Π-theorem generalization of the ice-age theory

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Abstract.

Analyzing a dynamical system describing the global climate variations requires, in principle, exploring
a large space spanned by the numerous parameters involved in this model. Dimensional analysis is
traditionally employed to deal with equations governing physical phenomena to reduce the number of
parameters to be explored, but it does not work well with dynamical ice-age models, because, as a rule, the
number of parameters in such systems is much larger than the number of independent dimensions. Physical
reasoning may however allow us to reduce the number of effective parameters and apply dimensional
analysis in a way that is insightful. We show this with a specific ice-age model (Verbitsky et al, 2018)
which is a low-order dynamical system based on ice-flow physics coupled with a linear climate feedback.
In this model, the ratio of positive-to-negative feedback is effectively captured by an adimensional number
called the "*V*-number", which aggregates several parameters and, hence, reduces the number of governing
parameters. This allows us to apply the central theorem of the dimensional analysis, the π-theorem,
efficiently. Specifically, we show that the relationship between the amplitude and duration of glacial cycles
is governed by a property of scale-invariance that does not depend on the physical nature of the underlying
positive and negative feedbacks incorporated by the system. This specific example suggests a broader idea,
that is, the scale invariance can be deduced as a general property of ice age dynamics, if the latter are
effectively governed by a single ratio between positive and negative feedbacks.

1. Introduction.

Mathematical modeling of Pleistocene ice ages using astronomically forced spatially-resolving models
of continental ice sheets, the ocean, and the atmosphere has always been, and remains a computational
challenge. Therefore, though higher resolution models (e.g., Abe-Ouchi et al, 2013) and models of
intermediate complexity (e.g., Verbitsky and Chalikov, 1986, Chalikov and Verbitsky, 1990, Gallée et al.,
1991, Ganopolski et al, 2010) are gaining popularity, it has been argued for a long time that significantly
less computationally demanding dynamical models may provide just as much insight as the models with
more degrees of freedom (Saltzman, 1990). However, even though the computational load for solving
dynamical equations is minimal, the work and number of experiments needed for spanning the full
parameter space is easily overwhelming. Analyzing a dynamical system of ice ages is thus, in principle, a
difficult task. In mathematical physics, the method of dimensional analysis (e.g., Barenblatt, 2003) has
been traditionally employed to take advantage of symmetry or invariance principles and, as a result, to
reduce the number of effective parameters. It has not been applied to low-order models of the global
climate dynamics, because in such models the number of governing parameters is much larger than the
number of independent dimensions. Indeed, the number of independent dimensions in a dynamical system
does not exceed the number of variables (it may be smaller if some variables have the same or dependent
dimensions), to which one adds time, which is always present in a dynamical system. For example, the
dynamical system of Saltzman and Verbitsky (1993) described the evolution of 4 variables: ice volume
(m^3), CO_2 concentration (ppm), ocean temperature (^oC), and bedrock depression (m). The number of
independent dimensions, including time, was thus 4. This system had 18 parameters, including the
amplitude and the period of the external forcing. In such case, the π-theorem (Buckingham, 1914) — the
tenet of dimensional analysis — is of little help to simplify the analysis and effectively provide physical
insight.

In Verbitsky et al (2018), we derived a dynamical model of the Pleistocene climate from the scaled
conservation equations of viscous non-Newtonian ice, and combined them with an equation describing the
evolution of the climate temperature. The work was motivated by the prospect of delivering a low-order,
parsimonious approach to the problem of understanding glacial-interglacial cycles. The state of the ice-
climate system is summarized by a 3-dimensional vector: glaciation area S (m^2), ice sheet basal temperature

θ (^{o}C), and climate temperature ω (^{o}C). The number of independent dimensions, including time, is thus 3. However, despite our effort to be parsimonious in the physical description, the model includes 12 parameters, which is still much larger than the number of independent dimensions. This was an obvious progress relative to the Saltzman and Verbitsky (1993) model, but not enough for an effective use of the π-theorem. The situation changed dramatically when we discovered that the dynamical properties of the system are largely defined by the dimensionless V-number incorporating 8 model parameters and measuring the ratio of climate positive feedback over the ice sheet's own negative feedback. At once, 7 parameters are effectively eliminated, and using the π-theorem became an attractive prospect. We first applied the π-theorem reasoning to investigate the propagation of millennial forcing into ice-age dynamics (Verbitsky et al, 2019a) and found that the millennial forcing introduces a disruption, i.e., shifts the system equilibrium point, and this disruption is proportional to the second degree of the forcing period.

