



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

MARLiN: Maritime Adaptation via Reservoir and Liquid Networks for Vessel Trajectory Prediction

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Introduction

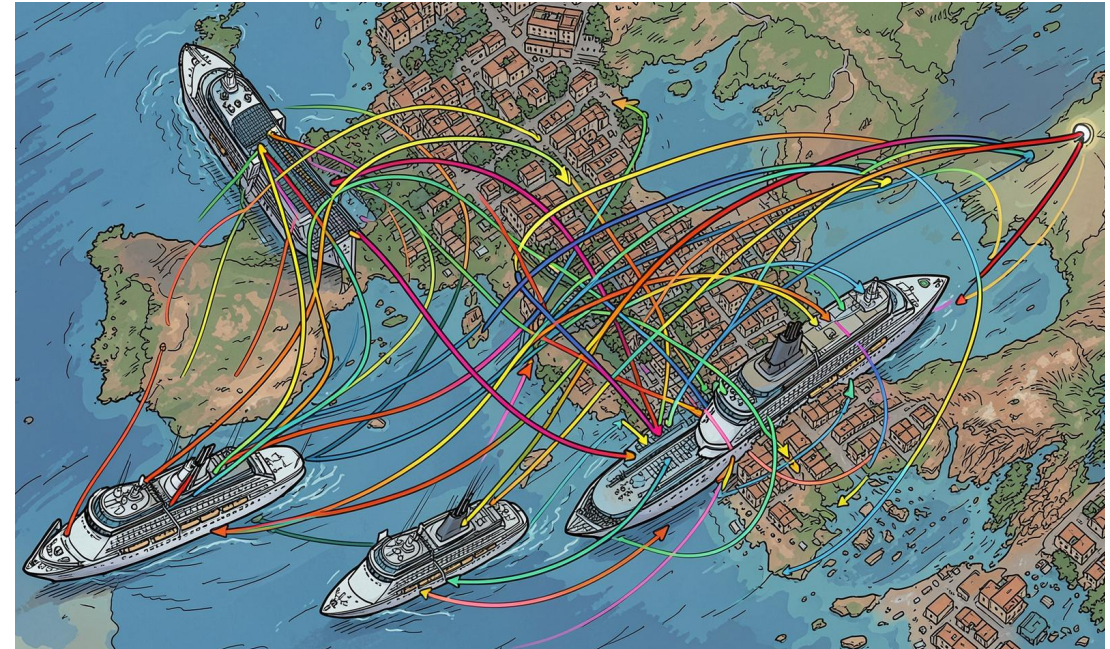
Predicting a trajectory of the **vessel** is critical for maritime safety and efficiency.

External Disturbances

Wind, currents, and sea states interact with nonlinear vessel dynamics in unpredictable ways.

Shifting Traffic Patterns

Traffic patterns shift seasonally; geopolitical issues and environmental conditions evolve unpredictably.



Traditional AI models are trained on static datasets and assume stationary data.
The performance degrades when conditions change.

Continual Learning

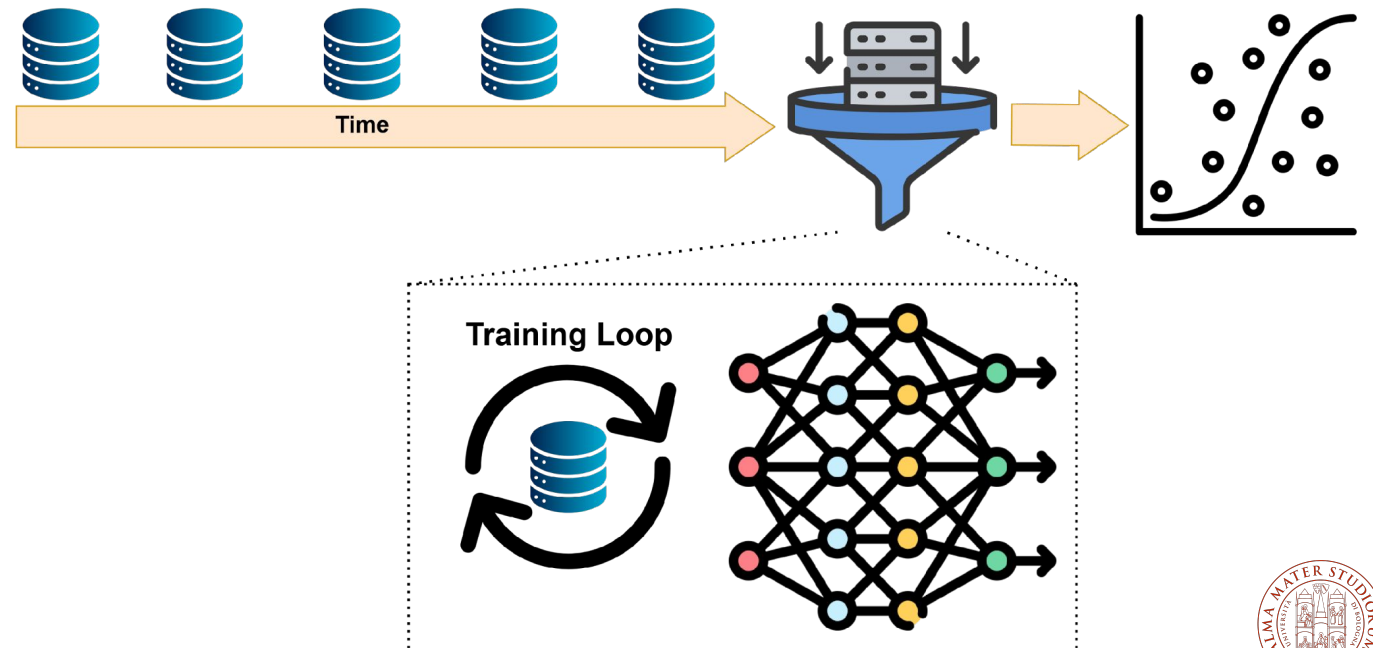
Continual Learning (CL) enables models to acquire knowledge from continuous data streams without forgetting previously learned patterns.

