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# Cumulated insolation: a simple explanation of Milankovitch's forcing on climate changes

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## Abstract

The occurrence of the sudden melting of the ice sheets during the glacial terminations is explained in this paper as the consequence of the combined role of the minima and the maxima of mean summer insolation on the Northern Hemisphere, providing a new contribution to understand the mechanisms ruling glacial forcing. Indeed, no satisfactory answer has been provided so far to the question why one specific maximum, after a series of consecutive maxima of insolation, has the potentiality to trigger a deglaciation. The explanation proposed in this paper accounts for a pre-conditioning factor, represented by "mild" (warmer) minimum, followed by a sufficiently warm maximum as the conditions that cause the end of a glacial cycle. These conditions are realized whenever the sum of the values of each consecutive minima and maxima ("cumulated insolation") on the curve of mean summer insolation at 65° N exceeds 742 Watt $m^{-2}$. The comparison of the succession of these cumulated insolation values with the astronomically tuned Oxygen isotopes record provides a satisfactory match with the occurrence of all the glacial terminations in the last 800 ka.


## 1 Introduction

A general decreasing trend in global temperature since about 3 ma, combined with the change in variability frequency around 1 ma, caused the Earth to enter into a "glacial state", commonly referred as "Glacial Pleistocene" (Shackleton, 1997). Whereas the causes of the planetary cooling process are still debated (Shackleton and Hall, 1984; Raymo, 1994; Ravelo et al., 2004), larger consensus exists about the forcing mechanism to the glacial cycles. Indeed, referring to the original Milankovitch's theory (1941), a majority of scientists believes that glacial cycles are controlled by the long-term variations of the incoming solar radiation caused by changes in the Earth's orbital geometry. Early support to this hypothesis came by evidence provided by Hays et al. (1976) that Oxygen isotopes ratio in deep-sea sediment cores, when calibrated to the newly developed geomagnetic timescale, varied with the same frequency of the change in obliquity of Earth's orbit (41 kyr), and of the aphelion position during the seasons (21 kyr). Several authors (Hays et al., 1976; Imbrie et al., 1992; Ghil, 1994) also noted that since about 800 ka the ice sheets have been growing and melting in asymmetrical periods of about 90 kyr and 10 kyr, respectively, and proposed a link with variation in eccentricity of Earth's orbit ($\sim$ 100 kyr). Since then, several calibration methods for establishing a correct timescale of the Oxygen isotopes curve (and, consequently, of the glacial cycles) have been proposed. Whereas the Early-Pleistocene glacial cycles have a 40 ky timescale and are readily attributed to changes in Earth's obliquity (e.g., Raymo and Nisancioglu, 2003; Huybers, 2006), the mid-Pleistocene cyclicity appears more complex and a wider range of hypothesis has been proposed to explain it (e.g., Imbrie et al., 1984; Saltzman and Sutera, 1987; Maasch and Saltzman, 1990; Shackleton et al., 1990; Berger et al., 1994; Ghil, 1994; Raymo, 1997; Paillard, 1998; Clark et al., 1999; Tziperman and Gildor, 2003; Ashkenazy and Tziperman, 2004; Laepple and Lohmann, 2009). Although a nonlinear response of the ice-sheet dynamics to the forcing (e.g., Imbrie and Imbrie, 1980), or internal oscillations of the climate system (e.g., Ghil and Le Treunt, 1981; Saltzman et al., 1984) have been also hypothesized, most of these models are based on the "astronomical tuning" to the insolation curves, the more classical one being the "full astronomical tuning" that relies on all the three abovementioned orbital parameters and, through the use of automated correlation algorithms, provides the best fit between maxima of insolation and positive peaks (warm stages) of the $^{18}O/^{16}O$ ratio (see Huybers, 2007 for a review). Among the possible "tuning targets", represented by different insolation curves, the mean summer insolation (21 June through 22 September) at latitude 65° N (Berger, 1978) is maybe the most accredited one; however, several authors have considered different curves matching, in example, the daily insolation of 21 July, or 21 June (e.g., Raymo, 1997; Raymo et al., 2006).

In contrast to these models which emphasize the "northern pacing" on variability of Earth's climate, recent works have suggested that local insolation at different latitudes also plays an important role, and have proposed a local time-dependent approach to complement the global Milankowitch hypothesis (Laepple and Lohmann, 2009, and references therein).

