Sussex Research Online

On the relationship of cosmic ray flux and precipitation

Article (Published Version)

Kniveton, Dominic R and Todd, Martin C (2001) On the relationship of cosmic ray flux and precipitation. Geophysical Research Letters, 28 (8). pp. 1527-1530. ISSN 0094-8276

This version is available from Sussex Research Online: http://sro.sussex.ac.uk/11686/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

http://sro.sussex.ac.uk

GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 8, PAGES 1527-1530, APRIL 15, 2001

On the Relationship of Cosmic Ray Flux and Precipitation

Dominic R. Kniveton
School of Chemistry Physics and Environmental Science, University of Sussex, Brighton, United Kingdom

Martin C. Todd
Department of Geography, University College London (UCL), London, United Kingdom

Abstract. This paper evaluates whether there is empirical evidence to support the hypothesis that solar variability is linked to the Earth's climate through the modulation of atmospheric precipitation processes. Using global data from 1979-1999, we find evidence of a statistically strong relationship between cosmic ray flux (CRF), precipitation (P) and precipitation efficiency (PE) over ocean surfaces at mid to high latitudes. Both P and PE are shown to vary by 7-9% during the solar cycle of the 1980s over the latitude band 45-90°S. Alternative explanations of the variation in these atmospheric parameters by changes in tropospheric aerosol content and ENSO show poorer statistical relationships with P and PE. Variations in P and PE potentially caused by changes in CRF have implications for the understanding of cloud and water vapour feedbacks.

Introduction

Precipitation (P) is one of the most fundamental of all climate variables due to its importance as a natural resource and its role in atmospheric dynamics. P influences the atmospheric circulation through the provision of energy to the surrounding air in the form of latent heat released in the condensation process. However, P also has an important effect on climate sensitivity through the related factor of precipitation efficiency (PE). The term PE refers to the efficiency with which atmospheric moisture is converted to P. Under an enhanced climate warming scenario it is thought that the upward moisture flux from the Earth's surface is likely to be increased, leading to a positive feedback. This feedback process may be influenced by changes in PE.

It has been suggested that variations in P and PE are sensitive to the input of electrostatic charge (electrification), increases in which may enhance contact ice-nucleation through electrofreezing *Tinsley et al.* [1994]; *Braslavsky and Lipson* [1998]. One source of electrostatic charge is believed to be the air-Earth current, part of the hypothesised global atmospheric electric circuit, hereinafter referred to as the electric circuit *Bering* [1995]. Described simply, this consists of a power source(s) (dominated by tropospheric weather systems, but also including contributions from the stratosphere, mesosphere, ionosphere and magnetosphere), conductors (the lower and middle atmosphere and Earth's surface) and a load *Bering* [1995]. According to *Tinsley* [1996], lower atmospheric conductivity is primarily determined by the incoming cosmic ray flux (CRF). CRF is known to vary out of phase with the 11-year solar sunspot cycle, due to changes in the interplanetary magnetic field related to solar activity. *Tinsley* [1996] further suggests that modulation of atmospheric conductivity by solar activity is generally confined to high latitudes due to the effect of Earth's magnetic field. It is thus proposed that increased (decreased) CRF, atmospheric conductivity and air-Earth current, at the solar minimum (maximum) causes increased (decreased) ice-nucleation, PE and PE at high geomagnetic latitudes and decreased (increased) ice-nucleation, PE and P at low geomagnetic latitudes.

There is a long history of solar-climate studies, many of which have shown correlations with high statistical significance between atmospheric parameters and solar variability (e.g. *Labitzke and van Loon* [1989, 1992]; *Lassen and Friis-Christensen* [1995]; *van loon and Labitzke* [1998]). *Svensmark and Friis-Christensen* [1997] suggest there exists a statistical relationship between total cloudiness and CRF was demonstrated, at low to middle latitudes. This work has proved controversial, prompting a number of reassessments *Jorgensen and Hansen* [2000]; *Kernthaler et al.* [1999]; *Kristjansson and Kristiansen* [2000]. Criticism of solar-climate studies has focused on the lack of physical explanation of how very low energy fluxes implicit in solar or solar wind variations are able to cause climate variability involving much higher energy fluxes. While this study does not set out to answer this complex question, we attempt, using recently released satellite and re-analysis data, to investigate further the theory that solar induced climate variability may be manifest through modulation of P and PE.