In this paper we will apply this approach systematically to all model variables. This will allow us to demonstrate that, in the model, glacial area and climate temperature are scale invariant in the orbital frequencies domain (in the case of the climate temperature – even beyond this domain), and observe that this property does not depend on the specific physical nature of the climate system feedbacks.

Accordingly, our paper is structured as follows. First, we will briefly recapture equations, parameters, and dimensions of the Verbitsky et al (2018) model. Then we will remind the essence of the π-theorem, apply it to all model variables, and discuss its implications.

2. A dynamical model of Pleistocene glacial rhythmicity.

The non-linear dynamical model of the global climate system (Verbitsky et al, 2018) is derived from the scaled equations of ice sheet thermodynamics, combined with a linear feedback equation involving an effective "temperature", which describes the climate state outside the ice region.

$$\frac{dS}{dt} = \frac{4}{5}\zeta^{-1}S^{3/4}(a - \varepsilon F_S - \kappa\omega - c\theta) \tag{1}$$

$$\frac{d\theta}{dt} = \zeta^{-1}S^{-1/4}(a - \varepsilon F_S - \kappa\omega)\{\alpha\omega + \beta[S - S_0] - \theta\} \tag{2}$$

$$\frac{d\omega}{dt} = \gamma_1 - \gamma_2[S - S_0] - \gamma_3\omega \tag{3}$$

The model variables and their dimensions are defined as follows: S (m^2) is the glaciation area, θ (^{o}C) is the basal ice sheet temperature, and ω (^{o}C) is the effective global climate temperature. The third equation implicitly accounts for the effect of the response of CO_2-concentration, along with other radiative feedbacks.

Model parameters along with their dimensions are: ζ (m$^{1/2}$) is the "shape" factor of the ice sheet; a (m/s) is the characteristic rate of snow precipitation; F_S is normalized mid-July insolation at 65°N (Berger and Loutre, 1991); ε (m/s) is the amplitude of the external forcing; κ (m s^{-1} ^{o}C^{-1}) and c (m s^{-1} ^{o}C^{-1}) are sensitivity parameters, describing, correspondingly, climate temperature and basal sliding impacts into ice-sheet mass balance; the dimensionless coefficient α describes basal temperature sensitivity to global climate temperature changes, coefficient β (^{o}C /m^2) defines basal temperature dependence on ice sheet dimensions, S_0 (m^2) is a reference glaciation area; γ_1 (^{o}C/s), γ_2 (^{o}C m^{-2} s^{-1}) and γ_3 (s^{-1}) define climate temperature evolution, $1/\gamma_3$, being a time constant. If the forcing is periodic, then we may consider that the system dynamics is described by an additional parameter: the forcing period T (s). Thus we have a system of 3 variables, 3 (including time) independent dimensions, and 12 parameters. The system (1) – (3) is not sensitive to initial conditions and, therefore, we do not include the latter into the list of parameters.

Physical reasoning and numerical experiments (Verbitsky et al., 2018) led to the suggestion that the system response is essentially determined by the V-number measuring a balance between positive and negative model feedbacks:

$$V = \frac{1}{\beta}\left(\alpha + \frac{\kappa}{c}\right)\left(\frac{\gamma_2}{\gamma_3} - \frac{\gamma_1}{S_0\gamma_3}\right) \tag{4}$$

Here parameter β is a measure of ice-sheet negative feedback. The term $(\alpha+\kappa/c)(\gamma_2/\gamma_3 - \gamma_1/\gamma_3/S_0)$ measures the climate system positive feedback (Verbitsky et al, 2018).

