A Determination of Balanced Normal Modes for Two Models

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ABSTRACT

Two versions of the NOGAPS model are used to generate normal-mode balanced datasets. The various forces that act on gravitational modes are then examined to determine the modes whose coefficient time tendencies are significantly smaller than terms which force them. Those modes are said to be balanced. Results for three different equivalent depths are presented. They indicate that only modes with natural periods shorter than one day appear balanced. That balance is adiabatic. These results agree with those reported by Errico for the NCAR CCM.

1. Introduction

The question of which atmospheric modes are dynamically balanced is an important one yet to be adequately answered. Its answer has direct applications to outstanding problems in numerical weather prediction (NWP); e.g., to which modes should nonlinear normal-mode initialization be applied, and what diagnostic relationships should an accurate analysis satisfy. Unfortunately, present observing systems are not sufficiently accurate or dense to enable direct investigation of this question. We can instead examine model-simulated data, which are accurately known and for which the governing physics is also well known. If the model is one used for NWP, then it is relevant to investigate its balance since it will tend to its own balance, even if it is different than that of the atmosphere. Such a study also contributes to understanding the effects of both physical and dynamical processes in the model.

This note is an extension of the study by Errico (1984). He investigated the forces acting on gravitational normal modes as simulated by the Community Climate Model (CCM version 0B) at the National Center for Atmospheric Research (NCAR). That model was low resolution (rhomboidal spectral truncation at zonal wavenumber 15, with nine levels in the vertical). Therefore, one remaining question has concerned the extension of his results to higher resolution. Also, the extent to which his results depended on the physics peculiar to the CCM was unknown. Both these questions are addressed here.

2. Model description

The present study uses as one model version 2.2 of the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS). This version has been described by Rosmond (1981). It is based on the general circulation model developed at the University of California at Los Angeles (Arakawa and Lamb 1977). Important for this study are that it includes: a resolution of 120 longitudes \( \times 76 \) latitudes \( \times 9 \) levels; the parameterized convection scheme described by Arakawa and Schubert (1974); the parameterized boundary layer described by Randall (1976) and Lord (1978); Fourier filtering near the poles; and a time integration scheme which combines centered and Matsuno-backward differences (the latter to limit generation of time-computational modes). The model is integrated for 20 days beginning from an analysis for 3 October 1987. By this time, the model data are expected to have achieved a natural dynamic balance, consistent with the model physics (as suggested by Errico 1984). This dataset will be denoted case 1.

As a second model, version 3.0 of NOGAPS is also used to simulate data. This is a recently developed spectral model by Rosmond and Hogan of NEPRF. The importance here is that it includes: a triangular spectral truncation at wavenumber 47 corresponding to a Gaussian grid of 144 longitudes \( \times 72 \) latitudes, defined on 18 levels; the parameterized convection

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scheme described by Arakawa and Schubert (1974); the parameterized boundary layer described by Louis (1979) and Louis et al. (1982), and a semi-implicit time scheme. Since it is a spectral model, it requires no additional Fourier filtering near the poles. For this model, data are produced from a 20-day forecast begun from 15 December 1985. This dataset will be denoted case 2. An initial time different than for case 1 has been chosen due to data availability.

The normal modes of each model are determined using a linearization about a resting, standard atmosphere. The modes are separated into types based on their frequencies $\omega$ (determined as eigenvalues). By expressing the eigenvalue problem in the proper form, a convention is established for the modes whereby the third with the greatest negative frequencies are westward gravitational (WG) modes; the third with positive-valued frequencies are eastward gravitational (EG) modes; the remaining third are rotational (RT) modes. According to this determination, Kelvin modes are type EG and mixed Rossby–gravity modes are type RT.

The vertical structures are denoted by index $l$ with values $1, \ldots, L$, ranging from largest to smallest equivalent depths, respectively ($l$ therefore indicates the external mode, and $L$ equals the number of model data levels). Zonal wavenumber 0 modes are excluded from consideration here, and for case 1, the $2\Delta x$ (zonal wavenumber 60) modes were also excluded. The modes are further separated into ones with $u$ (eastward wind component) and $\varphi$ (zonal component) either symmetric (SYM) or antisymmetric (ASY) about the equator. For version 2.2 of NOGAPS, the modes are determined as described in Barker (1982) following Temperton and Williamson (1981). For version 3.0, the determination follows Andersen (1977) instead, since it is for a spectral model. Only symmetric modes are presented for case 1 (due to programming considerations), but both symmetric and antisymmetric modes are presented for case 2.

Since the grid-point version of NOGAPS uses a staggered horizontal grid, computational modes having strong $2\Delta x$ components as described by Williamson and Dickinson (1976) are absent from the set of modes in case 1. Temperton and Williamson (1981) noted a similar result for the staggered grid-point model they used. However, due to the truncation in both the spectral and grid-point models, some modes should be considered computational, in the sense that both their structures and frequencies vary significantly as the model resolution is altered. This dependence on horizontal resolution becomes greater as more shallow modes are considered. In particular, the latitudes at which the most shallow modes are trapped depend strongly on horizontal truncation. Therefore, although these modes are the true model modes, they can be considered computational in the sense that they may be substantially different than those modes which would be determined for a continuous (nontruncated) system.

3. Methodology

The prognostic equation for a normal mode coefficient (i.e., complex amplitude) $c_j$ may be schematically written as

$$\frac{dc_j}{dt} = -i\omega_j c_j + N_j + C_j + D_j,$$

where $t$ is time, $i = \sqrt{-1}$, $N$ denotes all nonlinear adiabatic terms, and $C$ denotes all diabatic terms, excluding $D$ which denotes the boundary layer and dissipation terms. In particular, the convective heating rates project onto $C$. A mode $j$ is said to be balanced if an appropriate mean (denoted by an overline) of $dc_j/dt$ is significantly less than the largest of the similar means computed for each term on the right hand side (rhs) of (1). If this inequality is true, then some other term must balance (i.e., compensate for) the large term on the rhs, since all terms on the rhs must add to produce the small tendency. When such a type of balance exists, the largest term on the rhs is typically either $\bar{ioN}$ or $N$.

The various terms in (1) are computed using a greatly simplified version of the method of Errico (1984). In case 1, the tendency $dc_j/dt$ is computed by 1) running the model one additional (forward) time-step $\Delta t$ starting at some particular time ($t_d$) of the simulated data and including all physical parameterizations, 2) determining coefficients for both forecast and simulated data by simple projection onto the modes, and 3) computing

$$\left.\frac{dc_j}{dt}\right|_{\text{all}} = \frac{c_{\text{all}}(t_d + \Delta t) - c_{\text{sim}}(t_d)}{\Delta t},$$

where the subscript "all" indicates that all physics has been included and the subscript "sim" refers to values produced by the simulation. If the previous steps are repeated with the boundary-layer and dissipation parameterizations excluded from the model after time $t_d$, then the result of (2) is the sum

$$\left.\frac{dc_j}{dt}\right|_{\text{noD}} = -i\omega_j c_j + N_j + C_j,$$

and $D_j$ can then be computed as the residual

$$D_j = \left.\frac{dc_j}{dt}\right|_{\text{all}} - \left.\frac{dc_j}{dt}\right|_{\text{noD}}.$$

Analogously, if those steps are repeated a third time with all diabatic parameterizations excluded, the result is

$$\left.\frac{dc_j}{dt}\right|_{\text{noC+D}} = -i\omega_j c_j + N_j,$$
and \( C_J \) can then be computed as the residual
\[
C_J = \frac{dc_J}{dt} \bigg|_{t_n = D} - \frac{dc_J}{dt} \bigg|_{t_n = C + D}.
\] (6)

Also, since both \( \omega_j \) and \( c_J(t_d) \) are known, the linear term is easily computed as \(-\omega_j c_j(t_d)\), followed by the determination of \( N_j \) as the residual
\[
N_j = \frac{dc_J}{dt} \bigg|_{t_n = C + D} + \omega_j c_j(t_d).
\] (7)

All the terms are thereby determined, although no corrections have been added to account for discrepancies between starting the model and continuing a forecast (which yield different tendencies due to the models’ two-time level integration schemes). By ignoring these corrections, results may be biased toward absence of balance for modes whose frequencies are near the resolvable limit of the model (and thereby more affected by the time scheme). For case 2, (2) was computed using a centered difference at time \( t_d \) by actually comparing data from the model at three successive times, but tendencies for the model with physics removed were computed as in (2).

Since the simulations include all model physics, the values of \( c_{J,\text{sim}} \) and any balances are a result of the action of all the physics. The method of subsequently restarting the model at a time \( t_d \) and removing none or part of the model physics is only used to determine values of the various terms at time \( t_d \). The simplicity of the method is that the terms are thereby determined without modifying the standard model output.

Mean values of the magnitudes of various terms in (1) are computed as, for example,
\[
\bar{N}_k = \left( \sum_{j \in S_k} N_j^* N_j \right)^{1/2},
\] (8)

where \( S_k \) is a set of modes having similar natural frequencies (\( \omega_j \)) and identical vertical structures, and an asterisk indicates complex conjugate. The \( S_k \) are determined by ordering all the modes of a given type and vertical structure in terms of frequency, from smallest to largest magnitude, and then associating the index \( k = 1 \) with the first 59 of them, \( k = 2 \), with the next 59 of them, etc., through \( k = 39 \). (For case 2, there were 28 modes in each of 40 sets, except the last set which contained 36 modes.) For WG and EG modes, smaller values of \( k \) are thereby associated with larger horizontal scale (since the scale-dependence of their frequencies is like that of gravity waves), whereas for the RT modes, smaller values of \( k \) are associated with smaller horizontal scale (since the scale-dependence of their frequencies is like that of Rossby waves). This averaging over sets of modes was done to reduce the amount of data to be inspected. It was assumed that modes of similar scale would have sufficiently similar behavior so that the summing method was appropriate (as based on results reported in Errico 1984). Values of terms for individual modes were also examined to ensure the representativeness of the averaged results.

In order to facilitate presentation of the results, the mean magnitudes of the various terms for each \( S_k \) are normalized by the factor
\[
E_k = \left( \sum_{j \in S_k} c_j^* c_j \right)^{1/2},
\] (9)

which is the square root of twice the sum of the kinetic plus available potential energy contributed by the set \( S_k \). These normalized mean magnitudes will be denoted by tildes, as for example
\[
\tilde{N}_k = \frac{N_k}{E_k}.
\] (10)

These normalized values will be presented as functions of the geometric-mean frequency
\[
\tilde{\omega}_k = \left( \prod_{j \in S_k} |\omega_j| \right)^{1/M_k},
\] (11)

where \( M_k \) is the number of modes in set \( S_k \).

The method described in this section is similar to that used by Errico (1984) with some important exceptions. No time averages are considered in the computation of mean magnitudes here. Errico determined the diabatic forcing of the modes by direct projection of fields of forcing which were computed and output by his model, rather than by using the restart technique as described here. This restart technique is similar to the one used by Errico for separating the adiabatic forcing into contributions by rotational and gravitational modes. No such separation is done here.

4. Results

Spectra of terms for the two NOGAPS models for selected equivalent depths appear in Figs. 1–6. Due to the normalization (10), the linear term always appears as nearly a straight line of slope 1. For the same reason, it is only meaningful to compare spectra for identical values of \( k \). In particular, the normalized magnitudes of the same terms for different frequencies should not be compared. The presentation is designed to facilitate comparison of different terms for modes of similar frequency. The spectra in each figure are labeled as: \( i\omega_c \) (A); \( \tilde{N} \) (B); \( \tilde{C} \) (C); \( \tilde{D} \) (D); \( \tilde{dc}/dt \) (E). Only spectra for \( t_d = 20 \) days are presented, although other times were examined.

The spectra of normalized mean magnitudes of terms for \( l = 1 \) (external) WG modes for case 1 appear in Fig. 1. For \( \tilde{\omega} > 3 \times 10^{-3} \) s
\(-1\), \( \tilde{i}\omega_c \approx \tilde{N} \approx 20 \tilde{dc}/dt \). This indicates that adiabatic nonlinear balance is very accurate (5% error) for these modes. For \( \tilde{\omega} \approx 8 \times 10^{-4} \) s
\(-1\), \( \tilde{i}\omega_c \approx \tilde{N} \approx 8 \tilde{dc}/dt \). This indicates that adiabatic
nonlinear balance is also accurate (12% error) for these modes. However, for \( \mathbf{\omega} \approx 4 \times 10^{-4} \, \text{s}^{-1} \), or \( \mathbf{\omega} \approx 1.3 \times 10^{-3} \, \text{s}^{-1} \), \( \mathbf{i} \mathbf{w} \mathbf{c} \approx 2 \mathbf{d} \mathbf{c} / \mathbf{d} \mathbf{t} \). For these modes, neither adiabatic nor diabatic balance is a good approximation because the time-tendency term in (1) is not negligible compared to terms on the rhs. The reason for the imbalance at these frequencies is unclear, but will be discussed later. For the external modes, all diabatic terms are small at any time compared to the individual adiabatic terms. The apparent peak in the spectra of \( \mathbf{c} \) and \( \mathbf{D} \) at \( \mathbf{\omega} \approx 1.5 \times 10^{-3} \, \text{s}^{-1} \) is partly an artifact of the normalization of terms, and any discussion of such

Fig. 1. Spectra of terms for \( l = 1 \) WG modes for case 1.
Labels A–E are for terms \( \mathbf{i} \mathbf{w} \mathbf{c}, \mathbf{N}, \mathbf{\dot{c}}, \mathbf{\dot{D}}, \mathbf{d} \mathbf{c} / \mathbf{d} \mathbf{t} \), respectively.

Fig. 3. As in Fig. 1 but for \( l = 9 \) WG modes of case 1.

Fig. 2. As in Fig. 1 but for \( l = 3 \) EG modes of case 1.

Fig. 4. As in Fig. 1 but for \( l = 1 \) WG modes of case 2.
Both rotational and gravitational modes for all equivalent depths were examined. Only a small sample of results have been presented because these reflect the range of behaviors observed. The particular values of \( l \) were chosen because their associated equivalent depths correspond most closely to those of the modes presented in Errico (1984). The conclusions to be made after considering other gravitational modes will be discussed at the end of this section. No rotational modes have been included in our presentation because our interest regards balanced modes, which excludes all rotational modes except some large-depth Rossby–gravity modes (McAtee 1987), and because other results regarding rotational modes are in agreement with Errico (1984).

A case 1b was also examined. It used the same NOGAPS version as case 1, but was applied to data for 11 December 1985. Results for case 1b were similar to those for case 1. In particular, for \( l = 1 \), the lack of balance near \( \bar{\omega} \approx 4 \times 10^{-4} \text{ s}^{-1} \) and \( \bar{\omega} \approx 1.3 \times 10^{-3} \text{ s}^{-1} \) was also observed. For \( l = 3 \), the ratios between \( \bar{\omega} \) and \( d\bar{c}/dt \) were typically 25% smaller for case 1b than for case 1 for those modes which appeared adiabatically balanced. (Even so, those ratios were still as large as 10). Results for \( l = 9 \) varied even less between the cases. Other cases were also examined during the time we developed our procedures. The strong similarities suggest that the presented results are not case dependent, and that our results have not been significantly affected by a lack of time averaging as done by Errico (1984).

In Fig. 3, the spectra of normalized mean magnitudes of terms are presented for case 1, \( l = 9 \) WG modes. These modes have an equivalent depth of 0.36 m. At the largest horizontal scales (the left side of the figure), \( \bar{\omega} \approx \delta / \bar{c} / dt \). The linear term is small simply because \( \omega \) is small when both the equivalent depth is small and the horizontal scale is large. Most of these modes are equatorially trapped, so shallow tropical convection projects strongly on them. Although the diabatic effects are large, they act to actually change the mode amplitude in time rather than affect the mode in a quasi-balanced manner. At smaller horizontal scales (\( \bar{\omega} > 4 \times 10^{-3} \text{ s}^{-1} \)), the diabatic terms are less important, and neither a diabatic nor adiabatic balance exists.
The spectra of normalized mean magnitudes of terms for \( l = 1 \) WG modes for case 2 appear in Fig. 4. All modes appear well balanced since \( \tilde{\omega}c > 10 dc/dt \) for all \( \tilde{\omega} \). The balance is adiabatic. For these external modes, the convective and boundary layer diabatic processes are weak compared to the adiabatic (advective) processes. Notice that the largest value of \( \tilde{\omega} \) is nearly 10 times smaller than in Fig. 1, but the smallest value is twice as large. This result is due to a combination of the equivalent depth for the \( l = 1 \) modes in case 1 being 20% larger than in case 2 (the \( \omega \) are approximately proportional to the square root of the equivalent depth) and to the finer resolution of case 1 (its grid is smoothed less), which results in a significantly different selection of modes for each set \( S_l \).

In Fig. 5, the spectra of normalized mean magnitudes of terms are presented for case 2, \( l = 5 \) EG modes. These modes have an equivalent depth of 137 m. Note that the medium-depth modes with small horizontal scales which appear balanced in Fig. 2 (case 1) do not exist at a similar equivalent depth in case 2, due to the lower resolution of case 2. Therefore, none of the modes in Fig. 5 appear significantly balanced (\( \tilde{\omega}c < 2 dc/dt \) for almost all \( \tilde{\omega} \)).

The spectra of normalized mean magnitudes of terms for \( l = 15 \) WG modes for case 2 appear in Fig. 6. These modes have an equivalent depth of 0.36 m. No modes appear balanced. For this model, diabatic forcing by parameterized boundary-layer processes appears greater, at this vertical scale, than does forcing by convection.

All of the figures presented here may be compared with corresponding ones in Errico (1984): his 6 with our 1 and 4; his 8 with our 2 and 5; and his 9 with our 3 and 6. His spectra of \( \tilde{N}(r) + \tilde{N}(r^*g) \) and \( \tilde{F} \) may be respectively interpreted as our \( \tilde{N} \) and \( \tilde{C} + \tilde{D} \). Errico's results for the external modes resemble those of case 2 (Fig. 4). All are well balanced. In particular, no imbalance is observed near \( \tilde{\omega} \approx 1.3 \times 10^{-3} \text{s}^{-1} \) as observed for case 1 (Fig. 1). Instead, at those scales in Errico, \( \tilde{\omega}c \approx 80 dc/dt \), which is an even greater ratio than observed in case 2; i.e., the external mode in Errico appears to be even more balanced than in the NOGAPS spectral model.

The imbalance observed in case 1 near \( \tilde{\omega} \approx 1.3 \times 10^{-3} \text{s}^{-1} \) appears to be a model result, independent of the particular simulation. The adiabatic physics in the two NOGAPS models and the CCM should be somewhat equivalent, and the two NOGAPS models have the same convective parameterizations. Therefore, it is unclear what process generates the imbalances in case 1. The model in case 1 includes a Fourier filter applied near the poles for computational purposes, and it was thought that perhaps it affected the balance. However, its effect at the scales in question is minimal. A more likely explanation is that the periodic application of a Matsuno time-step every hour generates an artificial force of that period, to which gravitational modes with a similar period respond resonantly. The smaller peaks which appear at higher frequencies may similarly be due to the harmonics of that same force. This result was not examined further.

At equivalent depths near 150 m, neither Errico (1984) nor case 2 (Fig. 5) indicate strong balance. However, at the smaller horizontal scales which exist only in case 1, strong balance is observed. This is likely because the resonant periods of those modes are less than a few hours, which are very short periods with respect to the periods of the dominant atmospheric forcing at those scales. Although the structure of convective forcing may appear to project strongly on these mid-depth modes, many of these small horizontal-scale modes are extratropically trapped, such that they can only weakly feel effects of any tropical forcing, where convection is greatest. Therefore, the projection of high-frequency convective forcing on these modes is weaker than the projection of low-frequency adiabatic forcing. The net result is an adiabatic balance for these modes. Note that in Errico's result (and less so in case 2), there is also evidence of a similar balance existing at the smallest resolved horizontal scales.

Regarding very shallow modes (equivalent depths near 0.3 m), the lack of balance observed in either NOGAPS model is a significantly different result compared to the diabatic balance observed in the CCM. The former include a diurnal radiation cycle and a highly nonlinear boundary-layer parameterization, unlike in the CCM, which has no diurnal cycle and an approximately linear, boundary-layer parameterization. These differences in physics likely yield boundary-layer forcing of higher frequencies in NOGAPS compared within the CCM. For the latter, the boundary-layer forcing may have frequencies similar to those of Rossby waves, since it is characterized by frictional imbalances and Ekman pumping determined by the quasi-geostrophic flow. The NOGAPS results may be more atmospheric-like, since its parameterizations are thought to be more realistic.

