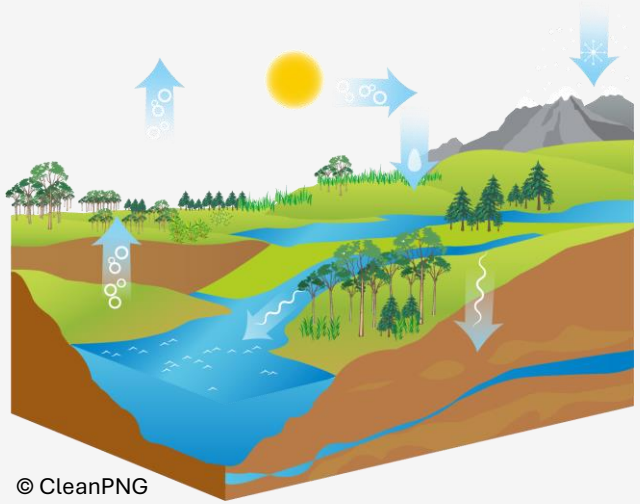
RiverMamba: A State Space Model for Global River Discharge and Flood Forecasting

Mohamad Hakam Shams Eddin, Yikui Zhang, Stefan Kollet and Jürgen Gall

[] Institute of Computer Science, University of Bonn
[] Lamarr Institute for Machine Learning and Artificial Intelligence
[] Institute of Bio- and Geosciences Agrosphere (IBG-3), Research Centre Jülich
[] Centre for High-Performance Scientific Computing in Terrestrial Systems, Geoverbund ABC/J

State-of-the-art in flood forecasting:



Hydrological model

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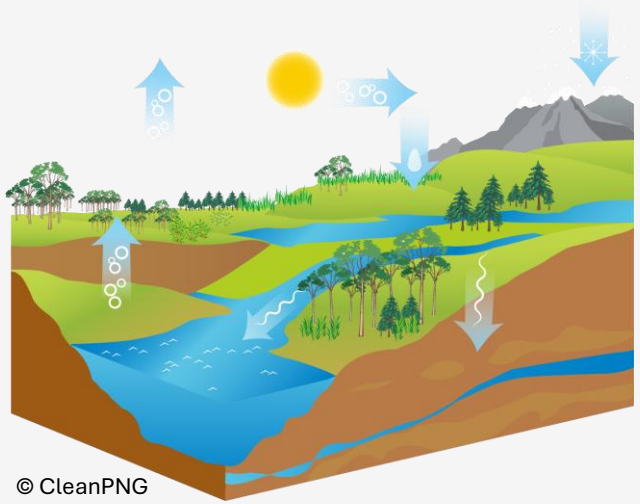
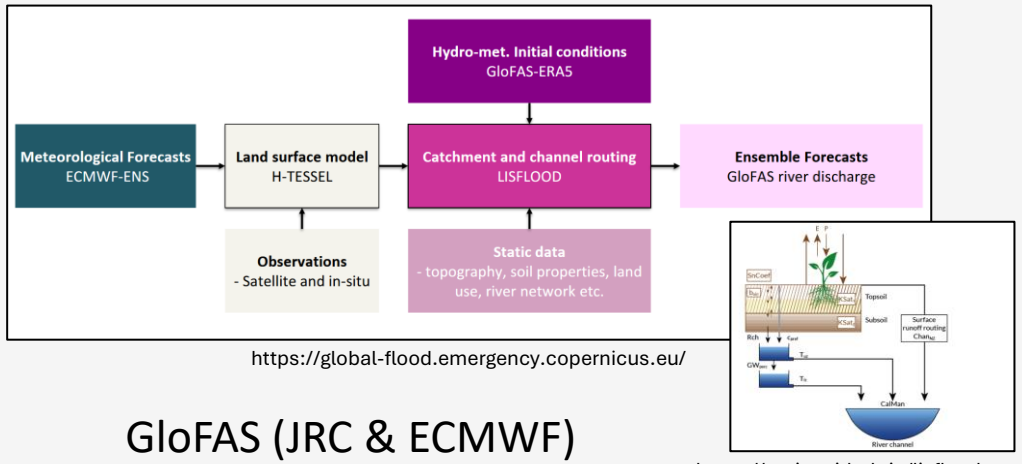


© CleanPNG

Hydrological model

Physics-based



https://global-flood.emergency.copernicus.eu/

GloFAS (JRC & ECMWF)

https://ec-jrc.github.io/lisflood-model/

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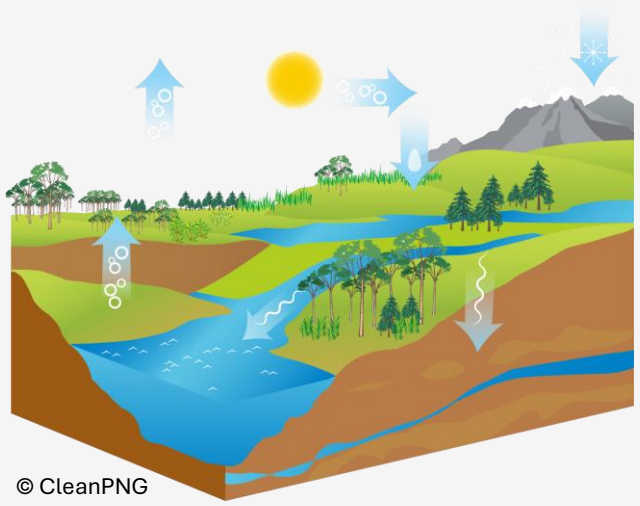

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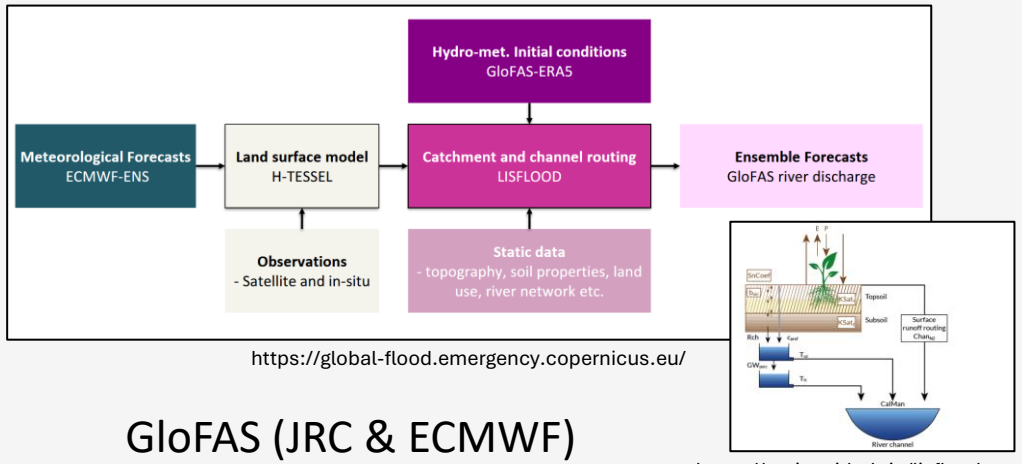

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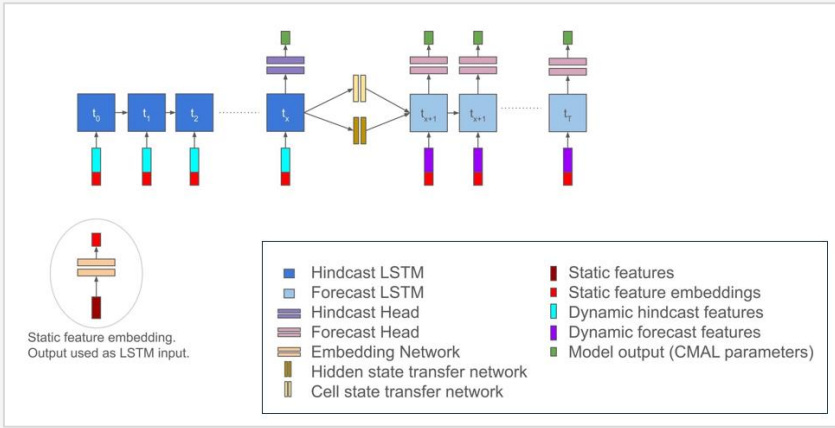
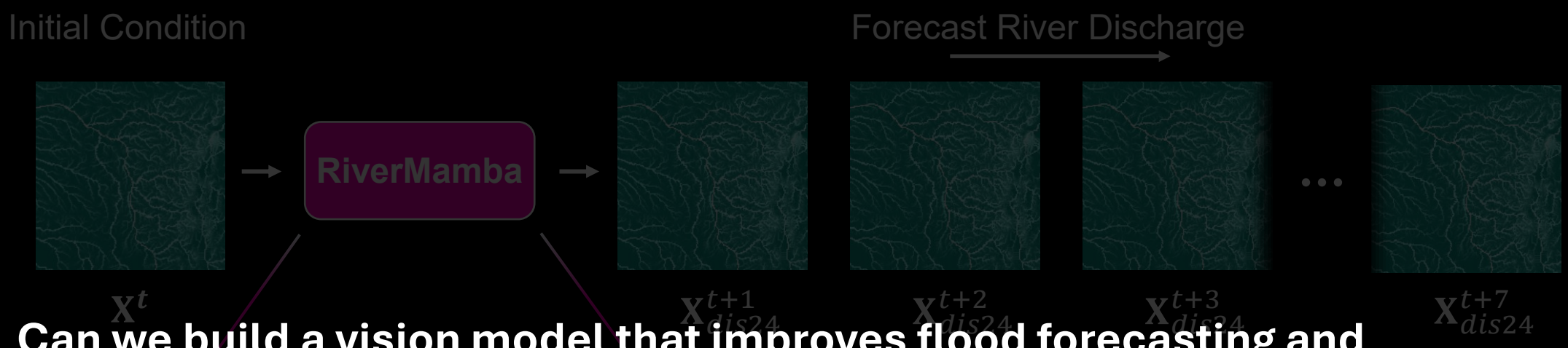
Time series analysis



