GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L21802, doi:10.1029/2006GL027820, 2006

Different response of clouds to solar input

Mirela Voiculescu,[1,2] Ilya G. Usoskin,[3] and Kalevi Mursula[4]

Received 9 August 2006; revised 12 September 2006; accepted 27 September 2006; published 1 November 2006.

[1] There is evidence that solar activity variations can affect the cloud cover at Earth. However, it is still unclear which solar driver plays the most important role in the cloud formation. Here we use partial correlations to distinguish between the effects of two solar drivers (cosmic rays and the UV irradiance) and the mutual relations between clouds at different altitudes. We find that the solar influence on cloud cover is not uniquely defined by one solar driver, but both seem to play a role depending on the climatic conditions and altitude. In particular, low clouds are mostly affected by UV irradiance over oceans and dry continental areas and by cosmic rays over some mid-high latitude oceanic areas and moist lands with high aerosol concentration. High clouds respond more strongly to cosmic ray variations, especially over oceans and moist continental areas. These results provide observational constraints on related climate models.

Citation: Voiculescu, M., I. G. Usoskin, and K. Mursula (2006), Different response of clouds to solar input, *Geophys. Res. Lett.*, *33*, L21802, doi:10.1029/2006GL027820.

1. Introduction

[2] The behaviour of clouds has important consequences for climate variations. The amount of clouds varies over the solar cycle, indicating that there is a connection between clouds and solar activity. Several mechanisms have been suggested as possible causes. One mechanism is the relationship between cosmic rays (CR) and low clouds (LC), first suggested by *Ney* [1959] and lately studied in a great detail by several groups [e.g., *Marsh and Svensmark*, 2000; *Pallé et al.*, 2004; *Usoskin et al.*, 2004b]. On the other hand, some other studies [*Kristjansson et al.*, 2004] suggest that LC correlate better with the total solar irradiance (TSI) than with CR. It has also been claimed that the correlation of LC with CR may be an artifact of low clouds obscuration by higher clouds in the satellite view [*Pallé*, 2005].

[3] Both solar irradiance and cosmic rays may affect the cloud cover via different mechanisms which are, however, poorly known. Admitting that there is a connection between clouds and solar activity, the correlation studies can hardly distinguish between CR and TSI mechanisms because of the strong interrelation between different solar indices. Physical mechanisms by which clouds, at all levels, could be affected by CR are described by *Tinsley* [1996] and *Yu* [2002]. *Yu* [2002] concluded that the low cloud amount (LCA) should vary in phase with the CR flux, the high cloud amount (HCA) should be in anti-phase with the CR flux, while variation of middle cloud amount (MCA) should not be related to CR at all. Possible mechanisms connecting the solar irradiance with clouds are described by *Kristjansson et al.* [2004] and rely on the effects of the sea surface temperature and/or tropospheric circulation variations induced by stratospheric response to UV [*Haigh*, 1996, 2002].

[4] Most of cloud studies use the satellite-based cloud data collected in the ISCCP database [*Rossow et al.*, 1996], which classifies the clouds into three types, depending on the cloud top pressure P: low (L) for $P > 680$ mb, middle (M) if $440 < P < 680$ mb and high (H) when $P < 440$ mb. However, concern has been raised about the purity of cloud definition in this database. On one hand, the low clouds may be obscured by middle and high clouds in the satellite view, since multi-layer clouds are identified in ISCCP by their tops [see, e.g., *Warren et al.*, 1985; *Liao et al.*, 1995; *Norris*, 2005; *Pallé*, 2005; *Rossow et al.*, 2005]. On the other, thick low clouds may affect the determination of higher clouds especially over water [*Hahn et al.*, 2001; *Rossow et al.*, 2005].

[5] In this Letter we have investigated if possible effects of two different solar related drivers, CR and UV, on clouds at three altitude levels can be distinguished between each other, and thus identify the most probable mechanism relating clouds to solar activity. We also aim to identify areas where the observed correlations between clouds at different levels and the two solar drivers are real and where they might be spuriously induced.