However, despite the general consensus that the basic assumptions of Milankovitch's theory are still accredited of, several doubts on the reliability of this hypothesis have been raised since its formulation, comprehending scepticism on the actual mechanism causing the abrupt end of the glacial cycles. Indeed, one of the most problematic aspects of the climate cyclicity during the last 800 ka is the asymmetrical behaviour of the temperature history, and the lack of any solid explanation to the trigger of the sudden melting of the ice sheets, which is referred as "glacial terminations" (Broecker, 1984), during one particular maximum of insolation, instead of any other one (e.g., Muller and MacDonald, 1997; Paillard, 1998).

One possible answer to this question comes from the recent proposal that deglaciations occur in correspondence of those maxima that are preceded by an anomalously mild (warmer) minimum of insolation (Marra et al., 2008) (Fig. 1). The major problem with this hypothesis, however, is that it implies a shift back of one precession cycle for most of the glacial terminations, which would result into an almost complete re-tuning of the oxygen isotopes curve. For this reason, an alternative triggering mechanism that may reconcile the astronomical tuning of the oxygen isotopes curve and the principle of the "mild minima" is proposed in this paper.

Unlike more sophisticated models that used a statistical approach to determine the coupling between different orbital parameters and the $\delta^{18}$O record (e.g., Huybers and Wunsch, 2005, and references therein), or other that, through the use of empirical transfer functions between daily insolation and daily temperature, highlighted the role of local insolation to model the Late Quaternary temperature evolution (Laepple and Lohmann, 2009), the proposed mechanism attempts at establishing a simple, direct causative effect between insolation and glacial cycles, that relies on the full orbital theory (mean summer insolation at 65° N latitude).

## 2 A "cumulated insolation" model for the glacial terminations

If we consider the occurrence of a mild minimum of summer insolation at 65° N latitude as the cause of the formation of a relatively smaller and thinner ice sheet on the boreal hemisphere, which also implies a reduced albedo, it is reasonable to assume that it will cause warmer global climatic conditions with respect to other glacial periods when more severe minima of insolation are recorded. It is intuitive then, if we rely on Milankovitch's climate theory, that the occurrence of a mild minimum may represent a pre-conditioning factor to trigger a glacial termination. It is also intuitive to assume that the actual occurrence of a dramatic melting of the ice sheets needs that a sufficiently warm temperature be reached during the incoming maximum of insolation. The simplest way to estimate the contribution of both these factors (warmer minimum coupled to a sufficiently warm maximum) is to consider the sum of insolation (in Watt $m^{-2}$) at each consecutive minima and maxima on the insolation curve.

The red and blue dots in Fig. 2a show the succession of "cumulated" insolation for each maximum of the 65° N mean summer insolation curve (Laskar et al., 2004) between 900 ka (kilo-years ago) and the Present. The values reported in Fig. 2a are indeed the sum of the insolation at each maximum and that at the preceding minimum, whose values are reported in Fig. 2b: in example, the first value at the right extreme of the graphic in Fig. 2a (739.5) is given by 349.5 W $m^{-2}$ (first minimum of insolation shown in Fig. 2b) +390 W $m^{-2}$ (successive maximum of insolation), and so on. These cumulated insolation values represent a quantitative estimate of the climate forcing occurring at each insolation cycle, and their succession is compared to that of the Oxygen isotopes stages (Lisiecki and Raymo, 2005) in Fig. 2a. By doing so, it is possible to estimate a threshold value of cumulated insolation (i.e. between 742 and 745 W $m^{-2}$, red horizontal shaded bar in Fig. 2a) above which a maximum of insolation triggers a glacial termination. The correspondent tracts of the insolation curve leading to a glacial termination are marked in red in Fig. 2b. All (and only) the maxima of insolation characterized by a cumulated insolation value $> 742$ W $m^{-2}$ (values reported in red in Fig. 2a)





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match a peak in the oxygen isotopes curve during the last 900 ka; in contrast, lower cumulated insolation values (in blue) correspond to maxima that are not producing any significant spike in the $\delta^{18}$O record. The only exception is provided by a cumulated maximum of insolation of 753 W m$^{-2}$, occurring around 370 ka (highlighted with a red shadow in Fig. 2a), which does not match any sharp variation of the $\delta^{18}$O. Indeed, an extra glacial termination between TV and TIV should be associated with this maximum of insolation, after the proposed mechanism. However, the cause of this exception can be explained within the same principle of cumulated insolation, when the concept of "sufficiently" warm maximum is defined better and quantified.