Data

Cosmic rays are comprised of energetic particles, originating from all directions in space and from both solar and non-solar sources. Cosmic ray data are recorded by ground based neutron monitors, which measure the low energy part of the primary cosmic ray spectrum. Although absolute values of CRF at different locations vary, the normalised variation in CRF for different stations remains very similar *Svensmark and Friis-Christensen* [1997]. Therefore for the purposes of this study data from a single neutron monitor (Huancayo, Peru, S12, W75, Alt=3400 m) were used as a measure of variation in the CRF, over the period 1979-1999. Previous studies of the influence of abrupt decreases in cosmic ray intensity (Forbush decreases) on climate have sought

Paper number 2000GL012536.
0094-8276/01/2000GL012536$05.00

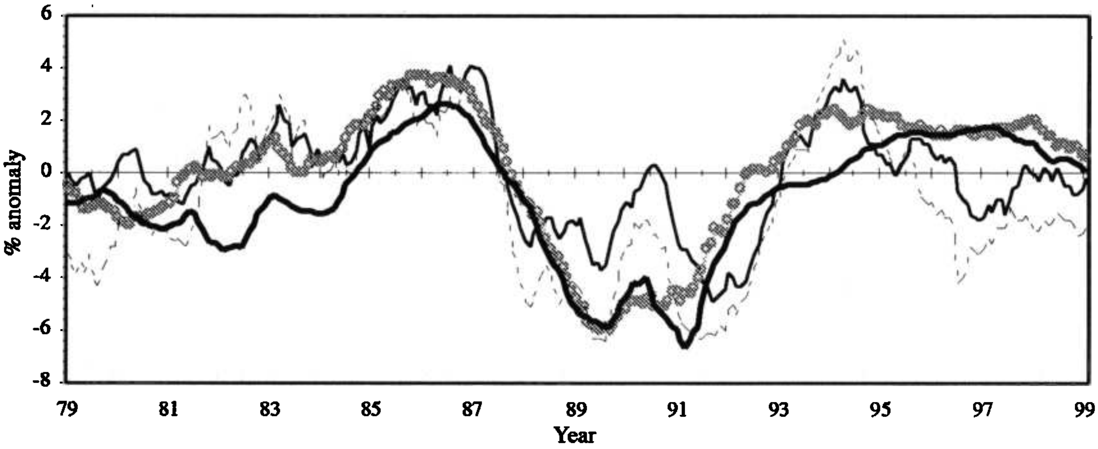

Figure 1. Anomalies, relative to the June 1979-May 1999 mean, of 12 month moving averaged percentage CRF (thick line), P (thin line) and PE (dashed line), for the latitudes 45-90°S over ocean surfaces. Standardised anomalies of (12 month moving averaged) CRF, adjusted for fluctuations due major magnetic storms (represented by the Ap index), are shown by the marked line (scaled by a factor of 3).

to remove the influence of solar proton burst events from their analysis because solar proton effects involve increases in stratospheric ionisation which are opposite to the Forbush decrease effects *Tinsley* [1996]; *Pudovkin and Veretenenko* [1995]. In this respect, we have taken a measure of geomagnetic activity, the Ap index, which is related to the number of major magnetic storms, to remove these effects from the CRF signal. It should be noted, however, that not all major magnetic storms are associated with solar proton events. The Ap index is an averaged planetary index of geomagnetic activity based on data from a set of geomagnetic observatories.

There are numerous definitions of PE *Frankhauser* [1988]; *Rauber et al.* [1996]. In this study, we are interested in PE at regional and hemispheric scales and use simply the ratio of P to total available moisture (i.e. the total columnar precipitable water). For estimates of P we use the Climate Prediction Center Merged Analysis of Precipitation (CMAP) product. This is derived from a weighted combination of rainfall estimates from satellite infrared and passive microwave data, numerical weather prediction model analyses and surface based observations, and provides the longest available record of global rainfall estimates, on a 2.5° grid from 1979 to present *Xie and Arkin* [1996]. Estimates of monthly global atmospheric moisture are obtained from the National Centers for Environmental Prediction (NCEP) reanalysis project *Kalnay* [1996].

