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# Satellite observations of the quasi 5-day wave in noctilucent clouds and mesopause temperatures

C. von Savigny,[1] C. Robert,[1] H. Bovensmann,[1] J. P. Burrows,[1] and M. Schwartz[2]

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[1] We report on simultaneous measurements of the westward propagating quasi 5-day wave in the occurrence rate of noctilucent clouds (NLCs) and the temperature field at NLC altitude during the 2005 NLC season in the northern hemisphere. NLCs are detected using SCIAMACHY/Envisat limb scattering measurements, and the temperature profiles are measured with MLS/Aura. Quasi 5-day wave signatures are clearly identified in both physical and wavelet space. We find good general agreement in the quasi 5-day wave activity of NLC occurrence rates and the mesopause temperature field, indicating that planetary wave signatures in the temperature field are the main driver of corresponding signatures in NLCs. **Citation:** von Savigny, C., C. Robert, H. Bovensmann, J. P. Burrows, and M. Schwartz (2007), Satellite observations of the quasi 5-day wave in noctilucent clouds and mesopause temperatures, *Geophys. Res. Lett.*, *34*, L24808, doi:10.1029/2007GL030987.

## 1. Introduction

[2] Noctilucent Clouds (NLCs), also known as Polar Mesospheric Clouds (PMCs) consist of $H_2O$-ice particles and are a summertime, high-latitude phenomenon. The formation and existence of NLC particles are affected by spatial and temporal variations of the mesopause temperature field. These variations include tides [*von Zahn et al.*, 1998], gravity waves [e.g., *Witt*, 1962] and planetary wave perturbations [e.g., *Merkel et al.*, 2003]. There are only a limited number of studies dealing with planetary wave signatures in NLCs. Quasi 5-day wave signatures were found in ground-based NLC sightings over Europe [*Gadsden*, 1985; *Kirkwood and Stebel*, 2003] as well as in satellite observations. *Merkel et al.* [2003] showed pronounced quasi 5-day wave signatures in NLC brightness measurements with the Student Nitric Oxide Experiment (SNOE). *Mackler* [2005] identified quasi 5-day wave signatures in the SBUV (Solar Backscatter UltraViolet) NLC data set. Furthermore, A. W. Merkel et al. (Observational studies of planetary waves in PMCs and mesospheric temperature measured by SNOE and SABER, submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Merkel et al., submitted manuscript, 2007) found both 5-day wave and 2-day wave signatures in SNOE NLC brightness measurements and SABER mesopause temperatures. The previously published studies suggest that the quasi 5-day wave is the most important planetary wave signature present in NLCs.

[3] The quasi 5-day wave corresponds to the symmetric Rossby (1, 1) normal mode oscillation which has been observed in a variety of atmospheric parameters, e.g., surface pressure [*Madden and Julian*, 1972], upper stratospheric temperatures [*Rodgers*, 1976], and mesospheric and lower thermospheric winds [*Wu et al.*, 1994]. Model simulations suggest that moist convection in the troposphere is a principal excitation mechanism for the quasi 5-day wave [*Miyoshi and Hirooka*, 1999]. *Garcia et al.* [2005] presented evidence for in-situ generation of planetary waves near the summer mesopause caused by baroclinic instabilities of the summertime jet. Recently *Jarvis* [2006] found evidence for long-term and solar cycle variations in the quasi 5-day wave signatures in magnetometer data.

[4] This paper reports on simultaneous observations of the 5-day wave in NLC occurrence rates – as observed with SCIAMACHY on Envisat – and mesopause temperatures measured with MLS on the Aura satellite.

## 2. Instrumental Description

### 2.1. SCIAMACHY/Envisat

[5] SCIAMACHY, the Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY [*Bovensmann et al.*, 1999] is one of ten instruments onboard the European Space Agency's Envisat spacecraft. Envisat was launched on March 1, 2002 from Kourou (French Guyana) into a near-polar, sun-synchronous orbit with a 10:00 LST (local solar time) descending node, and it completes about 14 orbits per day. SCIAMACHY measures solar radiation scattered by and transmitted through the atmosphere in Nadir, solar/lunar occultation and Limb scattering mode. For this study only Limb scattering observations – fully calibrated Level 1 data (version 5.04) – are employed.