If we assume that the *V*-number effectively captures the behavior of the model with respect to the 8 parameters included in its definition, then the number of parameters is effectively reduced to 5: $V, \zeta, a, \varepsilon,$ and T. We assume further that parameter ζ in equations (1) - (2) is a constant, thus assuming an invariant relationship between ice thickness H and glaciation area S ($H = \zeta S^{1/4}$, Verbitsky et al, 2018). We also

5 note that the *V*-number has been assembled using components of the steady-state solution of the system (1) – (3) (Verbitsky et al, 2018). Obviously, parameter ζ, as a multiplier, is not part of this steady-state solution. Therefore our hypothesis that the *V*-number defines the model's behavior, in fact also includes the assumption that the impact of the parameter ζ on the system behavior, at the reference value, is weak. As a result, we end up with the assumption that the system's response to external forcing is essentially

10 determined by no more than four parameters: $V, a, \varepsilon,$ and T. We will now learn how to take profit of this advantage.

3. Dimensional analysis of model variables.

15 **3.1 Period of the system response to the external forcing, *P*.**

We previously noticed (Verbitsky et al, 2018), that with weak climate positive feedback ($V\sim0$), the system, exhibits fluctuations in response to the astronomical forcing with a dominating period of about 40 kyr, which may arise either as direct response to obliquity, or as a doubled-period response to the forcing

20 associated with climatic precession (2 x 20 kyr). When the climate positive feedback intensifies such that $V\sim 0.75$ and external forcing is strong, the system evolves with a doubled obliquity period. We can therefore assume that the period of the system response to the external forcing, P, is a function of the *V*-number, the amplitude of the external forcing, ε, and of the period of the external forcing, T. We thus begin with the most general hypothesis:

25 $P = \psi(V, a, \varepsilon, T)$ (5)

This is at this stage that the π-theorem intervenes. Specifically, it stipulates that a physical relationship should not depend on a system of units and therefore, in the dimensionless form, the number of dimensionless arguments is equal to the total number of the governing parameters minus the number of

30 governing parameters with independent dimensions (Buckingham, 1914). If we select dimensions of ε and T as independent dimensions, then application of the π-theorem to the equation (5) gives us:

$P/T = \Psi(V, \varepsilon/a)$ (6)

35 $P = T\Psi(\Pi_1, \Pi_2), \Pi_1, = V, \Pi_2 = \varepsilon/a$ (7)
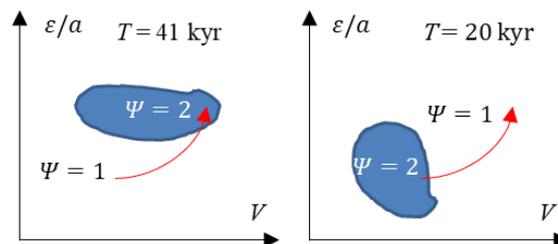
Fig. 1. A typical illustrative $\Psi(V, \varepsilon/a)$ function. Red arrow represents hypothetical trajectory of the

40 system's Pleistocene history: from doubled precession periods of the early Pleistocene to doubled obliquity periods of the late Pleistocene.

Fig. 1 presents a sketch of how the function $\Psi(V, \varepsilon/a)$ may look like, qualitatively. The underlying idea is that the Pleistocene history of the climate system may be understood as a trajectory in the $[V, \varepsilon/a]$ space (Crucifix and Verbitsky, 2019). The shape and location of the period doubling domain $\Psi = 2$ is expected to depend on the forcing period.