Results

Figure 1 shows the time series of twelve month moving averaged P, PE and CRF anomalies, relative to their respective mean values (June 1979 to May 1999), over ocean areas of the southern hemisphere geomagnetic latitude band 45-90°S. It is expected that by focusing on ocean surfaces the influence of surface heterogeneities on variations in P and PE will be reduced. The variation of both P and PE for mid to high latitudes shows a close relationship (in phase and magnitude) with variations in CRF. The correlation coefficients for P and PE are 0.62 and 0.58 respectively and are significant at the 99.8% level. Over the solar cycle of the 1980s all parameters exhibit a variation of 7-9% variation. When the effect of major magnetic storms (represented by the Ap index) is removed from the CRF data by linear regression, these correlations rise to 0.69 and 0.73 for P and PE, respectively.

Figure 2 shows the spatial distribution of correlation coefficients of (12 month moving averaged) P, and PE, on a 2.5° grid, versus CRF over the southern hemisphere (40-80°S) for the period 1979-1999. There is a strong positive relationship between CRF, and P and PE over the oceanic mid-latitude storm track region. Weak relationships are evident at lower latitudes. There are potential problems in interpreting the statistical significance of gridded fields of correlation coefficients, which stem from the effects of finite sample size and spatial autocorrelation in global climate datasets *Livezey and Chen* [1983]. To address this, the percentage area of locally significant correlations (globally) was tested for field significance using a randomised Monte Carlo simulation in which the probability density function of the percent area of locally significant correlations (at the 0.05% level) for random data was estimated. In each of the 1000 experiments the CRF time series was replaced with a random time series drawn from a normal distribution. The results indicated that the observed fields of locally significant correlations between CRF and global gridded P and PE over the entire globe are field significant at the 0.05% level.

While the analysis shown above suggests a relationship between P, PE and CRF, it is possible that internal climate mechanisms may be responsible for the observed variability in these parameters. It is well known that large-scale patterns of southern hemisphere mid-latitude P are modulated at inter-annual time scales by internal modes of climate variability, dominated by the El Niño-Southern Oscillation *Garreaud and Battisti* [1999] and the Antarctic Oscillation *Thomspon and Wallace* [2000]. The relationships between indices of these modes of variability and P and PE (over ocean areas of the southern hemisphere geomagnetic latitude band 45-90°S) for the entire period from June 1979-May 1999 are shown in Figure 3. Both the Southern Oscillation and Antarctic Oscillation exhibit statistically far weaker relationships with P (PE), (r=−0.09 (−0.24) and r=0.24 (0.24), respectively) than does CRF.