### 2.2. MLS/Aura

[6] The Microwave Limb Sounder (MLS) [*Waters et al.*, 2006] is one of four instruments onboard NASA's Earth Observing System (EOS) Aura satellite, which was launched 15 July 2004. Aura is in a near-polar, sun-synchronous, 705 km altitude orbit, with a 1:45 p.m. ascending equator-crossing time and completes about 14 orbits per day. Vertical profiles are measured every 165 km along the suborbital track and have a horizontal resolution of 165–250 km along-track and 10 km across-track. Here we use the first publicly-released version of the Aura MLS data, v1.51. Temperature is retrieved from 316 to 0.001 hPa. Validation of the temperature product is still preliminary above 0.1 hPa, but typical estimated precisions (single-profile) vary from 1 K at 0.1 hPa to 2 K at 0.001 hPa [*Froidevaux et al.*, 2006]. The vertical resolution of the

[1]Institute of Environmental Physics, University of Bremen, Bremen, Germany.
[2]Jet Propulsion Laboratory, Pasadena, California, USA.


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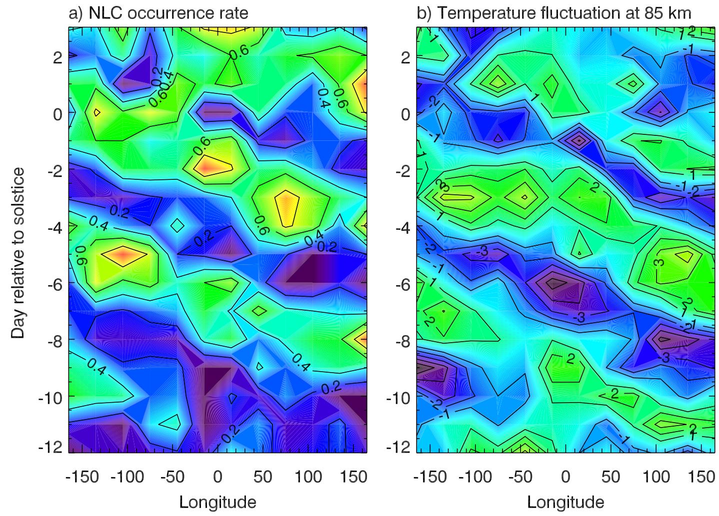


**Figure 1.** (a) Zonal and temporal variation of the NLC occurrence rate for the [60°N, 80°N] latitude bin and the period June 9–June 24, 2005. (b) Zonal and temporal variation of temperature fluctuations at 85 km.

v1.51 MLS temperature retrieval ranges from 4 km in the middle stratosphere to more than 12 km in the mesosphere.

## 3. Data Analysis

[7] NLCs are detected in SCIAMACHY limb scatter measurements in the UV spectral range using the method described by *von Savigny et al.* [2007]. For the following analysis daily NLC occurrence rates–i.e., number of detected NLCs divided by the total number of limb measurements–are determined for the 60°N–80°N latitude band and for 30° longitude bins. Due to problems with the SCIAMACHY data distribution not all orbits are available for all days during the northern hemisphere season 2005. For the 2005 northern NLC season there is one longitude bin on July 28 without SCIAMACHY measurements. This gap was filled by linear interpolation in time. The linear interpolation on scales of 1 day will not affect the results of the present analysis, which focuses on 5-day wave perturbations.

[8] The MLS temperatures at 85 km are averaged over the 60°N to 80°N latitude range and are binned in 30° longitude bins, similar to the treatment of the NLC occurrence rates. Note, that only data for the 2005 NLC season in the northern hemisphere are used for this study, because MLS temperature measurements are only available since August 2004, and the available SCIAMACHY data set has gaps during the other NLC seasons.

[9] In order to obtain localized frequency information in the NLC occurrence rate and mesopause temperature data we used wavelet analysis [*Torrence and Compo*, 1998]. The more traditional windowed Fourier transform–also providing local frequency information–is generally affected by aliasing due to frequencies outside the frequency range of the used window. Wavelet analysis is not affected by this problem.