Indeed, the curve of insolation during the time span encompassing glacial terminations V and IV is characterized by a succession of particularly small-amplitude minima and maxima (yellow shaded portion of the curve in Fig. 2b). Remarkably, despite this feature, MIS 11 occurring after TV is one of the most pronounced peaks in the isotopes curve. A fact that constitutes one of the principal objections to the validity of the Milankovitch theory (e.g., Paillard, 1998; Karner and Muller, 2000), but that is well explained when the actual factor to trigger a glacial termination is considered to be the cumulated insolation at two consecutive inversions of the curve, independent from how much strong is the maximum. Nevertheless, no glacial termination is associated to an even higher cumulated insolation value (753 W m$^{-2}$), occurring two precession cycles later (Fig. 2a and b). Explanation to this anomaly may be hinted observing that the insolation value (374.5 W m$^{-2}$) of the maximum preceding the tract of the curve responsible for the cumulated insolation of 753 W m$^{-2}$ (see enlarged spot of the curve in Fig. 2) is among the lowest maxima of insolation in the last 900 ka, and is lower than the weakest maximum of insolation (382 W m$^{-2}$) to which a glacial termination is associated with (blue horizontal line in Fig. 2c). Following this reasoning, we can assume that a value comprised between 374.5 and 382 W m$^{-2}$ is a threshold value for a maximum of mean summer insolation at 65° N to trigger a glacial termination (light blue bar below the dashed horizontal blue line in Fig. 2c).

In other words, the one of 374.5 W m$^{-2}$ should be considered a negligible maximum: the insolation history in this time interval can be represented as a single increasing tract between the minimum of 352 and the maximum of 382 W m$^{-2}$ (solid line replacing the dashed portion of the curve within the area highlighted in yellow in Fig. 2c). This gives a cumulated insolation of 734 W m$^{-2}$ (highlighted in yellow in Fig. 2d), below the threshold value of 742 W m$^{-2}$: not enough to trigger a glacial termination. In Fig. 2e the principle of "negligible" maximum of insolation is tentatively applied to all the values lower than 379 W m$^{-2}$ (reported in blue), in order to check if this assumption provides a better fit between the cumulated insolation values and the $\delta^{18}$O record. The insolation curve is therefore corrected eliminating the negligible maxima, by removing the correspondent portion of the curve (dashed tracts of the insolation curve). The succession of cumulated insolation values at each maximum resulting from the revised curve is reported in Fig. 2f. Besides eliminating the causative effect for the missing glacial termination (yellow shaded area #1 in Fig. 2f), this revised succession of values of cumulated insolation provides indeed a better overall match with the shape of the isotope curve. In order to enhance the fit between this revised insolation curve and the $\delta^{18}$O record, a succession of relative minima of insolation is reported in Fig. 2f along with the cumulated maxima. These minima (blue open circles in Fig. 2f) are obtained by reporting the actual difference between each maximum and minimum of insolation (corresponding to the blue descending tracts of the curve in Fig. 2e) after each maximum of cumulated insolation in Fig. 2f. The introduction of the minima provides a mean of comparison also with the intensity and duration of the cold periods depicted by the $\delta^{18}$O record.

As a general observation, no direct influence of the minima of insolation on the shape of the isotope curve is inferred: the progressive decreasing trend towards the negative peaks (lowstands) seems indeed ruled by the consecutive occurrence of moderate and "negligible" cumulated maxima of insolation (larger filled and smaller open blue dots in Fig. 2f, respectively). In contrast, the occurrence of particularly mild minima preceding and following MIS 11 (those within the yellow shaded area #2, above the





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dashed horizontal yellow line in Fig. 2f) may give reason of the anomalous long duration of this isotopic stage (e.g., Karner and Marra, 2003), as due to the absence of severe cold conditions during this time span. Finally, small inconsistencies between the $\delta^{18}$O record and the cumulated insolation curve are observed (a, b, c red shaded areas in Fig. 2f), which may depend on local bias of the isotopes record, according to the large range of shapes that characterizes the different curves provided in the vast literature.

