Review of “Ocean-Induced Weakening of George VI Ice Shelf” by Zinck et al.

General comments:

In this study, the authors uncovered a newborn basal channel within the extensive channelized network of the southern frontal area of George VI Ice Shelf. That channel exhibits remarkably higher basal melt rate than the surrounding area, and may have the potential to influence the ice shelf weakening. The authors argue that the emergence of that channel is likely linked to the 2015 ENSO event. I think the manuscript is well written and structured, and the uncovering of the new channel is intriguing, but I also do think the mechanism behind the generation of that channel and its influence on the ice-shelf instability are poorly demonstrated by the oceanic models the authors used in view of the quite inadequate horizontal resolution, fixed thermohaline forcing, inconsistence between the model parameter and the modeled results, and the insignificant thermal and speed differences between the BEFORE and AFTER experiments, etc. Please refer to my major comments for more details. As such, I regret that I could not support to publish this manuscript in its current form in The Cryosphere. Some minor suggestions are also provided.

Thank you for the review.

In this manuscript we have discovered a new channel on George VI through high-resolution remote sensing surface elevations. These high-resolution elevations are further used to calculate the basal melt rates using BURGEE (Zinck et al., 2023, 2024). The further purpose of this manuscript is then to investigate the potential drivers behind this fast-developing channel, with the hypothesis that the channel must either be a fracture, a basal melt channel, or a combination of the two, by making use of existing data and modelling results. To investigate the fracture theory we utilize available surface velocity data to explore temporal changes in speed and divergence across the channel. Secondly, to investigate changes in ocean heat and circulation within the ice shelf cavity we use MITgcm-based model results which allow us to investigate the changes in available (modified) circumpolar deep water, and thus the changes in ocean heat available to drive basal melting. Lastly, we utilize LADDIE to investigate potential changes in plume direction and melt pattern to be able to assess whether or not a melt plume is likely to follow the new channel, given its eccentric geometry and connection to the existing channel network.

We are, therefore, of the belief that there was a misunderstanding/misalignment between the goal of the manuscript and the reading of the reviewer. We have outlined that in the response to each of the major comments, where we also address how we aim to clarify this in the updated manuscript if applicable.

Major comments:

First of all, the adopted horizontal spacing in LADDIE is 500 m, and that in the previous MITgcm-based simulation the authors utilized is much coarser, that is, 2-4 km. In contrast, the width of the new channel unveiled here is rather narrow, that is, only 2 km (as shown in Fig. 4j). That means such a fine basal topography is not represented at all in the utilized

MITgcm model, and is also poorly represented in the LADDIE. Therefore, those coarse horizontal resolutions are far from adequate to resolve the interaction between the new channel and the underlying ocean.

It is absolutely correct that the resolution of the MITgcm-based simulation results which we use is too coarse to capture the new channel, as well as most other channels on GeorgeVI which are seldom wider than a few kilometers. That is why we only use the results for these two purposes:
i) To explore changes in ocean heat and salinity at each of the entrances to the ice shelf cavity as well as in the near vicinity of the new channel. Temperature and salinity anomalies from all three transects (Fig. 6) show a similar picture of, e.g., increasing temperature, throughout the study period. A higher spatial resolution will not change this conclusion, and we also do not draw any conclusions with regards to the temperature and salinity which are based on the spatial resolution of the model.
ii) To explore changes in ocean circulation in the vicinity of the new channel. In L254-258 we write
"In addition to changes in ocean temperature and salinity, MITgcm model outputs suggest alterations in ocean circulation near the channel (Fig. 7). Although there is a disparity in scale between the model grid size and the size of the channel, we can reasonably conclude that changes in ocean circulation likely occurred near the channel between 2010 and 2020, with higher current velocities near the channel. However, interpreting circulation changes in more detail and on a smaller scale, particularly in the immediate vicinity of the channel, remains challenging given the coarse model resolution."
We make it very clear that there is a disparity in scale between the model resolution and the size of the channel, and that all we can reasonably conclude is that changes **likely** did occur in the ocean circulation near the channel, but that we cannot draw any conclusions in the near vicinity of the channel due to the differences in resolution.
In the revised manuscript we will make sure to clarify this disparity in scale already in Sect 3.3. We will likewise emphasize our goal of using the MITgcm model results, which will help clarify this further.

We agree with the reviewer that a higher horizontal resolution in LADDIE would allow for better-resolved flow dynamics and a more accurate estimate of plume velocity, and consequently melt rates. However, since the primary focus of our study is to assess whether the meltwater flow is directed through the channel — rather than to precisely quantify its speed or consequent melt rate — we believe that a resolution of 500 m is sufficient for capturing the key pathway of the flow. We will clarify this in Sect. 3.4 of the revised manuscript.

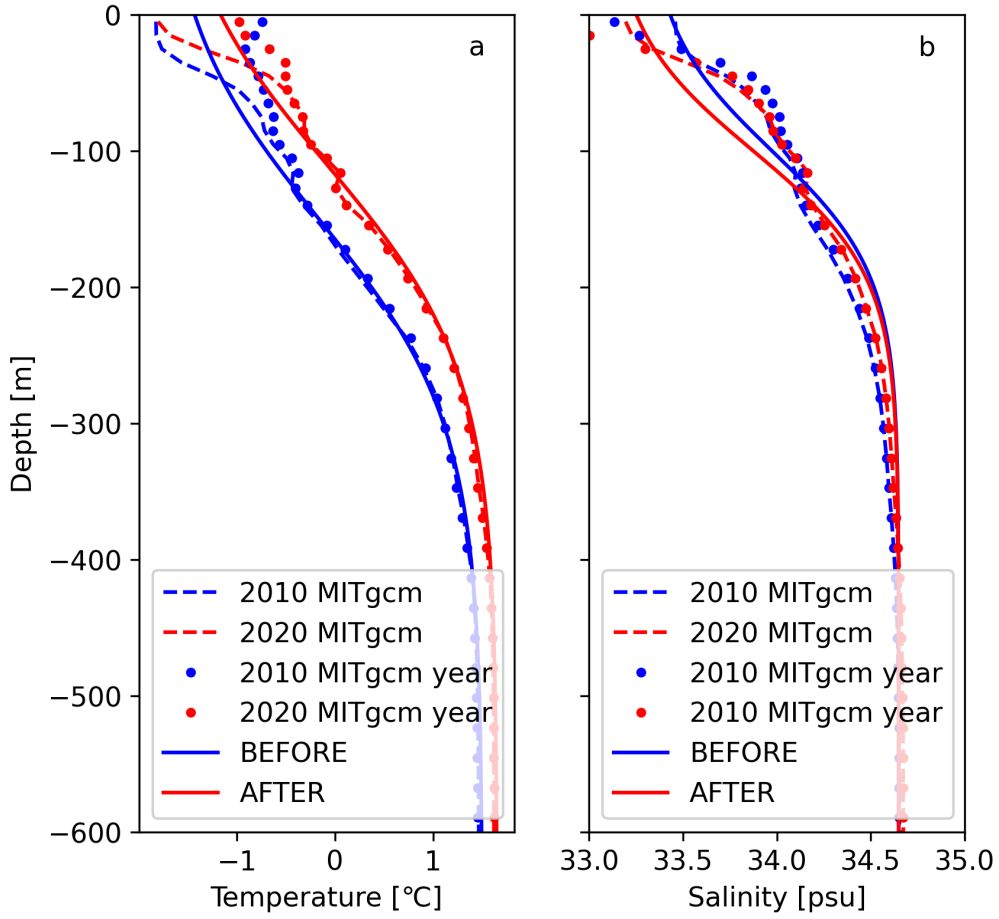
Second, as shown in Fig. 6b and h and Fig. 7c and f, the thermal and speed differences just below the ice base of the focused area between the BEFORE and AFTER periods are no more than 0.2 oC and 2 cm/s, respectively. Those small anomalies I think would not account for "the rapid emergence of a significant channel" with sufficient credibility.

