (3-4%) in global cloud cover with the solar cycle. The work has been extended by Svensmark (1998) and Marsh and Svensmark (2000). The implied forcing on climate is an order of magnitude greater than any previous claims. Are clouds the long sought "trigger mechanism"? This discovery is potentially so important that it should be corroborated by an independent database, and, furthermore, it must be shown that alternative explanations (*i.e.* El Niño) can be ruled out. We used the ISCCP data in conjunction with the Total Ozone Mapping Spectrometer (TOMS) data to carry out an in depth study of the cloud trigger mechanism.

B. EVIDENCE FOR AMPLIFICATION OF SOLAR FORCING BY CLOUDS

The most likely trigger for climate change is the cloud component of the hydrological cycle. We shall briefly discuss the remarkable properties of nonlinear behavior of water vapor (with respect to temperature) and the condensation of water vapor to form clouds. From a planetary perspective, we can understand why water feedback is so sensitive and hence so difficult to study from first principles. Although water vapor is a minor constituent of the atmosphere (on the order of 1% or less by volume), it plays a fundamental role in the climate of the Earth (see *e.g.*

Goody and Yung, 1989). The bulk of atmospheric H_2O is in the form of water vapor and it is the most important greenhouse molecule in the atmosphere. However, a small amount of H_2O (of the order of 1%) in the atmosphere can form clouds that play a major role in regulating the planetary albedo, and hence the amount of solar energy absorbed by the atmosphere and the surface. In other words, this 1% of H_2O in condensed form has about the same leverage on the atmospheric radiation budget as the 99% of H_2O in gaseous form. Indeed it is the release of latent heat (during cloud formation) that drives the atmospheric wind system, exchanges energy and momentum between the tropics and the poles of the Earth and accounts for nearly all weather and climate change. To further complicate matters, clouds can block outgoing longwave radiation, thus contributing to the greenhouse effect. According to a recent estimate (Hartmann, 1994, Table 3.3) the globally and annually averaged cloud radiative forcing is a cooling of 48 W/m^2 (due to increase of planetary albedo) and a warming of 31 W/m^2 (due to greenhouse effect), resulting in a net cooling of 17 W/m^2. Given the primitive state of our knowledge of clouds, these values will no doubt be refined, but the magnitudes of these numbers can best be appreciated if we compare them with the radiative forcing due to anthropogenic pollutants in the past and next century. Current estimates of the radiative forcing due to the increase of CO_2 since the last century is 2.5 W/m^2. The aerosol cooling in the same period is estimated to be about -2 W/m^2 in the Northern Hemisphere (the aerosol effect is smaller in the Southern Hemisphere) (Charlson et al. 1992). The radiative forcing due to CO_2 doubling in the next century is 5 W/m^2. Thus even a small secular variation (*e.g.* 10%) in the clouds has the potential of invalidating model simulations of these anthropogenic effects.

Sunspot-climate correlations were first suggested by the renowned astronomer Sir William Herschel nearly two centuries ago (Herschel, 1801). In the last two decades there have been increasing numbers of reports on the possible correlation between solar variations and climate (see reviews by Wilcox, 1975; Tinsley and Deen, 1991; Tinsley, 1997). However, the physical mechanisms behind these correlations are still under debate. On a day-to-day timescale, energetic particle changes instead of solar photon changes were reported to be well correlated to the meteorological parameters (for a recent review, see Tinsley and Deen, 1991). Ionization due to galactic cosmic rays, known to be strongly modulated by the solar cycle, was suggested to cause climate change (Ney, 1959; Dickinson, 1975). As discussed earlier, the irradiance and other energy flux changes over a solar cycle are very small (less than 0.3 W/m^2) while the energy needed to cause the reported climate change is much larger. Trigger mechanisms are required for any solar related modulation to have significant effects on climate. Several trigger mechanisms were proposed (*e.g.* Dickinson, 1975; Markson and Muir, 1980; Moses et al,. 1989; Lethbridge, 1990). Few of these ideas have been subjected to observational tests using global climatological datasets.

The "canonical" cloud dataset in climatology is that provided by the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer, 1991). The basic measurements consist of satellite images of radiation reflected from, or emitted by the Earth at frequencies 500-4000nm and in the thermal infrared (up to 12 μm). These measurements establish the existence of cloud cover and provide information on cloud optical thickness and cloud heights. What distinguishes this dataset is its high spatial resolution (1-10km) and time resolution (0.5-12hr). The archived data from July 1983 to September 1994 are currently available.