A further test of the hypothesized mechanism is provided in Fig. 3 by extending the principle of cumulated values of insolation to all the maxima of the insolation curve between 900 and 1800 ka, and by comparing the resulting succession of "effective" maxima (those marked with the red dot in Fig. 3a, exceeding 742 $W m^{-2}$) with the Oxygen isotope curve in this time span. Only 3 maxima of insolation out of a total of 42 do not obey at the principle that a cumulated insolation value greater than 742 $W m^{-2}$ is required to cause a sudden increase (spike) in the $\delta^{18}$O record (open red dots matching the peaks of the isotopes curve highlighted in yellow in Fig. 3a). Indeed, no one of the other 21 maxima of insolation below this threshold value (blue dots in Fig. 3a) is associated with any significant variation in the trend of the curve. In contrast, all the 20 maxima with cumulated insolation $>$742 $W m^{-2}$ (red dots) match one positive peak (highstand) of the curve. The small shift between several red dots and the peaks of the $\delta^{18}$O is very likely an offset generated by the automated correlation algorithms used for the tuning, which provide an average best fist with the maxima of insolation. However, when a selective principle to chose which maxima of insolation should be coupled to the maxima of the $\delta^{18}$O is established, an average mathematical best fit cannot be considered to provide the correct tuning of the curve. These observations suggest that the misfit for the three maxima of insolation lower than 742 $W m^{-2}$ (open red circles) that match as many peaks of the $\delta^{18}$O record (yellow areas in Fig. 3a) may be a consequence of an incorrect tuning, and that it may be eliminated by a different calibration of the curve. In example, a re-tuning of the $\delta^{18}$O curve to provide a complete fit with the effective maxima of insolation is tentatively proposed in Fig. 3a with the dashed portion





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of the isotope curve. The lack of any direct chronologic tie to the isotopes record in this time span prevents either to prove or to confute this assumption.

In conclusion, the proposed mechanism to explain the occurrence of the glacial terminations is probably the simplest and intuitive way to show how and why the insolation forcing works.

The cumulated insolation establishes a threshold value over which one maximum, after a series of weaker values of cumulated insolation, has the potentiality to trigger a deglaciation. It also accounts for variable duration and variable periodicity of the glacial cycles, which do not pace any frequency of the orbital parameters exactly. In particular, a uniform mechanism works during the apparent progression from 40 to ∼ 100 ky, without requiring any change in the physics of the glacial cycles. After the proposed mechanism the glacial cycles are ruled by a random succession of cumulated maxima deriving by the complex combination of these parameters, however, they are perfectly assessable by computing the cumulated value of insolation at each maximum on the mean summer insolation curve.

## References

Ashkenazy, Y. and Tziperman, E.: Are the 41 kyr glacial oscillations a linear response to Milankovitch forcing?, Quaternary Sci. Rev., 23, 1879–1890, 2004.

Berger, A.: Long-term variations of daily insolation and Quaternary climatic change, J. Atmos. Sci., 35, 2362–2367, 1978.

Berger, W. H., Yasuda, M., Bickert, T., Wefer, G., and Takayama, T.: Quaternary timescale for the Ontong Java Plateau: Milankovitch template for Ocean Drilling Program Site 806, Geology, 22, 463–467, 1994.

Broecker, W.: Terminations, in: Milankovitch and Climate vol 2, edited by: Berger, A. L., Imbrie, J., Hays, J. D., Kukla, G., and Saltzman, B., Reidel Publishing Company, Dordrecht-Holland, 687–698, 1984.

Clark, P., Alley, R., and Pollard, D.: Northern hemisphere ice-sheet influences on global climate change, Science, 5442, 1104–1111, 1999.

