Full point-by-point response to reviewers' comments on revised manuscript: #EGUSPHERE-2026-1583

Exploring the Cenozoic Earth system with extraterrestrial ^{3}He

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We would like to thank all three reviewers and the editor for providing constructive and thoughtful feedback that led to significant improvements in the manuscript.

Below, we address every reviewer comment line-by-line. Reviewer comments are displayed in black font, our responses are in green font, and direct quotes from the revised manuscript are in blue font.

Reviewer #1:

1) This manuscript presents a helpful and clear review of the use of extraterrestrial helium-3 (3HeET) to calculate vertical rain rates of marine sediments, and it argues that applications of this tool have been limited relative to its potential for providing insight into past climate and marine productivity changes. The writing is thoughtful and well-organized, and the manuscript presents two helpful case studies documenting how mass accumulation rates (MARs) estimated from 3HeET lead to very different results than previous work relying on age model-based MARs. The authors make a good argument that 3HeET should be more widely used in the field, and the manuscript is worthy of publication with a few revisions.

We thank the reviewer for their positive comments on our manuscript. We address all comments/concerns in detail below.

2) Much of the manuscript is essentially an updated version of section 4.2 of McGee and Mukhopadhyay (2013); that work also noted the advantages of 3HeET-based MARs over age model-based MARs and highlighted examples where use of 3HeET substantially changes conclusions, and it ended with a similar argument: "the use of 3HeET as a constant flux proxy has been relatively limited compared to its potential applications." That is not to say that this overlap makes the current manuscript unnecessary: reviews need updating every decade or so, and it is worthwhile to have such a review appear in a journal rather than a (rather obscure) book. Moreover, this manuscript is much more specifically addressed to the paleoceanography community.

We agree with the reviewer that this manuscript builds directly on several sections of a previously published book chapter by McGee and Mukhopadhyay (2013). In the revised version, we explicitly state that our new review/perspective builds on the foundation set by McGee and Mukhopadhyay (2013), with a focus on the paleoclimate community. We now say (L93-94):

"Building on an earlier, foundational review by McGee and Mukhopadhyay (2013), here we provide an updated, comprehensive perspective on 3HeET as a CFP and its utility to the paleoclimate community. Specifically, we:"

3) 67-69 This sentence is confusing.

We rephrased this sentence to provide clarity. We now say (L66-69):

"As such, our ability to develop reliable interpretations of the paleo-Earth system using sediment components such dust (e.g., Rea, 1994), organic matter and its bi-products (e.g., Schoepfer et al., 2015), and extraterrestrial material (e.g., Farley, 1995), relies on accurate quantification of the MARs of these constituents."

4) 76 "loss"->"lost"

We thank the reviewer for catching this mistake. We made this change.

5) 78 I suggest changing "at least from a MAR perspective" to "at least those based upon MARs"

We made this change.

6) 93 "Ee"->"We"

We thank the reviewer for catching this mistake. We made this change.

7) 104 I suggest changing "from an age model perspective" to "based on age models"

We made this change.

8) Fig 1 I was unclear about the meaning of this figure. The text doesn't explain how the higher-resolution age model was determined, beyond mentioning a "statistical tuning approach" in the caption. I guess the point is that there can be substantial MAR changes between low-resolution age model tie points, but a) this could be said more clearly, and b) the high-resolution MAR doesn't appear to average to the same value as the low-resolution MAR over the same intervals (e.g. see the interval from the coretop to ~15 ka), which is confusing.

We agree that our use of the late Quaternary age model-derived bMARs from Kinsley et al. (2022) and Abell et al. (2023), which are based on core-specific benthic oxygen isotope alignment to the Prob-stack global benthic oxygen isotope stack (Ahn et al., 2017) using the Hidden Markov Model (HMM)-Match software (Lin et al., 2014), overcomplicates the point we are trying to make here.

To simplify the figure and presented information, we now display randomly generated bMAR data for a hypothetic core that has a high-resolution age model and low-resolution age model.

The bin-width weighted high-resolution bMARs now average to the low-resolution age model bMARs. We also updated the figure caption accordingly.

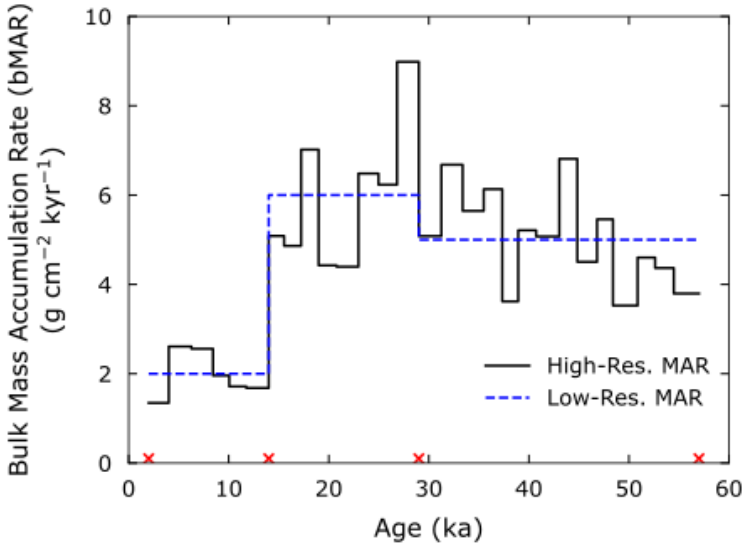


Figure 1: Idealized representation of bMAR dependence on the resolution of the available age model. The two lines are separate determinations of bMAR over the last ~60 kyr for a hypothetical marine sediment core using two age models of different resolutions. The red crosses denote four tie-points for the original, low-resolution age model, and the blue dashed line is the sediment bMAR based on this lower-resolution age model. The black line represents the sediment bMAR calculated using a higher resolution age model produced after the original. Note the substantial changes in bMARs that go unrecognized with the lower-resolution age model, while still producing the same overall average bMAR for the wider interval. DBD was assumed to be constant for the entire core.

9) 134 Equations 3 and 4 seem unnecessary and misleading – Equation 3 states an assumption, and Equation 4 states something that is usually but not always true. I think equations should be saved for definitions or relationships that are always true.

We agree, and have removed the original Equations 3 and 4.

10) 185 Change "thought of as the 'excess' or 'missing' sediment" to "thought of as the ratio of the total sediment"

We made this change.

11) 225 "works"->"work"

We thank the reviewer for catching this mistake. We made this change.

12) 226 "heavy particle scavenging" is confusing to me. Are you talking about scavenging by heavy particles, or about the extent to which vertical fluxes are impacted by scavenging?

We agree with the reviewer that this is a bit confusing. We changed this sentence for clarity to read (L:

"Recent work also suggests that 3HeET may provide additional advantages to 230Th in certain depositional environments because it is not affected by boundary scavenging, which can bias 230Th in settings proximal to hydrothermal systems or coastal locations with extremely high vMARs (Middleton et al., 2020; Pavia et al., 2024; Tomchovska et al., 2025). Overall, 3HeET offers numerous advantages over the traditional age model-based approach to reconstructing marine sediment fluxes, particularly prior to the late Quaternary."

13) 226 I don't find the age model-dependence argument to be a reason for favoring 3HeET over 230Th. My sense is that in most sediment core records of the last ~400-500 ka (i.e. where 230Th is an option), the age model-based uncertainty is only a small fraction of the total uncertainty in 230Th-based MARs; and if the age model is so uncertain that it is a dominant part of the 230Th uncertainty, then your flux time series is not going to be very useful for paleoceanographic purposes anyway.

We agree with the reviewer, and have removed this part of the sentence.

14) Fig 4 Why is Fig 4A the same as Fig 3C?

We initially separated these two figures because each figure is addressing a key concept (Fig. 3C was to compare the dearth of 3HeET data compared to 230Th, while Fig. 4 was meant to convey that even the 3HeET data we do have for the Cenozoic is quite temporally sparse. However, we agree that this duplication is unnecessary, and now combine the figures (new Fig. 3).

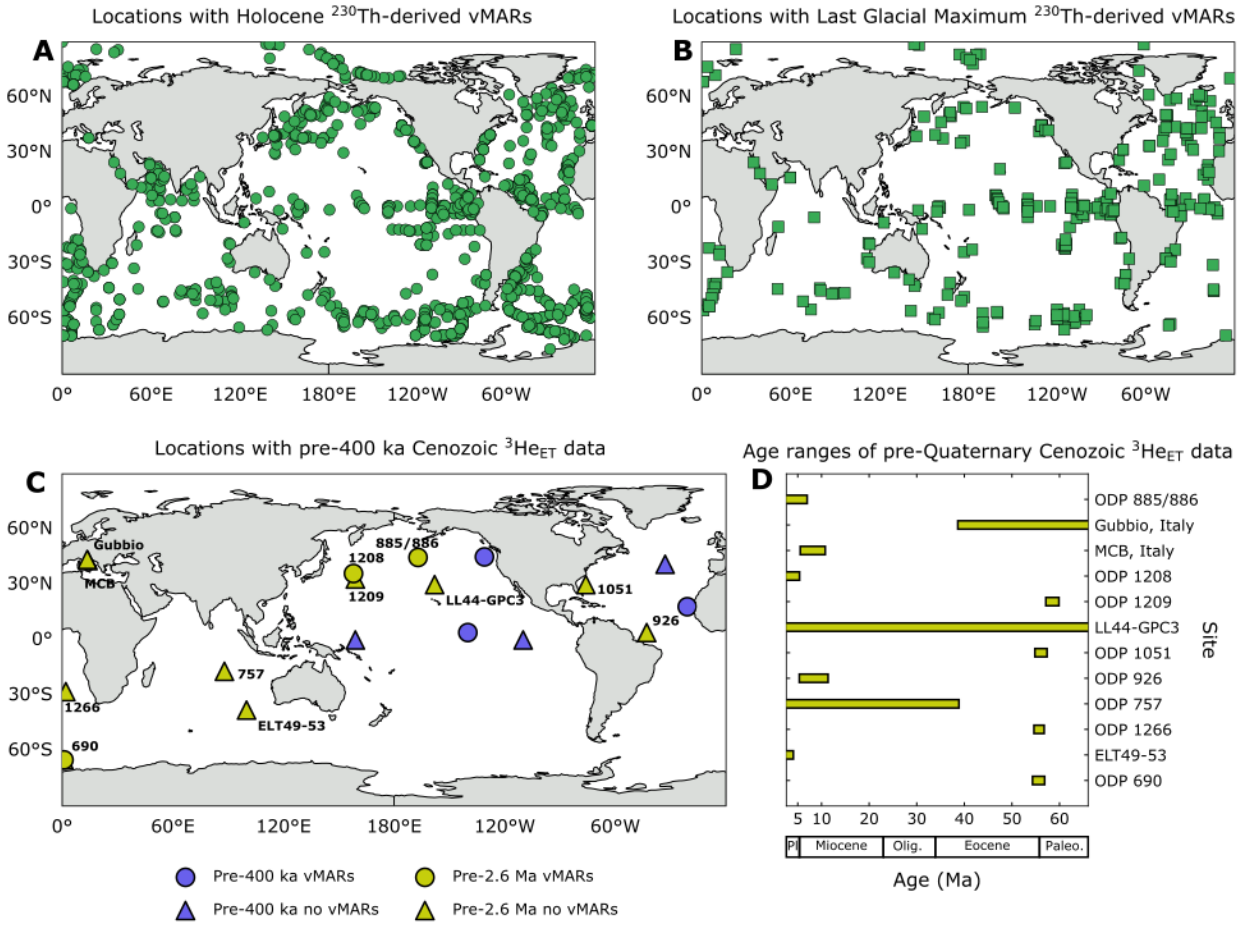


Figure 3: Available CFP data for various time intervals. A) Locations with late Holocene (5-0 ka) ^{230}Th-normalized sediment vMAR data (Costa et al., 2020). B) Locations of Last Glacial Maximum (23.5-18.5 ka) ^{230}Th-normalized sediment vMARs (Costa et al., 2020). C) Locations with any marine sediment $^{3}He_{ET}$ (or just ^{3}He) data for the Cenozoic prior to ~400 ka. No studies that produced $^{3}He_{ET}$ data from only ~0-400 ka (i.e., the approximate range where ^{230}Th can be applied) or prior to the Cenozoic are included here. Purple symbols indicate sites with $^{3}He_{ET}$ data that fall only within the Quaternary prior to ~400 ka (Farley and Patterson, 1995; Middleton et al., 2020; O'Mara et al., 2022, 2024; Patterson and Farley, 1998; Winckler et al., 2004, 2005). Yellow symbols represent sites with at least some $^{3}He_{ET}$ data for the Cenozoic prior to the Quaternary (Abell et al., 2021, 2023; Abell and Winckler, 2023; Farley, 1995; Farley et al., 2006; Farley and Eltgroth, 2003; Graham and Konrad, 2022; Marcantonio et al., 2009; Montanari et al., 2017; Mukhopadhyay et al., 2001b; Murphy et al., 2010). Circles indicate sites where $^{3}He_{ET}$ data have been used to calculate sediment constituent vMARs (Abell et al., 2021, 2023; Abell and Winckler, 2023; Middleton et al., 2020; O'Mara et al., 2022, 2024; Torfstein et al., 2010) Triangles represent sites where $^{3}He_{ET}$ data are not used to determine sediment constituent vMARs. These studies either 1) determine an influx of $^{3}He_{ET}$ using the site's age model (Farley, 1995; Farley et al., 2006; Farley and Patterson, 1995; Graham and Konrad, 2022; Montanari et al., 2017; Mukhopadhyay et al., 2001a; Patterson and Farley, 1998; Winckler et al., 2004) or 2) determine a flux of $^{3}He_{ET}$ using the site's age model and then calculate sediment accumulation rates and/or event durations using this value (Farley and Eltgroth, 2003;

Marcantonio et al., 2009; Murphy et al., 2010). 'MCB' stands for Monti dei Corvi Beach, Italy. D) Temporal coverage of $^{3}He_{ET}$ data from the beginning of the Cenozoic to the Pliocene.

15) Fig 4 "Gubbio" is misspelled in two places.

We thank the reviewer for catching these mistakes. We made these changes.

16) 285 Perhaps clearer to replace "LSRs" with "age models"?

We have made this change.

17) 288 can you be more specific about what is meant by "certain sedimentation patterns"? In general, this section could be more convincing in making the case that the 3HeET-based MARs at 885/886 are more accurate than age model-based MARs, not just that they're different.

We have rephrased this paragraph to better make the case that the age model-derived MARs are problematic for the Pliocene section of ODP 885/886 (L288-304).

"Both of the studies covered here primarily focused on the Pliocene (~5.3-2.6 Ma) sections of Ocean Drilling Program (ODP) marine sediment cores Sites 885/886 located in the central subarctic North Pacific Ocean (Rea et al., 1993). ODP Sites 885/886 contain biogenic opal, dust predominantly from Asia, and minor amounts of circum-Pacific volcanic material (Pettke et al., 2000; Rea et al., 1993, 1998; Snoeckx et al., 1995). Due to a lack of calcium carbonate, the age model (and in turn sediment fluxes) for the core are determined using a combination of magnetostratigraphy and biostratigraphy (Dickens et al., 1995; Morley and Nigrini, 1995; Rea et al., 1993). For much of the Pliocene and Quaternary, the resolution of the age model is on the order of several hundred thousand to millions of years, limiting our knowledge of sediment constituent bMARs on timescales less than this range. Additionally, several hiatuses (likely erosional) within the Cenozoic have been suggested based on the core's stratigraphy (Rea et al., 1993). Any unidentified erosional hiatus(es) would bias bMARs low within the remaining sections of a given interval containing one or more hiatuses. Finally, we note that early work suggested that opal sedimentation patterns at ODP Sites 885/886 are anomalous for much of the Pliocene compared to other productivity proxy records produced at these sites, and even at other sites within the subarctic North Pacific (Dickens et al., 1995; Morley and Nigrini, 1995; Rea et al., 1993; Snoeckx et al., 1995). Combined, these findings suggest the age model-derived LSRs and bMARs at ODP Sites 885/886 are potentially problematic, and make these cores optimal targets for applying the 3HeET method. The production of CFP-derived vMARs for ODP Sites 885/886 is even more relevant considering the number of Pliocene dust, carbonate, opal, and other flux datasets produced using these marine core sites (Bailey et al., 2011; Chen et al., 2024; Rea et al., 1998; Zhang et al., 2018, 2020, 2021)."

18) 303 It's unclear whether "contemporaneous" refers to the fact that the studies came out at around the same time, or whether they covered the same time interval.

We have changed this sentence to say:

"contrary to evidence from several other studies produced around the same time"

19) 318 Can you be clearer about what is meant by "core-specific characteristics"? I think it would be helpful to state specifically that the difference between the two MARs suggests that the sites are affected by substantial winnowing prior to 3.6 Ma, and that the large inferred increase in dust flux after 3.6 Ma instead reflects a decrease in winnowing/increase in focusing.

To address this concern, we have re-written the first two paragraphs of this section to read (L305-339):

"Together, the studies of Abell et al. (2021) and Abell and Winckler (2023) produced 3HeET-derived sediment vMARs spanning ~6.0-2.5 Ma at ODP Sites 885/886. For much of the Pliocene at ODP Sites 885/886, there are substantial discrepancies between the age model-derived bMARs and 3HeET-derived vMARs, particularly during the period of ~5.5-3.6 Ma (Fig. 4). Specifically, the 3HeET-derived sediment vMARs suggest that sediments at ODP Sites 885/886 spanning ~5.5-3.6 Ma 1) experienced substantial winnowing, and/or 2) contain at least one erosional hiatus that dramatically reduces the overall age model-derived bMAR for that interval. Because of the discrepant bMARs and vMARs, sediment vMARs at ODP Sites 885/886 determined using 3HeET (Abell et al., 2021; Abell and Winckler, 2023) produce completely different dust and opal MAR records at these sites when compared to earlier work (Fig. 5) (Rea et al., 1998; Snoeckx et al., 1995). As such, Abell et al. (2021) found no large increase in dust MARs during the Pliocene, a feature evident in the initial work of Rea et al. (1998). Additionally, while Snoeckx et al. (1995) previously suggested low opal accumulation (a proxy for productivity) in the central subarctic North Pacific during the early and mid-Pliocene (~5-3.6 Ma), contrary to evidence from several other studies produced around the same time (Arnold et al., 1995; Barron, 1998; Dickens and Barron, 1997; Dickens and Owen, 1996), Abell and Winckler (2023) found high vMARs of two productivity proxies in this interval (Fig. 5C and D). Abell and Winckler (2023) posited that this period of elevated productivity could be attributed to North Pacific deep water formation, although this hypothesis is still heavily debated (Burls et al., 2017; Novak et al., 2024). Regardless of the driver, by reconstructing opal vMARs using 3HeET at ODP Sites 885/886 during the early and mid-Pliocene, Abell and Winckler (2023) found that opal accumulation at these sites is consistent with other datasets from these same cores (Arnold et al., 1995; Dickens and Barron, 1997; Dickens and Owen, 1996) as well as many other ODP sites from the subarctic North Pacific (Barron, 1998). Finally, by comparing the Pliocene 3HeET-derived dust vMAR records from ODP Sites 885/886 to other another core with 3HeET-derived vMARs located in the North Pacific, Abell et al. (2021) showed that changes in atmospheric circulation, specifically the westerlies, occurred with the intensification of Northern Hemisphere Glaciation in response to shifts in Northern Hemisphere ice sheets and meridional temperature gradients.

We highlight the various paleoclimate-related findings of each of these individual studies in order to emphasize just how critical the use of the CFP 3HeET was to these datasets and interpretations. For ODP Sites 885/886, CFP-derived MARs not only produced fundamental differences in productivity and dust reconstructions by accounting for sediment winnowing

and/or unidentified hiatuses, they also greatly increased the resolution of the available MAR (in this case vMAR) data. It is integral to remember that even when combining lower resolution bMARs with higher resolution sediment constituent concentration data, the reliability of the derived higher-resolution constituent bMARs is still limited to the resolution of the age model. Using ODP Sites 885/886 as an example, any study directly using higher-resolution dust or opal bMARs for paleoclimate interpretations implicitly assumes that all changes in dust or opal bMARs between tie-points are driven by changes in their respective bMARs, not dilution. Turning to the multi-site approach of Abell et al. (2021),, the use of CFPs allowed for the normalization of variable sediment accumulation histories and age model resolutions across independent (and quite distal) sites, and thus provided internally consistent comparisons. Overall, without employing a CFP, core-specific issues such as age model resolution and sediment redistribution cannot be completely ameliorated."

20) Fig 6A I'm not sure where it would go in the manuscript, but I would encourage the authors to emphasize more than they currently do that the age model-based MARs for specific sedimentary constituents are in reality limited to the resolution of the age model; age model-based dust and opal flux records that appear to be high resolution (like those shown in Fig 6A and 6C) reflect an assumption that all changes in dust and opal concentration are from changes in flux rather than changes in dilution.

We agree with the reviewer that this fundamental flaw of using age model-derived bMARs should be explicitly reiterated. To address this concern, we have re-written the last paragraph in our first case study to read (L328-339):

"We highlight the various paleoclimate-related findings of each of these individual studies in order to emphasize just how critical the use of the CFP 3HeET was to these datasets and interpretations. For ODP Sites 885/886, CFP-derived MARs not only produced fundamental differences in productivity and dust reconstructions by accounting for sediment winnowing and/or unidentified hiatuses, they also greatly increased the resolution of the available MAR (in this case vMAR) data. It is integral to remember that even when combining lower resolution bMARs with higher resolution sediment constituent concentration data, the reliability of the derived higher-resolution constituent bMARs is still limited to the resolution of the age model. Using ODP Sites 885/886 as an example, any study directly using higher-resolution dust or opal bMARs for paleoclimate interpretations implicitly assumes that all changes in dust or opal bMARs between tie-points are driven by changes in their respective bMARs, not dilution. Turning to the multi-site approach of Abell et al. (2021),, the use of CFPs allowed for the normalization of variable sediment accumulation histories and age model resolutions across independent (and quite distal) sites, and thus provided internally consistent comparisons. Overall, without employing a CFP, core-specific issues such as age model resolution and sediment redistribution cannot be completely ameliorated."

21) 340 The use of the word "driver" here makes it sound like you are talking about a driver of the PETM, not a driver of the recovery from the PETM.

We agree with the reviewer. This sentence now reads (L360-362):

"One posited hypothesis for the recovery suggests that the efficiency of the marine biological pump shifted in response to the large carbon perturbation, ultimately reducing atmospheric CO2 and inducing a return to background conditions (Bains et al., 2000; Ma et al., 2014; Papadomanolaki et al., 2022; Stoll et al., 2007)."

22) 368 "be"->"can be"

We thank the reviewer for catching this mistake. We made this change.

23) 371 "less-than-optimal"->"low"

We made this change.

24) 381 It would be helpful to point out that this sensitivity of the 3HeET concentration leads to large uncertainties in the 3HeET-based fluxes. In general, I think the authors can be clearer in pointing out that use of 3HeET might not be possible in quickly accumulating sediments with high detrital content.

We made re-written this paragraph to explicitly address this concern (L399-408):

"Post-measurement, one must carefully consider which helium isotope ratios are used for the terrestrial and extraterrestrial endmembers (Eq. 8). As initially pointed out by Marcantonio et al. (1998), if the 3He/4He ratio of a given sample falls near the terrestrial endmember value, then the determined 3HeET concentration will be highly sensitive to the chosen terrestrial endmember value, ultimately imparting large uncertainties on the 3HeET-derived fluxes. Considering that terrestrial endmember helium isotope ratios have been suggested to span several orders of magnitude (Marcantonio et al., 1998; McGee et al., 2016), and high MARs and sediment detrital content both act to reduce measured 3He/4He ratios, there are likely certain types of depositional environments in the ocean where 3HeET concentrations are so uncertain that the application of 3HeET is not advisable. We suggest studies employing 3HeET as a CFP perform sensitivity analysis on their chosen terrestrial endmember value to evaluate its effects on calculated 3HeET concentrations (Abell et al., 2023; Abell and Winckler, 2023; Marcantonio et al., 1998; Middleton et al., 2016; O'Mara et al., 2022, 2024; Pavia et al., 2024, 2025)."

25) 422 Somewhere, the authors should point out that the inferred 3HeET fluxes for older time intervals may reflect site-specific differences in 3HeET loss (e.g. due to burial heating). For example, the data from Gubbio are from lithified, uplifted sediments that may have been heated.

The reviewer brings up a great point here. We now address this potential complication in our revised discussion of the flux of $^{3}He_{ET}$ from space (L440-479).

"The final, and potentially most important uncertainty to consider stems from the selection of F3HeET for the period of study. A plethora of studies have worked to determine F3HeET and its consistency in the modern and late Quaternary (Brook et al., 2000, 2009; Farley et al., 2021; Fénisse et al., 2025; Higgins et al., 2002; Marcantonio et al., 1995, 1996, 1999; McGee et al., 2010; McGee and Mukhopadhyay, 2013; Middleton et al., 2020; Winckler et al., 2004, 2005b;

Winckler and Fischer, 2006). While initially posited to vary on ~100-kyr timescales (Farley and Patterson, 1995; Patterson and Farley, 1998), comparisons with the CFP 230Th in a variety of marine depositional settings, as well as independent constraints from ice cores, support the notion that F3HeET was constant at ~0.8 pcc cm-2 kyr-1 on at least glacial-interglacial timescales over the last ~400-500 kyr. Unfortunately, the value of F3HeET in deeper time is, at present, under constrained. The only available estimates for F3HeET prior to the Quaternary are either determined under the assumption that the archive used did not experience sediment redistribution (Farley, 1995; Farley et al., 2006; Montanari et al., 2017; Mukhopadhyay et al., 2001a), or consider the potential for sediment redistribution for the site(s) in question, and in turn produce a 'relative' or 'implied' (i.e. site-specific) F3HeET value to use for determining MARs (Farley and Eltgroth, 2003; Marcantonio et al., 2009; Murphy et al., 2010). While proposed F3HeET values for much of the Cenozoic are less than the value derived for the late Quaternary, these are not consistent across sites (McGee and Mukhopadhyay, 2013). In the late Miocene, F3HeET values range from ~0.1 to 1.0 pcc cm-2 kyr-1 when comparing ODP Site 926 (Farley et al., 2006), ODP Site 757 (Farley et al., 2006), and Monte dei Corvi Beach, Italy (Montanari et al., 2017). A marginally reduced range (~0.1-0.7 pcc cm-2 kyr-1) of estimates for F3HeET are reconstructed for the late Paleocene and early Eocene across six sites (Farley, 1995; Farley and Eltgroth, 2003; McGee and Mukhopadhyay, 2013; Mukhopadhyay et al., 2001a; Murphy et al., 2010). Three possible explanations for these discrepancies include 1) loss of 3HeET due to post-depositional heating (likely to only influence terrestrial sites such as Gubbio and Monte dei Corvi Beach in Italy), 2) sediment focusing or winnowing biasing bMARs low or high, and 3) unidentified erosional hiatuses biasing bMARs low. While point #2 could impact any marine sediment core, point #3 is particularly relevant for sites with low-resolution age models, such as LL44-GPC3 in the central North Pacific (Fig. 3). In fact, LL44-GPC3 displays bMARs that generally scale with age model resolution (Doh et al., 1988; Doyle and Riedel, 1979; Farley, 1995; Prince et al., 1980), potential evidence for unidentified periods of non-deposition or erosion impacting this core (Sadler, 1981, 1999), and thus biased F3HeET values. We note that these points are speculative, and additional data from uplifted late Mesozoic marine rocks support a low early Cenozoic F3HeET of around ~0.1 pcc cm-2 kyr-1 (Blard et al., 2023). Specifically, the use of a Quaternary F3HeET value for the sites studied by Blard et al. (2023) would cause extremely large (a factor of ~10) discrepancies between bMARs and vMARs. However, another explanation for these data could be that the Quaternary value of F3HeET is appropriate for this interval, and ~90% of the 3HeET in these rocks was lost over time (potentially via heating during burial), which together would produce the same estimates of vMARs in the study (Blard et al., 2023). Preferential loss of 3HeET in sediments/rocks through time could also explain the lower F3HeET suggested for much of the Cenozoic (Farley, 1995; McGee and Mukhopadhyay, 2013). As previously mentioned, is it extremely difficult to discern which (if any) of these proposed processes are impacting F3HeET. Considering the abundance of uncertainties surrounding the value of F3HeET prior to the late Quaternary, we suggest that future studies relying on 3HeET to determine marine sediment fluxes prior to the Quaternary use both the late Quaternary value and another estimate from the period of interest and evaluate the dataset's sensitivity to the chosen value. Importantly, as long as F3HeET is constant over the period of interest, interpretations regarding relative changes in vMARs are still viable. Further constraints on the value of F3HeET for at least the late Neogene and Quaternary could be provided via combined analyses with other geochemical tracers that have known production

rates. One example is meteoric 10Be (Frank et al., 2002; Winckler et al., 2005a), although 10Be is not without its own complexities (Middleton et al., 2026; Savranskaia et al., 2024)."

26) 438 I'm not clear that the Elderfield proxy curve applies to 3HeET…did 3HeET go through a "Pessimism" phase? If so, the authors should provide evidence of this phase – maybe it was during the time when people were suggesting cyclic 100-kyr changes in 3HeET flux to Earth? I feel like (as the authors later state), the real issues are lack of analytical facilities, the slow pace of data gathering (due to analytical procedures and the need for replicates), and the continued need for community education about the importance of CFPs (which this manuscript aims to address).

We agree with the reviewer that it is likely not appropriate to invoke the Elderfield proxy curve for $^{3}He_{ET}$. As such, we have removed the figure and adjusted the associated text accordingly.

27) 449 I am conflicted about writing this, but for #2 I guess feel that the McGee and Mukhopadhyay chapter also tried to "describ[e] 3HeET's utility to the broader Earth science community"? Again, it's clear this manuscript has an important role to play, but I think the authors could be a bit more specific in stating how this manuscript is different from previous work.

We agree with the reviewer that McGee and Mukhopadhyay (2013) did address this topic. To both highlight this fact and state how our manuscript differs from previous work, the paragraph now reads (L490-498):

"So, what is standing in the way of applying this influential method to every marine sediment core to develop both short- and long-term accurate records of changes in the Earth system across the Cenozoic? In a practical sense, the simple answers to this question at present are 1) a scarcity of laboratories making measurements of marine sediment noble gases, 2) the analytical challenges of generating reliable sediment helium isotope data, and 3) limited attempts to describe 3HeET's utility to the broader Earth science community (McGee and Mukhopadhyay, 2013). While points #1 and #2 are not amenable to a 'quick fix', we have expanded on the previous review of McGee and Mukhopadhyay (2013)in an effort to address point #3. Specifically, not only do we provide a systematic overview of age model-derived bMARs and CFP-derived vMARs and their associated uncertainties, but also incorporate new findings accumulated over the last ~15 years to provide a paleoclimate-centric perspective on the benefits of applying 3HeET as a CFP to explore the pre-Quaternary Cenozoic Earth system."

28) 460 to me, "heavily stymied" is a bit of an awkward phrase.

We agree with the reviewer. We replaced "stymied" with "reduced".

Reviewer #2:

1) This perspective provides an overview of the potential of extraterrestrial helium-3 (3HeET) as a tool for estimating mass accumulation rates (MAR) in deep-sea sediments. The authors

compare the 3HeET-based method with other approaches, including age-model-based techniques and 230Th-based estimates, highlighting both strengths and limitations. The paper makes a compelling case for broader adoption and further exploration of 3HeET in paleoceanographic studies. As someone working with conventional (i.e., age model-based) MAR reconstructions but lacks direct experience with 3HeET measurements, I offer the following comments aimed at improving clarity—particularly for readers with a similar background.

We thank the reviewer for their positive comments on our manuscript. We address all comments/concerns in detail below.

2) A key assumption underpinning the use of 3HeET as a constant-flux proxy (CFP) is the temporal constancy of its delivery to Earth. While the manuscript acknowledges this assumption, it would benefit from a more critical evaluation of its validity across different timescales. For example, it would be helpful if the authors expanded on: (i) whether the 3HeET flux can be considered constant over the last glacial cycle (e.g., since the LGM), (ii) potential long-term trends across tens to hundreds of thousands of years, or even millions of years, and (iii) any observational evidence that supports or challenges these assumptions.

We have added text to this section briefly summarizing the findings of the late Quaternary studies, which together show that F_{3HeET} is constant on glacial-interglacial timescales (and shorter) for at least the last ~400-500 kyr. We also added a substantial discussion on evidence that both supports and challenges F_{3HeET} estimates across the Cenozoic. The text now reads (L440-479):

"The final, and potentially most important uncertainty to consider stems from the selection of F3HeET for the period of study. A plethora of studies have worked to determine F3HeET and its consistency in the modern and late Quaternary (Brook et al., 2000, 2009; Farley et al., 2021; Fénisse et al., 2025; Higgins et al., 2002; Marcantonio et al., 1995, 1996, 1999; McGee et al., 2010; McGee and Mukhopadhyay, 2013; Middleton et al., 2020; Winckler et al., 2004, 2005b; Winckler and Fischer, 2006). While initially posited to vary on ~100-kyr timescales (Farley and Patterson, 1995; Patterson and Farley, 1998), comparisons with the CFP 230Th in a variety of marine depositional settings, as well as independent constraints from ice cores, support the notion that F3HeET was constant at ~0.8 pcc cm-2 kyr-1 on at least glacial-interglacial timescales over the last ~400-500 kyr. Unfortunately, the value of F3HeET in deeper time is, at present, under constrained. The only available estimates for F3HeET prior to the Quaternary are either determined under the assumption that the archive used did not experience sediment redistribution (Farley, 1995; Farley et al., 2006; Montanari et al., 2017; Mukhopadhyay et al., 2001a), or consider the potential for sediment redistribution for the site(s) in question, and in turn produce a 'relative' or 'implied' (i.e. site-specific) F3HeET value to use for determining MARs (Farley and Eltgroth, 2003; Marcantonio et al., 2009; Murphy et al., 2010). While proposed F3HeET values for much of the Cenozoic are less than the value derived for the late Quaternary, these are not consistent across sites (McGee and Mukhopadhyay, 2013). In the late Miocene, F3HeET values range from ~0.1 to 1.0 pcc cm-2 kyr-1 when comparing ODP Site 926 (Farley et al., 2006), ODP Site 757 (Farley et al., 2006), and Monte dei Corvi Beach, Italy (Montanari et al., 2017). A marginally reduced range (~0.1-0.7 pcc cm-2 kyr-1) of estimates for F3HeET are reconstructed for the late Paleocene and early Eocene across six sites (Farley, 1995; Farley and

Eltgroth, 2003; McGee and Mukhopadhyay, 2013; Mukhopadhyay et al., 2001a; Murphy et al., 2010). Three possible explanations for these discrepancies include 1) loss of 3HeET due to post-depositional heating (likely to only influence terrestrial sites such as Gubbio and Monte dei Corvi Beach in Italy), 2) sediment focusing or winnowing biasing bMARs low or high, and 3) unidentified erosional hiatuses biasing bMARs low. While point #2 could impact any marine sediment core, point #3 is particularly relevant for sites with low-resolution age models, such as LL44-GPC3 in the central North Pacific (Fig. 3). In fact, LL44-GPC3 displays bMARs that generally scale with age model resolution (Doh et al., 1988; Doyle and Riedel, 1979; Farley, 1995; Prince et al., 1980), potential evidence for unidentified periods of non-deposition or erosion impacting this core (Sadler, 1981, 1999), and thus biased F3HeET values. We note that these points are speculative, and additional data from uplifted late Mesozoic marine rocks support a low early Cenozoic F3HeET of around ~0.1 pcc cm-2 kyr-1 (Blard et al., 2023). Specifically, the use of a Quaternary F3HeET value for the sites studied by Blard et al. (2023) would cause extremely large (a factor of ~10) discrepancies between bMARs and vMARs. However, another explanation for these data could be that the Quaternary value of F3HeET is appropriate for this interval, and ~90% of the 3HeET in these rocks was lost over time (potentially via heating during burial), which together would produce the same estimates of vMARs in the study (Blard et al., 2023). Preferential loss of 3HeET in sediments/rocks through time could also explain the lower F3HeET suggested for much of the Cenozoic (Farley, 1995; McGee and Mukhopadhyay, 2013). As previously mentioned, is it extremely difficult to discern which (if any) of these proposed processes are impacting F3HeET. Considering the abundance of uncertainties surrounding the value of F3HeET prior to the late Quaternary, we suggest that future studies relying on 3HeET to determine marine sediment fluxes prior to the Quaternary use both the late Quaternary value and another estimate from the period of interest and evaluate the dataset's sensitivity to the chosen value. Importantly, as long as F3HeET is constant over the period of interest, interpretations regarding relative changes in vMARs are still viable. Further constraints on the value of F3HeET for at least the late Neogene and Quaternary could be provided via combined analyses with other geochemical tracers that have known production rates. One example is meteoric 10Be (Frank et al., 2002; Winckler et al., 2005a), although 10Be is not without its own complexities (Middleton et al., 2026; Savranskaia et al., 2024)."

3) Figures 5-6 present compelling data showing divergent trends between vMAR derived from 3HeET and bulk MAR (bMAR) estimates. Notably, 3HeET-based vMAR is several times higher than bMAR during the late Miocene and early Pliocene. For readers unfamiliar with the site-specific context, this discrepancy raises important interpretive questions: does this discrepancy also reflect a fundamentally different age model in the 3HeET approach compared to the one used for bMAR? Alternatively, if the age models are consistent, could the higher vMAR inferred from 3HeET indicate enhanced winnowing during the late Miocene and early Pliocene when surface productivity was also higher? While the authors reference prior studies, a brief synthesis of the proposed mechanisms for this divergence would enhance clarity.

The reviewer raises an excellent point here, which we address in two specific ways.

First, the actual age of the samples where CFP-derived vMARs are determined are always dependent on the age model. This would be the same for any samples with age model-derived bMARs. The key difference is that the CFP-derived vMAR value is not reliant on the age model,

while the bMAR value is directly dependent on the age model (it is calculated from it). To be more explicit about this point, we added the following text in Section 3 (L219-225):

"It is important to again stress that, as with any application of CFPs to determine vMARs, the ages determined for all samples from a particular site still rely on the age model for the core. The key difference, in terms of vMARs and bMARs, is that the determined vMARs for each sample of a given age do not depend on the age model, while bMARs are directly dependent on the age model (as described in section 2). Put another way, if the age model for a marine sediment core is later refined and tie-points are altered, CFP-derived sample vMARs will only shift in age, not value, while age model-derived sample bMARs will be both change in age and value."

Second, yes, the reviewer is correct that the higher vMARs at ODP Sites 885/886 from ~6-3.6 Ma suggest either intense winnowing or one or more unidentified hiatuses within this interval that bias the age model-derived bMARs low. While an erosional hiatus would also not preserve 3HeET, it would not impact the 3HeET concentrations (and thus vMARs) for sediments around the hiatus within the two age model tie-points. We have added some additional details to Section 5.1 to better elaborate on these points (L305-312).

"Together, the studies of Abell et al. (2021) and Abell and Winckler (2023) produced 3HeET-derived sediment vMARs spanning ~6.0-2.5 Ma at ODP Sites 885/886. For much of the Pliocene at ODP Sites 885/886, there are substantial discrepancies between the age model-derived bMARs and 3HeET-derived vMARs, particularly during the period of ~5.5-3.6 Ma (Fig. 4). Specifically, the 3HeET-derived sediment vMARs suggest that sediments at ODP Sites 885/886 spanning ~5.5-3.6 Ma 1) experienced substantial winnowing, and/or 2) contain at least one erosional hiatus that dramatically reduces the overall age model-derived bMAR for that interval. Because of the discrepant bMARs and vMARs, sediment vMARs at ODP Sites 885/886 determined using 3HeET (Abell et al., 2021; Abell and Winckler, 2023) produce completely different dust and opal MAR records at these sites when compared to earlier work (Fig. 5) (Rea et al., 1998; Snoeckx et al., 1995)."

4) In Section 6, the authors discuss several caveats related to the use of 3HeET as a CFP. However, the role of post-deposional dissolution of biogenic material may warrant further attention. The dissolution of biogenic calcareous and siliceous remains occurs widely across the seafloor and varies spatially with depth, ocean chemistry, and circulation, as well as temporally with climate and oceanographic changes. Such processes likely alter the relative proportions of sediment components and thus affect the average concentration of the proxy [CFPavg]. How might this influence the estimation of vMAR?

The reviewer raises an excellent point, and we added a sentence in Section 6 to address the impacts of biogenic carbonate and opal dissolution of vMARs (L436-439).

"A related sedimentary process that does impact CFP-derived vMARs is dissolution of biogenic sediments. Under this scenario, both age model-derived bMARs and CFP-derived vMARs would only reflect the remaining sediment, as long as the CFP in question is not lost to the water column (Costa et al., 2020)."

Minor Comments

5) Line 93: Typo: “Ee aim to achieve”

We thank the reviewer for catching this mistake. We made this change.

6) Line 211: Consider defining [3HeET] and its unit

We now define this variable and its units (L213-214).

“where [$^{3}He_{meas}$] is the measured concentration of ^{3}He (typically in pico-cubic centimeters (pcc) g^{-1}), and [$^{3}He_{ET}$] is the determined $^{3}He_{ET}$ concentration in the same units”

Line 214: The unit “pcc” should be defined at first use

We now define this unit.

Line 250: I do not see “circles with dashed borders” in the figure.

We thank the reviewer for catching this mistake. This text was for a previous version of this figure. It has been revised.

Line 288: “Early work suggested that certain sedimentation patterns…” the term “certain patterns” is vague. Please specify which patterns are being referenced.

We have rephrased this paragraph to better explain the discrepancies in productivity proxies (including opal bMARs) from earlier work (L288-304).

“Both of the studies covered here primarily focused on the Pliocene (~5.3-2.6 Ma) sections of Ocean Drilling Program (ODP) marine sediment cores Sites 885/886 located in the central subarctic North Pacific Ocean (Rea et al., 1993). ODP Sites 885/886 contain biogenic opal, dust predominantly from Asia, and minor amounts of circum-Pacific volcanic material (Pettke et al., 2000; Rea et al., 1993, 1998; Snoeckx et al., 1995). Due to a lack of calcium carbonate, the age model (and in turn sediment fluxes) for the core are determined using a combination of magnetostratigraphy and biostratigraphy (Dickens et al., 1995; Morley and Nigrini, 1995; Rea et al., 1993). For much of the Pliocene and Quaternary, the resolution of the age model is on the order of several hundred thousand to millions of years, limiting our knowledge of sediment constituent bMARs on timescales less than this range. Additionally, several hiatuses (likely erosional) within the Cenozoic have been suggested based on the core’s stratigraphy (Rea et al., 1993). Any unidentified erosional hiatus(es) would bias bMARs low within the remaining sections of a given interval containing one or more hiatuses. Finally, we note that early work suggested that opal sedimentation patterns at ODP Sites 885/886 are anomalous for much of the Pliocene compared to other productivity proxy records produced at these sites, and even at other sites within the subarctic North Pacific (Dickens et al., 1995; Morley and Nigrini, 1995; Rea et al., 1993; Snoeckx et al., 1995). Combined, these findings suggest the age model-derived LSRs and bMARs at ODP Sites 885/886 are potentially problematic, and make these cores optimal

targets for applying the 3HeET method. The production of CFP-derived vMARs for ODP Sites 885/886 is even more relevant considering the number of Pliocene dust, carbonate, opal, and other flux datasets produced using these marine core sites (Bailey et al., 2011; Chen et al., 2024; Rea et al., 1998; Zhang et al., 2018, 2020, 2021)."

Reviewer #3:

1) This manuscript by Abell et al. is somewhat of a hybrid between a review article and a perspective (viewpoint) paper. Because it is intended for a broad readership, including researchers who are not specialists in extraterrestrial ^{3}He and ^{230}Th, I believe it is a valuable contribution. It provides a clear and pedagogical overview of both the potential and the limitations of these methods. I recommend publication after minor to moderate revisions, taking into account the following comments.

We thank the reviewer for their positive comments on our manuscript. We address all comments/concerns in detail below.

2) Recommendation to use the Quaternary F_{3HeETF} as a default flux (Section 6)
I agree that there are clear spatial and temporal variations in extraterrestrial ^{3}He flux F_{3HeETF} throughout the Cenozoic. However, the range of fluxes reported for the Cenozoic remains substantially lower than the Quaternary value. Therefore, I do not think that recommending the Quaternary flux as the default choice is appropriate.
In this context, I would like to draw the authors' attention to our recent work on Mesozoic marl-limestone alternations (Blard et al., EPSL, 2023). In that study, the total sedimentation rates (carbonate + silicate) reconstructed from extraterrestrial ^{3}He are in excellent agreement with independent biostratigraphic sedimentation rates when using the Cretaceous extraterrestrial flux independently determined by Farley et al. 2012 (~0.1 pcc cm^{-2} kyr^{-1}). If the Quaternary flux, which is approximately an order of magnitude higher, had been used instead, the reconstructed sedimentation rates would also have been overestimated by roughly one order of magnitude. Given that the average F_{3HeETF} is approximately 0.5 pcc cm^{-2} kyr^{-1} throughout the Cenozoic, compared with about 1 pcc cm^{-2} kyr^{-1} during the Quaternary, available data suggest that the extraterrestrial ^{3}He flux preserved in marine sediments decreases with geological age. Whether this apparent trend reflects preservation biases or genuine temporal variations in the incoming extraterrestrial flux remains an open question. I therefore suggest revising this section to better acknowledge these long-term variations and the implications for selecting an appropriate reference flux.

We thank the reviewer for their insight into this topic. We agree that further discussion of the pre-~500 ka F_{3HeET} value is necessary. As such, we have expanded this section. Specifically, we now provide a more detailed assessment of published estimates of F_{3HeET} throughout the Cenozoic as well as their associated uncertainties, and incorporate the findings of Blard et al. (2023) as potential evidence for a lower value in the early Cenozoic. See below for the new text (L440-479).

“The final, and potentially most important uncertainty to consider stems from the selection of F3HeET for the period of study. A plethora of studies have worked to determine F3HeET and its consistency in the modern and late Quaternary (Brook et al., 2000, 2009; Farley et al., 2021; Fénisse et al., 2025; Higgins et al., 2002; Marcantonio et al., 1995, 1996, 1999; McGee et al., 2010; McGee and Mukhopadhyay, 2013; Middleton et al., 2020; Winckler et al., 2004, 2005b; Winckler and Fischer, 2006). While initially posited to vary on ~100-kyr timescales (Farley and Patterson, 1995; Patterson and Farley, 1998), comparisons with the CFP 230Th in a variety of marine depositional settings, as well as independent constraints from ice cores, support the notion that F3HeET was constant at ~0.8 pcc cm-2 kyr-1 on at least glacial-interglacial timescales over the last ~400-500 kyr. Unfortunately, the value of F3HeET in deeper time is, at present, under constrained. The only available estimates for F3HeET prior to the Quaternary are either determined under the assumption that the archive used did not experience sediment redistribution (Farley, 1995; Farley et al., 2006; Montanari et al., 2017; Mukhopadhyay et al., 2001a), or consider the potential for sediment redistribution for the site(s) in question, and in turn produce a ‘relative’ or ‘implied’ (i.e. site-specific) F3HeET value to use for determining MARs (Farley and Eltgroth, 2003; Marcantonio et al., 2009; Murphy et al., 2010). While proposed F3HeET values for much of the Cenozoic are less than the value derived for the late Quaternary, these are not consistent across sites (McGee and Mukhopadhyay, 2013). In the late Miocene, F3HeET values range from ~0.1 to 1.0 pcc cm-2 kyr-1 when comparing ODP Site 926 (Farley et al., 2006), ODP Site 757 (Farley et al., 2006), and Monte dei Corvi Beach, Italy (Montanari et al., 2017). A marginally reduced range (~0.1-0.7 pcc cm-2 kyr-1) of estimates for F3HeET are reconstructed for the late Paleocene and early Eocene across six sites (Farley, 1995; Farley and Eltgroth, 2003; McGee and Mukhopadhyay, 2013; Mukhopadhyay et al., 2001a; Murphy et al., 2010). Three possible explanations for these discrepancies include 1) loss of 3HeET due to post-depositional heating (likely to only influence terrestrial sites such as Gubbio and Monte dei Corvi Beach in Italy), 2) sediment focusing or winnowing biasing bMARs low or high, and 3) unidentified erosional hiatuses biasing bMARs low. While point #2 could impact any marine sediment core, point #3 is particularly relevant for sites with low-resolution age models, such as LL44-GPC3 in the central North Pacific (Fig. 3). In fact, LL44-GPC3 displays bMARs that generally scale with age model resolution (Doh et al., 1988; Doyle and Riedel, 1979; Farley, 1995; Prince et al., 1980), potential evidence for unidentified periods of non-deposition or erosion impacting this core (Sadler, 1981, 1999), and thus biased F3HeET values. We note that these points are speculative, and additional data from uplifted late Mesozoic marine rocks support a low early Cenozoic F3HeET of around ~0.1 pcc cm-2 kyr-1 (Blard et al., 2023). Specifically, the use of a Quaternary F3HeET value for the sites studied by Blard et al. (2023) would cause extremely large (a factor of ~10) discrepancies between bMARs and vMARs. However, another explanation for these data could be that the Quaternary value of F3HeET is appropriate for this interval, and ~90% of the 3HeET in these rocks was lost over time (potentially via heating during burial), which together would produce the same estimates of vMARs in the study (Blard et al., 2023). Preferential loss of 3HeET in sediments/rocks through time could also explain the lower F3HeET suggested for much of the Cenozoic (Farley, 1995; McGee and Mukhopadhyay, 2013). As previously mentioned, is it extremely difficult to discern which (if any) of these proposed processes are impacting F3HeET. Considering the abundance of uncertainties surrounding the value of F3HeET prior to the late Quaternary, we suggest that future studies relying on 3HeET to determine marine sediment fluxes prior to the Quaternary use both the late Quaternary value and another estimate from the period of interest and evaluate the

dataset's sensitivity to the chosen value. Importantly, as long as F3HeET is constant over the period of interest, interpretations regarding relative changes in vMARs are still viable. Further constraints on the value of F3HeET for at least the late Neogene and Quaternary could be provided via combined analyses with other geochemical tracers that have known production rates. One example is meteoric 10Be (Frank et al., 2002; Winckler et al., 2005a), although 10Be is not without its own complexities (Middleton et al., 2026; Savranskaia et al., 2024)."

3) Discussion of the two Cenozoic case studies
The two case studies highlighted in the manuscript are convincing examples of the potential of the method. However, I believe that some of the underlying assumptions and limitations deserve a more thorough discussion.
First, the manuscript suggests that the magnetostratigraphic/biostratigraphic age models may be affected by hiatuses. It would be useful to distinguish between:

- erosional hiatuses, for which extraterrestrial ^{3}He cannot recover the missing sediment, and
- periods of non-deposition, which may indeed be identified using extraterrestrial ^{3}He.

This distinction is important because the implications are fundamentally different.
Second, these records span several million years. Over such timescales, variations in extraterrestrial ^{3}He flux are not uncommon in the geological record. How can the authors justify assuming a constant extraterrestrial flux throughout these intervals? I think this issue deserves further discussion.

We thank the reviewer for bringing up an important point here. Hiatuses were 1) identified in several portions of ODP Sites 885/886 (Rea et al., 1993), and 2) suggested as a potential cause for the discrepancy between age model-derived bMARs and CFP-derived vMARs at these sites (Abell et al., 2021; Abell and Winckler 2023). These were assumed to be erosional hiatuses, as no substantial, short-lived peaks were identified in the $^{3}He_{ET}$ concentrations (Abell et al., 2021; Abell and Winckler 2023). While it is true that $^{3}He_{ET}$ cannot 'recover' information about the missing sediment from the erosional hiatus, the vMARs derived from the sediment surrounding the hiatus but still within the interval between age model tie-points where the hiatus occurred are not impacted by the erosional hiatus, unlike the age model-derived bMARs. We have now added additional text to clarify the role of the age model for CFPs and the impact of hiatuses at ODP Sites 885/886 point.

In Section 3 (L219-225):

"It is important to again stress that, as with any application of CFPs to determine vMARs, the ages determined for all samples from a particular site still rely on the age model for the core. The key difference, in terms of vMARs and bMARs, is that the determined vMARs for each sample of a given age do not depend on the age model, while bMARs are directly dependent on the age model (as described in section 2). Put another way, if the age model for a marine sediment core is later refined and tie-points are altered, CFP-derived sample vMARs will only shift in age, not value, while age model-derived sample bMARs will be both change in age and value."

In Section 5.1 (L305-339):

“Together, the studies of Abell et al. (2021) and Abell and Winckler (2023) produced 3HeET-derived sediment vMARs spanning ~6.0-2.5 Ma at ODP Sites 885/886. For much of the Pliocene at ODP Sites 885/886, there are substantial discrepancies between the age model-derived bMARs and 3HeET-derived vMARs, particularly during the period of ~5.5-3.6 Ma (Fig. 4). Specifically, the 3HeET-derived sediment vMARs suggest that sediments at ODP Sites 885/886 spanning ~5.5-3.6 Ma 1) experienced substantial winnowing, and/or 2) contain at least one erosional hiatus that dramatically reduces the overall age model-derived bMAR for that interval. Because of the discrepant bMARs and vMARs, sediment vMARs at ODP Sites 885/886 determined using 3HeET (Abell et al., 2021; Abell and Winckler, 2023) produce completely different dust and opal MAR records at these sites when compared to earlier work (Fig. 5) (Rea et al., 1998; Snoeckx et al., 1995). As such, Abell et al. (2021) found no large increase in dust MARs during the Pliocene, a feature evident in the initial work of Rea et al. (1998). Additionally, while Snoeckx et al. (1995) previously suggested low opal accumulation (a proxy for productivity) in the central subarctic North Pacific during the early and mid-Pliocene (~5-3.6 Ma), contrary to evidence from several other studies produced around the same time (Arnold et al., 1995; Barron, 1998; Dickens and Barron, 1997; Dickens and Owen, 1996), Abell and Winckler (2023) found high vMARs of two productivity proxies in this interval (Fig. 5C and D). Abell and Winckler (2023) posited that this period of elevated productivity could be attributed to North Pacific deep water formation, although this hypothesis is still heavily debated (Burls et al., 2017; Novak et al., 2024). Regardless of the driver, by reconstructing opal vMARs using 3HeET at ODP Sites 885/886 during the early and mid-Pliocene, Abell and Winckler (2023) found that opal accumulation at these sites is consistent with other datasets from these same cores (Arnold et al., 1995; Dickens and Barron, 1997; Dickens and Owen, 1996) as well as many other ODP sites from the subarctic North Pacific (Barron, 1998). Finally, by comparing the Pliocene 3HeET-derived dust vMAR records from ODP Sites 885/886 to other another core with 3HeET-derived vMARs located in the North Pacific, Abell et al. (2021) showed that changes in atmospheric circulation, specifically the westerlies, occurred with the intensification of Northern Hemisphere Glaciation in response to shifts in Northern Hemisphere ice sheets and meridional temperature gradients.

We highlight the various paleoclimate-related findings of each of these individual studies in order to emphasize just how critical the use of the CFP 3HeET was to these datasets and interpretations. For ODP Sites 885/886, CFP-derived MARs not only produced fundamental differences in productivity and dust reconstructions by accounting for sediment winnowing and/or unidentified hiatuses, they also greatly increased the resolution of the available MAR (in this case vMAR) data. It is integral to remember that even when combining lower resolution bMARs with higher resolution sediment constituent concentration data, the reliability of the derived higher-resolution constituent bMARs is still limited to the resolution of the age model. Using ODP Sites 885/886 as an example, any study directly using higher-resolution dust or opal bMARs for paleoclimate interpretations implicitly assumes that all changes in dust or opal bMARs between tie-points are driven by changes in their respective bMARs, not dilution. Turning to the multi-site approach of Abell et al. (2021),, the use of CFPs allowed for the normalization of variable sediment accumulation histories and age model resolutions across independent (and quite distal) sites, and thus provided internally consistent comparisons. Overall, without employing a CFP, core-specific issues such as age model resolution and sediment redistribution cannot be completely ameliorated.”

As for the assumption of a constant F_{3HeET} for the Pliocene in these studies, we agree that a change in F_{3HeET} cannot be absolutely ruled out. However, no evidence exists for a short duration shift in F_{3HeET} for this interval (e.g., Farley, 1995; Graham and Konrad, 2022), so the assumption of a constant F_{3HeET} is not unrealistic. Additionally, as stated in those original studies, the application of the Farley (1995) estimate of F_{3HeET} for the Pliocene (~0.5 pcc cm^{-2} kyr^{-1}) would not impact the records (assuming no short-druation event), as all vMAR-based reconstructions would shift in the same direction by equal amounts. Ultimately, we agree with the reviewer that any future work utilizing $^{3}He_{ET}$ in any interval is subject to the possibility of missing a change in F_{3HeET}.

4) Interpretation of Figure 2 (compilation of ^{230}Th focusing factors)
Figure 2 shows that more sites have focusing factors greater than one than less than one. In other words, the mean focusing factor of the compiled dataset appears to be significantly larger than unity. This is somewhat surprising. At the scale of an ocean basin, sediment focusing and winnowing should compensate each other, since sediment removed from one location is redistributed elsewhere. Therefore, one would expect the basin-wide average focusing factor to be close to one, assuming conservation of sediment mass. Could the authors comment on this apparent imbalance? Does it reveal a methodological bias, for example a systematic bias in the assumed ^{230}Th production rate? One interesting possibility would be to use this global compilation to constrain the production rate itself, by imposing that the mean focusing factor equals one and treating P_{CFP} as an unknown parameter to be calibrated. If feasible, this would considerably strengthen the impact of the study.

We thank the reviewer for raising these interesting points. The most straightforward explanation for this phenomenon is that coring and drilling expeditions tend to aim for areas with thicker sediment packages (when this can be ascertained), which are more likely to reflect sediment focusing rather than winnowing. Put another way, it is just site selection bias when retrieving marine sediments.

As the reviewer points out, one way to test our coring bias hypothesis against another suggesting issues with either ^{230}Th, $^{3}He_{ET}$, or both, would be more to compare joint ^{230}Th-$^{3}He_{ET}$ data at sites across the global ocean, and see if the distribution of focusing/winnowing shifts. This would allow for more in-depth insight into the processes driving the dominance of focusing in the available data. The authors of this perspective/review are currently generating data to accomplish this task. We thank the reviewer for suggesting possible ways to utilize this new data once generated!

5) Line 5: Fossils and biominerals may partly overlap. Please check whether these categories should be distinguished more clearly.

We thank the reviewer for pointing out the overlap here. For simplicity, we removed "biominerals" as a separate category and incorporated it into the first listed category.

6) Line 82: Additional limitations include (i) environments characterized by highly variable sedimentation rates (e.g., turbidite-hemipelagite alternations), and (ii) sedimentary archives that

cannot easily be dated because suitable chronostratigraphic markers (e.g., carbonate-rich material) are absent.

We thank the reviewer for pointing out these additional processes impacting age model-derived bMARs. Because both of these technically fall under the categories of 'lateral sediment transport' and 'age model resolution', and for the sake of simplicity, we request to leave these out at present.

7) Lines 89–91: You could also mention that cobalt accumulation has been proposed as a long-term MAR proxy, based on the assumption of a nearly constant hydrothermal cobalt input (Kyte et al., 1993; Dunlea et al., 2015). This approach is mainly applicable in distal pelagic settings where terrigenous cobalt inputs remain negligible.

We thank the reviewer for pointing out the cobalt accumulation method, and absolutely agree that this approach can be useful for determining long-term MARs in certain settings. However, because we are focusing on the two most widely applied methods CFP methods, and would likely not delve into the cobalt method outside of this sentence, we feel it is unnecessary to introduce this additional approach. However, we are open to adding it if the reviewer feels it is necessary for a comprehensive discussion of CFPs.

8) Line 93: "We" instead of "Ee"?

We thank the reviewer for catching this mistake. We made this change.

9) Line 156: Please provide the units of the production rate. Which parameters are required for its calculation? Since ^{230}Th scavenging depends on particle surface area, does sediment grain size influence the estimate?

We now provide the units for the production rate. The value is determined using the decay constant of ^{230}Th and activity of uranium in seawater. As such, particle scavenging does not play a role in the production of ^{230}Th. Salinity is the only additional consideration, as uranium scales with salinity in seawater, but for the range of salinities in seawater, the variability in production is quite minor (Costa et al., 2020).

10) Line 168: Are you sure this statement is correct? Since scavenging is surface-area dependent, I imagine that the granulometry may affect the restuts. Can ^{230}Th be measured reliably in sandy fractions as well as in hemipelagic muds?

It has been suggested that there can be a grain size fractionation of ^{230}Th concentrations (e.g., Kretschmer et al., 2010; Lyle et al., 2005; 2014; Marcantonio et al., 2014). We currently note this in the manuscript (L174-181):

"Additionally, it has been shown that, for most settings and within the ~30% uncertainties of the assumed constancy of the 230Th burial rate, 230Th likely travels with horizontally redistributed sediments in nearly the same proportion as the originally deposited material (Costa et al., 2020; Francois et al., 2004; McGee et al., 2010; Tomchovska et al., 2025). This characteristic of 230Th

is why CFP-derived MARs are considered to reflect vMARs, not bMARs. There are certain locations where this assumption has been called into question (e.g., Kretschmer et al., 2010; Lyle et al., 2005, 2014). Generally, however, provided that the [230Th] of laterally transported sediment is the same as the sediment of the site of interest, then horizontal sediment redistribution will not substantially bias 230Th-based vMARs (Costa et al., 2020)."

The impact of grain size on ^{230}Th has been extensively detailed and summarized by Costa et al. (2020), who concluded that even in areas where this effect can be substantial, the inaccuracies produced by instead using age model-derived bMARs are likely still more influential. Except in regions impacted by boundary scavenging, the uncertainty from grain size fractionation is generally within the assumed ~30% uncertainty of this CFP approach. Because this is a review/perspective focused on $^{3}He_{ET}$, we do not feel it would be beneficial to provide additional details on this topic beyond what is currently present.

11) Lines 183 - 184: Please define the units of CFP and P_{CFP}. I assume these are atoms g^{-1} and atoms cm^{-2} yr^{-1}, respectively.

Because the use of [CFP] and P_{CFP} are proxy agnostic in that specific section, we do not feel defining units would be helpful to the reader. However, we now provide units for these variables both in the ^{230}Th and $^{3}He_{ET}$-specific subsections.