[10] For this study a 4th order Paul mother wavelet was used, which provides higher time resolution than the standard Morlet wavelet. The wavelet power spectra are normalized by the variance of the original time series and are presented as a function of Fourier equivalent period [e.g., *Torrence and Compo*, 1998]. Confidence levels are determined based on the assumption that the time series can be approximated by red-noise processes with lag-1 autocorrelation values obtained from each time series.

## 4. Results

[11] Figure 1 shows the zonal and temporal dependence of the NLC occurrence rate (Figure 1a) and the temperature fluctuations at 85 km (Figure 1b) for the period June 9–June 24, 2005. This period was chosen, because it is one with the most obvious quasi 5-day wave signature in the NLC occurrence rates. Both panels show a clear westward propagating (i.e., occurrence rate maxima and minima propagate from east to west) wave signature of wavenumber 1 (i.e., the zonal variation on a given day corresponds to one $2\pi$ cycle of a sine wave) and a period of about 5 days. Therefore, the signature corresponds to the quasi 5-day wave, or the symmetric Rossby (1, 1) normal mode oscillation. Temperature minima coincide with maxima in the NLC occurrence rate and vice versa. The excellent agreement between the wave signature in the NLC occurrence rates and the mesopause temperature fluctuations suggests that the quasi 5-day wave signature in the temperature field is the main driver for the NLC wave signature. The temperature fluctuations show maximum quasi 5-day wave amplitudes of about 3 K. Note, that the actual temperature amplitude at 85 km may differ from the observed one, because of the rather poor vertical resolution of the MLS temperature profiles near the mesopause (12–15 km).

[12] Figure 2 shows the temporal evolution of the NLC occurrence rates for the [−120°, −90°] longitude bin and illustrates that the quasi 5-day wave can have a very large impact on the NLC occurrence rates for a certain geographical location. This is in line with the ground-based NLC sightings reported by *Kirkwood and Stebel* [2003].

[13] Figure 2 also shows that during certain parts of the 2005 NLC season, high variability in the NLC occurrence

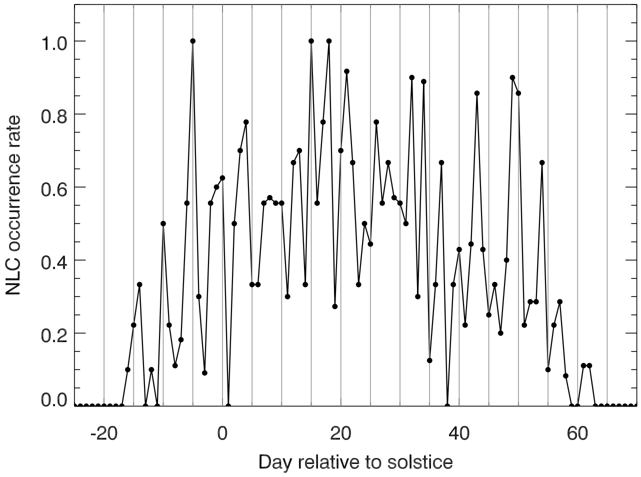


**Figure 2.** NLC occurrence rate during the northern hemisphere 2005 NLC season for the [−120°, −90°] longitude bin and latitudes between 60°N and 80°N. A pronounced variation with a period of about 5 days is clearly visible between days −15 and 10 and around day 50. The number of measurements per daily bin is 8.8 ± 1.4 and the minimum number of measurements is 5.

rates on shorter time scales is present, e.g., between days 30 and 40. Whether this variability is related to the 2-day wave (e.g., Merkel et al., submitted manuscript, 2007) remains to be investigated.

[14] In order to determine the amplitudes of the 5-day wave signature in physical space we FFT-filtered the NLC occurrence rate and the mesopause temperature time series with a 4 day–6 day band-pass filter. The FFT-filtered time series are shown in Figure 3 for two selected longitude bands. The maximum temperature amplitudes are about 2–3 K, in good quantitative agreement with the results presented by Merkel et al. (submitted manuscript, 2007) and *Garcia et al.* [2005]. Due to the different vertical resolutions of the SABER (about 2 km) and the MLS temperature profiles (12–15 km near the mesopause) this is not necessarily expected, particularly considering the distinct altitude structure in the 5-day wave signature in the temperature field (Merkel et al., submitted manuscript, Figure 6, 2007). Figure 3 also illustrates the fact, that temperature and NLC wave signatures are anti-correlated, except for a few limited periods.