3.2 Amplitude of the glacial area variations, $\acute{S}$.

We begin again with the most general hypothesis. We suggest that the amplitude of glacial area variations $\acute{S}$ is a function of the V-number, of the characteristic rate of snow precipitation, a, of the amplitude of the external forcing ε, and of the period of the system response P as it is described by equation (7). The relationship between the period of the response and that of the forcing may therefore be non-trivial. It means that the system response may exhibit original forcing periods or multiples of them.

$$\acute{S} = \varphi(V, a, \varepsilon, P) \tag{8}$$

If the hypothesis (8) is true, then, taking dimensions of ε and P as independent dimensions, and using the π-theorem, we obtain:

$$\acute{S}/(\varepsilon^2 P^2) = \Phi(V, \varepsilon/a) \text{ , and finally:}$$

$$\acute{S} = \varepsilon^2 P^2 \Phi(\Pi_1, \Pi_2) \tag{9}$$

Neither Π_1 nor Π_2 contain P. Equation (9) therefore implies that, at constant amplitude of the external forcing ε, the amplitude of glacial area variations is scale invariant with a frequency slope equal 2. Fig. 2 ($\acute{S}$, reference parameters values) presents a numerical test of the hypothesis (8) and of its implication (9).
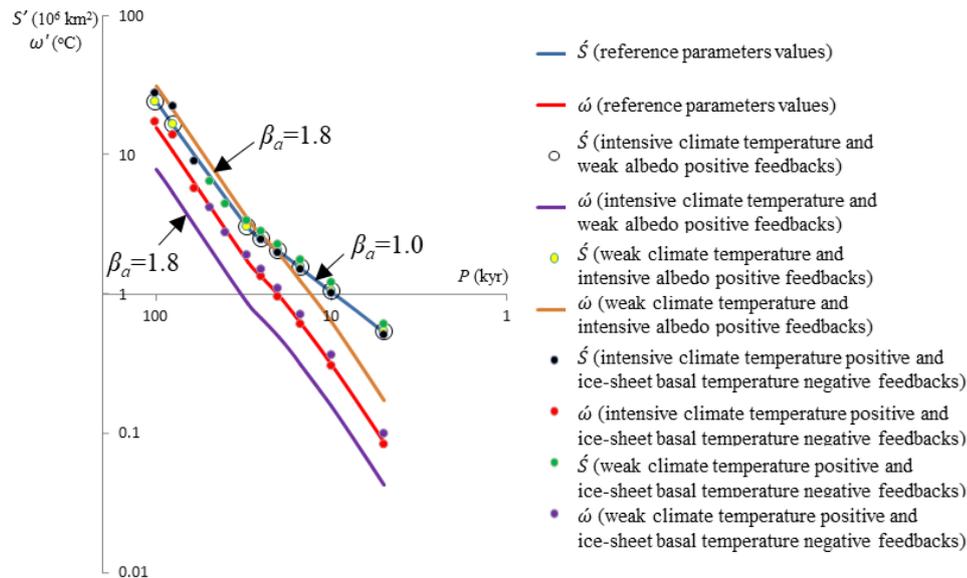
Fig. 2 The system response to a single-sinusoid external forcing of constant amplitude and different periods

Here, we measure the system response to single-sinusoid forcings of constant amplitude and periods T varying from 5 kyr to 50 kyr. The system responds to this forcing with periods P ranging from 5 kyr to 100 kyr, because forcing periods T of 40 kyr and 50 kyr produce response periods P of 80 kyr and 100 kyr, correspondingly. It can be seen that the $\acute{S}$-amplitude frequency slope, β_a, is close to 2 (i.e., $\beta_a = 1.8$) for

periods between 30 ky and 100 ky. It means that the *amplitude of glacial area variations is scale invariant in the orbital domain.*