Ghil, M.: Cryothermodynamics: the chaotic dynamics of paleoclimate, Physica, D77, 130–159, 1994.
Ghil, M. and Le Treut, H.: A climate model with cryodynamics and geodynamics, J. Geophys. Res., 86, 5262–5270, 1981.
Hays, J. D., Imbrie, J., and Shackleton, N. J.: Variations in the Earth's orbit: pacemaker of the ice ages, Science, 194, 1121–1131, 1976.
Huybers, P.: Early Pleistocene Glacial Cycles and the Integrated Summer Insolation Forcing, Science, 313, 508–511, doi:10.1126/science.1125249, 2006.
Huybers, P. and Wunsch, C.: Obliquity pacing of the late Pleistocene glacial terminations, Nature, 434, 491–494, doi:10.1038/nature03401, 2005.
Imbrie, J. and Imbrie, J. Z.: Modelling the climatic response to orbital variations, Science, 207, 943–953, 1980.
Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L., and Shackleton, N. J.: The orbital theory of Pleistocene climate: support from a revised chronology of the marine $d^{18}O$ record, in: Milankovitch and Climate vol 1, edited by: Berger, A. L., Imbrie, J., Hays, J. D., Kukla, G., and Saltzman, B., Reidel Publishing Company, Dordrecht-Holland, 269–305, 1984.
Imbrie, J., Boyle, E. A., Clemens, S. C., Duffy, A., Howard, W. R., Kukla, G., Kutzbach, J., Martinson, D. G., McIntyre, A., Mix, A. C., Molfino, B., Morley, J. J., Peterson, L. C., Pisias, N. G., Prell, W. L., Raymo, M. E., Shackleton, N. J., and Toggweiler, J. R.: On the structure and origin of major glaciation cycle 1. Linear responses to Milankovitch forcing, Paleoceanography, 6, 205–226, 1992.
Karner, D. B. and Muller, R. A.: A Causality Problem for Milankovitch, Science, 288, 2143–2144, 2000.
Karner, D. B. and Marra, F.: $^{40}Ar/^{39}Ar$ dating of Glacial Termination V and duration of the Stage 11 highstand, in: Earth's Climate and Orbital Eccentricity: The Marine Isotope Stage 11 Question, American Geophysical Union, Geoph. Monog., 137, 61–66, 2003.
Laepple, T. and Lohmann, G.: Seasonal cycle as template for climate variability on astronomical timescales, Paleoceanography, 24, PA4201, doi:10.1029/2008PA001674, 2009.
Laskar, J., Robutel, P., Joutel, F., and Gastineau, M.: A long-term numerical solution for the insolation quantities of the Earth, Astron. Astrophys., 428, 261–285, 2004.
Lisiecki L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic $d^{18}O$ records, Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071, 2005.



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Maasch, K. and Saltzman, B.: A low-order dynamical model of global climatic variability over the full Pleistocene, J. Geophys. Res., 95, 1955–1963, 1990.
Marra, F., Florindo, F., and Boschi, E.: The history of glacial terminations from the Tiber River (Rome): insights to glacial forcing mechanisms, Paleoceanography, 23, PA2205, doi:10.1029/2007PA001543, 2008.
Milankovitch, M.: Kanon der Erdbestrahlung und Seine Anwendung auf das Eiszeitenproblem, 133, 633 pp., Akad. R. Serbia, Belgrade, 1941.
Muller, R. A. and MacDonald, G. J.: Glacial Cycles and Astronomical Forcing, Science, 277, 215–218, doi:10.1126/science.277.5323.215, 1997.
Paillard, D.: The timing of Pleistocene glaciations from a simple multiple-state climate model, Nature, 391, 378–391, 1998.
Ravelo, A., Andreasen, D., Lyle, M., Lyle, A., and Wara, M.: Regional climate shifts caused by gradual global cooling in the Pliocene epoch, Nature, 429, 263–267, 2004.
Raymo, M.: The initiation of Northern Hemisphere glaciation, Annu. Rev. Earth Planet. Sci., 22, 353–383, 1994.
Raymo, M. and Nisancioglu, K.: The 41 kyr world: Milankovitch's other unsolved mystery, Paleoceanography, 18, 1011, doi:10.1029/2002PA000791, 2003.
Raymo, M. E., Ruddiman, W. F., Backman, J., Clement, B. M., and Martinson, D. G.: Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic Deep Water circulation, Paleoceanography, 12, 577–585, 1989.
Saltzman, B. and Sutera, A.: The mid-Quaternary climatic transition as the free response of a three-variable dynamical model, J. Atmos. Sci., 44, 236–241, 1987.
Saltzman, B., Hansen, A. R., and Maasch, K. A.: The late Quaternary glaciations as the response of a three component feedback system to Earth-orbital forcing, J. Atmos. Sci., 41, 3380–3389, 1984.
Shackleton, N. J.: The Deep-Sea Sediment Record and the Pliocene-Pleistocene Boundary, Quatern. Int., 40, 33–35, 1997.
Shackleton, N. J. and Hall, M.: Oxygen and carbon isotope stratigraphy of Deep-Sea Drilling Project hole 552a: Plio-Pleistocene glacial history, DSDP Initial Reports, 81, 599–609, 1984.
Shackleton, N. J., Berger, A., and Peltier, W. R.: An alternative astronomical calibration of the Lower Pleistocene timescale based on ODP site 677, Trans. R. Soc. Edinburgh Earth Sci., 81, 251–261, 1990.