2. Data, Methods and Nomenclature

[6] The usual bivariate (Pearson's linear) correlation, e.g. R_{XY}, accounts for all possible links between the X- and Y-variables, including also indirect relations via other, mutually correlated, variables denoted here by Z. The partial correlation reflects the direct "real" link between X and Y if the intervening Z-variable is constant. The degree of the $Z-$variable intervention is given by the difference between the partial and bivariate correlations, $D_{X(Z)Y} = P_{X(Z)Y} - R_{XY}$. When R_{XY} and $D_{X(Z)Y}$ have opposite signs, i.e. their product $R \cdot D < 0$, the Z-variable partly intervenes in the X-vs-Y relation. If $R \cdot D \geq 0$, the correlation between X and Y is real, i.e. either not affected or even suppressed by the Z-variable. Thus, studying direct and partial correlations, one can determine the nature and level of spurious correlation between two variables in the presence of the third related variable.

[7] We make use of the annual cloud amount (percentage of the area covered by clouds of a given type) for the period 1984–2004 given by the ISCCP-D2 IR data set (http://isccp.giss.nasa.gov), in a geographical grid of 5 × 5 degrees. As a CR related quantity, we use the cosmic ray

---

[1] Department of Physics, "Dunarea de Jos" University of Galati, Galati, Romania.

[2] Also at Department of Physical Science, University of Oulu, Oulu, Finland.

[3] Sodankylä Geophysical Observatory, (Oulu Unit), Oulu, Finland.

[4] Department of Physical Science, University of Oulu, Oulu, Finland.

0094-8276/06/2006GL027820$05.00

induced ionisation (CRII) in the troposphere, computed by the model described by *Usoskin et al.* [2004a] and *Usoskin and Kovaltsov* [2006] for three layers of barometric pressure of 700, 500 and 300 mb, respectively, corresponding to L-, M- and H- clouds. The global UV irradiance (UVI) was computed using the MgII core-to-wing index given by the NOAA Space Environment Center (http://www.sec.noaa.gov/Data).

[8] We have first calculated the bivariate correlations, *R*, between each type of cloud amount - low (LCA), middle (MCA) and high (HCA) - and the UVI, as well as the CRII, for each geographical grid cell. Next we have computed the partial correlations, *P*, between each type of cloud cover and UVI (CRII) fixing the other solar index CRII (UVI) and, finally, the corresponding differences, *D*, between partial and direct correlations. If clouds appear to be related to both CRII and UVI in some areas, we considered the relation having the highest partial correlation coefficient. As a result, the prevailing factor, CRII or UVI, responsible for the solar cycle modulation of the cloud cover was identified in each grid cell, and global maps of the correlation between the cloud cover and each solar proxy have been plotted for each type of cloud (see Figure 1). We have included in subsequent analysis only those cells where the absolute value of the correlation coefficient is higher than 0.37, which corresponds to a confidence level of 0.9 for the standard formula with 19 degrees of freedom or 0.85 for the non-parametric random phase test [*Ebisuzaki*, 1997] (see details given by *Usoskin et al.* [2006]).

[9] Next, we have calculated the partial correlations and the corresponding differences between each cloud type and CRII or UVI, keeping now the other two types of clouds constant (e.g. $P_{LCA(HCA)CRII}$, $D_{LCA(HCA)CRII}$, $P_{LCA(HCA)UVI}$, $D_{LCA(HCA)UVI}$, etc.). In this way we have identified the areas with real and spuriously induced cloud-solar driver correlations. All these results are presented in a concise and comprehensive way in the global maps in Figures 1a–1c, where each grid cell is represented by either blank (no significant correlation) or hatched square (see Figure 1 caption for definitions). Only cells with differences larger than 0.2 are shown.

3. Results

3.1. LCA Correlations

[10] The LCA correlation map (Figure 1a) is dominated by its anticorrelation with UVI, (pattern #2), while the positive correlation between LCA and CRII (pattern #5) is restricted to smaller but well-defined areas. This suggests that the correlation between the LCA and solar activity is not uniquely defined by its relation to CRII [*Marsh and Svensmark*, 2000] or to solar irradiance [*Kristjansson et al.*, 2004], but each of the two drivers seems to dominate in certain geographical locations.

[11] The solar effect upon LCA is due to CRII over relatively small areas over the Atlantic at mid latitudes in both hemispheres, in small patches over the Pacific, and over some continental areas, i.e. Europe and Middle East, the central South America, partly over the northern and eastern Asia and along the eastern coast of North America. The intervening effect of higher clouds on the LCA correlations (patterns #3 and 4) is important especially over the mid-latitude Atlantic ocean, with some spots of spurious correlation over the coastal America. The whole Europe, Mediterranean region and parts of Asia remain areas of real LCA-CR correlation.

