Major comments:

> *1) Suitability and transferability of the framework need to thoroughly addressed/clarified. At the first point what makes this surrogate toolbox tailored for applying to landslide tsunamis and not any other type of tsunamis. The output parameters of the deterministic model for training the surrogates are tsunami characteristics but this could be valid for any generation mechanism. Are the stochastic variables specific to landslide physical/geometric characteristics? If that is so, what is the range of variables that can be used with respect to influence for tsunamigenesis, such as the initial depth of the submarine landslide, that are not being studied.*

Answer: We thank the reviewer for raising this point regarding the specificity and transferability of the Landslide-Tsurrogate framework. We clarify that the presented framework is tailored to landslide-generated tsunamis because the stochastic variables correspond to physical and geometric characteristics of submarine landslides, such as landslide volume and shape and friction angle in the landslide rheological law. While tsunami characteristics are indeed the outputs of the deterministic simulations, the input space is specifically designed to reflect uncertainties associated with landslide initiation and dynamics, which are unique to landslide tsunamis. However, the gPCE method can and is currently used to generate surrogate models for tsunamis generated by other sources (e.g., for meteotsunamis generated by atmospheric disturbances).

Regarding the depth of the landslide, we note that it is not treated as an independent stochastic variable. Instead, it emerges naturally from the site-specific conditions that determine where landslides are likely to occur. These conditions can be informed by a variety of data sources, including bathymetry, geotechnical surveys, and geophysical investigations, depending on the site. As a result, the influence of depth on tsunamigenesis is inherently captured without needing to explicitly sample it as a separate stochastic parameter.

To clarify the rationale behind the stochastic variables and the site-specific nature of the inputs, we will rewrite section 3.1 1) User Specifications*, in the manuscript as follows:

"This step involves defining the stochastic variables used to represent the uncertain characteristics of potential submarine landslides. These variables describe the physical and geometric properties of the landslide source and can be grouped into three main categories: (1) soil parameters, such as cohesion, friction angle, and density; (2) landslide geometry, including the thickness, length, width, and orientation of the shapes used to represent the landslide volumes; and (3) initial conditions, such as the mean sea level, which may vary due to tidal fluctuations and long-term sea-level rise.

In principle, the initial released mass and failure characteristics of a submarine landslide could be determined using mechanical slope stability models that incorporate measured soil properties (e.g., density, cohesion, internal friction angle), as well as hydrogeological conditions, structural discontinuities, and fault networks. However, such detailed information is rarely available for offshore environments or sometimes only available at specific locations. Consequently, many landslide properties remain poorly constrained and represent a major source of epistemic uncertainty in landslide-tsunami hazard assessment.

Within the Landslide-Tsurrogate v1.0 framework, these uncertainties are explicitly represented through stochastic variables. Potential landslide locations, for example, may be identified using geomorphological indicators such as steep seabed slopes, sediment accumulations, or previously mapped instability features. Landslide volumes, geometric parameters, and rheological properties can then be sampled within plausible ranges derived from regional geological knowledge, previous studies, or expert judgment. Similarly, mean sea level can be treated as an additional stochastic variable to capture the nonlinear interactions between tsunami propagation, tidal variability, and long-term sea-level rise.

By representing the uncertain landslide characteristics using a limited set of stochastic variables (e.g., location, volume, friction angle, and sea level), the dimensionality of the problem can be kept manageable while still capturing the dominant sources of uncertainty affecting landslide-generated tsunamis. These variables define the stochastic parameter space used to generate the deterministic landslide-tsunami simulations required to construct the surrogate models. The stochastic space is subsequently sampled using sparse quadrature rules, allowing the surrogate models to efficiently approximate the response of the deterministic simulations across the range of possible landslide scenarios.

Finally, it is important to note that the definition of stochastic variables and their ranges is inherently site dependent. Some uncertainties reflect natural variability in environmental conditions (aleatory uncertainty), while others arise from limited knowledge of subsurface properties and landslide triggering mechanisms (epistemic uncertainty). The proposed framework does not prescribe a unique parameterization but instead provides a flexible structure for propagating these uncertainties through the deterministic simulations.”