Results for the first internal modes (\( l = 2 \)) in each model were similar to those of the corresponding external modes. Results for equivalent depths less than 10 m were similar to those for the shallowest modes presented here. Results for other medium-depth modes were also similar to those presented for depths near 150 m. These similarities agree with those described in Errico (1984). That report should be consulted if further details of the CCM results are desired.

5. Summary and conclusions

The dynamical forcing and responses of gravitational modes were investigated with two global atmospheric simulation models: the NOGAPS grid-point model and
the NOGAPS spectral model. Results were compared with those reported by Errico (1984) for the NCAR CCM. All the models had different resolutions and physical parameterizations, although some similarities existed (in particular, both NOGAPS models used the convection scheme described by Arakawa and Schubert 1974). Dynamic fields and tendencies were examined after long integrations, so that each model had sufficient time to develop a dynamic balance consistent with its own adiabatic and diabatic processes.

Deep modes in all the models were very well balanced, with the exception of some modes in the NOGAPS grid-point model. The reason for the imbalance observed in that NOGAPS model was unclear. It did not appear to be due to convective or boundary-layer effects, nor due to Fourier-filtering at the poles, but was likely an effect of the periodic application of a Matsuno time-step. The deepest gravitational modes all had high resonant frequencies, corresponding to natural periods shorter than 1 day.

For medium-depths (near 100 m), small horizontal scale modes (corresponding to natural periods shorter than 4 hours for the NOGAPS grid-point model) also appeared balanced. The location of the scale (or period) cutoff which separated balanced modes from unbalanced modes was model dependent, perhaps due to resolution. For none of the medium-depth modes was any diabatic balance indicated. Either the convective forcing of the mode was weak (in the case of small horizontal scale, extratropical modes), or where it was strong, no balance existed because the mode tendency was non-negligible. This property is further discussed in Errico (1984) and in Errico and Rasch (1988).

A diabatic balance (which excluded convection) was observed for the shallowest modes in the NCAR CCM as reported by Errico (1984). No such balance existed in either NOGAPS model. This result is easily explained as due to the higher frequencies of the boundary-layer forcing in the latter models due to their diurnal cycle (absent in the CCM) and nonlinear parameterization of the planetary boundary layer. Since inclusion of those parameterizations is more realistic than their absence in the CCM, the lack of boundary-layer balance may be more indicative of the real atmosphere than the balance reported for the CCM.

In conclusion, it appears that the nonlinear normal-mode balance produced and maintained by models used for numerical weather prediction is characteristically adiabatic. For large vertical scales, all horizontal scales appear balanced, but as the vertical scale decreases, the horizontal scales at which balance is observed decreases. This is consistent with the view that only modes whose natural periods are shorter than some cutoff value should be initialized using a normal-mode procedure. It also appears that appropriate cutoff values should be vertical-mode dependent.

This conclusion is not to imply that some type of diabatic initialization may not improve forecast skill relative to some adiabatic scheme. For example, if slow modes such as internal Kelvin modes are very poorly analyzed, then even imposing an unrealistic diabatic balance may tend to reduce analysis errors by at least producing initial amplitudes of reasonable magnitude. Similar improvements have been shown for unrealistic imposition of linear or nonlinear balance of external modes when the analysis errors are great (e.g., see Washington and Baumhefner 1975; Daley et al. 1981; Errico and Rasch 1988). However, the improvement is not an indication of any appropriateness of diabatic balance. In fact, imposing such a balance probably masks the real (analysis) problem, with the result that further research may be hindered.

The conclusions in this report have simple explanations regarding the mathematical similarity between gravity waves and forced and damped harmonic oscillators. (For details see Errico and Rasch 1988.) Therefore, they are expected to be applicable to other simulation models and perhaps also to the atmosphere. The analysis method used here is necessary for a proper determination of which modes to initialize for numerical weather prediction (but it is only one step in that determination). The method is easy to apply once a model and normal-mode (or equivalent) initialization scheme exist. For these important reasons, it is recommended that other investigators duplicate this study with their models, to learn more about their models, to learn more about the atmosphere, and to help answer the question of how to properly apply nonlinear normal-mode initialization.

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