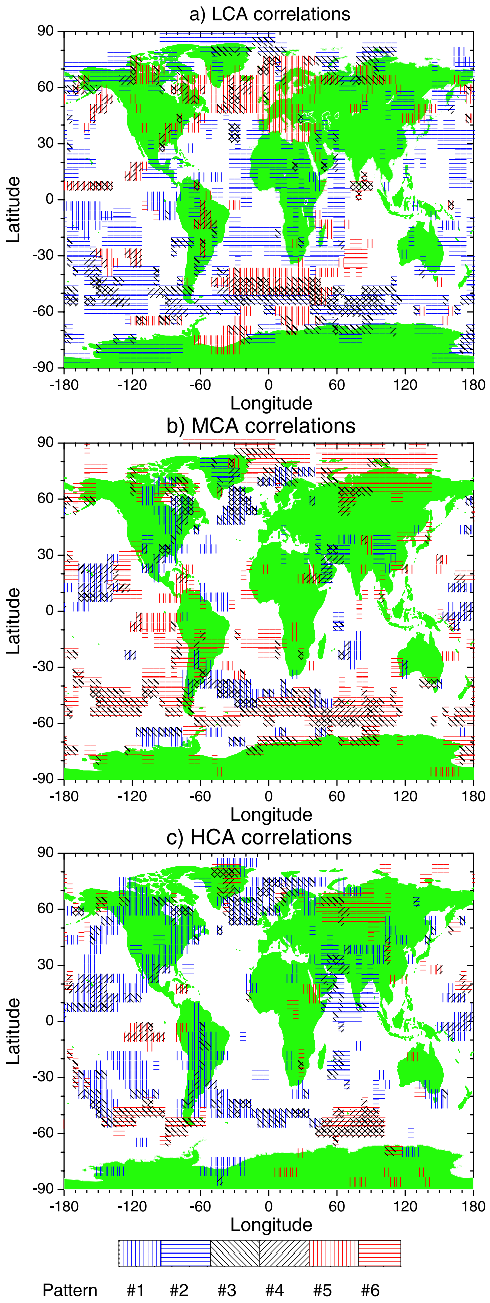

Figure 1. Geographical distribution of the studied relations between the cloud cover, for (a) low, (b) middle and (c) high clouds, and UVI or CRII. The patterns 1,2,5,6 are common for each plot, i.e. horizontal lines stand for the correlation of the studied clouds with UVI, vertical lines for correlation with CRII, red is positive, blue is negative. Patterns 3 and 4 show the areas where the correlation is spuriously induced by other clouds and are denoted as follows: Figure 1a, 3-middle clouds, 4-high clouds; Figure 1b, 3-low clouds, 4-high clouds; Figure 1c, 3-low clouds, 4-middle clouds. Colors in the on-line version and PDF.

[12] There are also small areas where LCA is anticorrelated with the CR – detached oceanic areas at the equator, east of the Caribbean, west of Peru and further west over the central Pacific. There is also an indication that they continue over Indonesia but, due to the limitations imposed on the correlation coefficient, this is not clear.

[13] The oceanic areas where the clouds are anticorrelated with UVI (pattern #2) include the Arctic, the central and west Pacific, except the narrow equatorial belt previously described, the equatorial and tropical Atlantic, western Indian Ocean and at high latitudes in the southern hemisphere. Negative LCA-UVI correlation exists also over the continental areas of Africa, Central America and the eastern coast of Southern America and Asia. We note that the correlation between LCA and UVI is real over all the above mentioned continental areas but it is partly affected by higher clouds over some oceanic areas, especially in the southern hemisphere at high latitudes. Nonetheless, most of the LCA-UVI relation over oceanic regions in the tropics can be considered real also.

[14] Therefore, we conclude that LCA is affected mainly by UVI over almost all oceanic areas except of the Atlantic. This is in line with the mechanism connecting the solar irradiance variations with low clouds proposed by *Kristjansson et al.* [2004]. The continental areas where LCA is anticorrelated with UVI are either dry, with a limited water vapour supply, or under the influence of neighboring oceans, where the same LCA-UVI relationship dominates.

[15] The CRII affects the cloud cover in the northern continental areas whose climate is moist or wet and over the high latitude ocean. The LCA-CRII correlation mechanism relies on the increased production of cloud condensation nuclei for a higher ionisation [*Marsh and Svensmark*, 2000; *Yu*, 2002] and this process also depends on the concentration of aerosols. In particular, the strong CRII influence above Europe and North America might be due to the fact that these are important industrial areas, where the aerosol concentration is high.