- *In general, I would place the information on the experimental design earlier in the manuscript.*

> *2) Following the point above, it needs to be clarified whether the framework is suited for subaerial landslide tsunamis (as the dynamics of such events differ significantly from their submarine counterparts) and how transferable it may be across different bathymetric domains*.

Answer: The two above points as well as the first point of the minor comment section will be addressed by partially rewriting the introduction (L55) as follows:

“In this study, a surrogate modelling framework specifically designed to support probabilistic tsunami forecasting (PTF) workflows for landslide-generated tsunamis is presented: the Landslide-Tsurrogate v1.0 model. The framework combines sparse sampling (Smolyak, 1963; Gerstner and Griebel, 1998; Constantine et al., 2012) with generalized Polynomial Chaos Expansions (gPCE; Xiu and Karniadakis, 2002; Soize and Ghanem, 2004) in order to approximate the response of computationally expensive tsunami models while requiring only a limited number of deterministic simulations and simultaneously providing direct access to sensitivity indices and uncertainty quantification metrics. Consequently, gPCE-based surrogate modelling offers an efficient alternative to machine learning approaches that often require extensive training data and may provide limited interpretability regarding the influence of uncertain input parameters.

Importantly, the surrogate modelling strategy is not tied to a specific generation mechanism. The gPCE approach approximates the response of the numerical tsunami model as a function of a set of uncertain input parameters, and is therefore applicable to any tsunami source that can be described by a finite set of stochastic variables. The main adaptation required for different tsunami sources lies in the definition of these input variables and their probability distributions. The framework can therefore be readily adapted to other tsunami sources provided that the dominant uncertain parameters controlling tsunami source generation can be identified.

For example, in the case of submarine landslides considered in this study, the stochastic variables describe the physical and geometrical properties of the landslide (e.g., location, volume, etc.). For other tsunami sources, the same framework can be applied by defining appropriate source parameters. In the case of subaerial landslides entering the ocean, the parameters could be exactly the same as for submarine landslides (location, volume, friction angle). Other parameters could be used if the model does not describe the subaerial flow such as the landslide mass entering water, entry velocity, impact geometry, or impact location. Similarly, for seismic tsunamis, the stochastic variables may represent earthquake source parameters such as fault slip, rupture length, or hypocentral location. Finally, for the forecast of

atmospheric tsunamis (or meteotsunamis), the methodology has already been applied by defining the parameters of pressure disturbances (e.g., amplitude, direction, speed, period, etc.) driving these events in the Adriatic Sea (Denamiel et al., 2019). [the rest of the introduction will remain unchanged from L57: This broadly applicable approach ...]"

> *3) The authors should improve the readability of the manuscript as it is currently limited, the current form would be more suited for a chapter. Consider moving some sub-sections (in sections 2 or 3) of the manuscript as appendix or supplementary material to highlight the novelty of the work, (plus more on experimental design) and increase readability.*

Answer: We thank the reviewer for this constructive suggestion regarding the structure of the manuscript. We agree that some parts of the technical description may resemble a user-oriented documentation of the model. However, as this manuscript is submitted to Geoscientific Model Development, providing a clear and transparent description of the model implementation is an important requirement of the journal to ensure reproducibility and usability by the community.

Following the reviewer's recommendation and to improve the readability of the manuscript, we will reorganize the paper accordingly. Section 3.2 (Technical description), which details the practical implementation of the Landslide-Tsurrogate framework, will be moved to the Appendix. This restructuring will allow the main manuscript to focus more strongly on the scientific aspects of the framework, including the methodological development, the probabilistic modelling strategy, and the application to the Mayotte case study, while still making the full technical description available for users interested in implementing the model.

Figures 4, 5 and 13 will also be transferred to the Appendix together with the technical description they illustrate.

Overall, this reorganization aims to maintain the level of transparency expected for model description papers while improving the focus and readability of the main manuscript.

> *4) The term PTHA appears many times within the manuscript. Current literature for PTHA usually refers to the scientific method that quantifies the probability of a specific location experiencing a tsunami of a certain intensity within a given timeframe. Under these terms the return period of the tsunamigenic landslides is also being considered, meaning we assess the probability of when a 1 in 500 or a 1 in 50 years event is expected. Although the hazard is studied probabilistically, the concept of time is not considered in this work I would refrain from using this term to be consistent with current terminology.*

Answer: We thank the reviewer for this important comment. We agree that the term PTHA should not be applied in this context and will remove its use from the manuscript and replace it with probabilistic tsunami forecast (PTF).