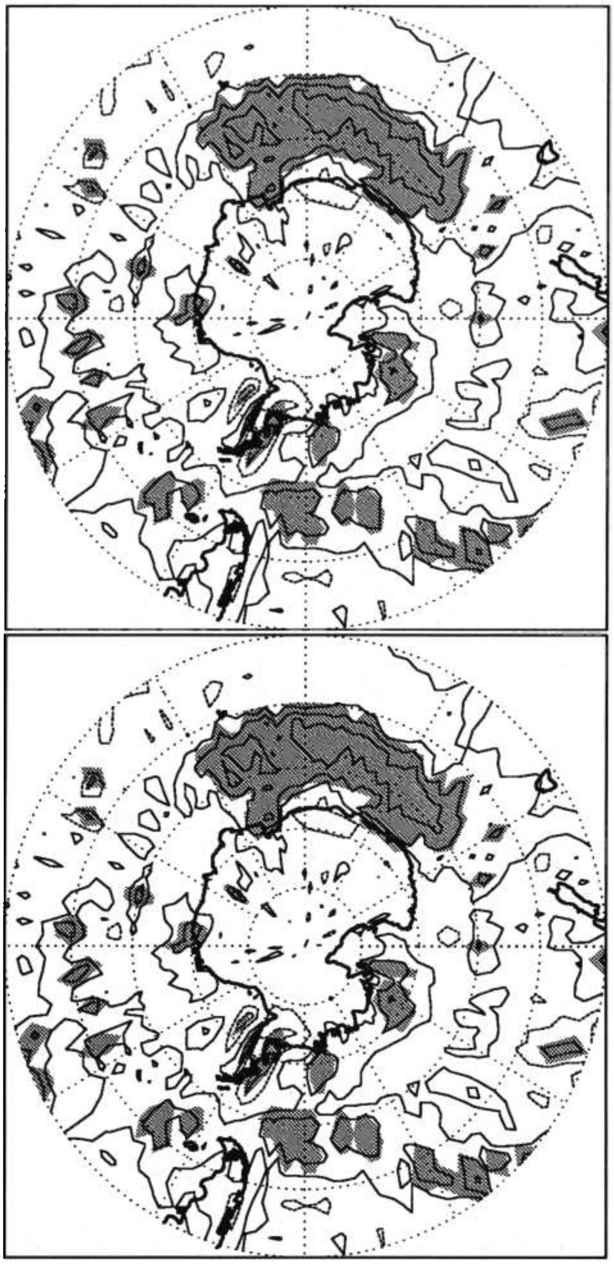

Figure 2. Correlation coefficients between 12 month moving averaged CRF and (a) P, and (b) PE. Positive (negative) correlation coefficients are shown as solid (broken) lines. Shading indicates areas with locally significant correlations at the 0.05 % level. The contour interval is 0.2 and the zero contour is omitted.

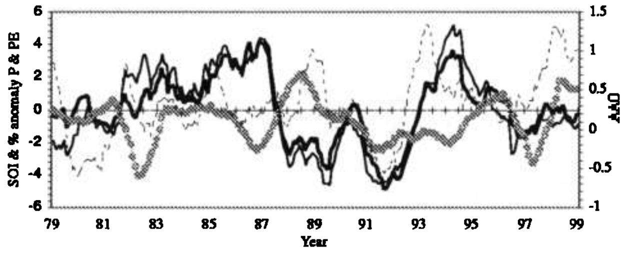

Figure 3. Time series of 12 month moving averaged percentage anomalies of P (thick line), PE (thin line) (anomalies relative to June 1979-May 1999), the Southern Oscillation Index (SOI) (dashed line) and the Antarctic Oscillation Index (AAO)(marked line).

Jorgensen and Hansen [2000] suggest that tropospheric aerosols from volcanic eruptions can influence precipitation processes. Estimates of upper tropospheric aerosol extinction data are available from the SAGE II sensor from 1984 to 1997, with a gap from 1991-1993 (due to excessive stratospheric aerosol overburden as a result of the eruption of Mount Pinatubo). These data have been uncontaminated of cloud along the optical path using the method of Kent et al. [1998]. Figure 4 shows the time series of twelve month averaged P and PE anomalies, relative to their respective mean values for June 1979 to May 1999, over ocean areas of the southern hemisphere latitude band 40-80°S and the twelve month average 1.0 μm aerosol extinction (10^{-4} km^{-1}) for the altitudes from 6.5 to 11.5 km for the latitude bands of 40-60°S and 60-80°S. These latitude bands were chosen due to the ease of availability of the SAGE II data and displayed separately due to the absence of aerosol readings for June-August in the band 60- 80°S. Although only available for a short period the aerosol data appear to exhibit weaker relationships with P and PE than does CRF. It should be noted that this weak relationship of SAGE II estimated tropospheric aerosols with P and PE might result partly from the restriction of retrievals to cloud free regions and non-uniform spatial sampling of the instrument at monthly time scales.

Discussion and Conclusion

In this study, we present evidence of a statistical relationship between large-scale P, PE and CRF. This raises the question of whether modulation of the climate by changes in CRF can occur through changes in the global atmospheric electric circuit. According to *Tinsley* [1996], through this mechanism it should be expected that P and PE would be positively (negatively) related to CRF at higher (lower) latitudes. Our results are broadly consistent with this theory. As such, the strong similarity in the relationship of P and PE with CRF is notable.

The results suggest that variability in CRF is a possible explanation of the observed inter-annual variability in P and PE in the southern hemisphere mid and high latitude region. Of course, these statistical results do not prove a causal relationship between the variables. Previous work has suggested dynamical mechanisms by which

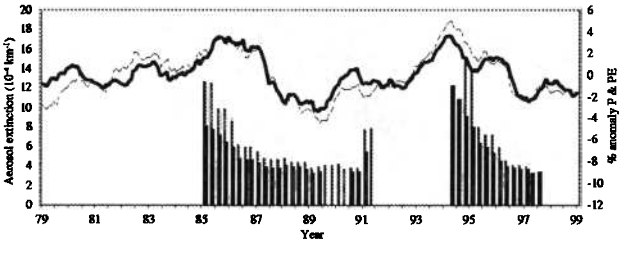

Figure 4. Anomalies, relative to the June 1979 May 1999 mean, of 12 month moving averaged P (line), PE (dashed line) for the latitudes 40-80°S over ocean surfaces and upper tropospheric aerosol extinction data for 40-60°S (thin column) and 60-80°S (thick column).

the 11-year cycle in solar irradiance modulates the lower atmospheric circulation *Haigh* [1996, 1999]; *Labitzke and van Loon* [1989, 1992]; *van loon and Labitzke* [1998]. However, we see no evidence of a meridional dipole in the correlation structure that might be expected to result from a shift in the position of the southern hemisphere mid-latitude storm track identified in model simulations of the effect of solar irradiance changes *Haigh* [1996, 1999]. In addition, *van Loon and Labitzke* [1998] indicate that at solar maximum (minimum) there is an increase (decrease) in the tropic to pole temperature gradient in the upper troposphere, which would be expected to strengthen (weaken) mid-latitude westerlies. In contrast, our results suggest that mid/high-latitude P, in the southern hemisphere, increases with CRF, peaking near solar minimum. This suggests that the structure of variability in P and PE identified here is more likely to be related to variations in CRF than to those in solar irradiance. The results encourage further research to investigate the mechanisms by which CRF may influence PE and P, including the use of general circulation models to separate the effects of CRF and solar irradiance.

Finally, certain caveats must be attached to interpretation of the results presented here. First, due to limitations in global observations of P our study is based on data from a relatively short period. Second, errors in the data used are not uniform in space and time and are likely to be highest over the mid to high latitudes of the Southern Hemisphere. Third, although we have tried to assess other possible influences on PE and P variability there remains the possibility of other explanations of the observations.

Acknowledgments. The authors would like to thank Dr. Neil Arnold of the University of Leicester for valuable discussions during the preparation of this paper. In addition, we are grateful to NOAA Climate Prediction Center for supplying the P data, to the NGDC Solar and Upper Atmospheric Data Services for the CRF data, and to the Radiation and Aerosols Branch of NASA Langley Research, Center for the SAGE II aerosol data.

References

Bering E.A. III, The global circuit: Global thermometer, weather by product or climate moderator? *Rev. Geophys.*, *33*, 845, 1995.

Braslavsky I. and S. G. Lipson, Electrofreezing effect and nucleation of ice crystals in free growth experiments, *Applied Physics Letters*, *72*, 264-266, 1988.

Frankhauser J. C., Estimates of thunderstorm precipitation efficiency from field measurements in CCOPE, *Mon. Weather Rev.*, *116*, 663-684, 1988.

Garreaud, R.D and Battisti, D.S., Interannual (ENSO) and interdecadal (ENSO-like) variability in the southern hemisphere tropospheric circulation, *Journal of Climate*, *12*, 2113-2123, 1999.

Haigh J.D., The impact of solar varaibility on climate. *Science*, *272*, 981-984, 1996.

Haigh, J.D., A GCM study of climate change in response to the 11-year solar cycle, *Q. J. R. Meteorol. Soc.*, *125*, 871-892, 1999.

Jorgensen T.S. and A. W. Hansen, Comments on "Variation of cosmic ray flux and global cloud coverage - a missing link in solar-climate relationships" by Henrik Svensmark and Eigil Friis-Christensen *Journal of Atmospheric and Solar-Terrestrial Physics, 59* (1997) 1225-1232], *Journal of Atmospheric and Solar-Terrestrial Physics*, *62*, 73-77, 2000.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne and D. Joseph, The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meterol. Soc.*, *77*, 437-471, 1996.

Kent G.S., C. R. Trepte and P. L. Lucker, Long-term Stratospheric Aerosol and Gas Experiment I and II Measurements of Upper Tropospheric Aerosol Extinction, *J. Geophys. Res.*, *103*, 28863-28874, 1998.

Kernthaler S.C., R. Toumi and J. Haigh, Some doubts concerning a link between cosmic ray fluxes and global cloudiness, *Geophys. Res. Lett.*, *26*, 863-865, 1999.

Kristjansson J. E. and J. Kristiansen, Is there a cosmic ray signal in recent variations in global cloudiness and cloud radiative forcing, *J. Geophys. Res.*, *105*, 11851-11863, 2000.

Labitzke K. and H. van Loon, Association between the 11 year solar cycle, the QBO and the atmosphere. Part III: Aspects of the Association, *Journal of Climate 2*, 554-565, 1989.

Labitzke K. and H. van Loon, Association between the 11 year solar cycle and the atmosphere. Part V: Summer, *Journal of Climate 5*, 240-251, 1992.

Lassen K., and E. Friis-Christensen, Variability of the solar cycle length during the past five centuries and the apparent association with terrestrial climate, *J. Atmos. Terr. Phys.*, *57*, 835, 1995.

Livezey B.C. and W.Y. Chen, Statistical field significance and its determination by Monte-Carlo techniques, *Mon. Weather Rev.*, *111*, 46-59, 1983.

Pudovkin, M.I. and S.V. Veretenenko, Cloudiness decreases associated with Forbusch-decreases of galatic cosmic rays, *Journal of Atmospheric and Solar-Terrestrial Physics*, *57*, 1349-1355, 1995.

Rauber R. M., N. F. Laird and H. T. Ochs, Precipitation efficiency of trade wind clouds over the north central tropical Pacific Ocean, *J. Geophys. Res.*, *101*, 26247-26253, 1996.

Svensmark H. and E. Friis-Christensen, Variation of cosmic ray flux and global cloud coverage A missing link in solar-climate relationships, *Journal of Atmospheric and Solar-Terrestrial Physics*, *59*, 1225-1232, 1997.

Thompson, D. W. J, and J. M. Wallace, Annular modes in the extratropical circulation. Part I: Month-to-month variability, *Journal of Climate*, *13*, 1000-10016, 2000.

Tinsley, B. A. Correlations of atmospheric dynamics with solar wind-induced changes of air-earth current density into cloud tops, *J. Geophys. Res.*, *101*, 29701-29714, 1996.

Tinsley B. A., J.T. Hoeksema, and D. N. Baker, Stratospheric volcanic aerosols and changes in air-earth current density at solar wind magnetic sector boundaries as conditions for the Wilcox tropspheric vorticity effect, *J. Geophys. Rev.*, *99*, 16805, 1994.

van Loon, H., and K. Labitzke, The global range of the stratospheric decadal wave. Part I: Its association with the sunspot cycle in summer and in the annual mean, and with the troposphere, *Journal of Climate*, *11*, 1529-1537, 1998.

Xie P. P. and P. A. Arkin, Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions. *Journal of Climate*, *9*, 840-858, 1996.

D.Kniveton, CPES, University of Sussex, Brighton, BN1 9QJJ, UK. (e-mail: d.r.kniveton@sussex.ac.uk)

M.Todd, Dept. of Geography, UCL, 26 Bedford Way, London, WC1H OAP, UK. (m.todd@geog.ucl.ac.uk)

(Received October 26, 2000; revised January 23, 2001; accepted January 29, 2001.)