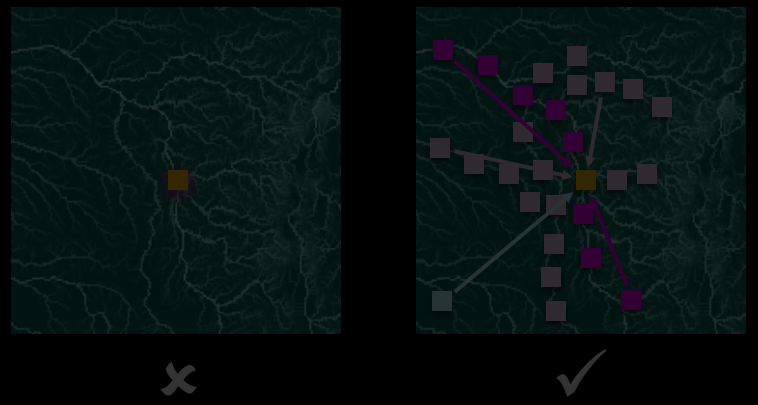
Google LSTM (Nearing et al. 2024 & Kratzert et al. 2019)

Motivation behind RiverMamba:

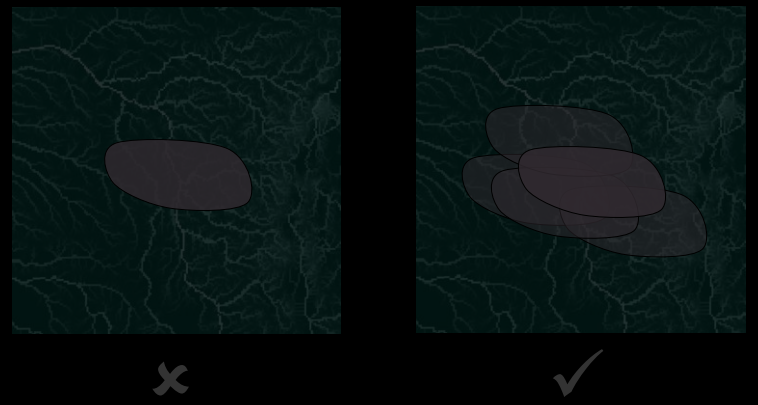


Can we build a vision model that improves flood forecasting and provides high-resolution predictions globally?

Build a vision-based model



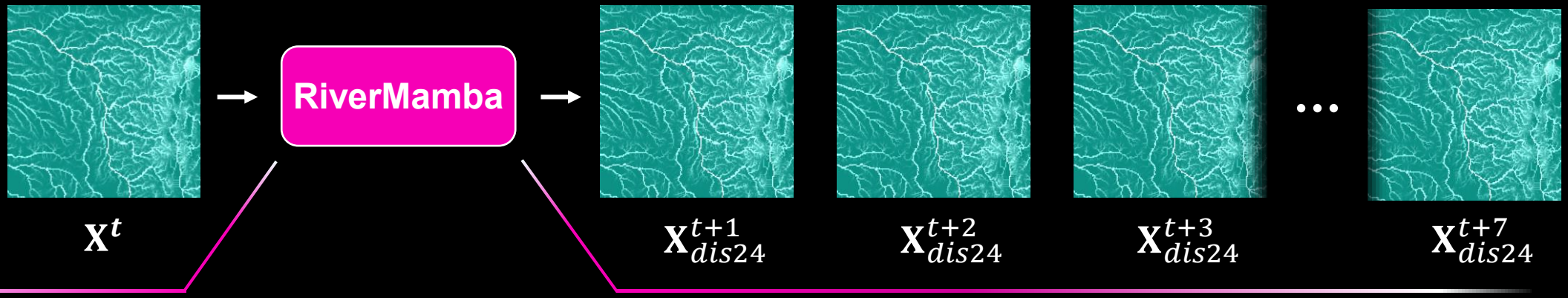
Consider uncertainty in meteorological forcing



Motivation behind RiverMamba:

Initial Condition

Forecast River Discharge



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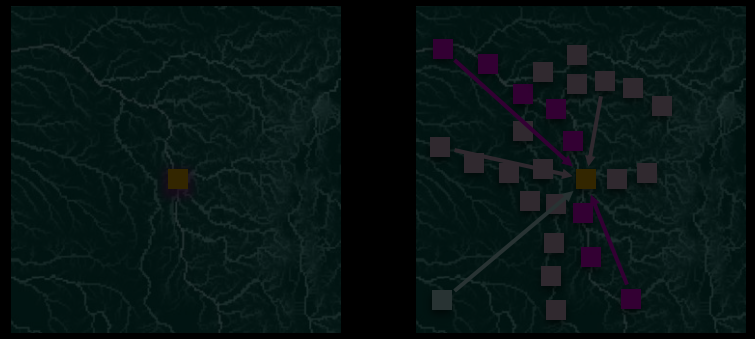

✗ ✓

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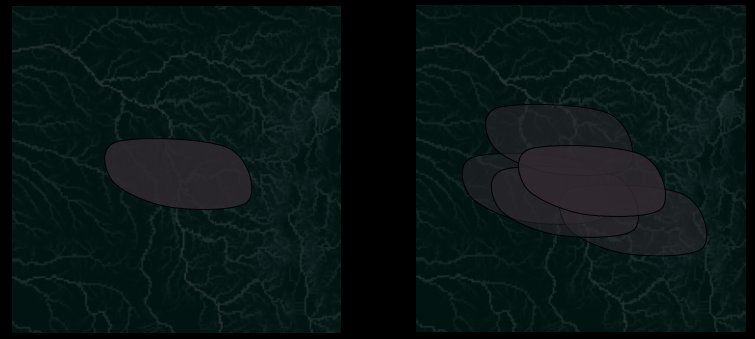

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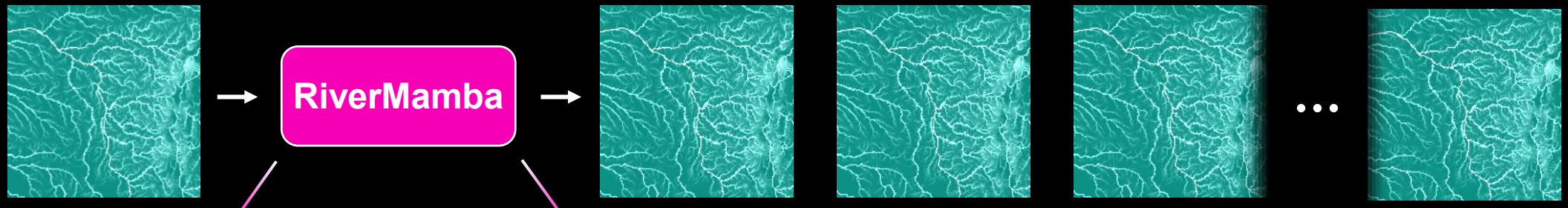

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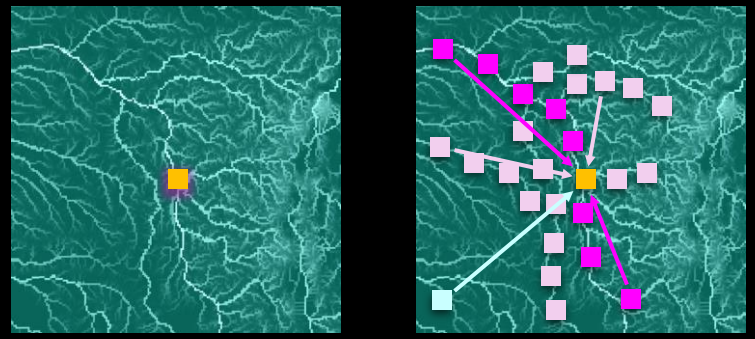

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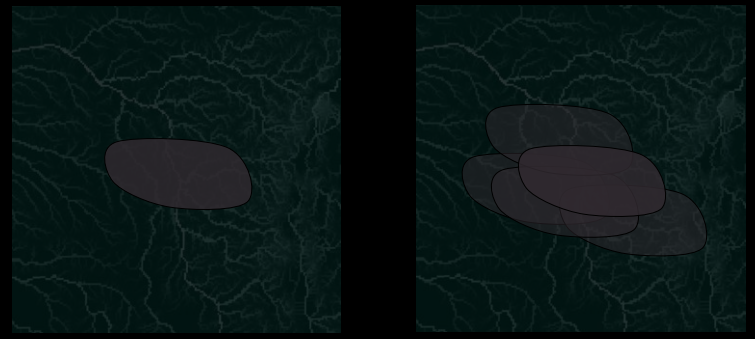

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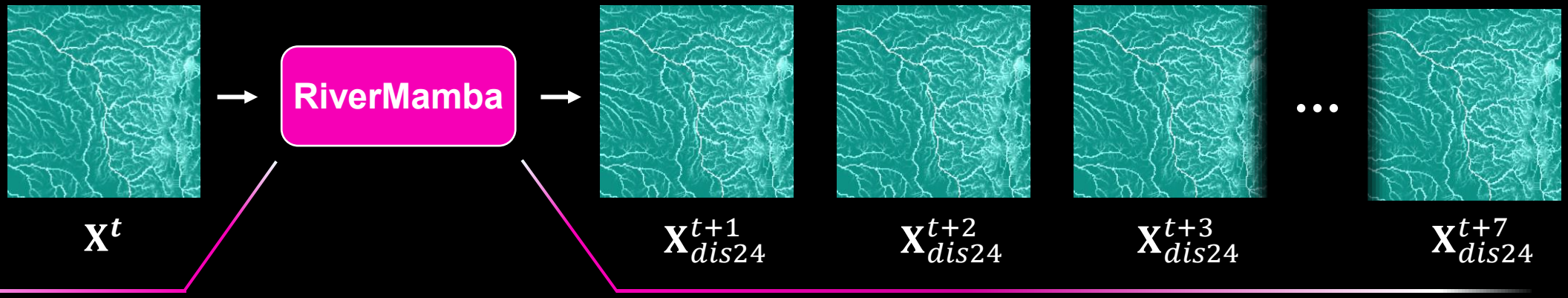

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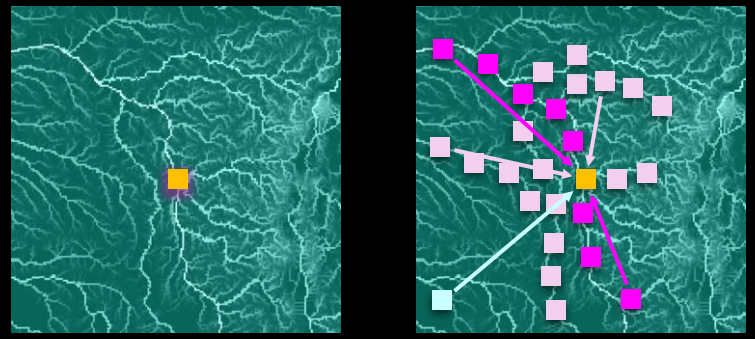