> *5) L255 User specification: this section should be further clarified in terms of what can be achieved within this framework (also point 1). There are also some important variables in tsunamigenesis that need to be highlighted here such as the depth of the landslide, mode of failure, initial acceleration, maximum velocity, runout etc. It needs to be clarified whether these are assessed.*

Answer: please see answer to point 1). Concerning the important variables in tsunamigenesis, for the Mayotte test case specifically, we indeed do not simulate the failure mechanism itself. Instead, we prescribe an initial landslide volume released instantaneously with zero initial velocity. The numerical model then dynamically computes the subsequent evolution, including maximum velocity and runout distance, which therefore do not need to be prescribed as input parameters.

We would like to stress, however, that this choice is case-specific and does not reflect a limitation of the Landslide-Tsurrogate model. The framework is inherently flexible and can accommodate different modelling strategies depending on the application. In particular, it can be adapted to include more complex or physically-based representations of the failure process, as well as alternative parameterizations of landslide dynamics when such information is available or required. To clarify this point, we will expand section 3.1 3) Deterministic Simulations*, in the manuscript as follows:

> **"This step primarily involves selecting and running a numerical model to simulate the landslide-generated tsunamis based on the input parameters generated in the previous step. The surrogate models developed in Landslide-Tsurrogate v1.0 are trained on deterministic tsunami simulations, which therefore constitute a fundamental component of the overall framework. The choice of the numerical model used to generate these simulations should be guided by the physical complexity of the system considered. Depending on the characteristics of the landslide source, the bathymetry, and the relevant hydrodynamic processes, different levels of model complexity may be required. In some cases, depth-averaged shallow-water models may provide adequate accuracy for hazard assessment, while in other settings more sophisticated approaches, such as dispersive or fully three-dimensional models, may be necessary to properly represent the generation mechanism and the resulting wave field. The surrogate model does not impose constraints on the deterministic solver and can in principle emulate the outputs of any numerical model, provided that the training**

> **dataset sufficiently samples the parameter space and that the underlying simulations capture the relevant physical processes. Consequently, the reliability of the probabilistic hazard estimates ultimately depends on the adequacy of the deterministic model used to generate the training simulations. [the rest of the section (describing different models available) remains unchanged]"**

> *6) Section 4 Mayotte test case: More information on the design of experiments is needed as to why the three stochastic variables selected take precedence over other important landslide properties for tsunami generation.*

Answer: we will explicitly justify the choice of the three stochastic variables for the Mayotte application by modifying the paragraph at line 485 in subsection 4.1 Steps 1 and 2: User Specifications and Input Parameters:

> **"Lemoine et al. (2020), Poulain et al. (2022) and Marboeuf et al. (2025) provided numerical simulation of potential submarine landslides and associated tsunamis in Mayotte, related to the on-going seismo-volcanic activity. They showed that the most impacting submarine landslide scenarios were located on a large portion of the transition between the lagoon and offshore zones, presenting the steepest slopes. The volume of these landslide scenarios varies greatly. Consequently, both the location and volume have been chosen as stochastic variables. In this first attempt to apply the Landslide-Tsurrogate v1.0 framework, we limit the number of stochastic variables to three. Given the uncertainties around friction angles in the landslide rheology and their high impact on the granular flow and deposit, friction angles are selected as the last stochastic variable.Furthermore, of all the free parameters involved in the model, it has been shown that these friction angles have the strongest impact on the wave field, compared to the Manning coefficient and the interlayer friction coefficient.**
>
> **In this study, submarine landslide locations are pragmatically located along the isolines of steepest slope close to the seismic swarm related to the seismo-volcanic activity [the rest of the paragraph line 489 remains unchanged.] "**

> *7) L523 1035 simulations carry an associated computational cost for training with 3 parameters, even though across five regions. Have any tests been performed to understand whether convergence can be achieved with a smaller of simulations?*

Answer: The results concerning the convergence of the surrogate models are presented in section 4.3.2 1). They are calculated for orders between 0 and 6 and clearly demonstrate that the optimum balance between cost and accuracy is obtained for p=5. However, to further quantify the cost of the deterministic simulations, we will add the following paragraph at the end of section 4.2.1 in the manuscript:

“To quantify the computational performance of the Landslide-Tsurrogate v1.0 framework for the Mayotte test case, the cost of the deterministic simulations required to construct the surrogate models using Multilayer HySEA is addressed. Each deterministic simulation required approximately 50 minutes of runtime when executed on 1 NVIDIA GPU A100 card (40GB) of the S-CAPAD/DANTE platform at IPGP, France. Because the simulations associated with the quadrature nodes are independent, the training dataset was generated using a parallel workflow in which multiple deterministic simulations were executed simultaneously. A total of 1035 simulations were required to construct and validate the surrogate models across the five landslide zones considered in this study. When distributed across 6 GPU cards, the total wall-clock time required to generate the full dataset was approximately 5.6 days, whereas the equivalent sequential runtime would be approximately 36 days. This parallelization strategy substantially reduces the computational burden associated with constructing the surrogate models and makes the framework tractable for large parameter studies or probabilistic hazard analyses involving multiple potential landslide sources.”

> *8) L670-672 Basal friction influences the acceleration and maximum velocity of a landslide which are both important parameters on the magnitude of tsunamis. How do the findings of friction not playing an important role compared to studies of similar type?*

Answer: The friction does play an important role (see Marboeuf et al. (2025) for example). But the volume and location are much more influential than the friction angle. This is commented on lines 671: “Its role appears minor compared to volume and location”.

> *9) L707 An important question here is how these 1000 hypothetical scenarios add to the knowledge of the hazard that could not be acquired with the 200 computational runs. Beyond speed what are the additional gains of the surrogate modelling.*

Answer: We thank the reviewer for the comment and the opportunity to clarify the role of the surrogate model. While the 200 deterministic simulations provide a discrete set of possible landslide-tsunami scenarios, they are limited in terms of coverage of the stochastic parameter space. The surrogate model, once trained on these deterministic simulations, allows rapid evaluation across a much larger number of stochastic realizations (e.g., 1,000 or more) without additional full numerical simulations.

This expansion provides two main benefits beyond computational speed:

1. Enhanced probabilistic representation of hazard: By efficiently sampling the stochastic parameter space, the surrogate model captures the full range of potential landslide characteristics and their resulting tsunami impacts, allowing for more robust statistical estimates of wave heights, arrival times, and maximum speed probabilities.
2. Flexibility for scenario analysis: Surrogate models can explore combinations of landslide parameters that were not explicitly simulated in the original deterministic runs, supporting sensitivity analyses, risk quantification, and decision-making under uncertainty.

In short, the surrogate does not replace the deterministic simulations but amplifies their value, providing a probabilistic hazard assessment that would be computationally prohibitive with only full numerical simulations. We will clarify this in the revised manuscript to highlight the additional gains of the surrogate modeling framework.

To clarify this aspect we will modify the manuscript (L706-L714) as follows:

> **“However, the physical constraints of the Mayotte setting highlight the short delay between the landslide and the impact on the coast (a few minutes in some cases). Consequently, running deterministic simulations in real time, even with rapid computational tools, may be challenged by the speed of tsunami onset. Once trained using the deterministic simulations, the Landslide-Tsurrogate v1.0 framework enables rapid exploration of the stochastic parameter space describing potential submarine landslides. In this study, the probabilistic hazard associated with 1,000 stochastic realizations of landslide parameters at 211 coastal locations along Petite Terre can be evaluated in less than 2 seconds. This capability makes it possible to characterize the statistical variability of tsunami impacts across a large number of plausible landslide scenarios, which would be computationally impractical using only full deterministic simulations.**
>
> **The resulting probabilistic simulations (Fig. 14) indicate that tsunamis generated in the Piton zone can reach the airport and nearby settlements in less than three minutes for a significant subset of the explored scenarios. This result highlights the extremely short warning times associated with nearby submarine landslide sources and illustrates how the surrogate framework enables rapid evaluation of arrival-time distributions across a wide range of possible landslide parameters. Such short warning times strongly limit the feasibility of traditional evacuation strategies and emphasize the need for complementary adaptation measures. These may include vertical evacuation shelters, reinforced structures, pre-**

identified safe zones, clear evacuation protocols, and automated alert systems—strategies that have been studied in Mayotte (Leone et al., 2023) and implemented in other tsunami-prone regions such as Japan and Indonesia.”

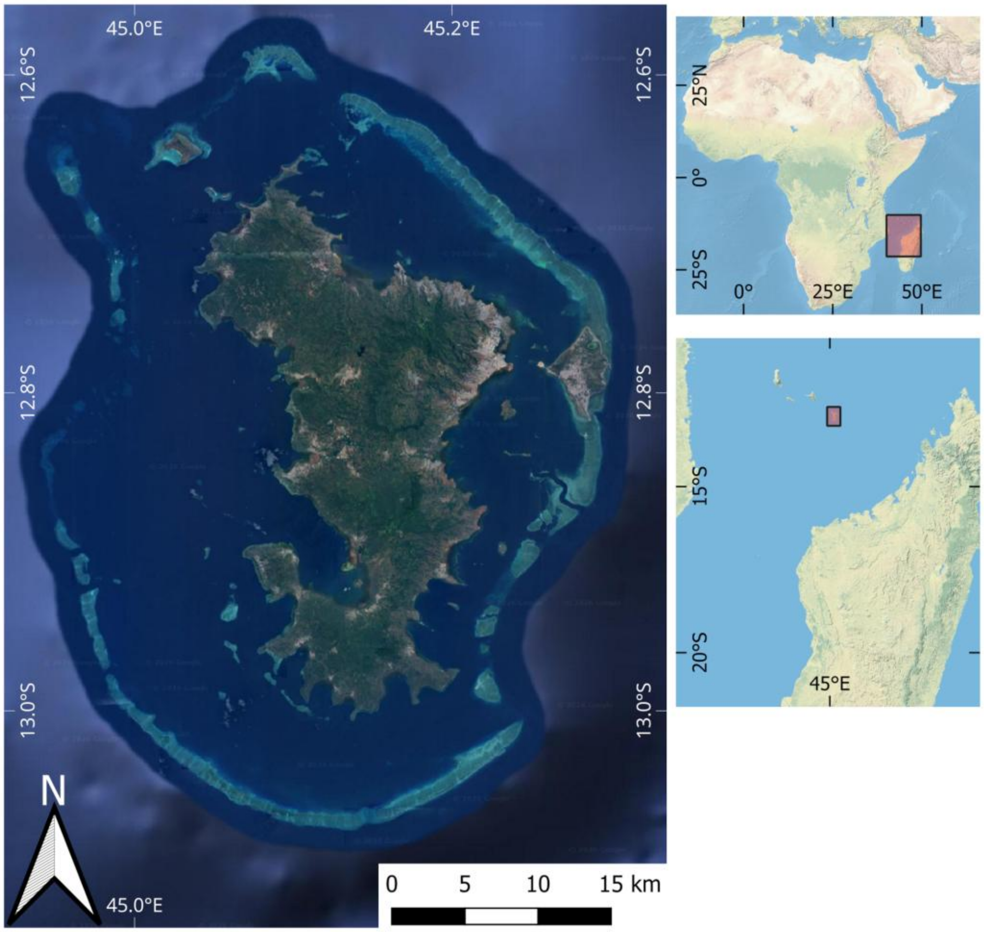
Minor points:

- Introduction There are several approaches for building surrogate model, it would be good to have an understanding upfront in the introduction why this method is attractive and how this work contributes to other works on machine learning for landslide tsunamis.

Answer: please see answer to point 1)

- Figure 1 needs to be improved as the regions are not clearly seen in the larger map.

Answer: We thank the reviewer for pointing out that the figure could be improved for clarity. Figure 1 will be replaced with the new figure below.



- *L78-80 I agree, however it also needs to be stressed that real-time forecasting is still cumbersome as often there is no information on the magnitude of the tsunamigenic source when it comes to landslides. Surrogates are useful to provide a quantification of the uncertainty in that sense.*

Answer: We thank the reviewer for pointing out that the sentence was unclear. Our intention was to emphasize that submarine landslides themselves are rarely monitored or detected in real time, which makes numerical modelling approaches necessary for hazard assessment. The sentence will be removed.

- L500 please specify these values refer to basal friction rather than internal friction?