Using the ISCCP data from 1983 to 1990, Svensmark and Friis-Christensen (1997), in a remarkable paper, reported a large variation in global cloudiness that was found to be strongly correlated with the solar cycle. That is, the mean cloud cover of the Earth as reported by ISCCP was 3-4% higher during the solar minimum (around 1987), when the solar magnetic field contracts and offers the least shielding of the inner solar system from galactic cosmic rays. The authors argued that the enhanced cosmic rays produce more ions, which in turn cause more nucleation, resulting in an increase of cloudiness. The work has been augmented by data from 1983 to 1994 by Svensmark (1998) and Marsh and Svensmark (2000).

Is this the evidence of the long sought trigger of climate change? If confirmed, this finding would provide strong support for galactic cosmic rays as the missing link between solar variability and climate (Tinsley, 1997).

C. SUMMARY OF MAJOR RESULTS

Based on a detailed analysis of the cloud data obtained by the International Satellite Cloud Climatology Project (ISCCP) in the years 1984-1990, we conclude that cloud variation during a solar cycle is not simply a 3% variation in cloudiness as reported by Svensmark and Friis-Christensen (1997). In fact, this variation consists of two distinct components for optically thin and optically thick clouds. The solar cycle variation of thin cloud amount is 6% and is in phase with the cosmic rays flux while variation of thick cloud amount is 3% and has the opposite phase as the cosmic rays flux. The total cloud variation is about 3%, in agreement with previous study. We argue that galactic cosmic rays increase the cloud amount by producing ions that enhance cloud nucleation when there are no clouds, or when the clouds are thin. However, in thick clouds, enhanced cosmic ray flux could accelerate the coalescence growth of water droplets, thus inducing precipitation and reducing the total cloud amount.

Anthropogenic sulfate aerosols may impose radiative perturbations on climate by indirectly modifying the cloud formation process and droplet size (Twomey 1974, Charlson et al. 1987). Using ultraviolet reflectivity measurements from the Total Ozone Mapping Spectrometer (TOMS), we report anomalous reflectivity of clouds off the Peru Coast that may be interpreted as evidence for the indirect aerosol effect. The reflectance of two marine sites off the Peru Coast over the months when stratocumulus clouds are prominent is consistently higher than that of the surroundings. The regions of reflectivity enhancement coincide with large anthropogenic SO_2 emission sources associated with copper smelting at or near the cities of Lima and Ilo in Peru. The magnitude of the enhancement has a strong seasonal dependence that is related to the seasonal cloud movement. A rough estimate indicates that the radiative forcing could be as high as 35 W/m^2 in August, a value that is much higher than current model estimates.

By means of Empirical Orthorgonal Functions (EOFs), we identify patterns in the interannual albedo variations of the Northern Hemisphere (NH). We use the ultraviolet reflectivity measured by the Total Ozone Mapping Spectrometer (TOMS) as a proxy to the broad-band visible albedo. We find that the leading variation patterns, or EOFs, of the albedo field are clearly related to major NH circulation patterns such as the North Atlantic Oscillation and the Pacific-North

American patterns. The potential feedback between albedo variations and the circulation patterns requires further modeling studies.

D. PUBLICATIONS SUPPORTED BY THIS GRANT

Z. Kuang, Y. Jiang, and Y. L. Yung, "Cloud Optical Thickness Variations During 1983-1991: Solar Cycle or ENSO?" *Geophys. Res. Lett.*, **25**, 1998, pp. 1415-1417.

Z. M. Kuang and Y. L. Yung, "Observed Albedo Decrease Related to the Spring Snow Retreat", *Geophys. Res. Lett.*, **27**, 2000, pp. 1299-1302.

Z. M. Kuang and Y. L. Yung, "Albedo Variations Off the Peru Coast: Evidence for Indirect Aerosol Effect on Clouds", *Geophys. Res. Lett.* **27**, 2000, pp. 2501-2504.

Z. M. Kuang and Y. L Yung, "Observed Albedo Feedback of the Shrinking Arctic Sea Ice", submitted to *Geophys. Res. Lett.*, 2000.

E. AGU PRESENTATIONS

Z. Kuang, Y. Jiang, and Y. L. Yung, "Cloud Optical Thickness Variations During 1983-1991", Supplement to EOS Transactions, AGU, 79, F153, 1998.

Kuang, Z., and Yung, Y. L., "Interannual Albedo Variations Related to the Northern Hemisphere Circulation Patterns", EOS Transactions, American Geophysical Union, Vol. 81, No. 48, A51D-04, p. F41, December 15-19, 2000.

Yung, Y. L., and Kuang, Z., "Anomalous Reflectivity Off the Peru Coast: Indirect Aerosol Effect on Clouds?" EOS Transactions, American Geophysical Union, Vol. 81, No. 48, A51A-06, p. F37, December 15-19, 2000.