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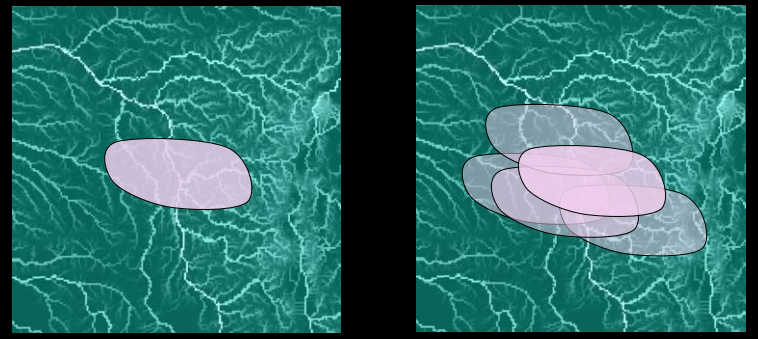
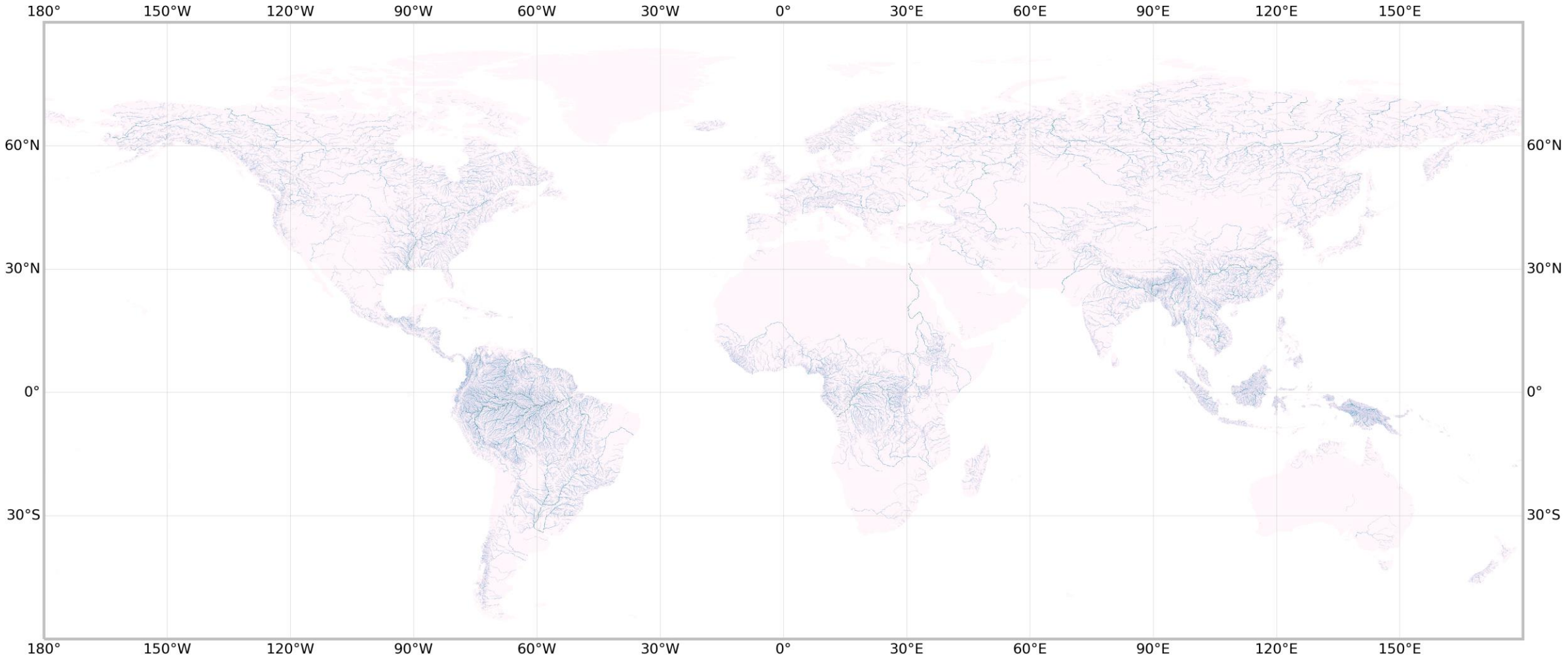
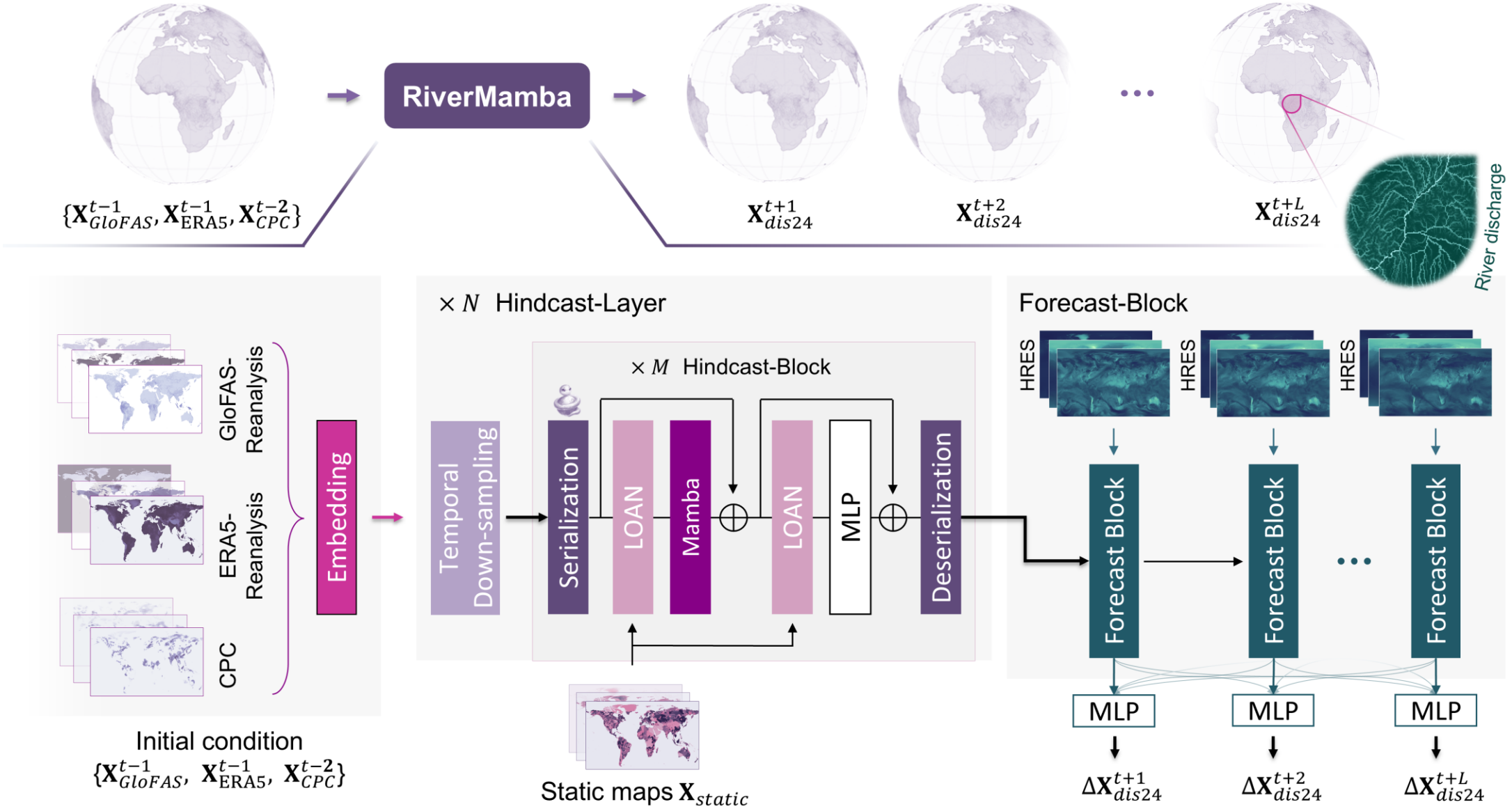


✘ ✓

Experiments: ~1.6 M points at 0.05° resolution (3000 x 7200 pix)



RiverMamba:


RiverMamba
$\{\mathbf{X}_{GloFAS}^{t-1}, \mathbf{X}_{\text{ERA5}}^{t-1}, \mathbf{X}_{CPC}^{t-2}\}$
$\mathbf{X}_{dis24}^{t+1}$
$\mathbf{X}_{dis24}^{t+2}$
$\mathbf{X}_{dis24}^{t+L}$
River discharge
GloFAS-Reanalysis
ERA5-Reanalysis
CPC
Embedding
Initial condition
$\{\mathbf{X}_{GloFAS}^{t-1}, \mathbf{X}_{\text{ERA5}}^{t-1}, \mathbf{X}_{CPC}^{t-2}\}$
$\times N$ Hindcast-Layer
$\times M$ Hindcast-Block
Temporal Down-sampling
Serialization
LOAN
Mamba
LOAN
MLP
Deserialization
Static maps $\mathbf{X}_{static}$
Forecast-Block
HRES
HRES
HRES
Forecast Block
Forecast Block
Forecast Block
MLP
MLP
MLP
$\Delta\mathbf{X}_{dis24}^{t+1}$
$\Delta\mathbf{X}_{dis24}^{t+2}$
$\Delta\mathbf{X}_{dis24}^{t+L}$

RiverMamba:

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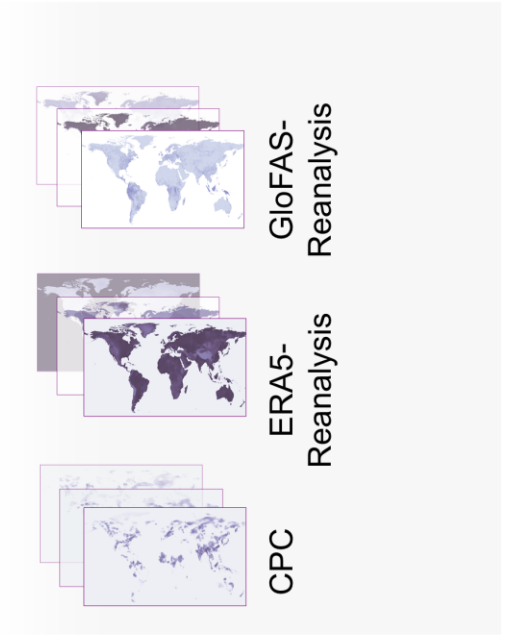
RiverMamba