The temperature anomaly in Fig 6b just below the ice base ranges from -0.28 to 0.27 degree C (so a difference of 0.55 degree C) and the speed difference of the area plotted in Fig. 7 ranges from -2.6 cm/s to 3.2 cm/s (a difference of 5.8 cm/s) in Fig. 7c and from -2.0 cm/s to 2.1 cm/s (a difference of 4.1 cm/s) in 7f. Whether or not these values are sufficient to cause

the rapid emergence of the channel is not something which we claim in the manuscript. We use the temperature anomaly as a proxy of the availability of (modified) circumpolar deep water, and draw the conclusion that the entire water column within the ice shelf cavity has warmed within our study period, and that this regime shift, as well as the emergence of the channel, coincide with the 2015 ENSO event. In the revised manuscript we will ensure to emphasize this latter point.

Third, the adoption of the constant (only winter-averaged in 2010 and 2020) profiles to force LADDIE seems to be some inappropriate in view of the fast-evolving southern part of George VI Ice Shelf as illustrated in this study.

We assume that the reviewer is referring to the fact that we use the winter-average of the two years (2010 and 2020) as opposed to the entire year. As mentioned in the text in L176-177 *"We only consider Austral winter months (May-August) to reduce the noise level from the seasonality in the upper ocean layers."* Furthermore, melting is typically initiated at the grounding line, and it is thus the temperature at the depth of the grounding line which is the more important factor when initializing melt plumes in LADDIE. In the Figure below which is similar to Fig. 3 in the manuscript, we have added a dotted line which indicates the average MITgcm temperature/salinity when considering the whole year as opposed to only the summer months (dashed lines). From this figure it can be seen that only the uppermost layers (0 to -100 m depth) are impacted by our choice of using winter months only.



In the updated manuscript we will emphasize that LADDIE is designed to simulate steady-state melt patterns for a given geometry and ambient ocean forcing and that we therefore want to compare the before and after state in a 'snapshot-manner'. We thus give two fixed profiles which are representative for the BEFORE phase and the AFTER phase, in between which we see a clear switch from cold to warm temperatures (Fig 6).

Fourth, there is a significant inconsistence between the large channelized basal melt rate (up to 30 m s -1 as shown in Fig. 1) and both low drag coefficient (310 -4) and plume speed (the maximum is only 0.15 m/s as shown in Fig. 8b and e), which would make me question the simulated results of LADDIE. At last, the LADDIE results shown in Fig. 8, for me, do not provide any new insights into the channelized meltwater plume and the corresponding basal melting. The plume tends to be topographically guided by the basal channels, and the basal melting is amplified therein. That finding has been proved in a wealth of literatures as listed at the end of this report.

We used an extend-triangle in the colorbar to indicate that higher and/or lower values are also present. We will clarify this better in the revised version and mention it explicitly in the figure captions where applicable. This implies that the maximum plume velocity is not 0.15 m/s as the reviewer suggests. The highest value within the new channel is 0.25 m/s, which together with the used drag coefficient and local plume temperature correspond to a melt rate above 30 m/yr when using the three-equation formulation (Holland and Jenkins, 1999) which is adopted in LADDIE (Lambert et al., 2023) but also by other similar models (e.g. Sergienko, 2013). In the updated manuscript we will extend the colorbar in Fig. 8b and 8e to 0.25 m/s to allow for better visualisation of the plume velocity.

To avoid confusion, we will make sure that all colorbars get adjusted throughout the manuscript, to ensure that the colorbars are only closed if no values are exceeding it, and otherwise with arrows as they are in Fig. 8. This change will apply to Fig. 6 and 7. We will likewise stress this in the caption.