Catastrophic Forgetting when a model learns new data sequentially, it tends to overwrite previously acquired knowledge.

Two complementary needs:

- **Model the continuous-time**, irregularly sampled nature of vessel dynamics.
- **Explicitly preserve knowledge** from past operating patterns.

Focusing on only one is insufficient a powerful temporal model still forgets, and replay alone cannot capture irregular VDR stream structure.



MARLiN - Our Proposal

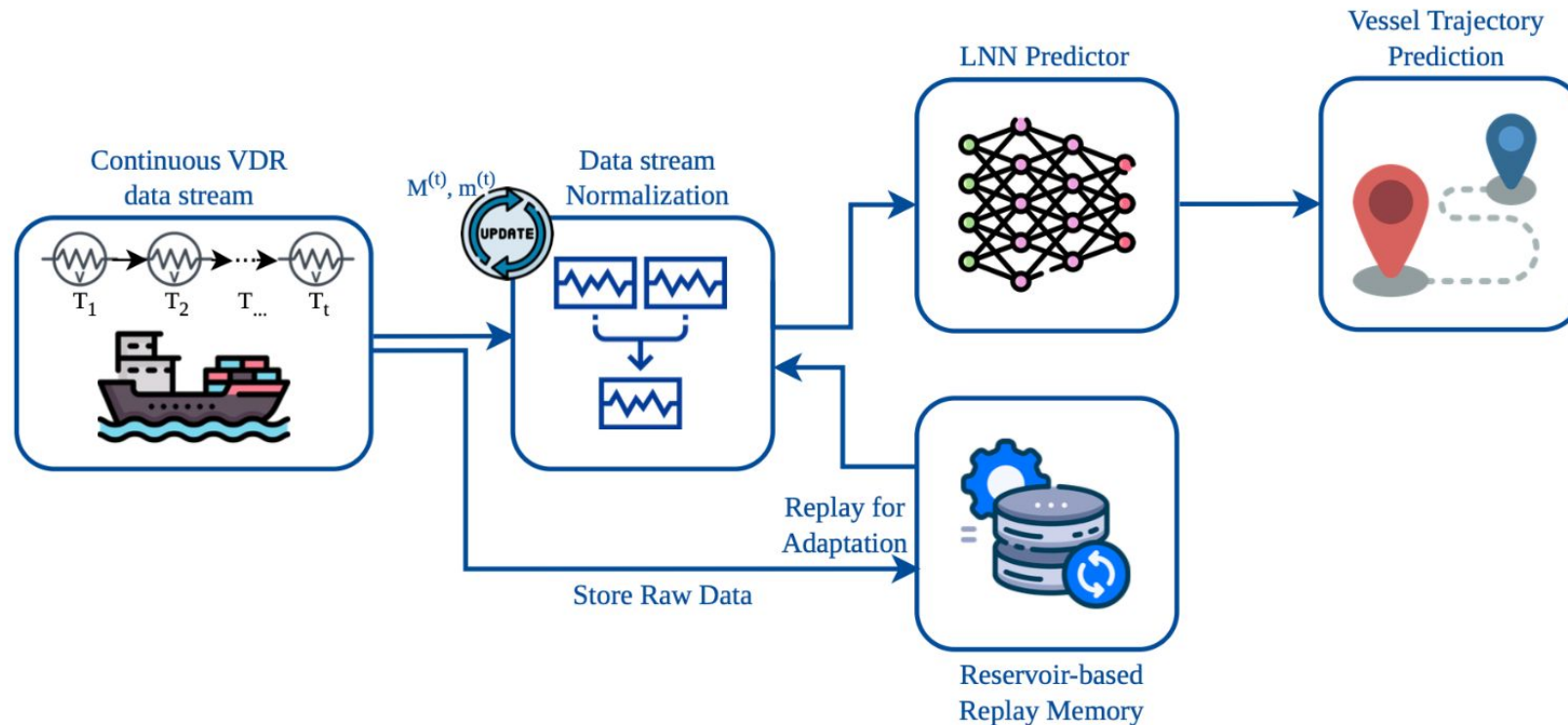


Fig. 1: MARLiN framework overview. The continuous data stream is partitioned into sequential tasks $\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_t$. At each task, raw sequences update the cumulative normalization statistics before being normalized and fed to the LNN predictor. Past sequences are stored in raw form in the Reservoir-based Replay Memory and re-normalized on-the-fly during replay to mitigate the catastrophic forgetting.

Datasets

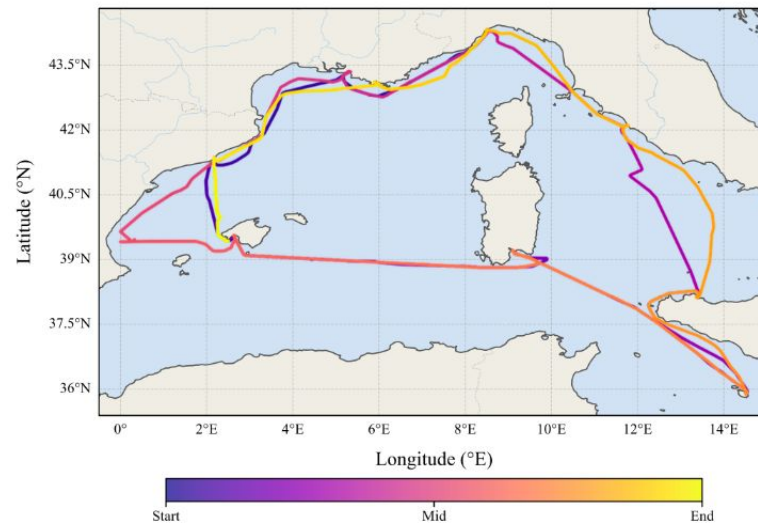
Two complementary cruise vessel benchmarks.

Concordia dataset

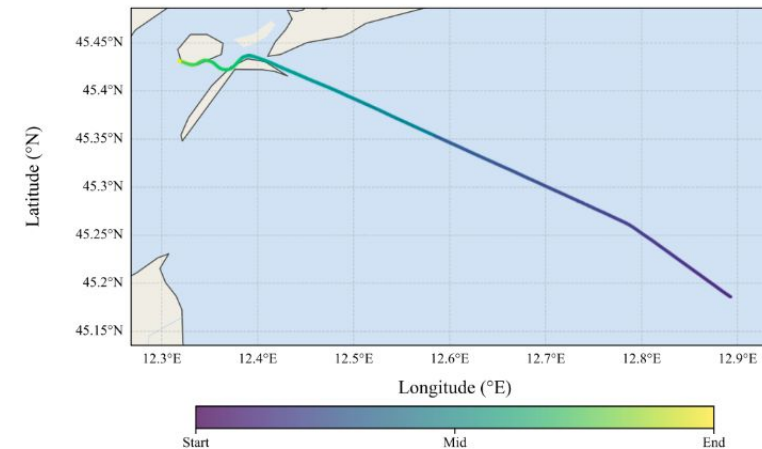
Abrupt, irregular distributional shifts: robustness test.

Opera dataset

Smooth, progressive drift ending in a regime transition: adaptation test.



(a) Concordia dataset



(b) Opera dataset

Fig. 2: Geographical trajectories of the two dataset vessels: (a) Concordia and (b) Opera. The color gradient indicates the temporal progression of each trajectory, from start to end.