[15] Figure 4 shows the longitudinal and time variation of the NLC occurrence rate for the 2005 NLC season in the northern hemisphere (Figure 4b) together with the normalized wavelet power spectrum (Figure 4c). The period with the strongest quasi 5-day wave activity around day −5 is clearly visible in the wavelet power spectrum. There are additional episodes with quasi 5-day wave activity around days 15, 25, 38 and 50, with the event around day 15 also including wavelet power at longer periods. The zonal and temporal variation as well as the normalized wavelet power spectrum of the temperature fluctuations at 85 km are shown in Figure 5. The wavelet power also exhibits 5-day wave peaks around days −5, 38, and 50 similar to the signatures in Figure 4, consistent with the view that the quasi 5-day wave signatures in the NLC fields are caused by quasi 5-day wave signatures in the temperature field. Figures 4d and 5c show the normalized wavelet power averaged over the days −20 to 60. The quasi 5-day component is clearly visible in both Figures. Note that for the wavelet power spectra in Figures 4c and 5b the displayed ranges are outside the cone of influence, where edge effects may affect the spectra.

[16] Figure 6 shows the temporal variation of the NLC occurrence rate and temperature fluctuation wavelet power averaged over Fourier equivalent periods of 4 to 6 days. Several peaks in the wavelet power occur in both time series (1, 2, 3, 6, 7) whereas other, mainly minor peaks, occur only in one time series (4, 5). The large quasi 5-day wave signature in the temperature field around day 60 is not present in the NLC occurrence rates, because the mesopause temperatures are too high and the NLCs have basically disappeared.

## 5. Discussion

[17] Planetary scale perturbations like the quasi 5-day wave affect the geographical distribution of NLCs, the 'NLC limb brightness' or the 'NLC nadir albedo,' as well as the NLC particle sizes in a non-trivial way. Long-term and possible solar cycle variations in planetary waves may have important implications for similar changes in NLCs. Recently published observations are consistent with the view that quasi 5-day waves observed near the mesopause are in part caused by upward propagating planetary waves,

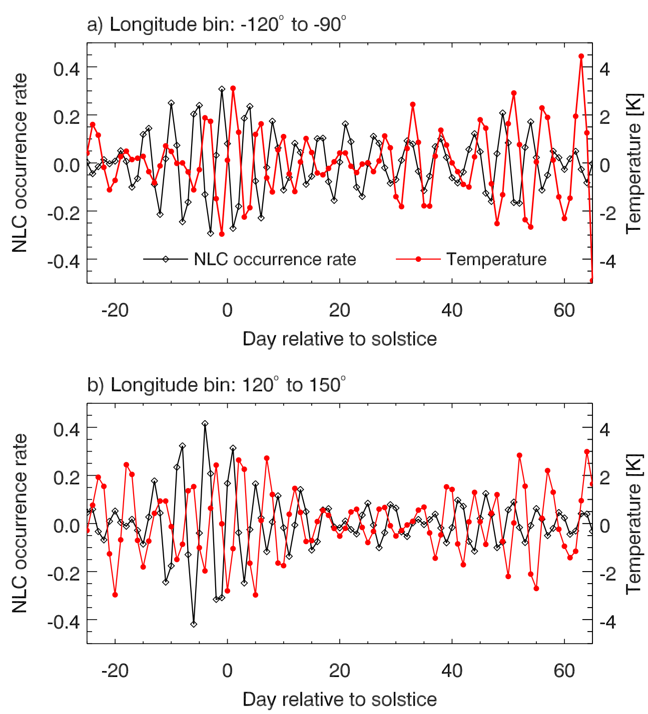


**Figure 3.** Band-pass filtered time series of NLC occurrence rate and temperature at 85 km altitude for the 0.16̄ day$^{-1}$ to 0.25 day$^{-1}$ wavenumber range and two selected longitude bins.