It is correct that plumes tend to be topographically guided and that this finding is not new. However, the new channel is of a very obscure geometry, cutting through the old channel. It is therefore not a given that the meltwater plume would use it as a pathway. Secondly, the point of this manuscript is to investigate all possible origins and causes of this channel, and not including LADDIE would therefore give an incomplete picture. Further, the LADDIE results explain and support the remote-sensing-derived basal melt pattern which shows a combination of the BEFORE and AFTER LADDIE melt patterns, as mentioned in L264-268.

Therefore, after reviewing this manuscript I still have no idea why that channel was born, and what it will bring about for the upcoming evolution of George VI Ice Shelf. I think that could not be simply attributed to ocean warming, the link of which to ENSO, however, remains unclear (as stated in Line 277). Although the authors have acknowledged that “there is a disparity in scale between the model grid size and the size of the channel (Line 255)” and “interpreting circulation changes in more detail and on a smaller scale, particularly in the immediate vicinity of the channel, remains challenging given the coarse model resolution (Line 257-258)”, it is the model flaws they mentioned above that are **SO** critical to resolve my

concern. In that sense, maybe the coupled ice sheet-ocean models (as used in Gladish et al., 2012 and Sergienko, 2013) but with sufficiently high resolution would be an effective way.

As mentioned previously, the goal of the manuscript is to investigate all of the possible drivers behind the rapid channel-formation as well as shedding light on its nature (fracture, melt channel, or a combination). To confidently be able to answer why the channel was born most likely does require high-resolution coupled ice-ocean modelling. However, since we do not know whether this channel is a fracture, a basal melt channel or a combination of both, it would require an ice sheet model with a sophisticated fracturing mechanism scheme, a detailed ocean model and a solid coupling of the two in a realistic setup and not just an idealized one. Such a model does not yet exist - at least not in a published version - and that is also out of the scope of this manuscript.
We do not attribute the sole reason for its emergence to ocean warming and ENSO. We conclude that its appearance coincides with changes in both ocean forcing and ice divergence and that both of these align with ENSO: *"The appearance of the channel aligns with both changes in ocean forcing, most notably increased ocean temperatures and salinity, and subtle changes in ice divergence, both of which coincide with the timing of a major ENSO event. While the exact link between ENSO and the development of this channel remains speculative, the temporal correlation suggests that large-scale climate patterns may have a role in amplifying basal melting and possibly in re-routing meltwater pathways on Antarctic ice shelves."* (L307-311). We will stress this better in the revised version.

Specific comments:

The title: I think the temporal scale of this weakening should be specified.
We could potentially change the title to *"Ocean-Induced Weakening of George VI Ice Shelf between 2010 and 2022"*. However, we are afraid that including a specific temporal scale in the title could be interpreted as if we suggest that the weakening has stopped. We will leave it to the editor to decide on which title is more appropriate.

Line 16: "…, largely due to the unknown response of ice shelves."_response to what? From my point of view, the response of ice shelves to the changing oceanic and climatic conditions is really not unknown in view of increasing relevant literatures, but with deep uncertainty.
We will change it to *"..., largely due to the uncertain response of ice shelves."*

Line 24-25: "In some regions of … (warm cavity ice shelves)"_please add some supporting references.
We will add the following reference: Silvano et al., 2016

Line 63: which "two time periods"?
We will change it to *"two time periods (2010-2016 and 2016-2022)".*

Line 141-142: "two scenarios: i) … (AFTER experiment)."_confusing statement: you mean the periods of January 2010 to July 2016 and July 2016 to December 2020 respectively for the BEFORE and AFTER experiments?
We will change it to *"two scenarios: i) January 2010 to July 2016 (BEFORE experiment), and ii) July 2016 to December 2022 (AFTER experiment)."*

Line 179: “where the surface temperature (T0) is based on the surface salinity (S0)”_you should explicitly state that the surface temperature is set to the surface freezing point.
We will change it to *“the surface temperature (T0) is set to the surface freezing point based on the surface salinity (S0)...”*

Line 186-188: “The salinity is in LADDIE, however, described by a quadratic function, … as for the temperature, following”_It appears to be some redundant to mention the quadratic function.
We will exclude the part on the quadratic function and instead write *“We use a similar tangent hyperbolic function for the salinity (S), following…”*
Line 197: “Ocean models approximate physical processes, which implies that they need to be tuned in order to match observations.”_the logical relationship between the former and latter clauses is confusing.
We will change it to *“Because ocean models approximate physical processes, they require tuning to better match observations.”*

Line 206: “The basal melt rate trend from 2010 to 2022, shown in Fig. 1,”_actually, no trend is shown in Fig. 1.
We will change it to *“The basal melt rate from 2010 to 2022, shown in Fig. 1”.*

Line 230-231: “in both 2014/15 and 2015/16 (Fig. 5a and b) from ~370 m/yr to almost ~400 m/yr”_such a large increase in ice speed only occurred in 2014/15; “almost ~400 m/yr” => “395 m/yr”.
We will change it to *“Our analysis of ice speed and divergence across the channel show speeds along the transect fluctuating substantially in both 2014/15 (372 m/yr to 395 m/yr, Fig. 5a) and 2015/16 (375 m/yr to 397 m/yr, Fig. 5b) with an isolated peak in the ice speed at the channel location in 2015/16.”*

Line 241: “revealing a regime shift from cold and fresh conditions to warmer and saltier conditions across all profiles” => “revealing both warming and salinization trends across all profiles”, and you should indicate the depth range for that; the surface layer is the exception.
We will change it to *“revealing a regime shift from cold and fresh conditions to warmer and saltier conditions below the surface layer across all profiles.”* We have chosen to keep the original structure of this sentence to emphasize the regime shift.

Line 304: “, like Pine Island and Totten, which both have a higher projected potential sea level rise contribution.”_ please add some supporting references.
We will add and refer to the following two references: Seroussi et al. 2020 and 2023.

Typos:

Line 25: “warm cavity ice shelves” => “warm-cavity ice shelves” throughout the whole text
We will change it according to your suggestion.

Line 53: give the full spelling of “REMA” for the first appearance

We will change it according to your suggestion.

Line 126: “has a monthly temporal resolution” => “has a monthly temporal output”?
We will change it to *“has a monthly temporal output”*.

Line 176: “Austral winter months” => “austral winter months”
We will change it according to your suggestion.

Line 252: “have their outflow” => “have their outflows”
We will change it according to your suggestion.

Line 298-299: “in-situ field measurements” => “in-situ measurements” or “field measurements”
We will change it to *“field measurements”*.

Figures:

Fig. 1: in caption “the old and new channel” => “the old and new channels”; “by the white square shows” => “by the white square show”; “Two similar zoom-ins of the highly channelized area marked by the white square”_these two zoom-ins are the same, aren’t they?
We will apply the following changes: *“the old and new channel” => “the old and new channels”*; *“by the white square shows” => “by the white square show”*.

Yes, the two zoom-ins are indeed similar, but with different things marked on them. We found that adding all of the needed “labels” made it impossible to actually get a zoom-in of the melt rate in the channel, so that is the reason for the two similar zoom-ins, as also stated in the figure itself. We suggest to do the following changes in the caption:
“Two similar zoom-ins of the highly channelized area marked by the white square shows BURGEE melt rates both with the approximate location of the surface depression of the old and new channel in year 2016 in teal, the new channel pointed out by the white arrow, as well as the red transect used in Fig. 4 and 5.”
=>
“Two similar zoom-ins of the highly channelized area marked by the white square show BURGEE melt rates. The upper zoom-in further shows the approximate location of the surface depression of the old and new channel in year 2016 in teal as well as the red transect used in Fig. 4 and 5. The lower zoom-in allows for better visualisation of the melting within the channel with the new channel pointed out by the white arrow”

Fig. 2: I cannot fully understand the correlation between the statement and the corresponding diagram in each subplot, which needs to be much more understandable and clearer.
In the updated manuscript we will adjust Sect. 3.4.1 such that all steps presented in the text are linked to a specific sub-panel of Fig. 2. Example of how we will do that L155-158:
“For the surface elevation for the BEFORE geometry, all strips up to 2016-07-01 are firstly displaced to their location as of 2013-01-01 using MEaSURES ITS_LIVE velocities (Fig. 2a, Gardner et al., 2022). Secondly, these strips are further displaced using feature tracking

relative to the median elevation map between 2012-07-01 and 2015-07-01 to ensure alignment across strips (Fig. 2b).”