Answer: Yes these values refer to basal friction. Note, however, that basal friction accounts empirically for all dissipative processes occurring within the flow.

- L507 please clarify what is considered the northernmost point?

Answer: We thank the reviewer for pointing out that this definition was not sufficiently explicit. The "northernmost point" refers to the point with the maximum latitude along the considered isoline of steepest slope, which is used as the reference point from which the along-isoline distance D is measured. This clarification will be added to the manuscript as follows:

> **"Practically, for each of the five selected zones, the Landslide-Tsurrogate v1.0 framework is implemented with three stochastic variables: the along-isoline distance from the northernmost point (i.e., the point with the maximum latitude; D) …"***4.2.1 More information is needed on the computational cost and spatial resolution, bathymetry data sources of the deterministic simulations.*

Answer: Concerning the computational cost, please see answer to point 7) above. Concerning the bathymetric data sources, spatial resolution, and computational grid used in the deterministic simulations, information was already provided in Section 4.2.1. In particular, the topo-bathymetric dataset originates from Lemoine et al. (2020) and combines multiple sources with resolutions ranging from 1 m to 100 m, which were merged to construct an initial 10 m Digital Elevation Model (DEM). For the tsunami simulations, this DEM was resampled to a 30 m resolution in order to provide a suitable compromise between spatial accuracy and computational efficiency.

To improve clarity, we will expand and reorganize the corresponding paragraph in the revised manuscript to make these aspects more explicit, including the data sources, grid resolution, and computational domain used in the deterministic simulations:

> **“The topo-bathymetric dataset used in this study is derived from the compilation presented by Lemoine et al. (2020), which combines multiple data sources with spatial resolutions ranging from 1 m to 100 m. These datasets were merged to construct an initial Digital Elevation Model (DEM) with a horizontal resolution of 10 m. For the deterministic tsunami simulations, this DEM was resampled to a 30 m resolution by removing rows and columns from the raster grid. This resolution was selected as a compromise between spatial accuracy and computational efficiency while maintaining a realistic representation of the coastal and nearshore bathymetry.**
>
> **The computational domain covers a 21 × 25.5 km area defined by the local coordinate bounds [xmin, xmax] × [ymin, ymax] = [520075, 541075] × [8570890, 8596390] in the EPSG:4471 (RGM04 / UTM zone 38S) coordinate system. The coastline from the SHOM Histolitt dataset is represented in the figures by a bold black line. The resulting computational grid and bathymetric dataset used in the simulations are shown in Fig. 6.”**

- L570 There is some freedom across the values of paraboloid length, width and thickness that result in similar values, how were these determined?

Answer: The paraboloid length, width and thickness are fully determined by the parametric optimization to reach the targeted volume. The triplet length, width and thickness is not unique for a given volume but we just need one triplet to produce the failure surface and properly initialize Multilayer HySEA.

- L570 Please clarify why the value of 211 locations (not more or less) is chosen, is this associated to a spatial interval in the deterministic runs?

Answer: We thank the reviewer for this comment. The 211 locations correspond to target points distributed along the Petite Terre coastline in areas where the hazard assessments are required. These points are placed along the coastline at nearshore depths of approximately 1.0–1.5 m in order to capture tsunami characteristics immediately offshore of the inundation zone. The number of points therefore results from the spatial discretization of the coastline determined by the resolution used to produce the deterministic simulations. We will clarify this point in the revised manuscript as follows:

> **“To provide PTF along all vulnerable Petite Terre coastal areas, the surrogate models are built pointwise (i.e., with no spatial correlation between the sites) at targeted depths of 1.0–1.5 m outside of the inundation zone. These target locations are distributed along the Petite Terre coastline in areas where inundation maps are required for risk reduction, emergency preparedness, and evacuation planning.**

> **Practically, the spatial discretization used in the deterministic simulations leads to a total of M = 211 coastal target points (Fig. 9).”**

- *L595 as inundation is not studied in this work since the emulators are offshore, please remove the word inundation as this can be confusing for the reader.*

Answer: To avoid any confusion the sentence will be modified as follows:

> **“For each landslide scenario, tsunami propagation is simulated, and relevant hazard metrics such as maximum tsunami elevation, maximum tsunami speed and time of arrival are extracted at the coastal target points.”**