3.2. MCA Correlations

[16] The direct negative correlation between MCA and CRII (see Figure 1b) exists in some limited areas, including parts of the western tropical and equatorial Atlantic and around 40–60° in both hemispheres, the central Pacific between 0° and 30°N, central Indian Ocean and the eastern part of the North America, except for the Hudson bay. However, this relation is real only in the Indian Ocean and the inland North American continental areas and spuriously induced by other clouds in all other regions. The MCA-CRII relation becomes positive (pattern #5) over the ocean surrounding the central America and west off Peru, where a reversal of the LCA-CRII relationship was also observed. Like for LCA, this relationship is real.

[17] The correlation between MCA and UVI is generally positive and covers larger areas, but it is less evident than the same relationship for low clouds. The MCA co-varies with the UVI over the southern mid latitudes and in the eastern Pacific, between 30°N and 60°S, except for a region near the equator, over the Arctic Ocean, eastern equatorial and tropical southern Atlantic and the mid-high latitudes of the southern hemisphere (Atlantic and Indian Ocean). There are also continental areas where MCA is positively correlated with UVI, generally bordering with similarly behaving oceanic areas, namely the southern half of South America, the far North America around the Hudson bay, Canadian lakes and western Alaska, Siberia and the eastern Asian coast at equatorial to mid-latitudes.

[18] This correlation is unbiased over continental areas and is spuriously induced by LCA over oceans only at southern high latitudes, while HCA have almost no influence. Most of the continental areas remain free of any MCA correlation, except for the tropical Asia, where the correlation with UVI is negative but spurious. However, this is also a problematic area in ISCCP observations, where the boundary between the footprints of two geostationary satellites used in the ISCCP retrievals may induce some biases [*Rossow and Garder*, 1993; *Marsh and Svensmark*, 2003; *Kristjansson et al.*, 2004].

[19] In conclusion, the anticorrelation of MCA with CRII is mostly induced by other clouds, but the MCA-UVI correlation is less affected by other clouds and shows a distinctive pattern: it appears over cold oceanic waters and over some continental areas prone to those oceanic influences.

3.3. HCA Correlations

[20] Figure 1c shows that the area covered by the HCA negative correlation with CRII is larger than the area where the positive correlation with UVI dominates. The HCA anticorrelates with the CRII over the Pacific between 50°S and 30°N, except for an equatorial band over the central and eastern Pacific. This anticorrelation extends to higher latitudes along the North American coast and is seen at the equator near Indonesia and coastal waters. As in the previous cases, HCA is anticorrelated with CRII over parts of the Atlantic ocean, close to 50°S and N. Continental regions of negative HCA-CRII correlation include Canada, eastern coast of the North America, South America almost entirely, partly the east of Asia and small areas in the west of Africa, and continental areas surrounding the Mediterranean. The correlation is partly affected by the underlying clouds over the oceanic areas, mostly over the Atlantic. The continental areas are basically free of intervening effect of other clouds, except for a part of the central South American continent. HCA is positively correlated with the CRII over the area westward of Peru (cf. with LCA and MCA odd correlations with CRII), but this relation is spuriously induced by MCA.

[21] The positive HCA-UVI correlation is restricted to the continental dry areas of Russia and central Africa, where it is real, and to the southern high latitudes of Indian Ocean and eastern Pacific, where it is spuriously induced by both LCA and MCA. The southern Asia and the coastal waters of the Indian Ocean correspond to (partly induced by the MCA) HCA-UVI anticorrelation, similar to the MCA. We note again that this is the possibly problematic area of distorted satellite observations.

[22] Concluding, a clear pattern is seen that the continental areas with positive HCA-UVI correlation are dry, while moist or wet continental areas as well as most of the oceanic areas, correspond to negative correlations between HCA and CRII. However, high clouds seem to have very small

sensitivity to the solar irradiance over the oceans, where most of it is spurious.

4. Discussions

[23] The above detailed results reveal some general features of the relation between clouds at different altitudes and the solar related drivers. Generally, the relation of each cloud type with CRII agrees with theoretical expectations [*Yu*, 2002]: CRII correlates positively with LCA, negatively with HCA, while for the MCA the (negative) relation is hardly reliable and occurs only in limited areas.

[24] We have found that low clouds respond more extensively to the UVI changes than to CRII, covering most of the globe, in agreement with earlier studies [*Kristjansson et al.*, 2004]. MCA shows positive correlations with UVI, which, however, is real only in Arctic and south Atlantic and Pacific regions. HCA does not depict significant correlations with UVI, except for the central Eurasia.

[25] There are two areas, the northern and southern mid-to-high- latitude Atlantic, where all clouds are influenced by CRII but where none of the corresponding relations is free of the intervening effect of other clouds. This indicates that satellite based identification of clouds is problematic in these areas [cf. *Marsh and Svensmark* 2003]. Nevertheless, since all cloud types appear to be modulated by the CRII in these areas, we conclude that the correlation between clouds and CRII indeed exists, even if the degree of the correlation cannot be established for each cloud type. We note that these areas lie at high latitudes, where the CR effect is expected to be the strongest, and that they are close to continental areas from where both northern and southern Atlantic receives continental aerosol via SE and NE winds blowing at these latitudes. This could increase the organic aerosol concentration (which plays an important role in growing of condensation nuclei to cloud condensation nuclei [*Yu*, 2002]) over these areas, making the clouds more sensitive to the CRII influence. We also note that Europe, a region with many paleoclimatic data sets, is within the area of real LCA-CRII correlation.

[26] The observed relations between clouds and solar proxies might be affected by some large internal phenomena in the climatic system, like El Niño/Southern Oscillation (ENSO) or major volcano eruptions [e.g., *Mass and Portman*, 1989; *Marsh and Svensmark*, 2003]. For example, an inverted relation, observed in the tropical Pacific zone for all plots, corresponds to the area where ENSO effect can be strong. In order to verify that the observed results are not spuriously induced by these internal drivers, we have repeated the analysis excluding the years of strong ENSO events (1987, 1997, 1998) as well as the Mt. Pinatubo eruption (1991–1992) when dust/ash was loaded into the stratosphere [*McCormick et al.*, 1995]. The results (not shown here) for LCA and MCA remain essentially the same as shown in Figure 1, but yield better correlation (HCA-vs-CRII) for HCA. This implies that the relation between clouds and solar drivers is not spuriously induced by the above mentioned internal climatic factors [cf. *Kirkby and Laaksonen*, 2000]. On the other hand, since the number of used annual points is reduced from 21 to 16 in the case of omitting ENSO and Mt. Pinatubo events, the statistical significance of the results is not enhanced with respect to the full data series.

5. Conclusions

[27] We have produced comprehensive global maps of the correlation of low, middle and high clouds with two solar activity proxies, CRII and UVI. Our results show that there is a strong solar signal in the cloud cover, which clearly depicts geographical patterns suggesting that (1) the solar influence on the cloud cover is not uniquely defined by one solar activity dependent parameter; (2) the solar influence on the cloud cover depends on climatic conditions; and (3) the type of solar signal is different at different altitudes. We have also checked that these results are not spuriously induced by major ENSO and volcanic eruption events but are related to the solar drivers. We conclude that low clouds are affected mostly by UVI over oceans and dry continental areas, but respond to CRII over moist continental areas with possibly high condensable vapor and aerosol concentration. High clouds respond stronger to cosmic ray variations, especially over oceanic and moist continental areas. Since both CRII and UVI have a dominant effect upon the cloud cover in different regions, it is probable that both effects act simultaneously and in a complementing way. The present results also show that clouds in areas with similar climatic conditions tend to respond similarly to solar activity variations. These results provide observational constraints on the related models.

[28] **Acknowledgments.** ISCCP project is acknowledged for the cloud data. Supports from the Academy of Finland and the Finnish Academy of Science and Letters Vilho, Yrjö and Kalle Väisälä Foundation are gratefully acknowledged. We thank anonymous reviewers for useful and constructive comments.

References

Ebisuzaki, W. (1997), A method to estimate the statistical significance of a correlation when the data are serially correlated, *J. Clim.*, *10*, 2147–2153.

Hahn, C. J., W. B. Rossow, and S. G. Warren (2001), ISCCP cloud properties associated with standard cloud types identified in individual surface observations, *J. Clim.*, *14*, 11–28.

Haigh, J. D. (1996), The impact of solar variability on climate, *Science*, *272*(5264), 981–984.

Haigh, J. (2002), The effects of solar variability on Earth's climate, *Philos. Trans. R. Soc., Ser. A*, *361*, 95–111.

Kirkby, J., and A. Laaksonen (2000), Solar variability and clouds, *Space Sci. Rev.*, *94*, 397–409.

Kristjansson, J. E., J. Kristiansen, and E. Kaas (2004), Solar activity, cosmic rays, clouds and climate: An update, *Adv. Space Res.*, *34*, 407–415.