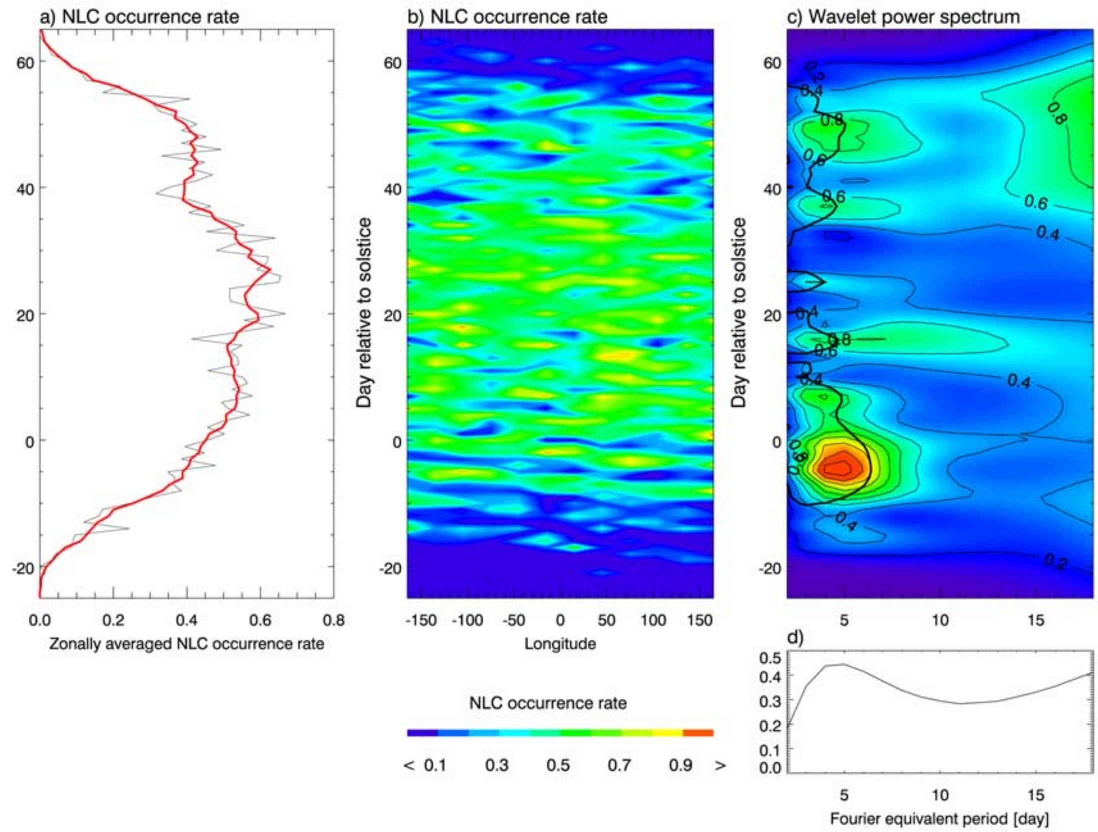


**Figure 4.** (a) Variation of zonally averaged NLC occurrence rate for the northern NLC season 2005. (b) Contour plot of the longitude and time dependence of the NLC occurrence rate. (c) Normalized wavelet power spectrum of the NLC occurrence rates. The thick solid line shows the 95% confidence level. (d) Normalized wavelet power averaged between days −20 and 60.

