Response to reviewers (reviewers' comments in blue)

Review RC 4

I find the topic interesting and I think effects like this should be explored further

We thank the reviewer for this assessment.

Major comments:

I think that discussion could be more thorough, i.e., results/discussion sections should be expanded.

- For example, how does lunar nodal cycle impact on global/regional mean temperature, NAO etc. compare with other processes that control decadal-multidecadal indices. Is it more or less important for climate system variability than other processes? Or perhaps the lunar nodal cycle is a cause for some of the variability? Maybe the different variabilities are out-of-phase and/or uncorrelated? Much like other comments I have seen, I agree that the results in this paper are overstated, also given the simplicity of the experiments.
    - In the Atlantic there is a 15–18-year cycle - see: Årthun, M., Wills, R. C. J., Johnson, H. L., Chafik, L., & Langehaug, H. R. (2021). Mechanisms of Decadal North Atlantic Climate Variability and Implications for the Recent Cold Anomaly, Journal of Climate, 34(9), 3421-3439
    - There are obviously also Pacific (inter-)Decadal variability, Atlantic Multidecadal variability, AMOC etc., which are briefly mentioned in the manuscript. See e.g.: Omrani, N.-E., et al., 2022: Coupled stratosphere-troposphere-Atlantic multidecadal oscillation and its importance for near-future climate projection. npj Clim. Atmos. Sci., 5:59
    - There are many more papers on the topic that could be further discussed.

This is a good point and we now discuss the size of the response in modes of variability in the context of other drivers in the text:

The geographical response of the model to the lunar nodal forcing can be better understood by putting it in context with other modes of variability. Figure 5 shows that the response of the north Atlantic Ocean has an amplitude of order 0.1 K. For context, this is about 20-30% of the size of SST anomalies associated with Atlantic Multidecadal Variability (Omrani et al. 2022). The results shown in Figure 7 can be better understood by being put in the context of other sources of variation in the North Atlantic region. The natural variability of the NAO in FORTE2 and observations which has a peak to peak amplitude of 3 hPa and 4 hPa respectively (Blaker et al. 2021): the lunar nodal response is smaller, but certainly noticeable. For added context, the response of the NAO to observed Atlantic decadal SST variability is 2-3 hPa (Årthun et al. 2021), while the response to solar variability is 3-4 hPa (Gray et al. 2016), suggesting that the lunar nodal cycle has a much smaller, but noticeable effect on Atlantic European winter climate and the NAO.

And

Future work regarding the nodal cycle in the Arctic should be carried out with a more realistic sea ice model, with other forcings included in order to assess potential nonlinear combinations of response.

See also our reply to reviewer RC2 (2nd major comment) regarding the results in the context of the global warming slowdown of the early 21st century.

- The authors state on l. 120, 125 there is insignificant response for everything, except maybe in MSLP in the Euro-Atlantic. How much variance in the NAO on this specific timescale does nodal cycle represent?

We now put the variability of the NAO in the context of other modes of variability and the mean variability in FORTE2:

The natural variability of the NAO in FORTE2 and observations which has a peak-to-peak amplitude of 3 hPa and 4 hPa respectively (Blaker et al. 2021): the lunar nodal response is smaller, but certainly noticeable. For added context, the response of the NAO to observed Atlantic decadal SST variability is 2-3 hPa (Årthun et al. 2021), while the response to solar variability is 3-4 hPa (Gray et al. 2016), suggesting that the lunar nodal cycle has a much smaller, but noticeable effect on Atlantic European winter climate and the NAO.

- L. 128-138: I think figures here need some uncertainty estimates. Also, I think this paragraph is overstated – other effects may be stronger than nodal cycle so I would like to caution against implying "nodal cycle will(has) cause(d) this". While I agree that decadal-multidecadal variability can cause delays in or speed-up the global warming trends (and affect the onset of 1.5 degree warming) I think you must be careful if you are not sure how much other modes of variability will contribute and to what extent – different effects may cancel out and then the statements in this paragraph are less meaningful.
    - Fig. 10: I am not sure how you added nodal cycle in for bottom panel in Fig. 10. Did you run the model? Statistically? Please elaborate.

The nodal cycle was added as a simple mathematical function. We now state this in the text:

The assessed 5-95% uncertainty range is indicated with shading for the two more extreme scenarios (SSP5-8.5 and SSP1-1.9; the magnitude is similar for the other scenarios). To highlight the effect of the lunar nodal cycle on these assessed projections, we add a sinewave with peak amplitude of 0.04K, with the correct lunar nodal cycle timing, to each of the curves (bottom panel).

- Also add uncertainty from climate models on top panel.

We have added the uncertainty from two scenarios to Figure 10.

I think methods should be provided in more detail (use appendix if needed).

- I think that the authors have a control run, but it is never mentioned in the methods.

We have now clarified this in the Method section:

FORTE2 is run for three configurations: pre-industrial control (as in Blaker et al. 2021), SCALED, and CONSTANT, for 2300 years, with years 1520-2280 being analysed, i.e. 760 years or 40 full cycles.

- On l. 55 they talk about 8 largest tidal constituents – since I am not a tidal expert I find this hard to follow – please elaborate what they are, their timescales, is lunar nodal cycle among them or do you impose it separately (this seems to be the case).

We have included a new table (Table 1 in revised manuscript) highlighting the important characteristics of the eight tidal constituents we use in our parameterisation of the 18.6-year lunar nodal cycle. The lunar nodal cycle is not a specific tidal constituent, it is imposed by adding an 18.6-year oscillation to ocean vertical diffusivity with the spatial distribution shown in Figure 1. The spatial distribution is derived from TPXO7.2 modelled horizontal velocities for each constituent, along with their nodal amplitude. We have also modified the Method section to clarify this:

The geographical shape of the function (Figure 1), determined by the relative strength of each tidal constituent at a given location and the constituent modulation amplitude, is multiplied by a normalised 18.6-year sinusoidal cycle to yield a spatially and temporarily varying modulation function. The phase of the modulation is such that, at most grid points, tidal currents are maximum at 4.75 years into the cycle (e.g., June 2006). The Pacific and Arctic Oceans…

- On l. 65-70 you mention geographical shape of the function – is this based on observations? Which?

The geographic shape of the function is based on horizontal current velocities for eight tidal constituents from the TPXO7.2 inverse model and their nodal amplitudes. This is described within the revised Methods section (second paragraph).

- Presumably tidal components are typically parametrized in models?

In climate models, tidal components are generally not separated out, but their total effects are parameterised by a globally-averaged diffusivity that can vary in depth. Newer models are beginning to calculate the effects of e.g. bottom topography, but our wish was to create a parameterisation that was suitable for most global ocean models and AOGCMs in use today.

- On l. 71-77: authors talk about "SCALED" and "CONSTANT" model configurations and say that the former provides underestimations and the latter overestimation. Is there an ideal way of simulating this or are these methods commonly used – what have you simplified here?

There is no ideal way of simulating the vertical contribution of tides to the background diffusivity, so the method used seeks to give an upper and lower bound to the surface effects of tidal dissipation. We have now changed the wording to reflect this (new wording in italics):

Given the uncertainties in the vertical contribution of tides to the background diffusion, two *idealised* perturbation runs have been performed, one in which the nodal cycle parameterisation is applied uniformly with depth to the vertical diffusivity ("Constant"), and one in which it is applied such that its amplitude linearly decreases from 1 at a depth of 5000 m to 0 at the ocean surface ("Scaled"), to mirror the effect of tidal dissipation.

- L. 79: how exactly is nodal cycle applied to the model? Please elaborate.

We have now added this text to the method, and changed the caption of Figure 1 to be consistent with the new text, and referring to the new equation (1):

The nodal cycle modulation is applied to the vertical diffusion with a period of 19 FORTE2 years, such that the total diffusion has the form has the form

$$K' = K*T(t)*M(x,y)*S(z) \quad (1)$$

where K is the standard background diffusion in FORTE2 (Blaker et al 2021), T(t) is the sinusoidal function of Figure 1 (top panel), M(x,y) is the geographically varying function in Figure 1 (bottom panel), and S(z) is unity for run CONSTANT, or the scaled function described above in run SCALED.

Figures should have better captions – more descriptive – half of the time I am left wondering what is actually plotted. I also think they should be revised.

We have revised figure captions 1, 2, 3, 5, and 6 especially with regard to describing the phase of the lunar nodal cycle, and equation (1) above. Figures 5-8 are now filled contours, and Figures 6 and 8 have cyclic contour intervals for clarity- see also the reply to reviewer RC1.

- Fig. 2,3,4 it is really hard to see if something is out-of-phase/in-quadrature etc. if lines are plotted in different figures – I suggest plotting such lines together in one figure. Or provide more details – maybe Fig. references are incorrect in text or maybe you need to mention "middle panel in Fig. 3" etc.?

We have provided more details to clarify the figures, e.g. we have altered the discussion of Figures 2 and 3 to explain more clearly what we mean and explicitly refer to the phasing in terms of years (as in Figure 1 top panel):

Old text:

In both SCALED and CONSTANT cases, the top 100-150 m of ocean displays a cooling (warming) in phase with maximum (minimum) vertical diffusion. In the absence of any feedback from the atmosphere, the global mean sea surface temperature cold anomaly would be expected to peak half-way through the nodal cycle. However, the atmosphere almost immediately responds to the anomalously cool sea surface temperatures by fluxing heat into the ocean (Figure 3), causing an increase in total ocean heat content (Figure 3). The uptake of heat by the ocean results in a global ocean heat content anomaly approximately in quadrature with the surface heat flux and nodal cycle (Figure 2).

New text:

In both SCALED and CONSTANT cases, the top 100-150 m of ocean displays a cooling in phase with maximum vertical diffusion in years 4-6. In the absence of any feedback from the atmosphere, the global mean sea surface temperature cold anomaly might be expected to peak half-way through the nodal cycle in years 9-10. However, as shown in Figure 3 (bottom panel), the atmosphere almost immediately responds to the anomalously cool sea surface temperatures by fluxing heat into the ocean during years 3-7, causing an increase in total ocean heat content between years 3 and 10 (Figure 3 middle panel). The uptake of heat by the ocean results in a global ocean heat content anomaly approximately in quadrature with the surface heat flux, i.e. maximum heat content is in years 9-10 (Figure 3 middle panel), while the maximum surface flux is at years 4-5, or approximately 4.5 years or 90º out of phase with the maximum heat flux.

- l. 107-117: I cannot say I can follow the text here related to Figs. 5-6. I am not sure where you see out-of-phase relationship between Tsurf and global response (of what?).

- Fig. 7: Top panel does look NAO-like, but bottom panel reminds me more of blocking-like structure. Also, top panel shows perhaps some wave-trains in the Southern Hemisphere. I think this figure can be discussed more.

- Many figures are present, but not discussed enough – either don't use them or discuss them in more detail.

We have reworded and significantly lengthened the discussions of Figures 5-8. In particular, we have separated out the discussions of amplitudes and phases for clarity, and put more detail into the description. In addition Figures 5-8 have been replotted as shaded contour plots, with the phases being plotted using a cycling colour map, for added clarity. This section (lines 107-123 of the submitted manuscript) now forms lines 152-190 of the revised manuscript.

Is there any observational support for the authors' claims? Even if it is just 20 years of data (i.e. 1 cycle)?
The only regions with signals large enough to be seen over one cycle are where tides are very large, e.g. in shelf seas. We note such regions in section 1 of the manuscript (lines 34-35).

I agree with the authors' final statements that such effects (if they are as relevant as the authors claim) should be better represented in climate models.
We thank the reviewer for this assessment.

Minor comments
l. 17: O (0.1K) – are you trying to say that it is of order 0.1K? Then just spell it out.
We have made this change.
l. 32: 3.7% and 11.5% - provide reference for the numbers.
The 3.7% modulation amplitude for M_2 and 11.5% for K_1 come directly from the nodal amplitudes now presented in Table 1 and are referenced to Pugh (1987).
l. 42, 174: OAGCM --> AOGCM (?)
We have replaced OAGCM with AOGCM everywhere in the text
l. 98, 99: Tg – is this supposed to be Tsurf? It is not defined anywhere.
We have removed all references to Tg in the text
l. 100-102: suddenly you talk about solar/volcanic forcing – where is this from?? Reference figure/previous study.
We now reference a previous study on the impacts of the 11-year solar cycle on climate.
l. 106: 'later' --> 'below' (?)
We have made this change.
l.269: I think top and bottom panel description is reversed.
We have altered the caption to correct this, and give more detail (see reply to L. 79 comment above).
Fig. 2 caption: Provide units.
The units (K) are in the caption, but we have expanded each caption to describe both tidal modulation and temperature response.
All Fig. captions: more details.