Liao, X., W. B. Rossow, and D. Rind (1995), Comparison between SAGE II and ISCCP high-level clouds: 2. Locating cloud tops, *J. Geophys. Res.*, *100*, 1137–1147.

Marsh, N., and H. Svensmark (2000), Low cloud properties influenced by cosmic rays, *Phys. Rev. Lett.*, *85*, 5004–5007.

Marsh, N., and H. Svensmark (2003), Galactic Cosmic ray and El Niño-Southern Oscillation trends in ISCCP-D2 low-cloud properties, *J. Geophys. Res.*, *108*(D6),4195, doi:10.1029/2001JD001264.

Mass, C. F., and D. A. Portman (1989), Major volcanic eruptions and climate: A critical evaluation, *J. Clim.*, *2*(6), 566–593.

McCormick, M. P., L. W. Thomason, and C. R. Trepte (1995), Atmospheric effects of the Mt Pinatubo eruption, *Nature*, *373*(6513), 399–404.

Ney, E. R. (1959), Cosmic radiation and the weather, *Nature*, 451.

Norris, J. R. (2005), Multidecadal changes in near-global cloud cover and estimated cloud cover radiative forcing, *J. Geophys. Res.*, *110*, D08206, doi:10.1029/2004JD005600.

Pallé, E. (2005), Possible satellite perspective effects on the reported correlations between solar activity and clouds, *Geophys. Res. Lett.*, *32*, L03802, doi:10.1029/2004GL021167.

Pallé, E., C. J. Butler, and K. O'Brien (2004), The possible connection between ionization in the atmosphere by cosmic rays and low level clouds, *J. Atmos. Sol. Terr. Phys.*, *66*, 1779–1790.

Rossow, W. B., and L. C. Garder (1993), Validation of ISCCP cloud detections, *J. Clim.*, *6*(12), 2370–2393, doi:10.1175/1520-0442.

Rossow, W. B., A. W. Walker, D. E. Beuschel, and M. D. Roiter (1996), International Satellite Cloud Climatology Project (ISCCP): Documentation of new cloud datasets, *WMO/TD-737*, 115 pp., World Meteorol. Org., Geneva.

Rossow, W. B., Y. Zhang, and J. Wang (2005), A statistical model of cloud vertical structure based on reconciling cloud layer amounts inferred from satellites and radiosonde humidity profiles, *J. Clim.*, *18*, 3587–3605.

Tinsley, B. A. (1996), Correlations of atmospheric dynamics with solar wind-induced changes of air-earth current density into cloud tops, *J. Geophys. Res.*, *101*, 29,701–29,714.

Usoskin, I. G., and G. A. Kovaltsov (2006), Cosmic ray induced ionization in the atmosphere: Full modeling and practical applications, *J. Geophys. Res.*, doi:10.1029/2006JD007150, in press.

Usoskin, I. G., O. G. Gladysheva, and G. A. Kovaltsov (2004a), Cosmic ray induced ionization in the atmosphere: Spatial and temporal changes, *J. Atmos. Sol. Terr. Phys.*, *66*, 1791–1796.

Usoskin, I. G., N. Marsh, G. A. Kovaltsov, K. Mursula, and O. G. Gladysheva (2004b), Latitudinal dependence of low cloud amount on cosmic ray induced ionization, *Geophys. Res. Lett.*, *31*, L16109, doi:10.1029/2004GL019507.

Usoskin, I., M. Voiculescu, G. Kovaltsov, and K. Mursula (2006), Correlation between clouds at different altitudes and solar activity: Fact or artifact?, *J. Atmos. Sol. Terr. Phys.*, in press.

Warren, S. G., C. J. Hahn, and J. London (1985), Simultaneous occurrence of different cloud types, *J. Appl. Meteorol.*, *24*, 658–668.

Yu, F. (2002), Altitude variations of cosmic ray induced production of aerosols: Implications for global cloudiness and climate, *J. Geophys. Res.*, *107*(A7), 1118, doi:10.1029/2001JA000248.

K. Mursula, Department of Physical Science, University of Oulu, Oulu, Finland.

M. Voiculescu, Department of Physics, "Dunarea de Jos" University of Galati, Str. Domneasca nr. 111, Galati, 800201, Romania. (Mirela.Voiculescu@ugal.ro)

I. G. Usoskin, Sodankylä Geophysical Observatory (Oulu Unit), POB 3000, University of Oulu, FIN-90014 Oulu, Finland. (ilya.usoskin@oulu.fi)