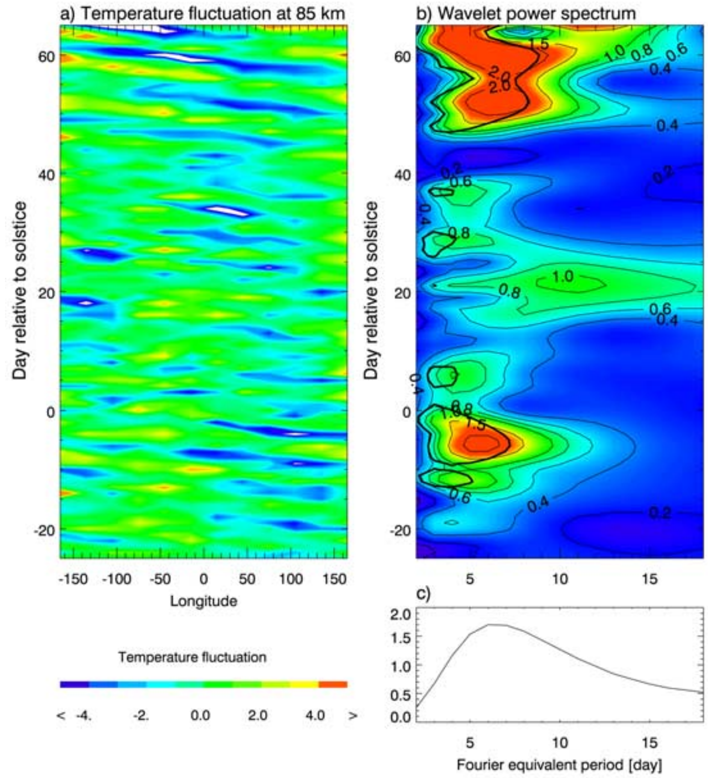


**Figure 5.** (a) Time and longitude dependence of the MLS temperature fluctuations at 85 km altitude. (b) Normalized wavelet power spectrum of the temperature fluctuations. The thick solid line corresponds to the 95% confidence level. (c) Normalized wavelet power averaged between days −20 and 60.

and in part by in situ forcing due to gravity waves [*Lawrence and Jarvis*, 2003] and baroclinic instabilities [*Garcia et al.*, 2005]. According to model simulations by *Geisler and Dickinson* [1976] the amplification of the upward propagating 5-day wave is modulated by the mean zonal wind. In this context, several studies show solar cycle variations as well as long-term trends in zonal wind speeds [e.g., *Bremer et al.*, 1997, and references therein]. Furthermore, *Jarvis* [2006] recently found evidence for a long-term decrease and a Hale-cycle (22 years) variation in the amplitude of quasi 5-day wave signatures in long-term magnetometer measurements. Therefore it appears possible that planetary waves may introduce long-term and solar cycle variations in NLCs. Long-term changes in the vertical propagation of the 5-day wave signature may be another key player–apart from changing temperature fields (both due to enhanced radiative cooling and possibly dynamically induced adiabatic temperature changes) and the $H_2O$ abundance–affecting long-term variations in NLC features.

## 6. Conclusions

[18] The coincident occurrence of quasi 5-day wave signatures in the mesopause temperature field and NLC occurrence rates indicates that the planetary wave signatures in the temperature are likely the main driver for the wave signatures in NLCs. Further investigations are required in order to fully understand the impact of planetary waves in the mesopause temperature field on NLCs. Moreover, the impact of long-term and possible solar cycle variations in planetary wave activity on long-term and solar cycle variations in NLC must be understood to evaluate the role of NLCs as early indicators of global change.

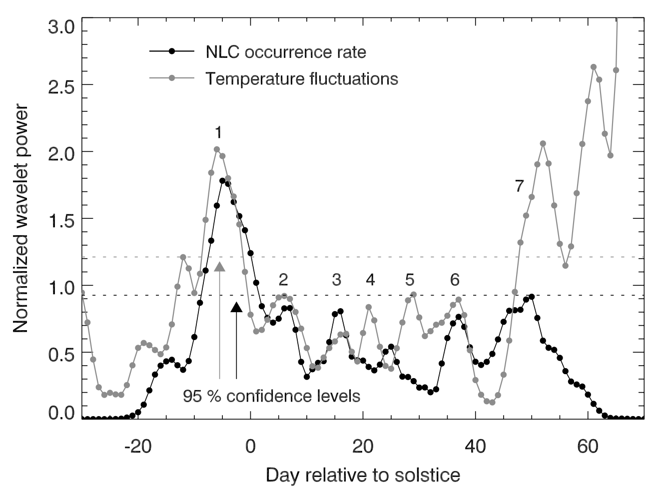


**Figure 6.** Time series of normalized wavelet power averaged over Fourier equivalent periods between 4 and 6 days. The horizontal lines show the 95% confidence levels.

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H. Bovensmann, J. P. Burrows, C. Robert, and C. von Savigny, Institute of Environmental Physics and Remote Sensing, University of Bremen, Otto-Hahn-Allee 1, D-28334 Bremen, Germany. (csavigny@iup.physik.uni-bremen.de)

M. Schwartz, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA.