Response to Reviewers 30/7/24

Editor

Please consider all the reviewers' comments and address their concerns as much as possible.

Additional private note (visible to authors and reviewers only):
Although two reviewers have suggested minor revisions for the manuscript, the third reviewer has recommended rejection. Please ensure that you thoroughly address the concerns raised by the third reviewer.

Please find below our responses to each reviewer in italics. As per our previous responses, we have labelled each significant reviewer comment with the code [reviewer]-[comment number], e.g. RC1-1.

We have provided detailed and thorough responses to reviewer three. In our opinion, the reviewer has not provided strong evidence for their claims, and we hope you find the reasoning and evidence in our rebuttals persuasive.

Note also that we have made a minor update to the datasets on the Zenodo repository. These updates include only very minor changes and do not impact the results of the manuscript in any way. The changes are as follows:

1. *All datasets now have their NDVI values clipped to the range 0-1. This step was included when analysing datasets in the manuscript, but the originally uploaded Zenodo datasets hadn't been clipped.*
2. *The AusENDVI-clim dataset is now gap-filled, and includes a QC layer.*
3. *The merged AusENDVI-noclim_MCD43A4_1982_2022 dataset was removed to simplify the number of datasets included in the repository. Users who want to join the noclim and MCD43A4 datasets can do so by clipping out MCD43A4 from the AusENDVI-clim_MCD43A4_gapfilled_1982_2022 dataset.*
4. *The accompanying Jupyter Notebook 'readme' has been updated.*

RC1

Authors did a good job responding to my concerns. I reread the paper in detail and it feels much more convincing and thorough. The following comments below are minor and, after their consideration, the manuscript should be ready for publication.

We thank the reviewer again for their comments in the first round of revisions and we are pleased to have addressed their initial concerns.

RC1-1 Line 31: "shows excellent agreement with observations", but what observations?

The synthetic NDVI dataset is compared with both MODIS and the recalibrated AVHRR datasets. We will update the text to be more specific here.

RC1-2 Line 33: The term "seamlessly joined" is somewhat uncertain and reminds me of a recent paper (https://doi.org/10.1029/2023EF004119). In this study, authors used a simple statistical approach to identify abrupt shift points in merged NDVI/LAI products (Fig. S7), suggesting more abrupt shift points in merged products compared to non-merged ones. Therefore, I recommend including this analysis as evidence supporting the "seamlessly joined" nature of AusENDVI.

We agree with the reviewer that 'seamlessly joined' is a vague phrase and we have removed the term 'seamlessly' from the text. The merging of AusENDVI with MODIS MCD43A4 is of course not perfectly seamless, especially in those regions where we identified lower correlations and higher error in the calibration (e.g., irrigated cropping regions, snow impacted high elevation regions). Our claim is really that AusENDVI is better calibrated to MODIS in terms of mean NDVI, interannual variability, and seasonal variability, than currently existing products and this warrants the joining of the datasets to create a >40 year record of vegetation condition.

We are reluctant to include a breakpoint analysis in the paper for two main reasons. Firstly, it is uncertain if the statistical approach shown in the linked paper could distinguish between breakpoints due to merging issues, or due to abrupt shifts in the climate, as breakpoint analysis is used for both purposes (de Jong et al. 2011; Tian et al. 2015). For example, at the transition between AVHRR and MODIS in the year 2000, Australia underwent a very strong La Niña event (with anomalously high rainfall over much of the continent) that resulted in widespread greening across Australia, this anomalous greening was immediately followed by a decade long drought (the "Millennium" drought) that led to widespread reduction in vegetation productivity (Van Djik et al. 2013). Secondly, we are reluctant to include more analysis and figures into an already long manuscript (currently 23 figures and tables). On Zenodo, we provide both the merged AusENDVI and MCD43A4 product, along with the unmerged AusENDVI datasets that span 1982-2013 (effectively re-calibrated Climate Data Record v5 AVHRR datasets for Australia). If a user is concerned about an artificial break at the join between AusENDVI and MODIS, then they can rely upon the unmerged products.

It's worth noting also that products such as GIMMS-PKU, which ostensibly have not undergone merging, are not immune to sudden and dramatic changes between generations of sensors. The figure in our response to RC3-3 (in this round of revisions) shows a dramatic 'break point' after the year 2000 in the long-term trend of inter-annual variability.

RC1-3 Line 70: the inconsistent findings can also include the interannual variability of vegetation greenness (https://doi.org/10.1029/2023EF004119).

Thank you for the link to this paper, we will update the introduction to include reference to this recent paper.

<u>RC1-4</u> Line 105: add citations regarding resampling techniques.

We would be happy to include a citation here but we are not sure who to reference for nearest-neighbour and average resampling techniques. Moreover, these are very well known geospatial processing techniques available in most, if not all, image processing software and packages.

<u>RC1-5</u> Figure 1: please use the standard flowchart symbols and notation.

We have updated Figure 1 in the manuscript with standard flowchart symbols.

<u>RC1-6</u> Line 261: extra "." at the end of sub-title 3.1

We have removed this in the updated manuscript.

<u>RC1-7</u> Lastly, I suggest that the authors thoroughly review the paper and consider shortening certain sections (e.g., abstract and research objectives) to maintain clarity and conciseness.

We have edited the abstract and research objective for conciseness.

<u>References</u>

De Jong, R., Verbesselt, J., Schaepman, M. E., & De Bruin, S. (2012). Trend changes in global greening and browning: contribution of short-term trends to longer-term change. Global Change Biology, 18(2), 642-655.

Tian, F., Fensholt, R., Verbesselt, J., Grogan, K., Horion, S., & Wang, Y. (2015). Evaluating temporal consistency of long-term global NDVI datasets for trend analysis. Remote Sensing of Environment, 163, 326-340.

Van Dijk, A. I., Beck, H. E., Crosbie, R. S., De Jeu, R. A., Liu, Y. Y., Podger, G. M., ... & Viney, N. R. (2013). The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resources Research, 49(2), 1040-1057.

RC2

Thanks to the author's efforts, which solved all my problems, I suggest that ESSD could accept the article. I still have some minor issues:

We thank the reviewer again for their comments in the first round of revisions and we are pleased to have addressed their initial concerns.

<u>RC2-1</u> Sources of global vegetation change include direct effects due to CO2 fertilization effects and indirect impacts due to climate change because of radiative effects. I am curious if changes in CO2 levels and current changes in NDVIs are an

identical or similar trend and I think this is worth exploring. The authors discuss the correlation of climate, especially precipitation, with NDVIs, and it might be good to include the correlation of CO2 changes and NDVI trends in the discussion section. I have doubts about whether NDVI can accurately reflect these kinds of complex changes, and I hope the authors can discuss this point.

We agree with the reviewer that the relationship between increasing atmospheric CO_2 and greening of vegetation is an important consideration. The reliance on satellite remote sensing of vegetation to attribute greening trends to CO_2 fertilisation and/or climate change has at times led to misattribution of trends where fusing of datasets has been poor (Wang et al. 2020). Likewise, remotely sensed vegetation condition datasets have been used to argue for fundamental changes to ecosystems in response to climate change (Donohue et al. 2013; Poulter et al. 2014). Yet, it's possible these changes have been overstated owing to spurious trends in inter-annual variability (Tian and Luo 2024). We argue that AusENDVI allows for a more robust addressing of these questions. As we wish to investigate some of the questions in subsequent work, we do not wish to pre-empt future work by including further analysis and discussion here, especially given the already considerable length of the manuscript.

References
Wang, S., Zhang, Y., Ju, W., Chen, J. M., Ciais, P., Cescatti, A., ... & Peñuelas, J. (2020). Recent global decline of CO2 fertilization effects on vegetation photosynthesis. Science, 370(6522), 1295-1300.

Tian, J., & Luo, X. (2024). Conflicting changes of vegetation greenness interannual variability on half of the Global vegetated surface. Earth's Future, 12(5), e2023EF004119.

RC3

RC3-1 In previous comments, I expressed my deep concerns and hoped the authors would greatly improve their dataset and manuscript with the points that have been elaborately listed. However, it's disappointing that far-less-than-expected improvements have been made in the new version. This time I'll point out major ones.

In their previous comments the reviewer provided a detailed evaluation of the manuscript, providing 33 comments. We provided detailed responses to every comment: for 13 of these comments we provided a general response, and for 20 of these comments we responded with changes to either the manuscript text, or through the inclusion or updating of figures and tables (we added four new figures and one new table, and updated three other figures). We believe this constitutes a significant enhancement to the manuscript and we are grateful to the reviewer for making it possible. We also note that two other reviewers considered our revisions as substantial and are now satisfied with the manuscript.

RC3-2 A new (or enhanced) dataset must show its significance or distinctiveness, for example, a new type of earth variable, wider spatiotemporal coverage, higher spatiotemporal resolution, or higher data accuracy in either absolute value or spatiotemporal patterns. This is what the authors failed to demonstrate in their

AusENDVI. The author claimed a 'comprehensive' evaluation of existing NDVI datasets in the abstract, but the evaluation is not.

Vegetation within semi-arid and arid ecosystems, of which the Australian continent is dominated, play a critical role in controlling the IAV of the global carbon dioxide growth rate (Donohue et al. 2013, Ma et al. 2016, Poulter et al. 2014, Zhu et al. 2016). Remotely sensed vegetation condition datasets have also been used to argue for fundamental changes to ecosystems in response to climate change (Donohue et al. 2013, Poulter et al. 2014). Thus, NDVI is an exceptionally important metric, too important to be left to just a few consolidated datasets, especially when both we and many others have shown that the commonly used global datasets contain substantial limitations. Having independent algorithmic approaches to creating a harmonised data set is important, and is a significant contribution. We have concentrated on making a dataset that works well for the Australian context where vegetation conditions are characterised by high interannual variability (discussed further below in RC3-3). Furthermore, we argue the manuscript is valuable not just in terms of the datasets created and their downstream applications, but also because the open-source and reproducible methods provide an iterative advancement. Though we focussed our study on the regional rather than global scale, we welcome others who may see merit in our methods and seek to apply them to other regions or the globe, either in terms of the algorithms used for harmonisation, the feature datasets used, or the gap-filling procedures.

On the evaluation of existing NDVI datasets: our manuscript utilises five global NDVI products. We evaluate the two most commonly cited global AVHRR NDVI datasets in the literature (GIMMS3g, CDR/LTDR), and the most recent global AVHRR dataset (GIMMS-PKU). The manuscript includes a total of seven figures (including the appendix) where various NDVI products are inter-compared. Whether or not this counts as 'comprehensive' is subjective, but we argue the assessment of three popular global AVHRR NDVI datasets provides substantial value to a reader who may be interested in using a long-term remotely sensed NDVI product to chart changes to vegetation conditions in Australia.

RC3-3 From the comparison between AusENDVI and PKU-consolidated, I noticed a comparable spatial resolution (0.05 vs 1/12=0.083), interannual variability (Figure 9a, despite the authors arguing a significant improvement), and phenology (Figure 3k and Figure 7c; considering the primal difference between MOD13C1 and MCD43A4).

On spatial resolution, we argue that a ~25 km^2 pixel is a substantial improvement over a ~64 km^2 pixel. The 0.05 degree resolution also brings the NDVI dataset in line with high quality regional meteorological datasets, of the kind used to consider relationships between the climate and vegetation (Jones et al. 2009).

The consistency of interannual variability (IAV) in AusENDVI is substantially improved over GIMMS-PKU. We argue that we have shown this clearly in Figure 9 where PKU does not track the IAV of Landsat, and PKU's sensitivity to rainfall more than doubles coinciding with the transition from the AVHRR era (1982-2000) to the MODIS era (2000-2022). To demonstrate this further, Figure 1 (below) maps the trends in IAV as indicated by the coefficient of variation (CV), following the methods described in Tian and Luo (2024). PKU shows a distinct lack of IAV in the pre-MODIS era (and no trend in IAV), then the IAV more than doubles (~0.05 to 0.115) from the early 2000's onwards (the figure shows 10-year *rolling mean CV where each time-stamp is centred in the middle of the 10-yr period). This dramatic jump in IAV coinciding with the switch to better quality AVHRR sensors from the early-to-mid 2000's onwards is highly unlikely to be natural, and indicates a substantial limitation in the PKU product (over Australia, it may be fine elsewhere - we haven't assessed it globally). Contrast this with AusENDVI-clim which shows a gradually increasing IAV through the 90's and into the 2000's that is far more realistic considering the likely impacts of steadily increasing atmospheric CO_2 and its role in increasing the water use efficiency of plants (Donohue et al 2009, Rifai et al. 2022).*

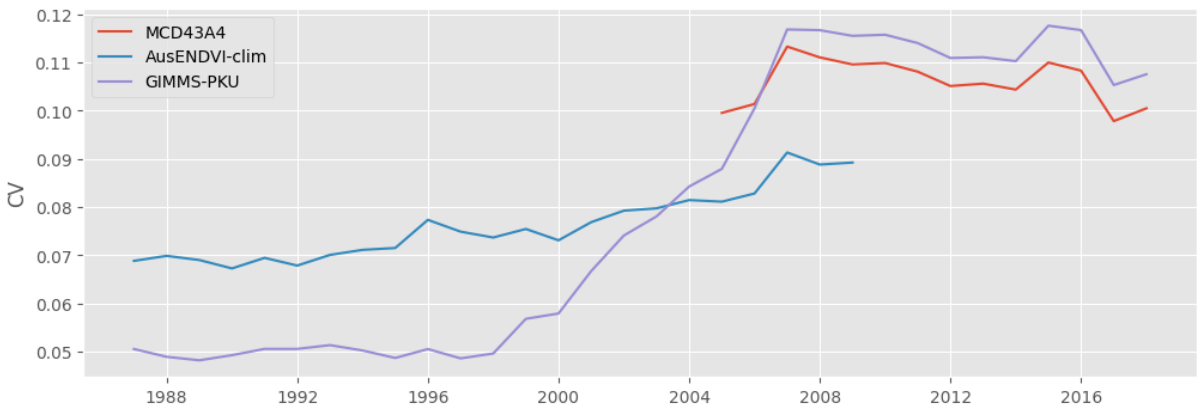

Figure 1: Temporal changes in the rolling 10-year average coefficient of variation (standard deviation / mean) indicating trends in inter-annual variability. CV was calculated per-pixel and then averaged over the continent.

On phenology, we agree that for the example regions shown in the manuscript, GIMMS-PKU and AusENDVI perform similarly, and we do not dispute this point in the manuscript.

RC3-4 However, (a) AusENDVI was not compared to individual reference datasets in terms of absolute value.

AusENDVI was cross-validated with MODIS MCD43A4 in terms of absolute NDVI values (see Figure 5; both MAE and RSME statistics are reported). This is the same approach as was taken for validating the GIMMS-PKU dataset, though they cross-validated against Landsat because that was their target dataset (Li et al. 2023). There are no ground-truth NDVI values that we could rely upon as reference datasets.

RC3-5 Landsat data were used in this study, but not for absolute value evaluation. Discrepancies between Landsat-5 and Landsat-7 were not cross-calibrated (as I mentioned but the authors did not try to solve). In the response, the authors argued in the Figure of RC3-7 (no Figure number provided) that the average line sits between the lines. This is obviously, not true. The average line basically overlaps Landsat-7, which means Landsat NDVI anomalies in the Landsat-7 era are systematically higher than the Landsat-5 era and the Landsat baseline itself may not be accurate.

There is no reason why absolute Landsat NDVI values should agree with AusENDVI values as the spectral sampling between the sensors is different, as the reviewers argued themselves in their earlier response (RC3-1 in the first review). We instead rely on Landsat as a validation of inter-annual variability in the pre-MODIS era as differences in absolute

NDVI values should not impact the annual temporal variability of the series. We showed that Landsat anomalies agree well with MODIS anomalies from 2000-2012 (Figure A2; included at the request of the reviewer), and that AusENDVI agrees well with Landsat anomalies from 1988-2012 (Figure 9a), indicating that AusENDVI can reliably reproduce climate driven variability in both in the pre-MODIS and post MODIS eras. This finding highlights the product's usefulness as a long-term indicator of the vegetation response to climate (change) - a key use case for long-term remotely sensed NDVI datasets.

The small differences in mean NDVI between Landsat 5 and Landsat 7 are immaterial to the use case here, which we argued convincingly in the first review (RC3-7). To reiterate, firstly, the absolute difference in NDVI values between the Landsat 5 and Landsat 7 time series shown in the earlier response (RC3-7; the figure is reproduced below for convenience, Figure 2) is equal to 0.004 NDVI, a negligible difference. As we are using Landsat to evaluate temporal variability, the range in NDVI values is arguably more important than the mean, and the range difference between Landsat 5 and Landsat 7 in Figure 2 are also negligible, equal 0.002 NDVI. Secondly, within each month we combine all Landsat 5 and 7 observations together using a median composite so the small difference between them is further ameliorated. Thirdly, we anomalize the data by subtracting the long-term mean so absolute differences in Landsat NDVI are irrelevant. We argue the reviewer has not made a convincing case as to why Landsat should not be suitable for assessing the IAV of AusENDVI in the pre-MODIS era.

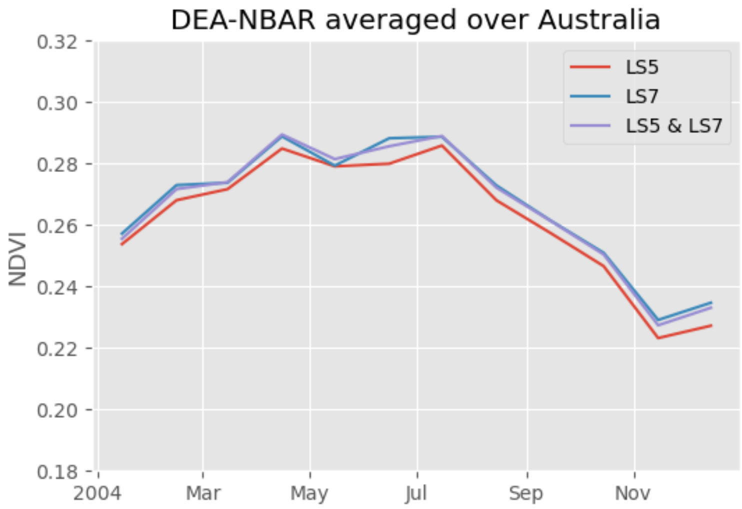

Figure 2: Landsat 5 and Landsat 7 over Australia for 2004, the first year of full overlap in the series. The Landsat data product is Collection 3 Landsat NBAR provided by Digital Earth Australia.

<u>RC3-6</u> The time interval for PKU-consolidated is half a month but for AusENDVI is a month. The temporal resolution is critical for tracking the quick change of vegetation under current climate change. Despite the authors arguing that a month is enough, many others have pointed out that half a month is not enough. Noting PKU-consolidated is a global dataset and AusENDVI is a regional one, the two flaws mentioned above are unacceptable.

In satellite images, high frequency variation is very often due to noise, and one means of ameliorating this noise is to calculate monthly composites to minimise spurious changes due *to clouds etc. Monthly resolution datasets are commonly used for long term studies of climate and vegetation (Gonsamo et al. 2020; Rifai et al. 2022) and we see no reason why the monthly resolution datasets of AusENDVI cannot be relied upon for this purpose.*

The reviewer has not provided any references or evidence to back up their claim that "...many others pointed out that half a month is not enough" for land-surface phenology (LSP) studies. LSP studies commonly start with fortnightly or monthly data and temporally upscale the datasets using curve fitting or interpolation techniques (Zeng et al. 2020). Users of AusEDNVI can do the same.

The reviewer did not provide references or evidence for the statement that "...temporal resolution is critical for tracking the quick change of vegetation under climate changes". Changes to vegetation dynamics from climate change are not 'quick' but rather take decades as plants respond to long term trends in temperature, CO_2, and rainfall patterns (Donohue et al. 2013; Garonna et al. 2015; Zhu et al. 2016; Winkler et al. 2021). Thus the need for reliable, very long term datasets to extract subtle trends in vegetation in response to climate change amidst the 'noise' of interannual and interdecadal variability.

RC3-7 The significance of AusENDVI should have been a more accurate characterization of rainfall in the specific country of Australia. I have raised it as a major comment, but the authors simply provided a correlation map with low correlation values in many regions. The authors claim strong correlations but note that the values could be lower than 0.3. No significance values and further in-depth analysis were provided.

We are surprised that the reviewer remains unconvinced that Australian ecosystems are predominantly water-limited given approximately seventy percent of Australia's land mass is classified as arid and semi-arid (see the Köppen climate classifications here). In the manuscript we provide three references that outline Australia's water-limited nature (Peters et al., 2021; Poulter et al., 2014; Broich et al., 2014), and the per-pixel correlation map shows most areas over Australia NDVI correlates with rainfall between 0.5 - 0.9 R (Figure 4c, this was included at the request of the reviewer). Of course, not every location in Australia is water-limited (e.g. tropical rainforests in Queensland, wet temperate forests in western Tasmania), but this does not negate the relationship between IAV in rainfall and IAV in vegetation condition over Australia when aggregated to the continental scale.

RC3-8 Moreover, when I re-evaluated the whole manuscript and tried to find (potentially) significant improvements raised not by me but by other reviewers, I figured out a newly introduced flaw. In Figure 9d, the authors tried to prove AusENDVI better follows variations in precipitation, by building a relationship between AusENDVI-clim and 12-month rolling rainfall. However, rainfall has been a contributor to the generation of AusENDVI-clim (section 2.3).

In Figure 9 we are not trying to show that AusENDVI has a higher correlation with rainfall ("better follows variations in rainfall"), but rather that AusENDVI's sensitivity to rainfall (the linear slope coefficient, i.e. how much NDVI responds per unit rainfall) is more consistent between the AVHRR and MODIS eras. This is in contrast to GIMMS-PKU which shows a more than doubling of sensitivity. This finding is further reinforced by Figure 1 in our *response above (RC3-3) where GIMMS-PKU shows a doubling of IAV (as shown through trends in the coefficient of variation) between the 1982-2000 and 2000-2022 periods. The inclusion of climate variables in the calibration is likely one reason why AusENDVI displays more consistent IAV throughout the time series, but we argue this is a positive development. Note also that the most important variable for the calibration and harmonisation models, by far, are the AVHRR NDVI values themselves, not rainfall, as shown through the SHAP feature importance plots in Figure A4 in the manuscript.*

<u>References</u>

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