12) Figure 2: Would it be worthwhile performing a similar compilation using published extraterrestrial ^{3}He datasets?

We thank the reviewer for this idea. Because the focus of this perspective is to illustrate the dearth of data for the Cenozoic prior to the interval where ^{230}Th is applicable, we do not present the late Quaternary $^{3}He_{ET}$ data. However, this is a topic that our group is actively generating data for, and we will use the reviewer's helpful suggestion when analyzing late Quaternary joint ^{230}Th-$^{3}He_{ET}$ data.

13) Line 213: Please provide the units of both $^{3}He_{ET}$ and F_{3He}.

We thank the reviewer for pointing out this missing information. These are now provided.

14) Lines 220 - 221: You may wish to cite our study on Jurassic-Cretaceous marl-limestone alternations (Blard et al., 2023), as well as Lucas' PhD thesis (Oxford, 2021) on the Cenomanian Turonian transition. Alternatively, if the list is intended only as illustrative, consider introducing it with "e.g.".

We have now added Blard et al. (2023) and Lucas et al. (2024) to this sentence.

15) Line 228: You may also wish to cite Tomchovska et al., GCA, 2025, who demonstrated contrasting behaviours of ^{3}He and ^{230}Th with respect to sediment focusing and scavenging.

We have now added Tomchovska et al. (2025) to this sentence.

16) Line 237: I suggest rephrasing this sentence. It could be interpreted as implying that duration studies do not require assumptions about extraterrestrial ^{3}He flux. In fact, studies reconstructing event durations also assume a value for F_{3He}. Converting duration into MAR is then straightforward, requiring only sediment thickness and dry bulk density.

We agree with the reviewer that this sentence is confusing. We have removed it entirely.

17) Figure 4: Why not extend this inventory to pre-Cenozoic sites?

While we appreciate that $^{3}He_{ET}$ data is continually being produced for intervals of the Mesozoic, this perspective/review is generally focused on the application of $^{3}He_{ET}$ to marine sediment cores, which are dominated by Cenozoic material (although there are exceptions). While the information presented in our manuscript can be applicable to older sediments and uplifted marine rocks exposed on land, these typically require additional considerations (e.g., post-depositional heating from burial, compaction, etc.) that we do not explicitly cover here outside of addressing the two Cenozoic records of F_{3HeET} derived from Italian limestone deposits (Mukhopadhyay et al., 2001; Montanari et al., 2017) and another Mesozoic record (Blard et al., 2023), again which is used to evaluate F_{3HeET}. We hope others will build on our work for the Cenozoic and provide follow-up perspectives on Mesozoic applications of $^{3}He_{ET}$.

18) Line 306: "Export" is rather vague. Please specify both the source reservoir and the receiving reservoir.

For simplicity, we removed the term “export production” and replaced it with “productivity”. Export production is a term used in the oceanography community to refer to the biogenic material (initially stemming from primary and secondary production) exported out of the mixed layer / upper ocean to the deep ocean (and in the case that sediments are the archive, the sediments). As such, marine sediment records of ‘productivity’ can only technically reflect the materials actually exported to the sediments, not surface productivity (which is typically what we would want to know in a perfect world. However, we do not feel this level of detail is beneficial to the reader, so we have simplified the phrasing. We thank the reviewer for drawing our attention to this point.

19) Line 339: It could also be mentioned that both the duration and the mechanisms responsible for the initial phase of the PETM remain debated.

We absolutely agree with the reviewer here. However, because we are only focused on describing how $^{3}He_{ET}$-derived vMARs provided insight into the recovery (from the paleo-productivity perspective), we would like to keep this sentence as is.

20) Line 370: Please define what is meant by a "typical" sample size.

We now define this term. It now reads (L390-392):

"When measuring typical sample sizes (~100-200 mg, but could be larger or smaller depending on the available equipment), the low abundance of the 3HeET-bearing IDPs in all but the slowest accumulating marine sediments can lead to low reproducibility in replicates."

21) Lines 370–375: Another possible strategy would be to adapt the sample size according to the expected extraterrestrial ^{3}He concentration, thereby ensuring that enough IDPs are analysed to achieve the desired counting statistics (Poisson uncertainty; Fenisse et al., 2025).

This is an interesting suggestion. While this approach is straightforward for air or ice (such as in Taylor et al., 2020 and Fenisse et al., 2025), it becomes somewhat complicated for marine sediments. If we are understanding the reviewer correctly, the idea is to utilize the sediment's assumed accumulation rate and a value for F_{3HeET} to estimate expected $^{3}He_{ET}$ concentrations (Farley et al., 1997), and adjust the sample size (or number of replicates) to optimize for this expected concentration. While we agree with this premise, this would technically require the vMAR (assuming CFPs function as we expect them to and travel horizontally with focused/winnowed sediments) for the sediment across the interval of interest to be known, which is not possible without a separate, independent CFP estimate. Another approach is to use the bMAR of the samples and assume this is close to vMAR. This could hypothetically then be used to estimate uncertainty on the $^{3}He_{ET}$ concentrations (or the sample size needed to achieve 'accurate representation') if we follow the atmospheric entry model of Farley et al. (1997)). At this point, we feel that between already stressing the measurement of multiple aliquots of a sample and stating the $^{3}He_{ET}$ approach may be inappropriate for higher vMAR and detrital-rich sites, we are adequately considering the form of uncertainty encapsulating in the reviewer's comment. However, if the reviewer feels strongly, we can add another section describing this concept.

22) Line 380: When the measured bulk $^{3}He/^{4}He$ ratio approaches the terrestrial end-member, the calculated extraterrestrial ^{3}He concentration becomes not only potentially biased but also much less precise. The propagated uncertainty derived from analytical uncertainties used in equation 10 may reach 100%, implying that $^{3}He_{ET}$ may be below the detection limit in some cases.

We absolutely agree with the reviewer, and thank them for pointing out our oversight in describing the impacts of the $^{3}He/^{4}He$ ratios in the original version of this manuscript. We have adjusted the text accordingly (L399-408).

"Post-measurement, one must carefully consider which helium isotope ratios are used for the terrestrial and extraterrestrial endmembers (Eq. 8). As initially pointed out by Marcantonio et al. (1998), if the 3He/4He ratio of a given sample falls near the terrestrial endmember value, then the determined 3HeET concentration will be highly sensitive to the chosen terrestrial endmember value, ultimately imparting large uncertainties on the 3HeET-derived fluxes. Considering that terrestrial endmember helium isotope ratios have been suggested to span several orders of magnitude (Marcantonio et al., 1998; McGee et al., 2016), and high MARs and sediment detrital content both act to reduce measured 3He/4He ratios, there are likely certain types of depositional environments in the ocean where 3HeET concentrations are so uncertain that the application of 3HeET is not advisable. We suggest studies employing 3HeET as a CFP perform sensitivity analysis on their chosen terrestrial endmember value to evaluate its effects on calculated 3HeET

concentrations (Abell et al., 2023; Abell and Winckler, 2023; Marcantonio et al., 1998; Middleton et al., 2016; O'Mara et al., 2022, 2024; Pavia et al., 2024, 2025)."

23) Line 388: You may wish to cite Fenisse et al. (2025), who showed from granulometric analyses of Concordia firn that the vast majority of extraterrestrial ^{3}He is carried by IDPs smaller than 25 μm.

We have added this citation.

24) Line 435: I do not think that Figure 5 convincingly demonstrates that extraterrestrial ^{3H}e is the only robust MAR proxy beyond the Quaternary. As discussed above, this conclusion may be affected by uncertainties associated with hiatuses and long-term variations in extraterrestrial flux.

We apologize for this mistake. We meant to reference Fig. 4 (now Fig. 3), which shows the dearth of ^{3}He$_{ET}$ in the pre-Quaternary Cenozoic.

25) Lines 446 - 450: This paragraph might fit better in the Introduction, as it primarily provides background and motivation for the review rather than discussing its conclusions.

The reviewer raises a good point. However, we have adjusted this paragraph to highlight what we provided throughout the manuscript that builds on the previous work of McGee and Mukhopadhyay (2013). It now reads (L490-498):

"So, what is standing in the way of applying this influential method to every marine sediment core to develop both short- and long-term accurate records of changes in the Earth system across the Cenozoic? In a practical sense, the simple answers to this question at present are 1) a scarcity of laboratories making measurements of marine sediment noble gases, 2) the analytical challenges of generating reliable sediment helium isotope data, and 3) limited attempts to describe 3HeET's utility to the broader Earth science community (McGee and Mukhopadhyay, 2013). While points #1 and #2 are not amenable to a 'quick fix', we have expanded on the previous review of McGee and Mukhopadhyay (2013)in an effort to address point #3. Specifically, not only do we provide a systematic overview of age model-derived bMARs and CFP-derived vMARs and their associated uncertainties, but also incorporate new findings accumulated over the last ~15 years to provide a paleoclimate-centric perspective on the benefits of applying 3HeET as a CFP to explore the pre-Quaternary Cenozoic Earth system."

Considering its new form, we would prefer to keep it at the end of the manuscript.

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