3.3 Amplitude of the basal temperature, $\acute{\theta}$.

The amplitude spectrum of the θ-variable cannot be derived unambiguously from the same simple considerations as we have employed for P and $\acute{S}$ because: (a) we cannot constrain ourselves with only parameters V, a, ε, and P, since the basal temperature θ is measured in °C, but neither ε, nor a, nor P contain °C, but (b) as soon as we disassemble the V-number, i.e., use all individual model parameters instead of V, the advantage of using the π-theorem is lost. Nevertheless, if we disassemble the V-number wisely, we can minimize the number of dimensional parameters and, as a result, we may be rewarded by discovering the identities of critical groups that define the scaling properties of θ. Accordingly, we will disassemble the V-number using not individual parameters involved but, instead, using dimensionless groups that are present in the V: $\alpha, \frac{\kappa}{c}, \frac{\gamma_1}{\beta\gamma_3 S_0}, \frac{\gamma_2}{\beta\gamma_3}$. If we consider that the group $\frac{\gamma_1}{\beta\gamma_3 S_0}$ is a dimensionless representation of the parameter γ_1, and the group $\frac{\gamma_2}{\beta\gamma_3}$ is a dimensionless representation of the parameter β, then the remaining parameters γ_2, γ_3, S_0 need to be represented individually in the dimensional form. Taking this together, this yields the following hypothesis:

$$\acute{\theta} = \chi\left(\alpha, \frac{\kappa}{c}, \frac{\gamma_1}{\beta\gamma_3 S_0}, \frac{\gamma_2}{\beta\gamma_3}, \gamma_2, \gamma_3, S_0, a, \varepsilon, P\right) \tag{10}$$

Taking γ_2, S_0 and P as independent dimensions, the π-theorem implies:

$$\acute{\theta} = \gamma_2 S_0 P X\left(\alpha, \frac{\kappa}{c}, \frac{\gamma_1}{\beta\gamma_3 S_0}, \frac{\gamma_2}{\beta\gamma_3}, \gamma_3 P, aPS_0^{-1/2}, \varepsilon PS_0^{-1/2}\right) \tag{11}$$

or, combining groups $\alpha, \frac{\kappa}{c}, \frac{\gamma_1}{\beta\gamma_3 S_0}, \frac{\gamma_2}{\beta\gamma_3}$ back into V-number:

$$\acute{\theta} = \gamma_2 S_0 P X\left(V, \gamma_3 P, aPS_0^{-1/2}, \varepsilon PS_0^{-1/2}\right) \tag{12}$$

Since $\Pi_2 = \varepsilon/a$,

$$\acute{\theta} = \gamma_2 S_0 P X(\Pi_1, \Pi_2, \Pi_3, \Pi_4) \tag{13}$$

where $\Pi_3 = \gamma_3 P, \Pi_4 = \varepsilon PS_0^{-1/2}$.

As Π_3 and Π_4 include P, then *the amplitude of basal temperature variations is not expected to be scale invariant.*

3.4 Amplitude of the climate temperature, $\acute{\omega}$.

Since equation (3) for ω is linear, it may provide us with a hint about the response scaling characteristics of this variable. In the orbital domain, $\Pi_3 = \gamma_3 P \gg 1$, so that equation (3) may be approximated to: $\gamma_3\omega \approx \gamma_1 - \gamma_2(S - S_0)$. Hence, $\acute{\omega} = \frac{\gamma_2}{\gamma_3}\acute{S}$. We may hypothesize therefore that in the orbital domain and possibly even beyond:

$$\acute{\omega} = \nu\left(V, \frac{\gamma_2}{\gamma_3}, a, \varepsilon, P\right) \tag{14}$$

Taking the dimensions of $\frac{\gamma_2}{\gamma_3}, \varepsilon,$ and P as independent and applying again π-theorem reasoning, we should expect that:

$$\acute{\omega} = \frac{\gamma_2}{\gamma_3}\varepsilon^2 P^2 N(\Pi_1, \Pi_2) \tag{15}$$

5   At constant amplitude of the external forcing ε, equation (15) implies that the amplitude of climate temperature variations $\acute{\omega}$ grows with the square of the response period. The results presented in Fig.2 ($\acute{\omega}$, reference parameters values) support the hypothesis (14) and its implication (15): The ω-variable amplitude frequency slope is close to 2 (i.e., $\beta_a = 1.8$) for periods between 5 kyr and 100 kyr. It means that in the orbital and millennial domains, the *amplitude of the climate temperature is scale invariant.*

