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Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 1980–1986

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

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The quasi-decadal modulation of running correlations involving the QBO

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Received 10 November 2005; received in revised form 13 July 2006; accepted 10 August 2006
Available online 20 September 2006

Abstract

Running correlations between "ideal" periodic sine series, $u(t)$ and $y(t)$, are analyzed in the present work, which, in this case, results in a kind of beating of the two waves. $u(t)$ is considered as a quasi-biennial periodic function standing for an idealized quasi-biennial oscillation (QBO). The beat frequency in the running correlation coefficient series will correspond to a decadal oscillation if periodicities in $y(t)$ are around 0.6–0.8 years greater or 0.4–0.5 years smaller than $u(t)$ period. The periodicities required by $y(t)$ to generate a decadal variation in the running correlation with $u(t)$, may appear in series associated to the 11-year solar activity cycle due to its asymmetry: solar activity rises to maximum levels faster than it falls to minimum levels. Therefore, running correlations between the stratosphere QBO and time series with a biennial or triennial oscillation, associated or not to the solar cycle, could present a decadal oscillation due merely to the statistics involved. Taking into account the idealization of the series considered, without any relationship or interaction between them, neither a decadal modulation in $u(t)$, we obtain a quasi-decadal oscillation in running correlations, as that obtained when certain empirical data series are correlated with the QBO in the stratosphere.

Keywords: QBO; Running correlation; Decadal variation; Beating frequency

1. Introduction

The interaction between the quasi-biennial oscillation (QBO) in stratospheric equatorial zonal winds and the solar activity cycle has been examined in several studies (Varotsos, 1989; Kodera, 1993; Labitzke and Van Loon, 1993; Naito and Hirota, 1997; Soukharev, 1999; Abarca del Rio et al., 2003; Labitzke, 2005). This interaction has been analyzed mainly through the possible connection between atmospheric parameters and solar activity, grouping data according to the QBO phases or through the running correlation method. Regarding the last method, Kodera (1993) estimated the running correlation of the QBO with the North Polar stratospheric temperature, Soukharev (1997, 1999), with total ozone content over Northeastern European stations, and Salby and Callaghan (2004) with wintertime tendency. They all obtained

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1364-6826/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2006.08.003

running correlation coefficients with a clear quasi-decadal modulation.

Troshichev and Gabis (1998), Soukharev and Hood (2001) and Gabis and Troshichev (2004) showed that the UV irradiance undergoes quasi-biennial periodicity which may have an effect on the stratospheric QBO. After this idea, Elias and Zossi de Artigas (2003) estimated the running correlation between the QBO signal in the 10.7 cm solar radio emission, F10.7, and the equatorial stratospheric QBO and found a quasi-decadal variation in the correlation coefficient series similar to what Kodera (1993), Soukharev (1997, 1999) and Salby and Callaghan (2004) found.

There are also statistical studies analyzing the connection between the equatorial stratosphere QBO and the solar activity cycle (Baldwin and Dunkerton, 1989; Hamilton, 1990; Salby and Shea, 1991; Salby et al., 1997). Following the idea of a statistical study, in this work artificially constructed series were used in order to analyze the quasi-decadal modulation of running correlations involving the QBO in stratospheric equatorial zonal winds. Section 2 presents first some examples of experimental evidences, followed by the statistical experiment in Sections 3 and 4.

2. Running correlations with experimental time series

The running correlation between the QBO and certain atmospheric and solar parameters, observed by some authors (Kodera, 1993; Soukharev, 1997, 1999; Elias and Zossi de Artigas, 2003; Salby and Callaghan, 2004; Zossi de Artigas and Elias, 2005), present a quasi-decadal modulation. As an example, we present in this section some results using experimental time series.

As a first example, we show in Fig. 1 the running correlation coefficients between the equatorial stratosphere QBO at 30 hPa (from a compilation by Naujokat (1986)) and F10.7, and also between the QBO and the storm time index, Dst (which monitors the disturbance of the horizontal component of the geomagnetic field at the dipole equator on the Earth's surface (Mayaud, 1980)). The running correlation involving F10.7 has been multiplied by −1 to make the figure more clear. The case of F10.7 is discussed in detail in Elias and Zossi de Artigas (2003) and that of Dst in Zossi de Artigas and Elias (2005), so we present here a brief description of the results.