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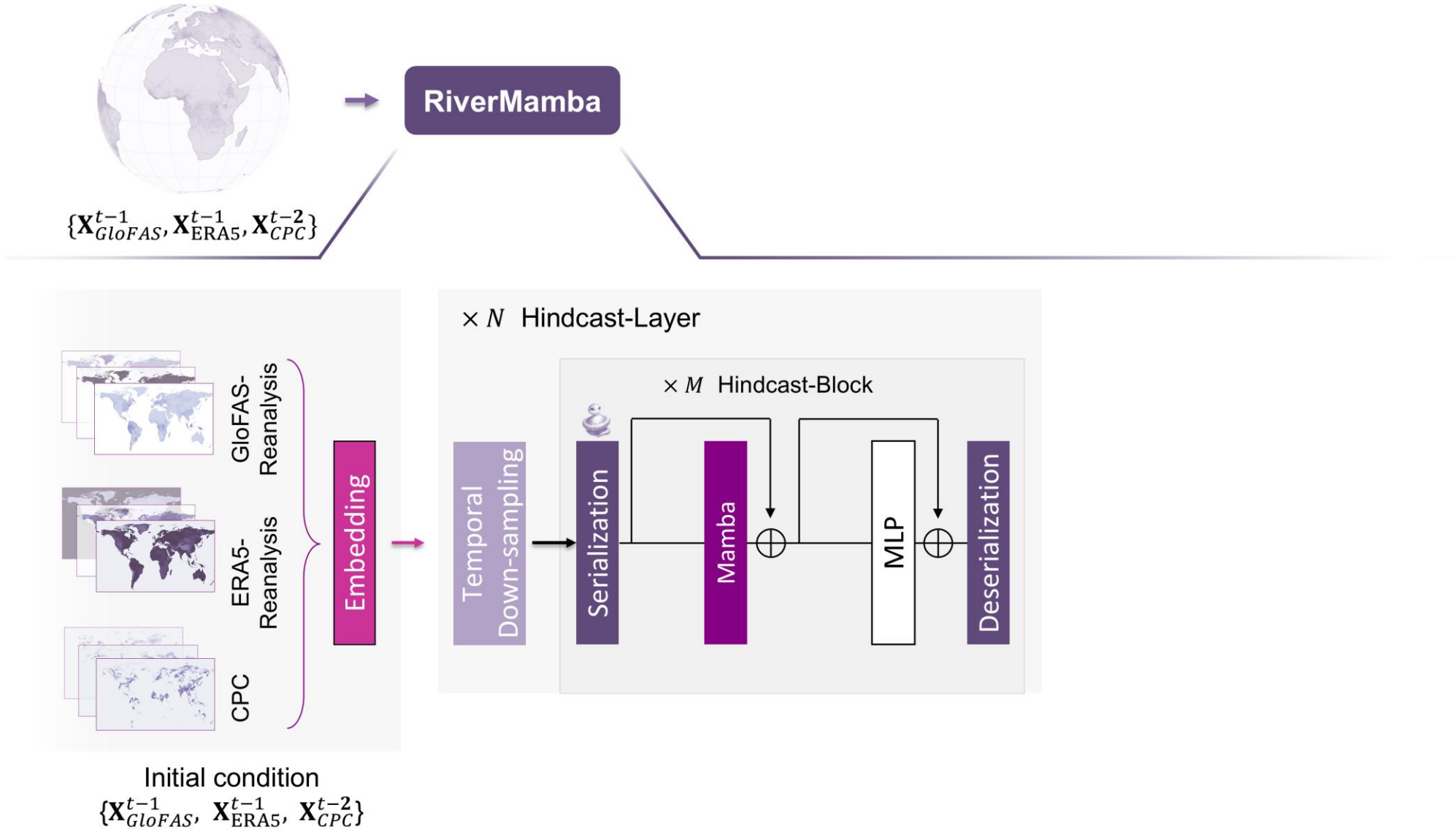
RiverMamba
$\{\mathbf{X}^{t-1}_{GloFAS}, \mathbf{X}^{t-1}_{\text{ERA5}}, \mathbf{X}^{t-2}_{CPC}\}$
GloFAS-Reanalysis
ERA5-Reanalysis
CPC
Embedding
Initial condition
$\{\mathbf{X}^{t-1}_{GloFAS}, \mathbf{X}^{t-1}_{\text{ERA5}}, \mathbf{X}^{t-2}_{CPC}\}$
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$\times M$ Hindcast-Block
Temporal Down-sampling
Serialization
Mamba
MLP
Deserialization

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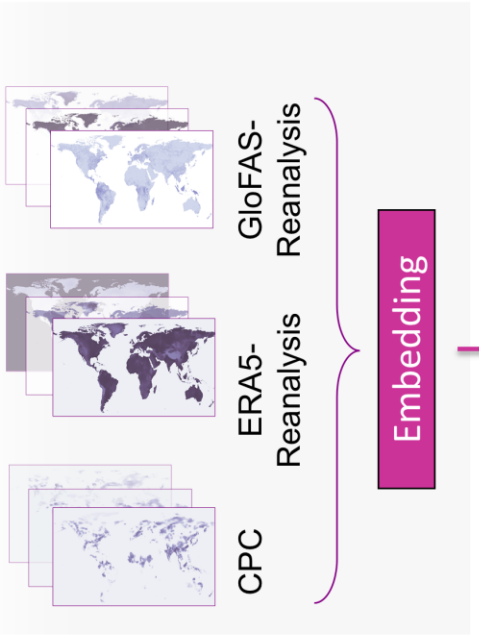
RiverMamba



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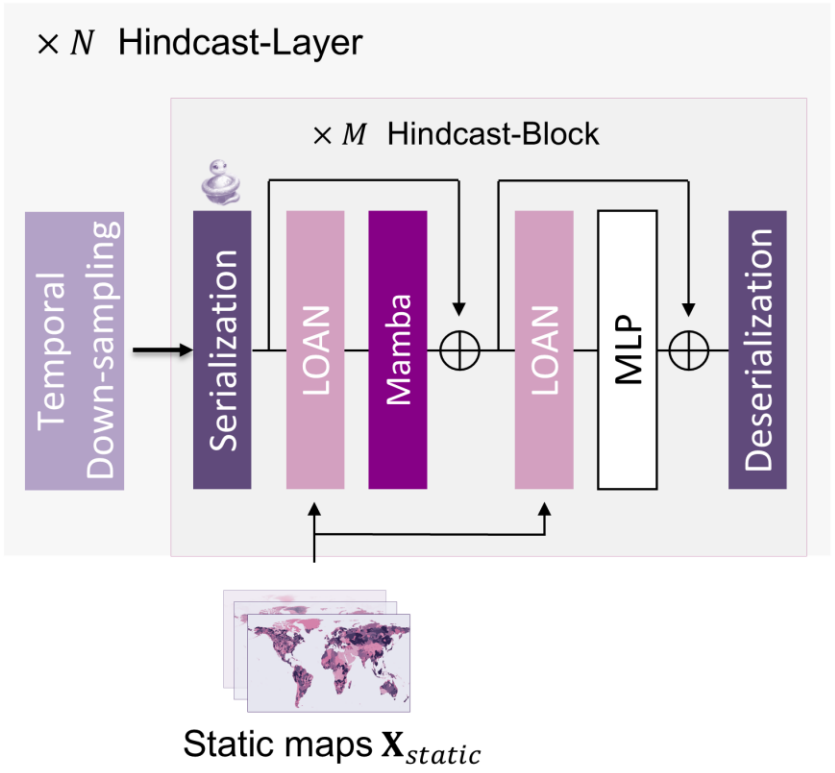
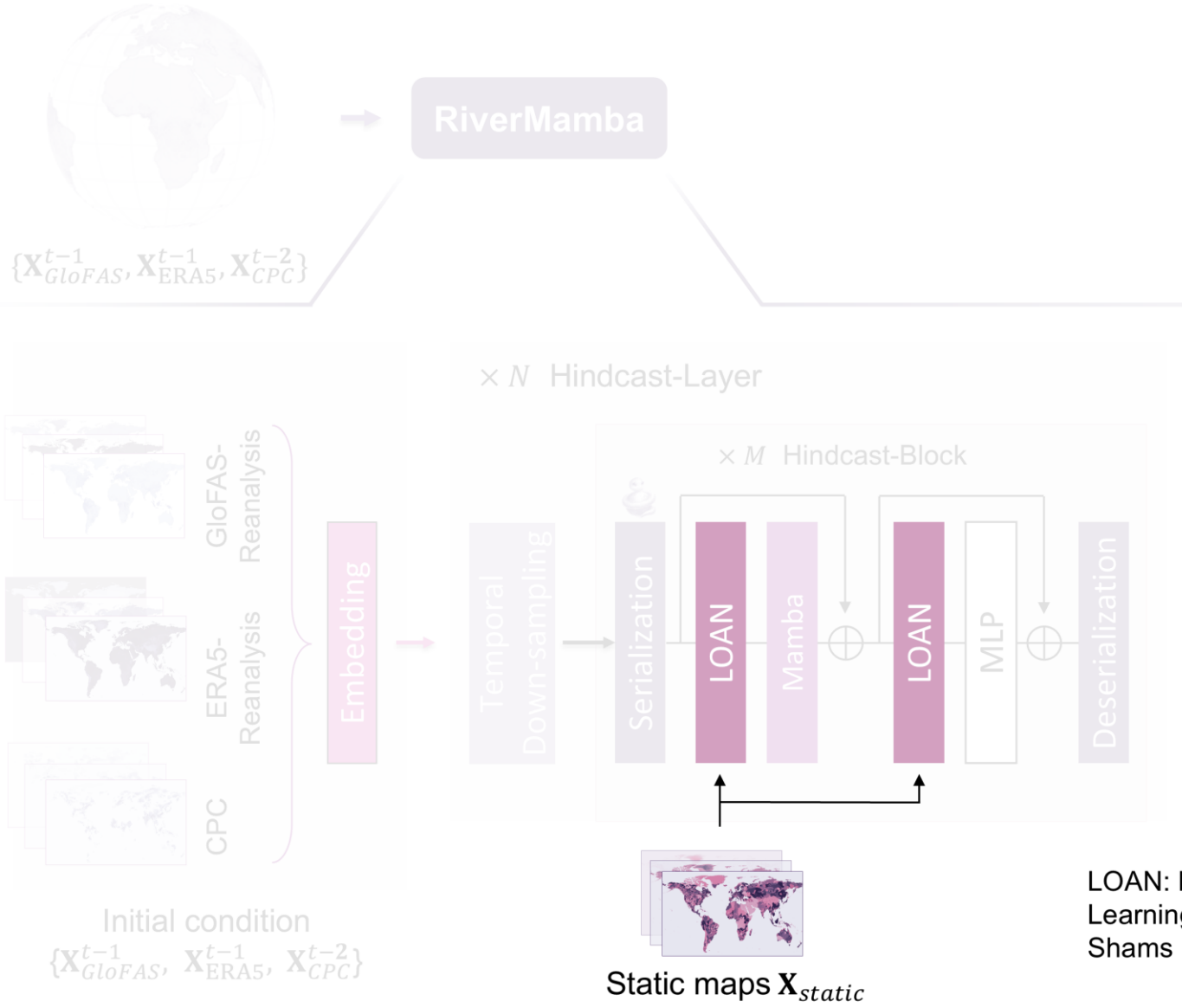