10   **4. Discussion.**

4.1 Scale invariance and a physical nature of the climate system feedbacks.

     So far, we based our implications of scaling relationships on the significance of an adimensional
15   number (in our case, the V-number) quantifying a mean ratio between positive and negative feedbacks. That is, the scaling relationships found should be robust across changes in the composition of V, provided that the value of V is unchanged. To illustrate this implication, we conducted four numerical experiments. In the first experiment, we increase coefficients α and κ two-fold and reduce γ_2 by a half relative to their reference values. This does not change the reference value of the V-number (see the equation (4) and note
20   that the reference value of $\gamma_1 = 0$), that is $V=0.75$, but transforms system (1) – (3) to a system where the positive feedback is dominated by the climate temperature affecting ice-sheet mass balance and its temperature regime. We then measure the system response to the single-sinusoid forcing of the same amplitude and periods $T = 5 - 50$ kyr. (Note, that periods $T = 40$ kyr and 50 kyr produce system response of periods $P = 80$ kyr and 100 kyr, correspondingly). In the second experiment, we decrease coefficients α and
25   κ by 50% and increase γ_2 two-fold relative to their reference values. Again, this does not change the reference value of the V-number, $V=0.75$, but transforms system (1) – (3) to a system where the positive feedback is dominated by the albedo feedback. In the third experiment, we increase coefficients α and κ by 50% as well as the coefficient β, thus creating the system with intensive climate-temperature positive feedback and intensive ice-sheet basal temperature negative feedback, the V-number still being equal to
30   0.75. And finally, we decrease coefficients α, κ, and β by 50%, making a system with weak climate-temperature positive and ice-sheet basal temperature negative feedbacks. The response of all four systems to the external forcing is shown in Fig.2. Despite different underlying physics, all four systems demonstrate the same: in the orbital domain, their amplitudes of glacial area variations are scale invariant with "1.8" frequency slope, and the amplitudes of the climate temperature are scale invariant in the orbital and
35   millennial domains with the same slope.

     This robustness is comforting. As we know, the physical interpretation of a low-order dynamical model can be partly ambiguous. For example, the mechanisms responsible for the changes in the "effective climate temperature", and how it impacts the ice mass balance are not fully described in this model. It is therefore reassuring to have been able to identify what seems to be the key ingredient for the scaling
40   relationship, in this case, that a single quantity (the V-number) grossly determines the dynamics of the system response. In other words, it relies on the fact that the number of effective parameters is smaller than is apparent from a more detailed description of the system.

     This, incidentally, shows how difficult it is to disambiguate the physical mechanisms responsible for a given behavior. Different assemblages yielding the same V-number will, indeed, produce slightly different
45   solutions, but less different than one could have perhaps expected. The dimensionless functions like, for example, function $\Phi(V, \varepsilon/a)$ in the equation (9),

$$\acute{S} = \varepsilon^2 P^2 \Phi(V, \varepsilon/a)$$

and function $\Phi'(V, \varepsilon/a)$ corresponding to the same value of the V-number but formed by the different physics (different set of parameters),

$$\acute{S} = \varepsilon^2 P^2 \Phi'(V, \varepsilon/a)$$

though are not identical, yield the same scaling behavior. If the amplitude of the external forcing ε is constant, the period P shows up only as a power-law monomial $\sim P^n$ and its power n makes the same scale-invariant amplitude-spectrum slope *regardless of the specific physics defining the V-number*. In other words, though the functions $\psi(V, a, \varepsilon, T)$, $\varphi(V, a, \varepsilon, P)$, $\chi(V, a, \varepsilon, P)$, and $\nu\left(V, \frac{\gamma_2}{\gamma_3}, a, \varepsilon, P\right)$ may change depending on the specific physics forming the V-number, their governing parameters always remain the same because they are determined by the structure of the system (1) – (3). Accordingly, the functions $\Psi(\Pi_1, \Pi_2), \Phi(\Pi_1, \Pi_2), X(\Pi_1, \Pi_2, \Pi_3, \Pi_4)$, and $N(\Pi_1, \Pi_2)$ may also change, but their dimensionless arguments (Π-groups) remain unaffected. As long as their groups, like, for example, Π_1 and Π_2, do not contain P, we have a possibility of scale-invariance. This observation makes the scale invariance a very general and expected property of the climate system.

