FINAL REPORT

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Title: A Mechanism For Solar Forcing of Climate: Did the Maunder Minimum Cause the Little Ice Age?

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The mechanism we wish to demonstrate exploits chemical, radiative, and dynamical sensitivities in the stratosphere to affect the climate of the troposphere. The sun, while its variability in total radiative output over the course of the solar cycle is on the order of 0.1%, exhibits variability in the UV output on the order of 5%. We expect to show that a substantially decreased solar UV output lessened the heating of the Earth's stratosphere during the Maunder Minimum, through decreased radiative absorption by ozone and oxygen. These changes in stratospheric heating would lead to major changes in the stratospheric zonal wind pattern which would in turn affect the propagation characteristics of planetary-scale waves launched in the winter hemisphere.

Until recently, there was no quantitative data to relate the changes in the stratosphere to those at the surface. There is now empirical evidence from the NCEP Reanalysis data that a definitive effect of the solar cycle on climate in the troposphere exists. Our recent work is summarized as follows (see complete list of publications in later part of this report).

Camp, Roulston and Yung (2003) studied the temporal and spatial patterns of the interannual variability of total ozone in the tropics using a recently constructed dataset combining the monthly mean column abundances collected by the TOMS and the Solar Backscatter Ultraviolet (SBUV and SBUV/2) instruments. This dataset provides a nearly continuous record from late 1978 to the present on a 5°×10° latitude-longitude grid. The precision and calibration of these measurements allow very small signals, ~1% of total column ozone, to be clearly seen. Using merged ozone data (MOD), we have carried out an empirical orthogonal function (EOF) study of the temporal and spatial patterns of the interannual variability of total column ozone in the tropics. The first four EOFs of our study capture over 95% of the variance of the deseasonalized data. The leading two EOFs, respectively accounting for 45% and 34% of the variance, display structures attributable to the quasi-biennial oscillation (QBO) and the solar cycle. The peak in the power spectrum of the 1st principal component (PC) occurs at 28 months. The power of the 2nd PC is dominated by a contribution from the 11 yr solar cycle. The peak in the power spectrum occurs at 11 yrs. The phase of the PC also matches that of the sun well, with the sun leading by about 0.5-1 yr. The solar minimum to solar maximum variation in the ozone is about 20 Dobson units (DU), or about 8% of the mean column ozone in the tropics (see Figure 3a). This is the first complete analysis of tropical ozone data using simultaneously the longitudinal, latitudinal and temporal patterns. Camp, Roulston and Yung (2003) also discovered a robust 11 yr solar cycle signal in the geopotential heights in the stratosphere in the NCEP Reanalysis data. The results are consistent with the analysis by Coughlin and Tung (2003), who extended the work to higher latitudes. This is definitive evidence for a manifestation of the solar cycle in the modulation of the thermal structure of the atmosphere.

A clear relationship between solar cycle variations and the NAM has been found for the current epoch covering 41 years of the NCEP Reanalysis data (Ruzmaikin and Feynman, 2002; see Figure 3 of this paper). In particular, the mean index of NAM was found to be systematically more negative (corresponding to a weaker polar jet) throughout both the stratosphere and the troposphere during low solar UV irradiance characteristic of solar minimum than during solar maxima. Based on this result Ruzmaikin *et al.* 2003 infer the temperature patterns due to the lowered NAM during the Maunder Minimum from the contemporary temperature distributions during the periods dominated by the lowest NAM index. The temperature patterns are compared with those empirically reconstructed by Mann *et al.* (1998). We find the expected cooling in Northern Europe and Siberia, and also a strong warming at the Labrador Sea. This pattern is in remarkable agreement with the pattern of correlations between sensitivity of empirically derived surface temperatures to solar irradiance variations (Waple, *et al.* 2002), thus providing the link between the Little Ice Age and the Maunder Minimum.

Papers Supported by this grant

Ruzmaikin, A., J. Feynman, Solar Influence on a major mode of atmospheric variability, *Journal of Geophysical Research-Atmospheres*, *107*, NO D14, 101029/2001JD001239, 2002.

Ruzmaikin, A., J. Lawrence, and C. Cadavid, Simple model of stratospheric dynamics, including solar variability, *Journal of Climate, 16*, 1593-1600, 2003. (partial support)

Camp, C. D., M. S. Roulston, and Y. L. Yung. (2003). "Temporal and Spatial Patterns of the Interannual Variability of Total Ozone in the Tropics." *J. Geophys. Res.*(108 (D20)): 464.

Ruzmaikin A, J. K. Lawrence and A. C. Cadavid, A simple model of solar variability influence on climate. *Adv Space Res. 34*, 349-354, 2004 (partial support).

Ruzmaikin A, J. K. Lawrence and A. C. Cadavid, A simple model of solar variability influence on climate. *Adv Space Res. 34*, 349-354, 2004 (partial support).

Ruzmaikin A, J. Feynman, X. Jiang, et al., The pattern of northern hemisphere surface air temperature during prolonged periods of low solar output. *Geophys. Res. Lett. 31* (12): Art. No. L12201 2004.

Conference Presentations Supported by this grant

Farrara, J., X. Jiang, S.S. Leroy, J. Feynman, A. Ruzmaikin, and Y. Yung, Effects of a Reduced Ozone Layer on the Lower Stratosphere and the Troposphere, AGU Fall Meeting, A11C-06, San Francisco, CA, 2001.

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Ruzmaikin, A., J. Feynman, J. Lawrence, and C. Cadavid, Influence of solar variability on stratospheric dynamics, 12th Conference on Middle Atmosphere, San Antonio, Texas, Nov., 2002. (partial support)

Ruzmaikin, A., Solar-stratosphere-troposphere interaction as a mechanism of solar influence on climate, EGS-AGU–EUG Joint Assembly. CL2.08 Climate variability as problem of solar-terrestrial physics: detection of connection in the Sun-Earth system, modeling the underlying processes and predictions, Invited Talk, Nice, France, April 2003. (partial support)

Feynman. J., A. Ruzmaikin, X. Jiang, D. Noone and Y. Yung, Solar Influence on Surface Air Temperature During the Maunder Minimum, Physical Processes Linking Solar Radiation and Solar Variability with Global Climate Change, 2003 SORCE Science Meeting, Sonoma CA., December 2003.

Ruzmaikin, A., J. Lawrence, and A. C. Cadavid, An Exploratory Model of Solar Influence on Stratospheric Dynamics, Physical Processes Linking Solar Radiation and Solar Variability with Global Climate Change, 2003 SORCE Science Meeting, Sonoma CA., December 2003. (partial support)

Camp, C. D., J. Feynman, X. Jiang, R.-L. Shia, C. Walker, T. Schneider, M. A. Allen and Y. L. Yung, Solar cycle variation in the ozone distribution simulated by a two-dimensional chemistry transport model, AGU Fall Meeting, SH52B-06, San Francisco, CA, 2003.

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Camp, C. D.: Temporal and Spatial Patterns of the Interannual Variability of Stratospheric Ozone and Dynamics. 2004, California Institute of Technology

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