Monthly F10.7 series, available at the World Data Center-A for Solar-Terrestrial Physics, and monthly mean Dst data, obtained from hourly data available at the World Data Center-C2 of the Kyoto University, were bandpass filtered with frequency bounds corresponding to periods of 12 and 39 months. The bandpass filter was constructed as the difference of a low-pass filter with a cutoff frequency of 12 months and another filter with a cutoff frequency of 39 months. Both of them are Boxcar filters (running means) with finite impulse response (FIR filter). The filtering is done mainly to eliminate the decadal solar activity variability,

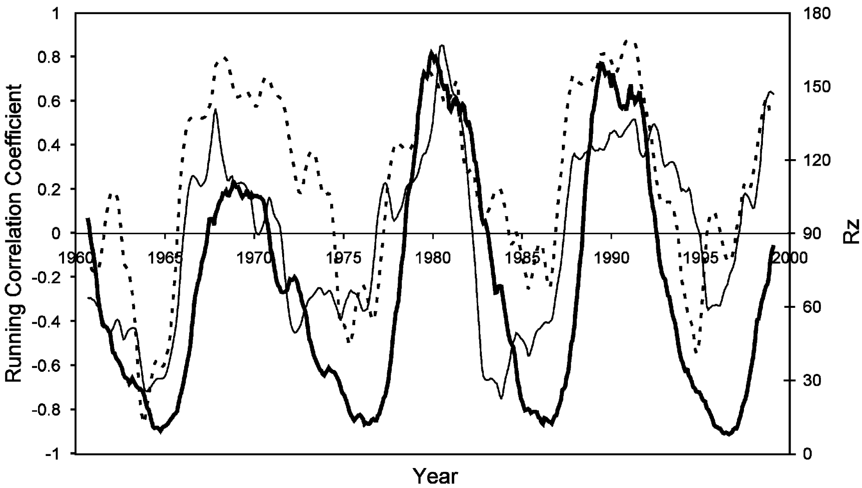

Fig. 1. Running correlation coefficient time series with a 4-year window-width between the monthly mean zonal equatorial wind QBO at 30 hPa and monthly Dst band pass filtered (solid line), and between the QBO and monthly F10.7 band pass filtered multiplied by −1 (dashed line). Rz after a 12-month running mean (enhanced line).

strongly present in both series. A quasi-decadal oscillation in the running correlation coefficient between the QBO and both, F10.7 and Dst, is clearly noticed in Fig. 1 almost coincident with that of solar activity (depicted in the figure by the sunspot number, Rz). In the case of F10.7, taken as a proxy of the UV solar radiation, it can be said that during maximum solar activity, higher UV levels are seen during the easterly phase of the QBO, and lower UV levels during the westerly phase. During minimum solar activity, this relationship is reversed. In the Dst case, taking into account that higher negative values correspond to stronger geomagnetic storms, it can be said that during maximum solar activity levels, higher geomagnetic activity coincides with the easterly phase of the QBO, and lower geomagnetic activity with the westerly phase. During minimum solar activity levels higher geomagnetic activity coincides with the westerly phase of the QBO, and lower geomagnetic activity with the easterly phase.

As another example, Fig. 2 shows the running correlation coefficients between the equatorial stratosphere QBO and the winter pole temperature at 50 hPa and between the QBO and the winter pole geopotential height at 100 hPa. Both pole parameters were obtained from the Berlin Stratospheric Data Series. Winter pole temperature at 30 and 100 hPa and geopotential height at 30 and 50 hPa present a behavior similar to that of Fig. 2. This data analysis, using stratosphere parameters, is discussed in detail by Kodera (1993), Soukharev (1997, 1999) and Salby and Callaghan (2004). The quasi-decadal variation in the running correlation series would imply that during maximum solar activity levels higher temperature and geopotential heights occur during the westerly phase of the QBO and lower temperature and geopotential heights take place during the easterly phase of the QBO. During minimum solar activity, this relationship is reversed.

Assuming that there is an association between the QBO and some stratosphere parameters and also between the QBO and some parameters linked to solar activity, the question is how can the transition from solar minimum to solar maximum change the sign of the association? There are some physical arguments, which can explain some or part of these observations. However, we do not intend here to explain the existence of physical processes by which the running correlation between the QBO and certain atmospheric and solar parameters show the observed decadal oscillation, implying a shift in the kind of association. Instead, we present a statistical play which generates the mentioned observations due to chance: the frequencies of the series involved happen to be those required by the statistical process to generate the observed result. Our results

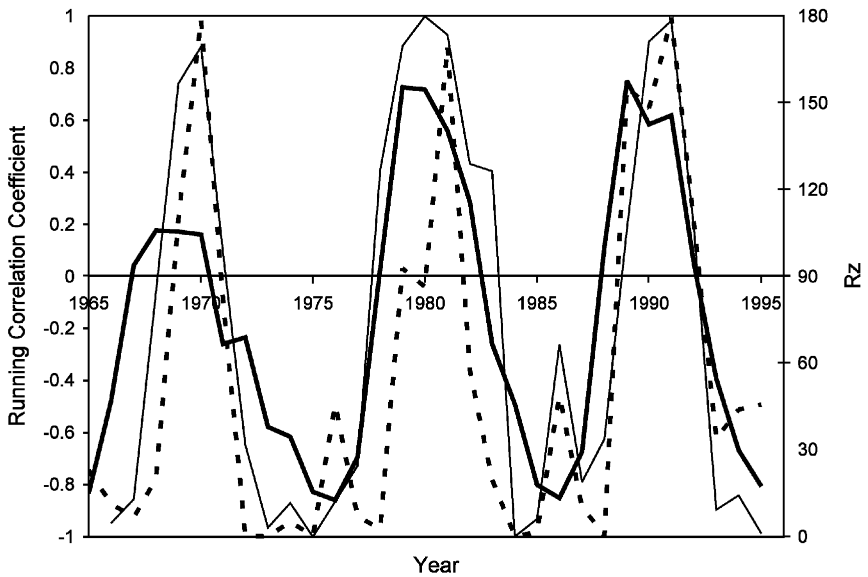

Fig. 2. Running correlation coefficient time series with a 3-year window-width between the monthly mean zonal equatorial wind QBO and winter pole temperature at 50 hPa (solid line), and between QBO and the winter pole geopotential height at 100 hPa (dashed line). Rz after a 12-month running mean (enhanced line).

do not rule out a physical origin, but just point out that a result obtained after a statistical analysis carries, in addition to the physics behind, the spurious byproducts of the method applied.

3. Statistical experiment

Two monthly sine series, $u(t) = \sin(\omega_1 t)$ and $y(t) = \sin(\omega_2 t)$, were artificially constructed where $u(t)$ stands for an "idealized" stratosphere QBO and $y(t)$ for any other time series. For different $u(t)$ quasi-biennial periods ($T_1 = 2\pi/\omega_1$), ranging between 2 and 3 years, and also for different $y(t)$ periods ($T_2 = 2\pi/\omega_2$), the running correlation r between $u(t)$ and $y(t)$ was estimated as (Kodera, 1993)

$$r_i = \frac{\frac{1}{M}\sum_{t=t_1-m}^{t_i+m}(y(t)-\bar{y})(u(t)-\bar{u})}{\sqrt{\frac{1}{M}\sum_{t=t_i-m}^{t_i+m}(y(t)-\bar{y})^2\,\frac{1}{M}\sum_{t=t_i-m}^{t_i+m}(u(t)-\bar{u})^2}}, \quad (1)$$

where $M = 2m+1$ is the window width (equal to 4 years in the present work, so $M = 49$ due to it must be odd) and the mean values of $y(t)$ and $u(t)$ correspond to:

$$\bar{y} = \frac{1}{M}\sum_{t=t_i-m}^{t_i+m} y(t) \text{ and } \bar{u} = \frac{1}{M}\sum_{t=t_i-m}^{t_i+m} u(t).$$

In this case the running correlation is like a beating between two waves, where the beat frequency depends on the difference in frequencies between the two sources (beat angular frequency = $\omega_1-\omega_2$). This can be deduced also from the result of the product of two sine functions: $\sin(\omega_1 t)\sin(\omega_2 t) = 1/2[\cos((\omega_1-\omega_2)t) - \cos((\omega_1+\omega_2)t)$, where the frequency $(\omega_1-\omega_2)$ determines the overall variation in r. The running correlation coefficients will oscillate then with a period T given by $T = T_1T_2/(T_1-T_2)$, where T_1 and T_2 are the periods of $u(t)$ and $y(t)$, respectively. This means that, assuming for example, a mean 2.4-year period for the QBO represented here by $u(t)$, any series with periodicities exceeding 2.4 by 0.6–0.8 years (i.e. between 3 and 3.2 years) or below it by 0.4–0.5 years (i.e. between 2 and 2.1 years) would result in a running correlation coefficients oscillating with a periodicity around 10–12 years. Fig. 3 shows, as an example, the running correlation between series of periodicities ranging between 1.8 and 2.8 years. It can be noticed in this case that a decadal modulation is obtained when the correlated series have periodicities of 2.4 and 2 years.

We can accurately estimate r in Eq. (1) by replacing summations by integrals. Then:

$$r = \frac{a_1 - a_2 - 4\frac{a_3 a_4}{m\omega_2\omega_1}}{\sqrt{\frac{1}{\omega_2\omega_1}\left(a_5 - 4\frac{a_3^2}{m\omega_2^2}\right)\left(a_6 - 4\frac{a_4^2}{m\omega_1^2}\right)}}, \quad (2)$$

where

$$a_1 = \frac{\sin[(\omega_2-\omega_1)(t_i+m)] - \sin[(\omega_2-\omega_1)(t_i-m)]}{2(\omega_2-\omega_1)},$$

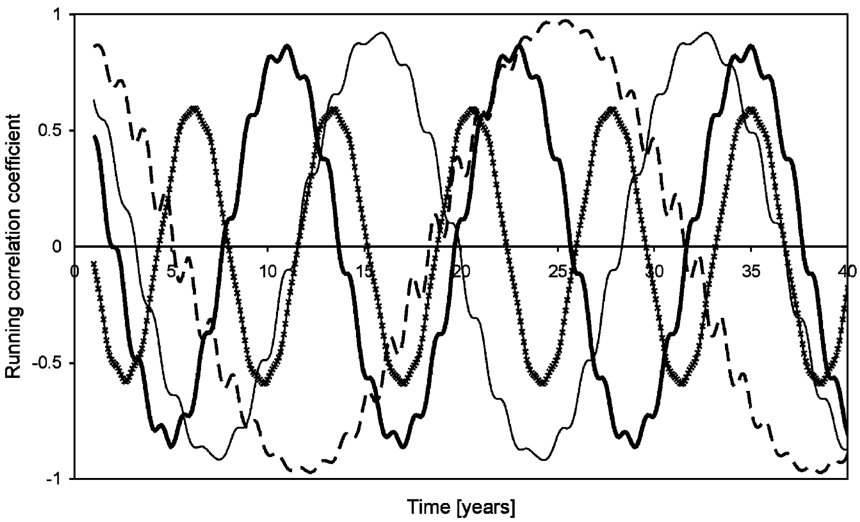

Fig. 3. Running correlation between monthly sine functions of periods 2.4 and 2.8 years (black thin line), 2.4 and 2.2 years (dashed line), 2.4 and 2 years (black enhanced line) and 2.2 and 1.8 years (black line with crosses). Window width $M = 49$ months.

$$a_2 = \frac{\sin[(\omega_2+\omega_1)(t_i+m)] - \sin[(\omega_2+\omega_1)(t_i-m)]}{2(\omega_2+\omega_1)},$$
$$a_3 = \sin(\omega_2 t_i)\,\sin(\omega_2 m),$$
$$a_4 = \sin(\omega_1 t_i)\,\sin(\omega_1 m),$$
$$a_5 = \omega_2 m - [\sin(2\omega_2 t_i)\,\cos(2\omega_2 m)]/2,$$
$$a_6 = \omega_1 m - [\sin(2\omega_1 t_i)\,\cos(2\omega_1 m)]/2.$$

In this way r is an oscillating function in terms of ω_1, ω_2, t_i and m. As already mentioned, for a given ω_1 there is a lower and a higher frequency ω_2 for which a quasi-decadal oscillation in r can be obtained.

In the case of time series linked to the solar activity cycle, as that used by Elias and Zossi de Artigas (2003), the sub-harmonics of the 11-year period which are around 2 and 3-year periodicities would be generating the quasi-decadal oscillation in the running correlation coefficient with the QBO. These periodicities are a result of the asymmetry in the 11-year solar activity cycle (it rises to maximum activity levels faster than it falls to minimum levels), whose spectrum presents peaks not only at the expected 11-year period, but also at its sub-harmonics corresponding to 5.5 years (11/5), 3.67 years (11/3), 2.75 years (11/4), etc. The filtering process of this kind of series reduces the amplitude of the 11-year peak, enhancing those corresponding to lower periods.

If the filtered series is approximated by $\alpha\sin(\omega_2 t)+\beta\sin(\omega_3 t)+\gamma\sin(\omega_4 t)$ where ω_2, ω_3 and ω_4 correspond to periodicities 11, 5.5 and 3.67 years, respectively, and α, β and γ to the corresponding amplitudes, we arrive to a function r in terms of α, β, γ, ω_1, ω_2, ω_3, ω_4, t_i and m. A quasi-decadal oscillation is obtained in r again with just one of the frequencies close to ω_1, and the corresponding amplitude not too different from the other two. Fig. 4 presents r considering $m = 24$, $\alpha = 2$, $\beta = 2$ and $\gamma = 1$, and $\omega_1 = 2\pi/2.8$, as an example. It is also shown the ideal case where the only frequency left in $y(t)$ after band-pass filtering is $2\pi/3.67$ years^{-1}. Changing the window width M $(2m+1)$ does not affect the periodicity of the oscillation in r; increasing the window decreases the oscillation amplitude. Varying α, β and γ, the following results are obtained: (a) when $\gamma \gg \alpha$ and β, the limit ideal case is obtained; (b) when α increases, the amplitude of the r-decadal modulation decreases without affecting the decadal period; and (c) when β increases, the decadal oscillation in r begins to be blurred being still clear until $\beta \approx 1.5\gamma$; for $\beta > 1.5\gamma$, the decadal oscillation disappears.

4. Statistical significance

The statistical significance of a computed sample correlation coefficient r for a sequence of N observations on two variables as in this case, y and u, can be computed through the t-statistic with a Student t distribution with $N-2$ degrees

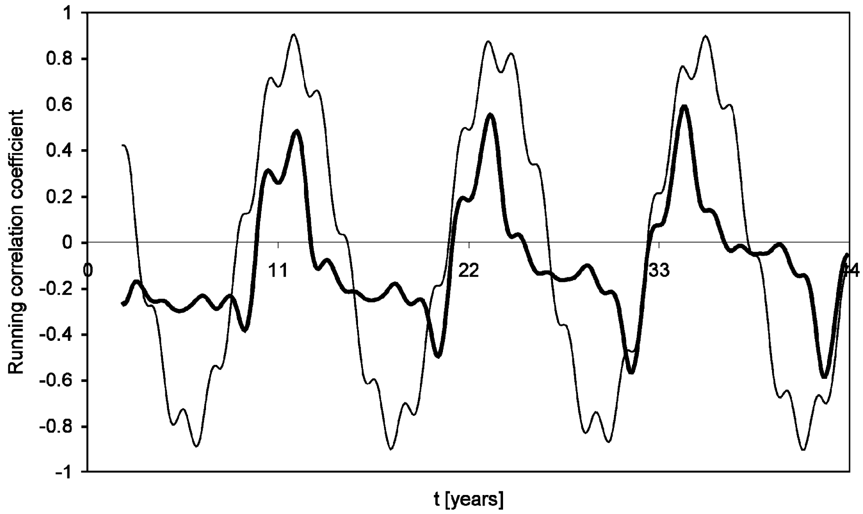

Fig. 4. Running correlation coefficient r estimated for $y(t) = \sin(2\pi/3.67t)$ (solid line) which corresponds to an ideal filtered asymmetrical solar activity cycle, where all the components with periodicities out of the filter bounds (like the 11- and 5.5-year components) are eliminated, and $y(t) = 3\sin(2\pi/11t) + 2\sin(2\pi/5.5t) + \sin(2\pi/3.67t)$ (enhanced line) which corresponds to a filtered asymmetrical solar cycle. Window width $M = 49$ months.