MARLiN - Results

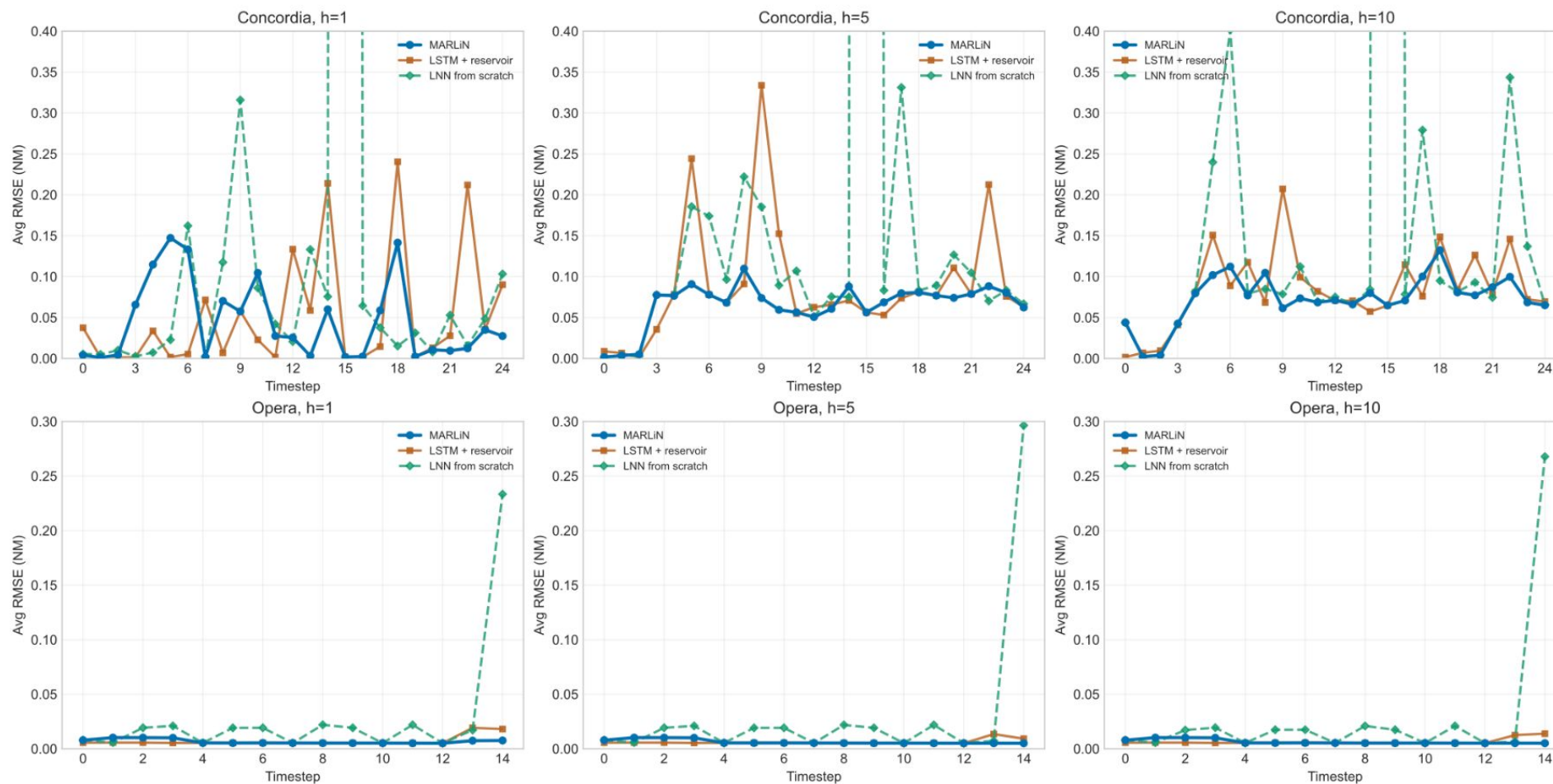


Fig. 4: Average RMSE comparison between MARLiN and LSTM with reservoir, and LNN without continual learning for the Concordia and Opera datasets across different prediction horizons.