4.2 Multi-sinusoid forcing.

Thus far we assumed a single-sinusoid external forcing with an amplitude ε and a period T. When we force our system with normalized mid-July insolation at 65°N (Berger and Loutre, 1991), this assumption is not valid any longer because both the amplitudes and the periods of precession and obliquity are different. Therefore, the hypothesis (5) must be re-written as:

$$P = \psi[V, a, \varepsilon_1, T_1, \varepsilon_2, T_2] \tag{16}$$

Here P is a period of the system response to a specific forcing component (a peak of the response spectrum), index "1" corresponds to obliquity, and index "2" corresponds to precession. Taking dimensions of ε_1 and T_1 as independent dimensions, and using the π-theorem, we obtain:

$$P_1 = T_1 \Psi_1[V, \varepsilon_1/a, \varepsilon_1/\varepsilon_2, T_1/T_2] \tag{17}$$

Here P_1 is a period of the system response to the obliquity forcing. Similarly, taking dimensions of ε_2 and T_2 as independent dimensions, and using the π-theorem, we have:

$$P_2 = T_2 \Psi_2[V, \varepsilon_2/a, \varepsilon_1/\varepsilon_2, T_1/T_2] \tag{18}$$

Here P_2 is a period of the system response to the precession forcing. Since in the case of the orbital forcing $\varepsilon_1/\varepsilon_2$ and T_1/T_2 are invariant, we can apply generalized π-theorem (Sonin, 2004) and to re-write (17) and (18) as:

$$P_1 = T_1 \Psi_1[V, \varepsilon_1/a] \tag{19}$$
$$P_2 = T_2 \Psi_2[V, \varepsilon_2/a] \tag{20}$$

It can be seen that equations (19) and (20) are identical to the equation (7) and the response periods to obliquity and to precession do not depend on each other. This result is not by any means intuitive.

We now repeat the same reasoning for the corresponding amplitudes of the system response:

$$\acute{S}_1 = \varphi_1(V, a, \varepsilon_1, P_1, \varepsilon_2, P_2) \tag{21}$$

$$\acute{S}_2 = \varphi_2(V, a, \varepsilon_1, P_1, \varepsilon_2, P_2) \tag{22}$$

$$\acute{S}_1 = \varepsilon_1^2 P_1^2 \Phi_1(V, \varepsilon_1/a, \varepsilon_1/\varepsilon_2, P_1/P_2) \tag{23}$$

$$\acute{S}_2 = \varepsilon_2^2 P_2^2 \Phi_2(V, \varepsilon_2/a, \varepsilon_1/\varepsilon_2, P_1/P_2) \tag{24}$$

Though in the case of the orbital forcing $\varepsilon_1\varepsilon_2$ and T_1/T_2 are invariant, P_1/P_2 is not an invariant (see Fig. 1), therefore:

$$\acute{S}_1 = \varepsilon_1^2 P_1^2 \Phi_1(V, \varepsilon_1/a, P_1/P_2) \tag{25}$$

$$\acute{S}_2 = \varepsilon_2^2 P_2^2 \Phi_2(V, \varepsilon_2/a, P_1/P_2) \tag{26}$$

We can see that although periods of the system response to the precession and obliquity forcings are independent, the amplitudes of the corresponding variations are interdependent and thus may deviate from a pure square-period law. This observation may have an important implication for our understanding of the paleo data. As we demonstrated before (Verbitsky et al, 2018), P_1/P_2 evolves over time, specifically $P_1/P_2 = 1$ for the early Pleistocene due to precession period doubling and $P_1/P_2 = 4$ for the late Pleistocene due to obliquity period doubling. It means that the *slope* of the spectrum of the system response may also evolve.