Fig. 7: in caption “which roughly corresponds to the layers” => “which roughly correspond to the layers”
We will change it according to your suggestion.

Fig. 8: in caption the arrows are also shown in (b) and (e).
We will adjust the caption accordingly.

References:

Cheng, C., Jenkins, A., Holland, P. R., Wang, Z., Dong, J., & Liu, C. (2024). Ice shelf basal channel shape determines channelized ice-ocean interactions. Nature Communications, 15, 2877.

Gladish, C. V., Holland, D. M., Holland, P. R., & Price, S. F. (2012). Ice-shelf basal channels in a coupled ice/ocean model. Journal of Glaciology, 58, 1227-1244.

Gourmelen, N., Goldberg, D. N., Snow, K., Henley, S. F., Bingham, R. G., Kimura, S., ... & van de Berg, W. J. (2017). Channelized melting drives thinning under a rapidly melting Antarctic ice shelf. Geophysical Research Letters, 44, 9796-9804.

Holland, D. M., & Jenkins, A. (1999). Modeling Thermodynamic Ice–Ocean Interactions at the Base of an Ice Shelf. Journal of Physical Oceanography, 29(8), 1787-1800.

Lambert, E., Jüling, A., van de Wal, R. S. W., & Holland, P. R. (2023). Modelling Antarctic ice shelf basal melt patterns using the one-layer Antarctic model for dynamical downscaling of ice-ocean exchanges (LADDIE v1.0). The Cryosphere, 17, 3203-3228.

Millgate, T., Holland, P. R., Jenkins, A., & Johnson, H. L. (2013). The effect of basal channels on oceanic ice‐shelf melting. Journal of Geophysical Research: Oceans, 118, 6951-6964.

Payne, A. J., Holland, P. R., Shepherd, A. P., Rutt, I. C., Jenkins, A., & Joughin, I. (2007). Numerical modeling of ocean‐ice interactions under Pine Island Bay's ice shelf. Journal of Geophysical Research: Oceans, 112, C10019.

Sergienko, O. V. (2013). Basal channels on ice shelves. Journal of Geophysical Research: Earth Surface, 118, 1342-1355.

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G. R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F.,

Sun, S., Trusel, L. D., Van Breedam, J., van de Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century, The Cryosphere, 14, 3033–3070, https://doi.org/10.5194/tc-14-3033-2020, 2020.

Seroussi, H., Verjans, V., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G. R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., Van Katwyk, P., van de Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: Insights into the vulnerability of Antarctic glaciers from the ISMIP6 ice sheet model ensemble and associated uncertainty, The Cryosphere, 17, 5197–5217, https://doi.org/10.5194/tc-17-5197-2023, 2023.

Silvano, A., Rintoul, S., and Herraiz-Borreguero, L.: Ocean-Ice Shelf Interaction in East Antarctica, Oceanography, 29, 130–143, https://doi.org/10.5670/oceanog.2016.105, 2016.

Zinck, A.-S. P., Wouters, B., Lambert, E., and Lhermitte, S.: Unveiling spatial variability within the Dotson Melt Channel through high-resolution basal melt rates from the Reference Elevation Model of Antarctica, The Cryosphere, 17, 3785–3801, https://doi.org/10.5194/tc-17-3785-2023, 2023.

Zinck, A.-S., Lhermitte, S., Wearing, M., and Wouters, B.: Exposure to Underestimated Channelized Melt in Antarctic Ice Shelves, Nature Climate Change [in review], NCLIM-24071992, pp. 0–26, https://doi.org/10.21203/rs.3.rs-4806463/v1, 2024.