Tziperman, E. and Gildor, H.: On the mid-Pleistocene transition to 100-kyr glacial cycles and the asymmetry between glaciation and deglaciation times, Paleoceanography, 18, 1001, doi:10.1029/2001PA000627, 2003.

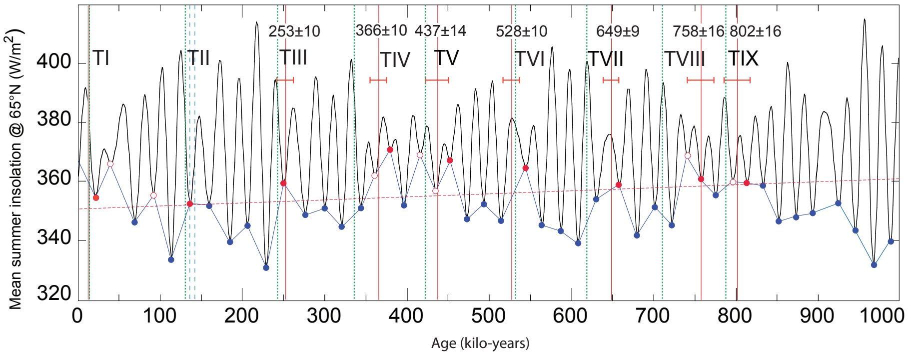


**Fig. 1.** Several independent ages (in kilo-years ago $\pm 2\sigma$ uncertainty) for glacial terminations provided by tephra layers interbedded at the transition from gravel to clay within the glacio-eustatically forced aggradational successions of the Paleo-Tiber River (vertical red lines: Marra et al., 2008) display a significant mismatch, over the associated analytical error (horizontal red bars), with respect to the correspondent astronomically tuned ages (vertical dashed green lines, after Lisiecki and Raymo, 2005). These independent ages for glacial termination IX through II are coupled to each first mild (less cold) minimum (red dots), above an empirical threshold value (dashed red line), in the curve of the mean summer insolation at latitude 65° N (Laskar et al., 2004). Based on this feature, Marra et al. (2008) suggested that the occurrence of particularly mild minima of insolation might be a pre-disposing factor to trigger a glacial termination.