of freedom:

$$t = r\sqrt{\frac{N-2}{1-r^2}}.$$

For $N = 49$ (since a 4-year window means 48 monthly data but we use 49 due to M must be odd), a significance of 95% and 99% is obtained when r is greater than 0.25 and 0.37, respectively. For this test, the observations are assumed to be independent of one another. But observations in a time series are seldom independent. Autocorrelation essentially reduces the number of independent observations and an "effective" sample size should be used. An equation of the effective sample size for computation, N', of a correlation coefficient between two autocorrelated time series is given by $N' = N(1-r_{1y}r_{1u})/(1+r_{1y}r_{1u})$ (Ezekiel and Fox, 1959), where r_{1y} and r_{1u} are the first-order autocorrelation coefficients of time series y and u. In this case, a significance of 95% and 99% is obtained when r is greater than 0.32 and 0.5, respectively. In our case, r exceeds 0.6 (as can be noted in Figs. 3 and 4).

Another consideration that should be taken into account is that fluctuations in running or "sliding" correlations between two correlated time series are sometimes over-interpreted. Windowed correlations are expected to wander to some extent as a result of stochastic behavior. Gershunov et al. (2001) emphasize this point, and suggest that bootstrap methods be applied to evaluate significance of fluctuations in windowed correlation. In our case, considering that r fluctuates around zero, the bootstrapped confidence limits at a 95% significant level are ± 0.5, which means that the running correlation obtained here is more variable on decadal timescales than should be expected from sampling variability alone.

A phase shift in the correlation for a given window with significant correlation, reduces r values progressively with increasing lag, until it begins to increase again. This happens due to the nature of y and u, which are ideal sine functions.

5. Discussion and conclusions

The decadal modulation in the running correlation coefficient time series involving the QBO can result from a beating between the QBO period and a biennial or triennial cycle in the other correlated series. In time series associated to the 11-year solar cycle, these periodicities can be the effect of the asymmetry in the solar cycle which gain importance after a filtering process. A similar result has been obtained by Salby et al. (1997), who showed that a decadal oscillation in the running correlation between stratospheric QBO and polar temperature follows from an interaction (statistical, non-physical) between the QBO and the biennial cycle in polar temperature.

Salby and Callaghan (2000) found a decadal change in the duration of westerlies which results in shorter QBO's period near solar maximum and longer periods near solar minimum. According to them, this decadal modulation in QBO's period would introduce a drift into the relative phase between equatorial wind and Northern Polar temperature explaining the decadal modulation of the running correlation between them and also the decadal oscillation in stratified records of temperature. McCormack (2003) through a model also showed that the QBO period would be associated to the solar cycle with a tendency for westerly QBO phase to be shorter on average during solar maximum relative to solar minimum. This possibility of a decadal modulation of the QBO westerlies and easterlies duration is not taken into account in the present idealistic statistical experiment.

According to our results the quasi-decadal oscillation in the running correlation coefficient time series, involving the QBO, is not necessarily due to the solar activity cycle. In fact this oscillation could be obtained without any relationship between the analyzed series, or a decadal modulation in the "idealized" QBO. However it should be taken into account the pure statistical character of the present study and the idealization of the series considered. As stated by Pittock (1978) in his analysis of statistical problems dealing with Sun–climate associations, a "step by step investigation of hypothetical mechanisms" should be made before arriving to any conclusion.

Acknowledgements

We acknowledge K. Labitzke and Collaborators, 2002: The Berlin Stratospheric Data Series, CD from Meteorological Institute, Free University Berlin. The authors thanks to anonymous referees for valuable and critical comments which improved this paper, and deeply acknowledges the useful suggestions and encouraging support of Katie Coughlin. Ana G. Elias thanks the Local Organizing Committee of IAGA 2005 and CAWSES (through Jan Lastovicka), for the financial support provided to attend the IAGA 2005 meeting and present this work.

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