Static maps $\mathbf{X}_{static}$

RiverMamba:



LOAN: Location-Aware Adaptive Normalization: A Deep Learning Approach for Wildfire Danger Forecasting
Shams Eddin et al., (2023)

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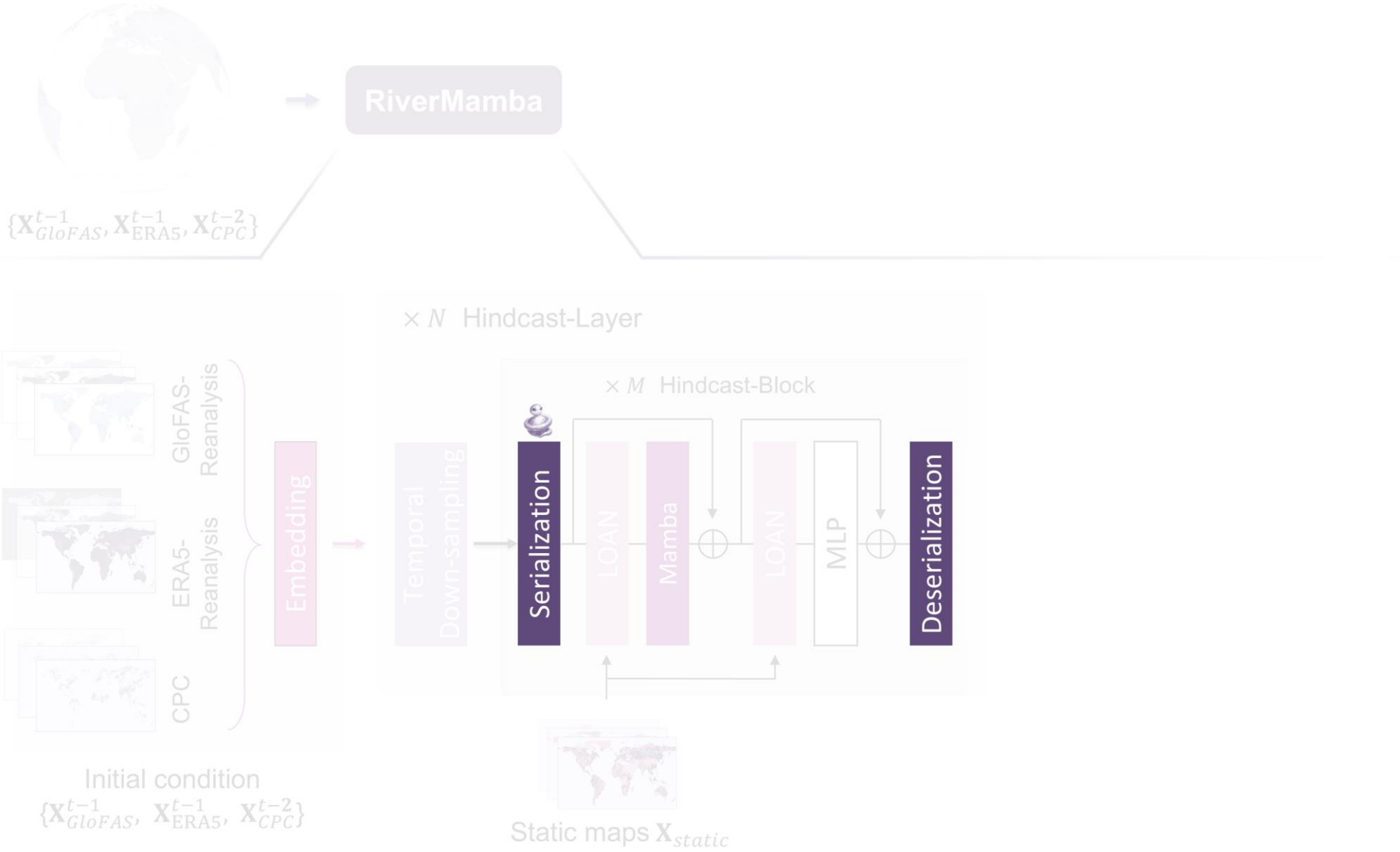
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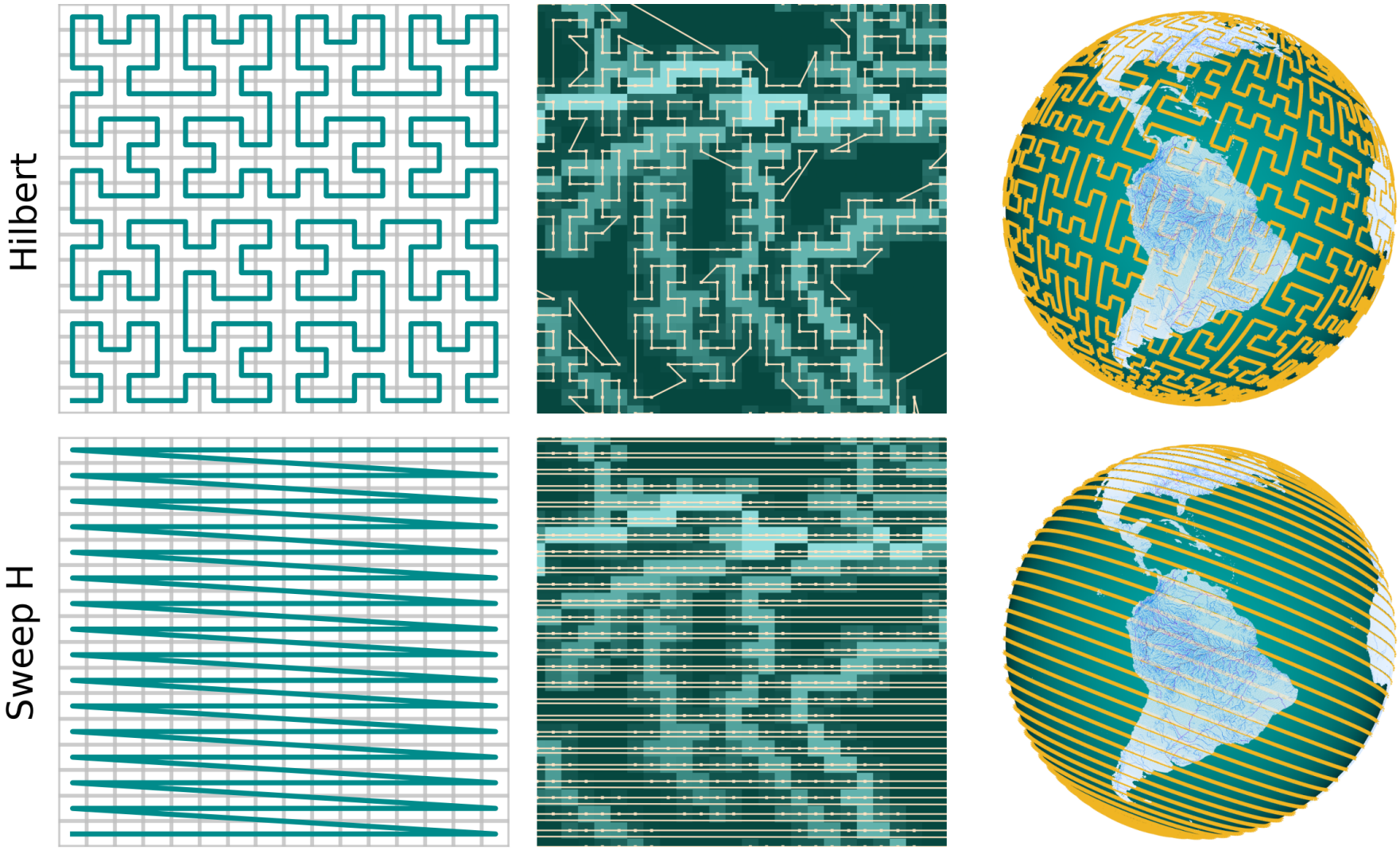
Space-filling curves: $\varphi\colon \mathbb{Z}^3 \to \mathbb{N}$



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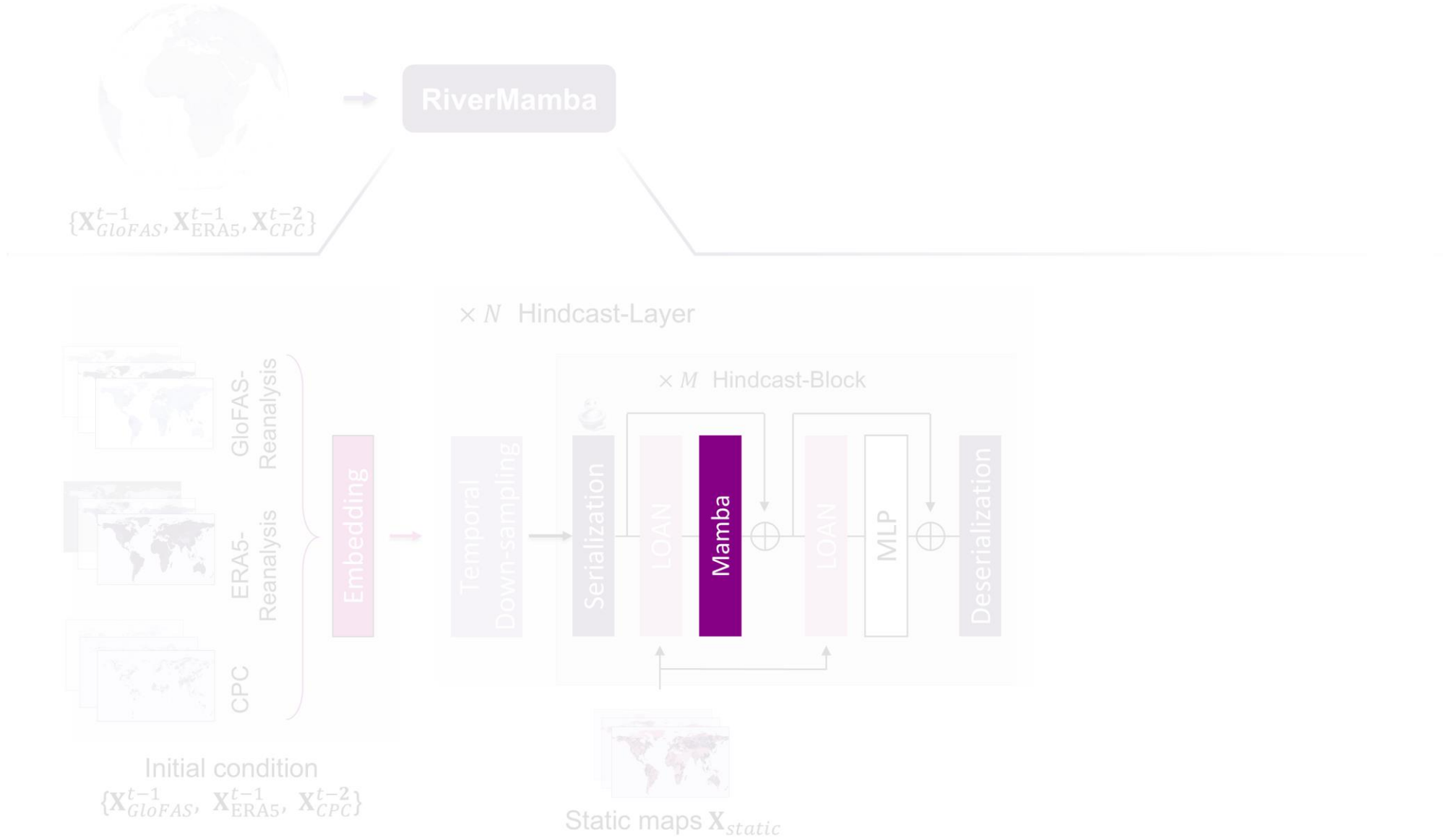
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Vision Mamba:

$$h'(t) = \mathbf{A}\, h(t-1) + \mathbf{B}\, x(t)$$
$$y(t) = \mathbf{C}\, h(t) + \mathbf{D}\, x(t)$$

$$h_t = \overline{\mathbf{A}}\, h_{t-1} + \overline{\mathbf{B}}\, x_t$$
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[Mamba: Gu, Albert and Dao, Tri, “Mamba: Linear-time sequence modeling with selective state spaces." arXiv preprint arXiv:2312.00752 (2023)]

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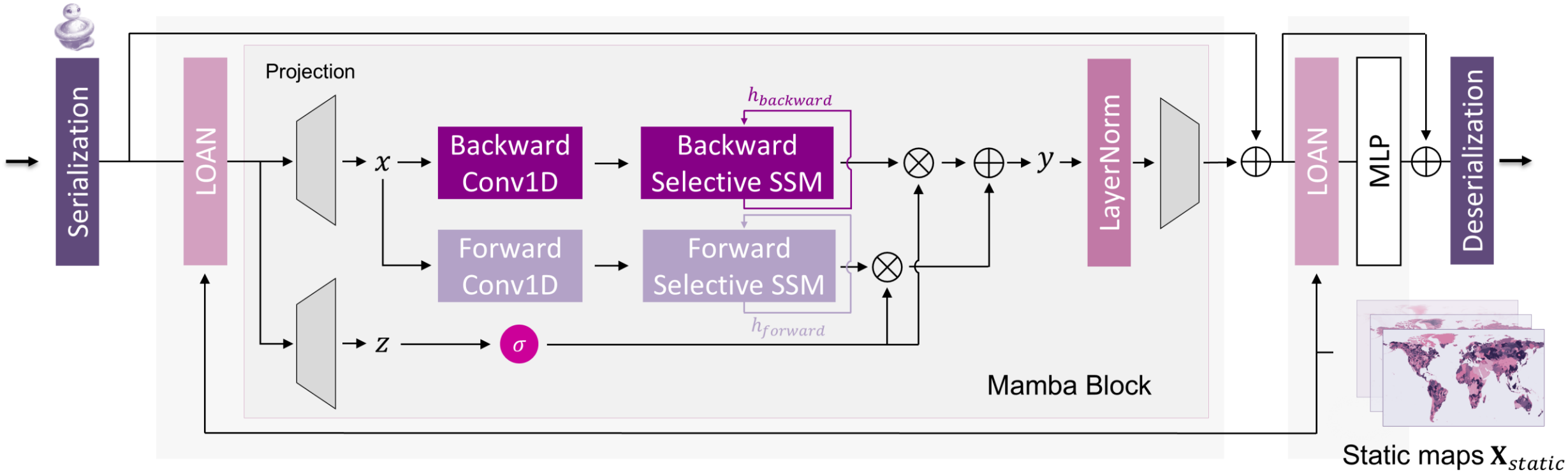

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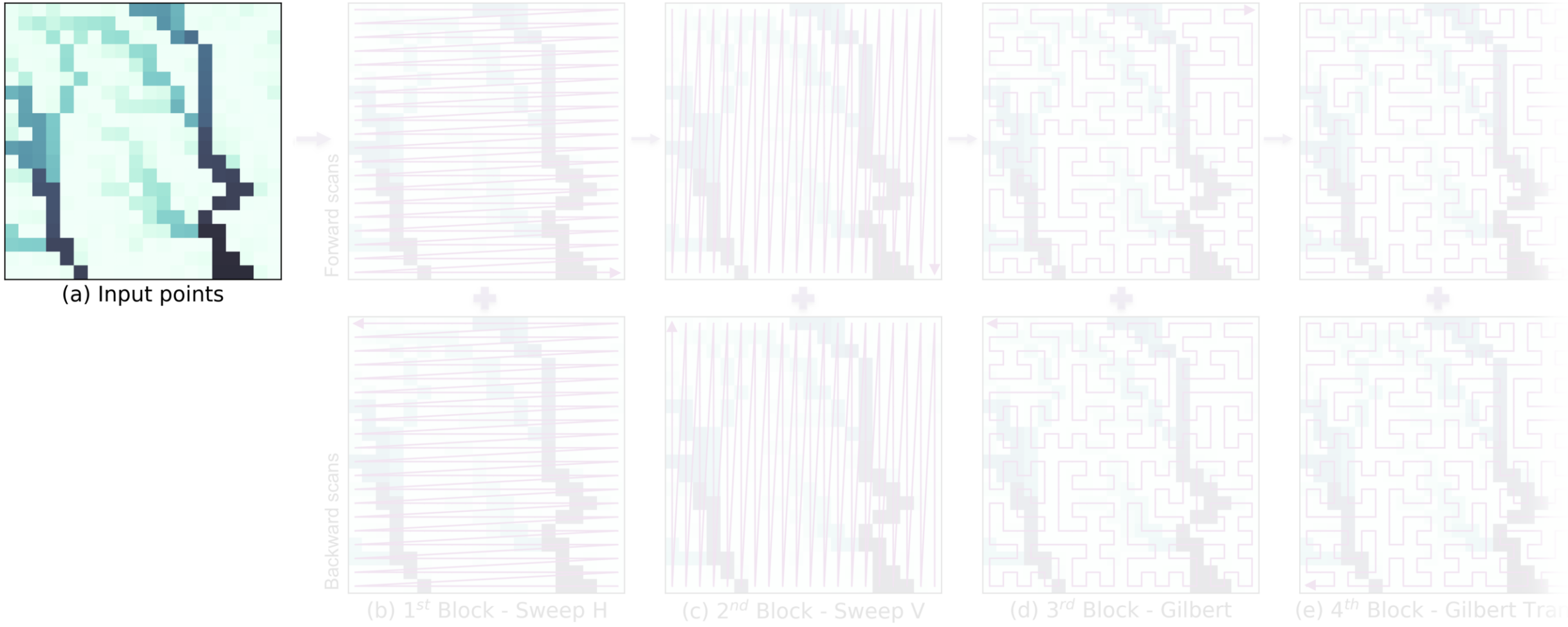

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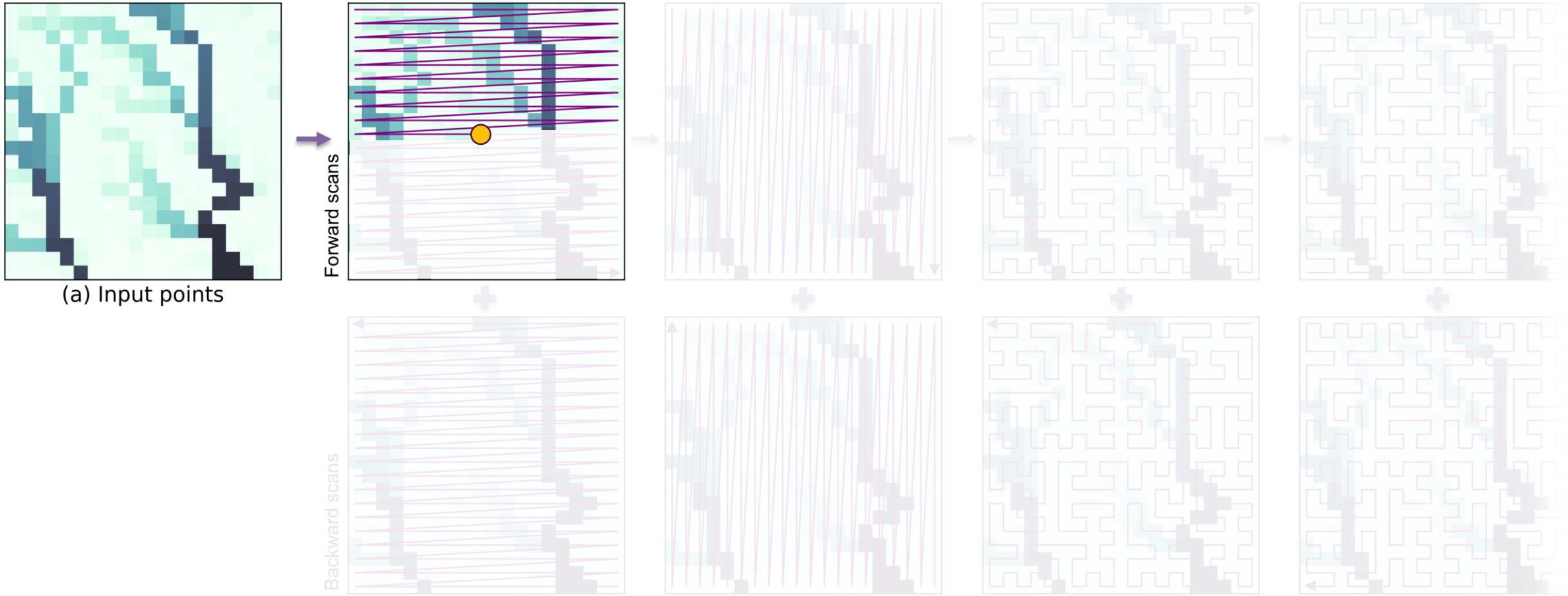

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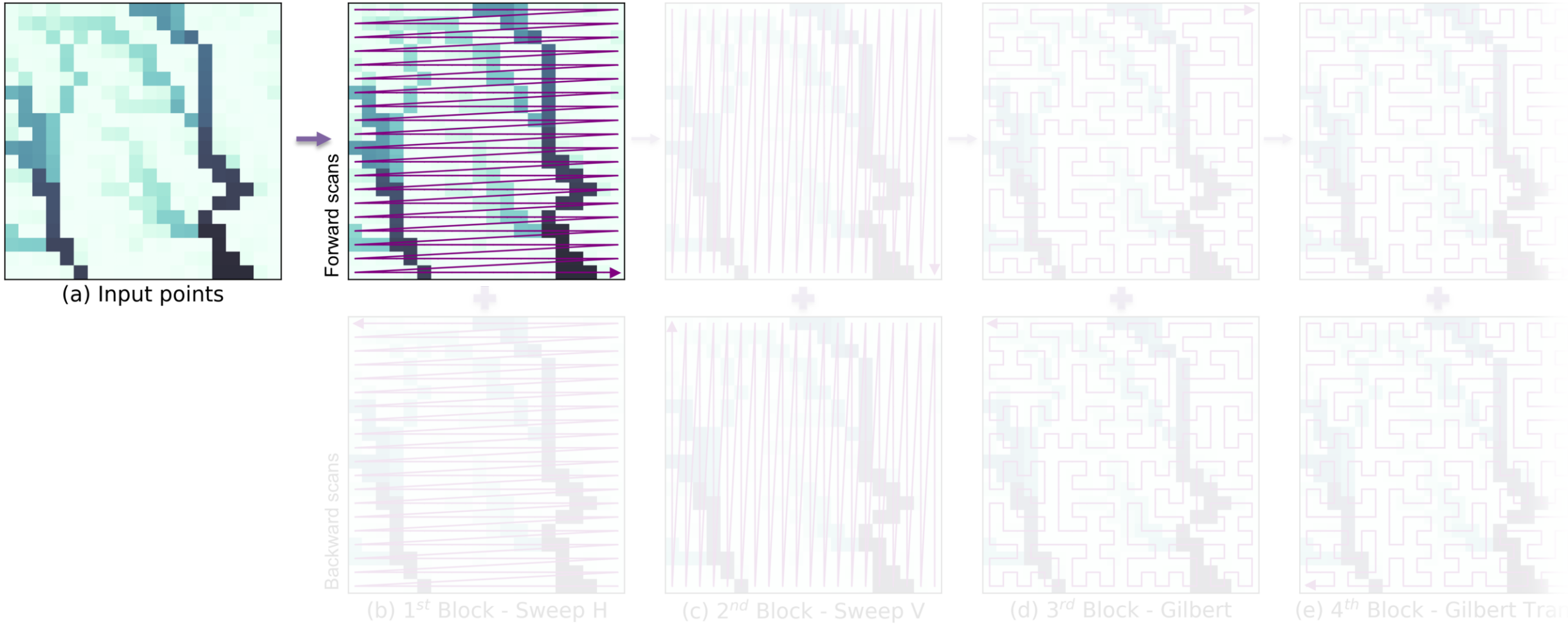

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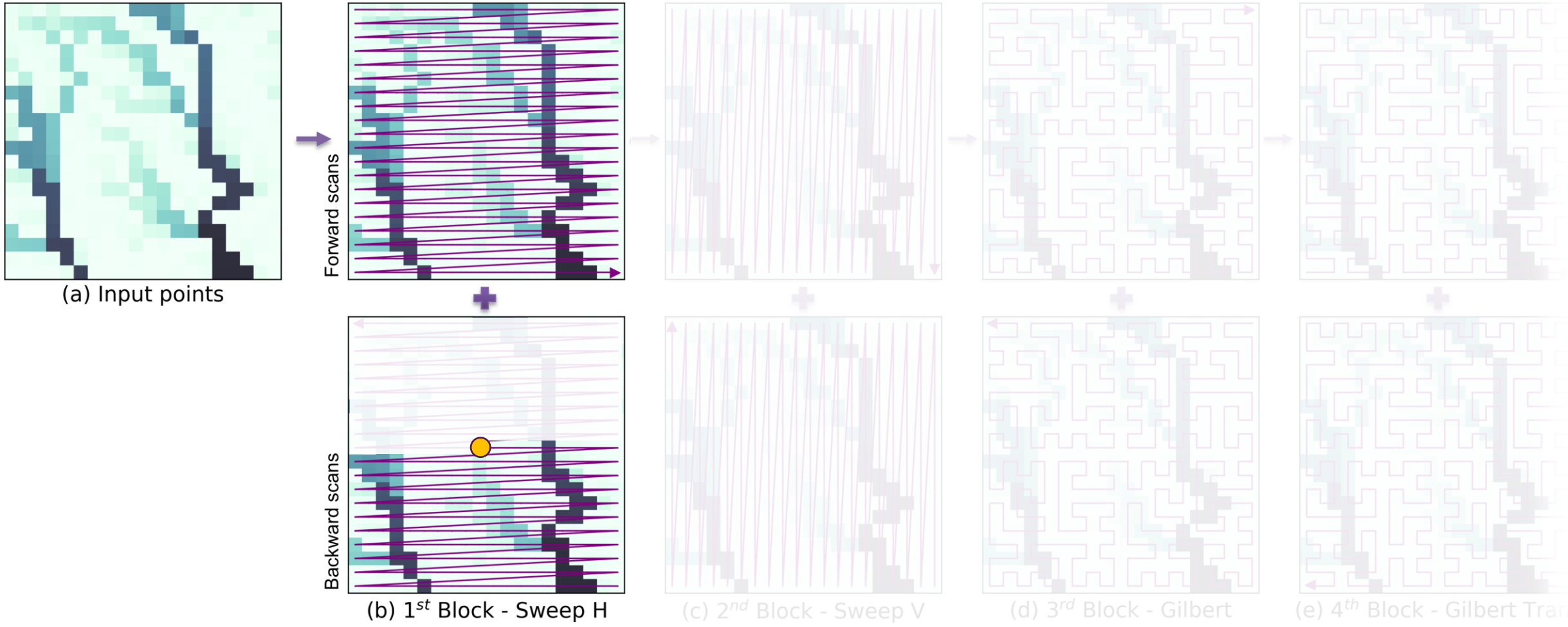

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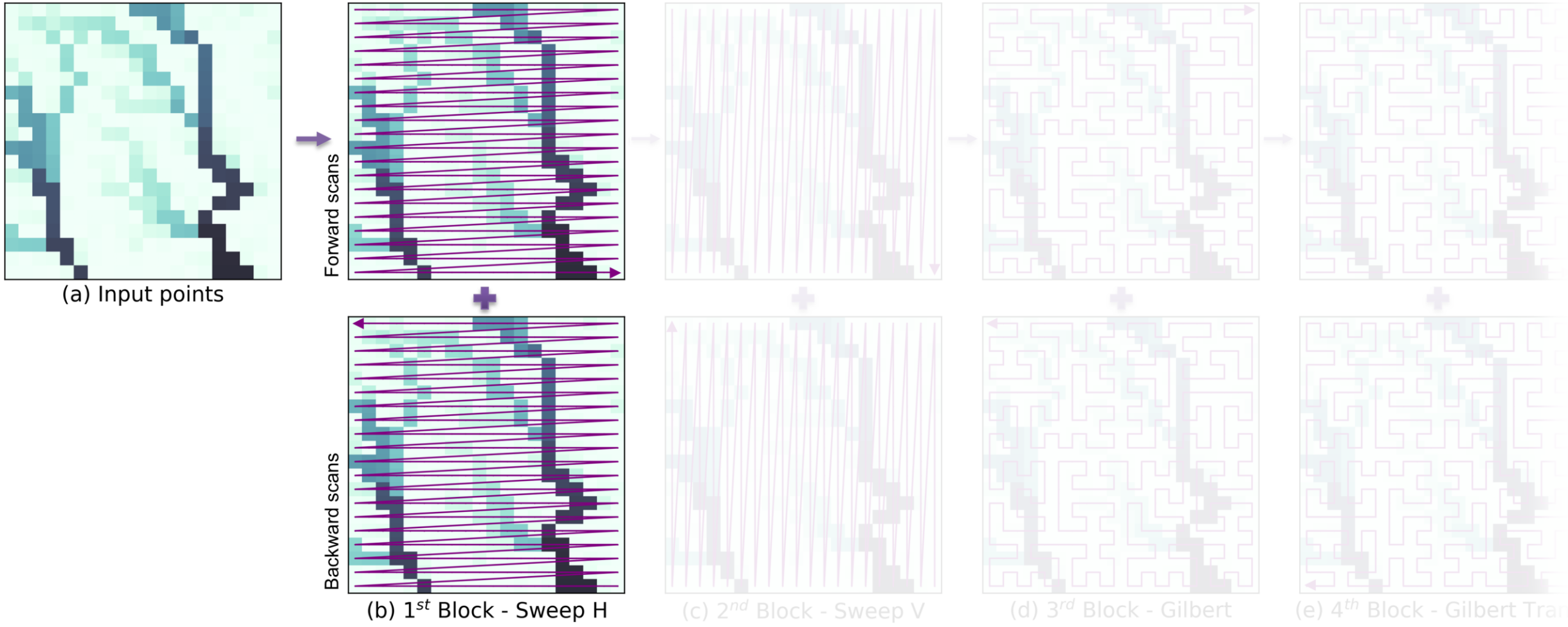