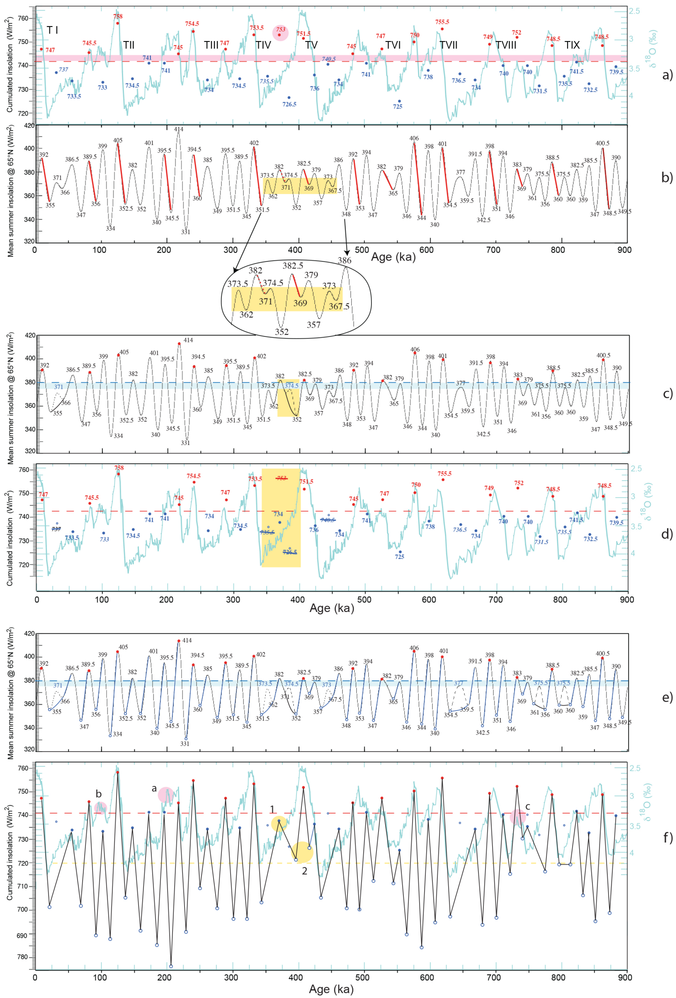






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**Fig. 2. (a–b)** A succession of cumulated values of insolation, resulting from the sum of the insolation at each consecutive minima and maxima of the curve of the mean summer insolation at 65° N (Laskar et al., 2004), is compared to the Oxygen isotopes curve (Lisiecki and Raymo, 2005). All the values (in red) above a threshold of cumulated insolation of $742\,\mathrm{W\,m^{-2}}$ (red horizontal bar) are associated with a steep increasing tract that identifies a glacial termination (TIX-I), or to an equivalent spike in the isotopes curve, with the exception of that within the red shaded circle (see text for discussion). **(c–d)** a threshold value above $382\,\mathrm{W\,m^{-2}}$ (blue horizontal bar) is assumed as the requisite for a maximum of insolation to trigger a glacial termination, whenever the value of cumulated insolation of $742\,\mathrm{W\,m^{-2}}$ is reached. Based on this assumption, the maximum of $374.5\,\mathrm{W\,m^{-2}}$ (yellow shaded area) is considered a negligible one and, along with the following minimum, is not considered to estimate the cumulated insolation. **(e)** the principle of negligible maximum is applied to all the maxima $< 379\,\mathrm{W\,m^{-2}}$ (dashed portions of the insolation curve), and **(f)** the succession of cumulated values of insolation is re-assessed providing a better fit with the succession of isotopic stages (see text for discussion).





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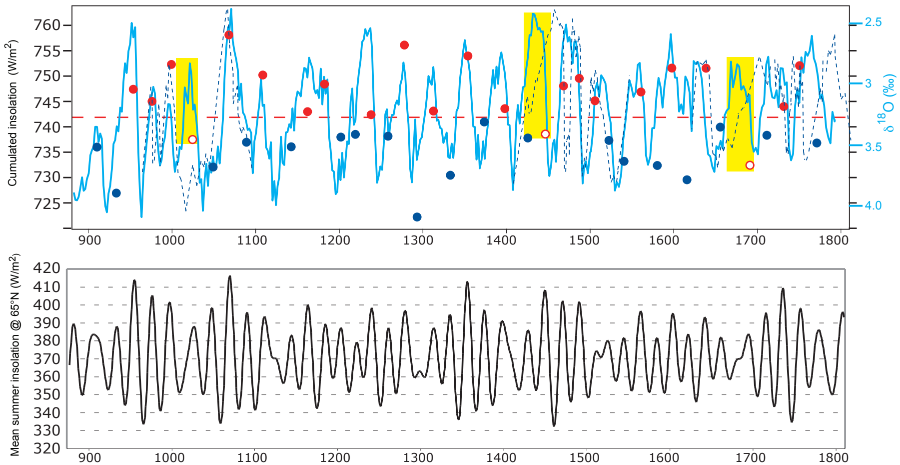


**Fig. 3.** The cumulated values of insolation between 900 and 1800 ka are shown. Only 3 maxima of cumulated insolation (open red dots matching the peaks of the isotopes curve highlighted in yellow) out of a total of 42 do not obey at the principle that a cumulated insolation value greater than 742 W m$^{-2}$ (red dots) is required to cause a sudden increase (positive isotopic stage) in the $\delta^{18}$O record. The misfit for the three maxima of insolation lower than 742 W m$^{-2}$ suggests that a different tuning of the $\delta^{18}$O curve may provide a complete fit with the effective maxima of insolation, like tentatively proposed with the dashed portion of the isotope curve.





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