Introduction of more sinusoids (for example, accounting for the millennial forcing) makes the situation even more complex. In such a case, a period of the system response to a specific forcing component depends on the amplitudes and the periods of all sinusoids:

$$P = \psi[V, a, \varepsilon_1, T_1, \varepsilon_2, T_{2,} \dots \varepsilon_i, T_i \dots] \tag{27}$$

Then, for example, P_1, the period of the system response to obliquity forcing, can be presented as:

$$P_1 = T_1 \Psi_1 \left[V, \frac{\varepsilon_1}{a}, \dots, \frac{\varepsilon_1}{\varepsilon_i}, \frac{T_1}{T_i}, \dots\right] \tag{28}$$

and corresponding amplitude of the glaciation area response

$$\acute{S}_1 = \varphi_1[V, a, \varepsilon_1, P_1, \varepsilon_2, P_{2,} \dots \varepsilon_i, P_i \dots] \tag{29}$$

$$\acute{S}_1 = \varepsilon_1^2 P_1^2 \Phi_1 \left[V, \frac{\varepsilon_1}{a}, \dots, \frac{\varepsilon_1}{\varepsilon_i}, \frac{P_1}{P_i}, \dots\right] \tag{30}$$

Equations (29) and (30) show that, generally speaking, every peak P and corresponding amplitude $\acute{S}$ of the system response depend on each forcing sinusoid. Such dependence may break the scale invariance we discussed earlier. For example, we have demonstrated in our previous study (Verbitsky et al, 2019a) that introduction of the millennial variability of significant amplitude (i.e., $\varepsilon_1\varepsilon_i \to 0$) may disrupt the system's response to the orbital forcing and essentially reduce the slope β_a. The empirical energy density spectrum of Huybers and Curry (2006) has the slope of B $\approx$ 2 in the orbital domain. Since the energy density slope B relates to the fluctuation amplitude slope β_a as B $= 2\beta_a +1$, B $\approx$ 2 corresponds to $\beta_a = 0.5 < 2$. We may therefore speculate that the observed spectrum of the climate variability could be significantly influenced by the millennial forcing propagated into the orbital domain.

5. Conclusions.

Dimensional analysis of the dynamical system described by Verbitsky et al (2018) reveals that *only two factors define most of the ice-age dynamics*: (a) a balance between intensities of climate positive and ice sheet negative feedbacks, $\Pi_1 = V$; and (b) the period, T, and the amplitude of the external forcing, ε, (specifically, a particular proportion between the external, e.g., orbital, and terrestrial ice sheet mass balance components, $\Pi_2 = \varepsilon/a$).

The analysis indicates that the amplitudes of glacial area variations and of climate temperature are *scale invariant* with a frequency slope of 2. The property of scale invariance does not depend on the

physical nature of the underlying positive and negative feedbacks incorporated by the system. It thus turns out to be one of the most fundamental properties of the Pleistocene climate.

Retrospectively, we could have inferred scale invariance from the mere assumption that the behavior of the continental glacial area (measured in m^2) depends on the mass influx to its surface (m/s) and the periodicity of the mass influx variations (s), but perhaps these assumptions are too simple to be convincing. In our study, we have chosen a bit more sophisticated but more credible approach. We derived a dynamical model from the scaled conservation equations of viscous non-Newtonian ice combined with an equation describing the evolution of the climate temperature. We observed that most of the dynamical system behavior can be explained by a balance between positive and negative feedbacks. This observation, finally, illuminated the crucial role of the mass influx and its periodicity, making application of the π-theorem effective and definitive.

Code and data availability. The MatLab R2015b code and data to calculate model response to periodical forcing as it is presented in Fig.2 (Verbitsky et al, 2019b) are available at http://doi.org/10.5281/zenodo.3473957, (last access: October 20, 2019)

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