MARLiN - Results

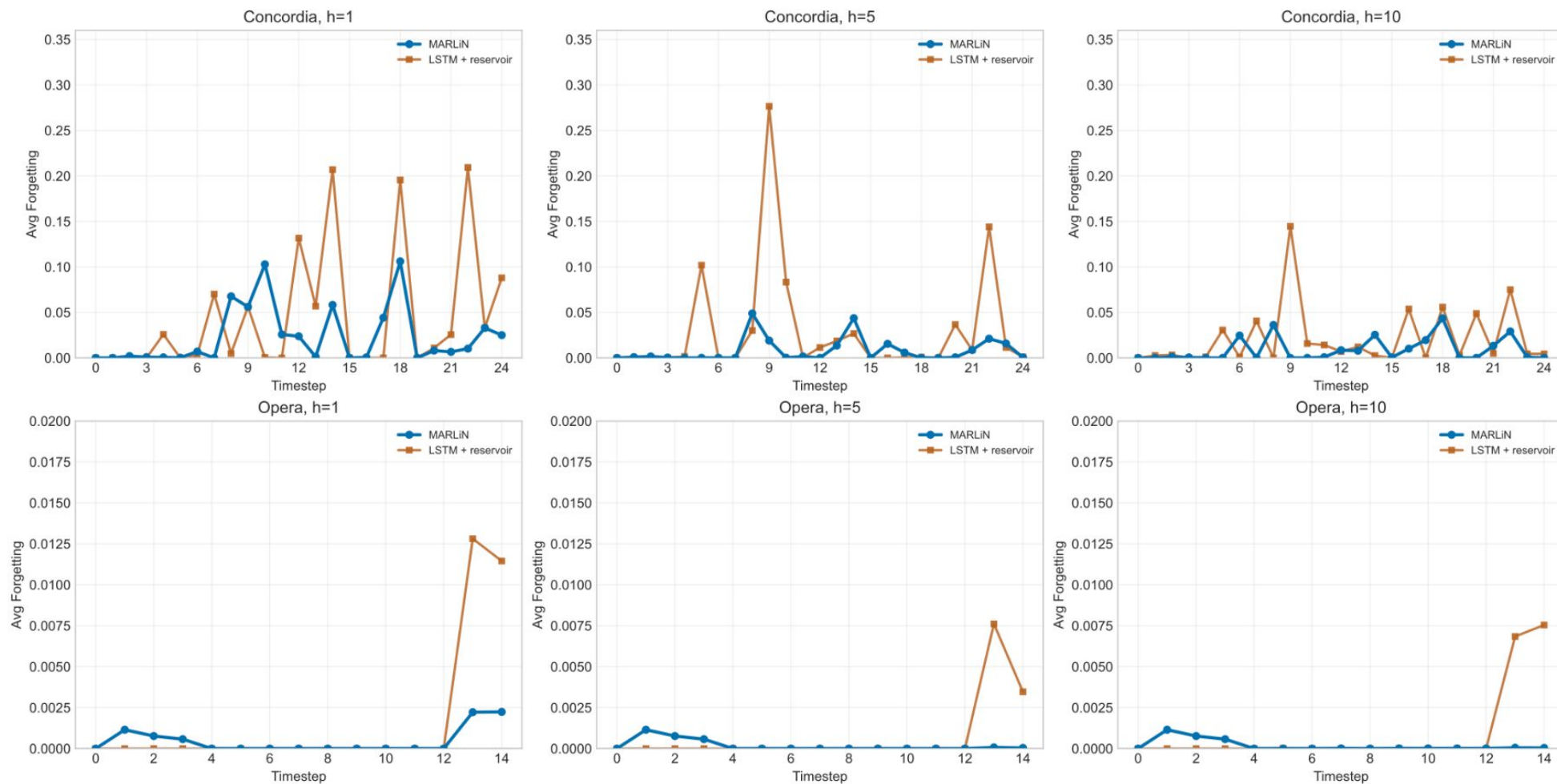


Fig. 5: Average Forgetting comparison between MARLiN and LSTM with reservoir for the Concordia and Opera datasets across different prediction horizons during the time.

MARLiN - Results

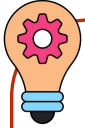
TABLE III: Model complexity, latency, and memory footprint.

Dataset	Model	#Params	Infer. (ms)	Buffer (MB)
Concordia	MARLiN	399,362	12.445 ± 0.037	480
	LSTM	205,314	0.441 ± 0.023	480
Opera	MARLiN	401,410	12.424 ± 0.039	80
	LSTM	209,410	0.442 ± 0.022	80

MARLiN is $\approx 2\times$ params, $\approx 28\times$ latency but it acceptable for maritime forecasting intervals that are on the order of seconds.



Conclusions



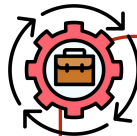
Key Innovation

Unified framework coupling LNN continuous-time dynamics, reservoir-based replay, and streaming-aware normalization purpose-built for non-stationary maritime environments.



What MARLiN Achieves

Competitive trajectory forecasting across multiple horizons, more stable forgetting profile than LSTM baseline, and avoids catastrophic error spikes of periodic from-scratch retraining.



Future works

Extend MARLiN to detect anomalous trajectory deviations, potentially indicating adversarial attacks or malicious route manipulations enabling cyber-physical security in maritime systems.





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