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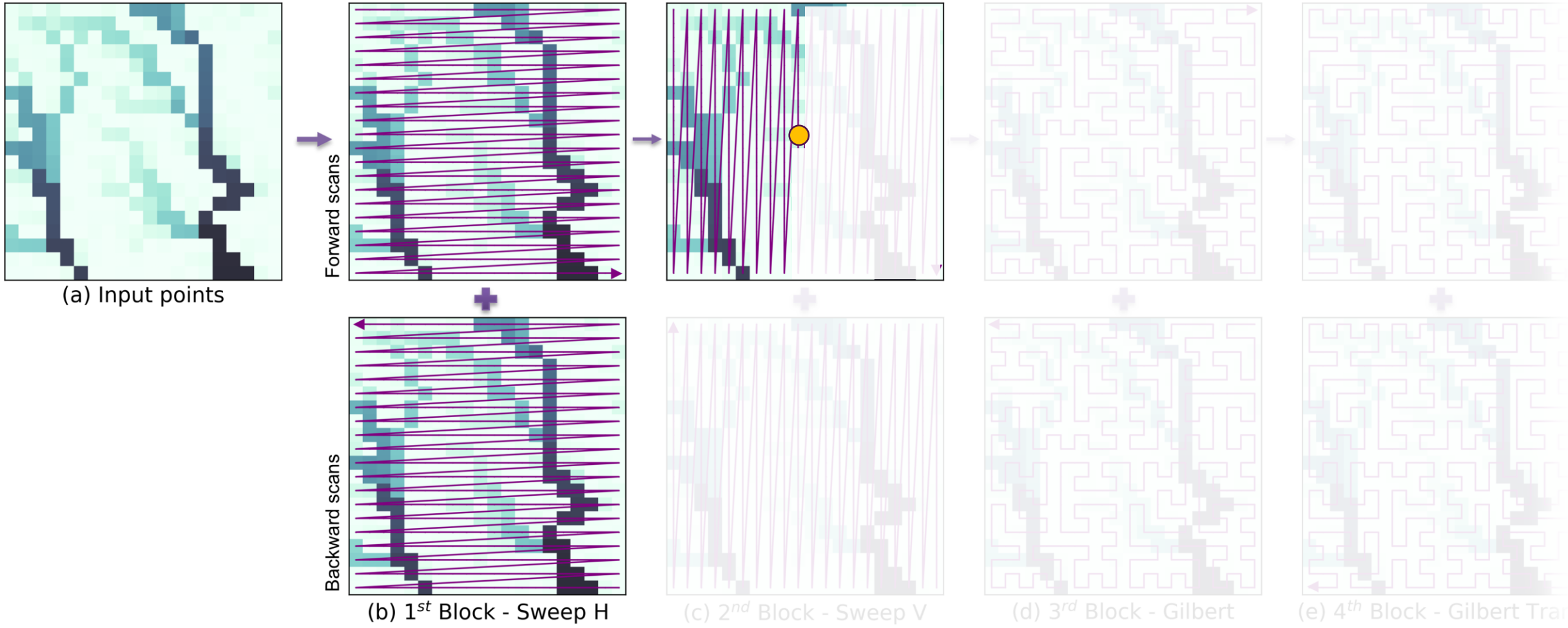

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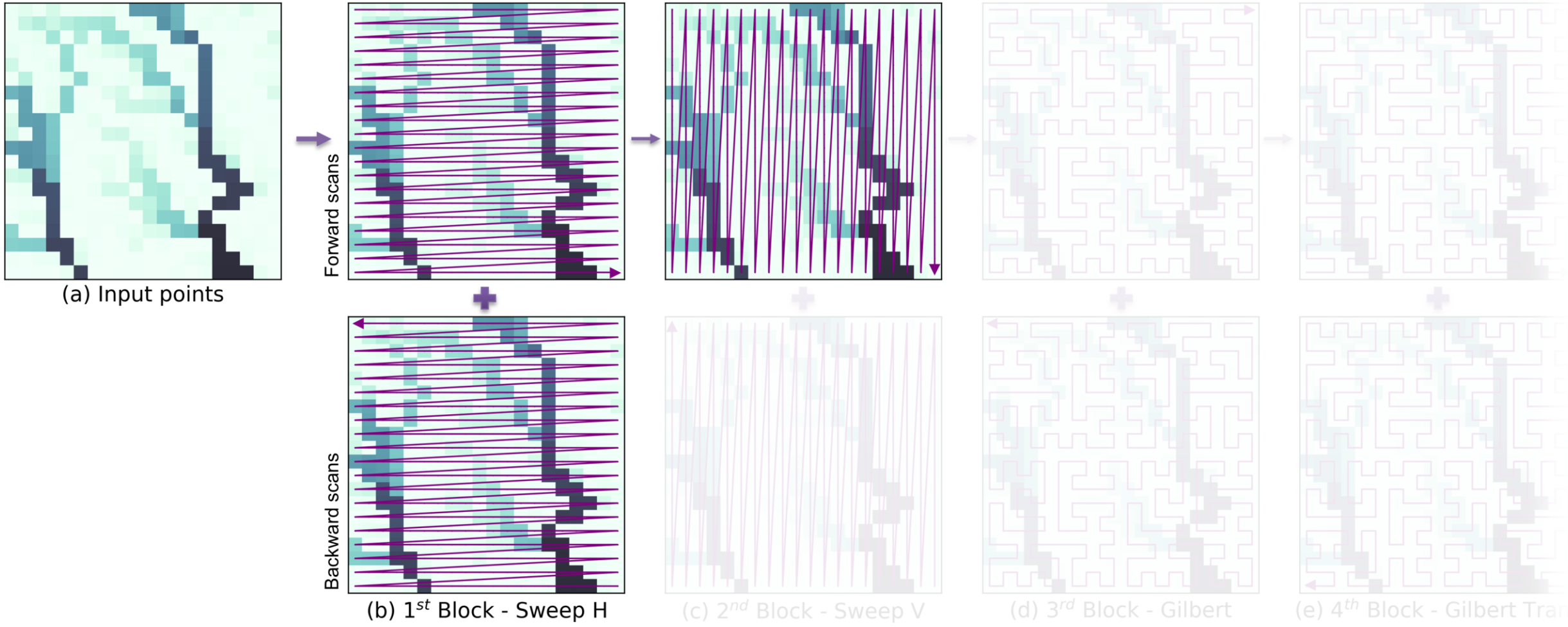

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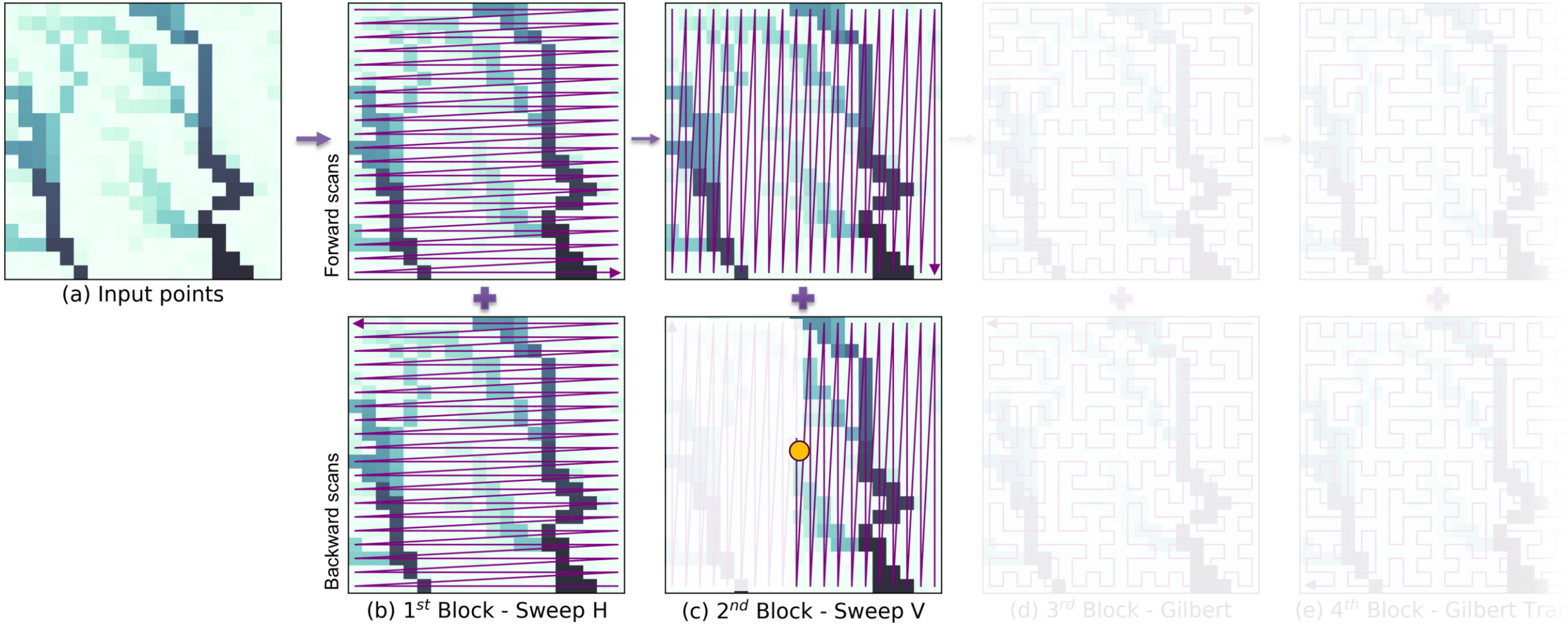

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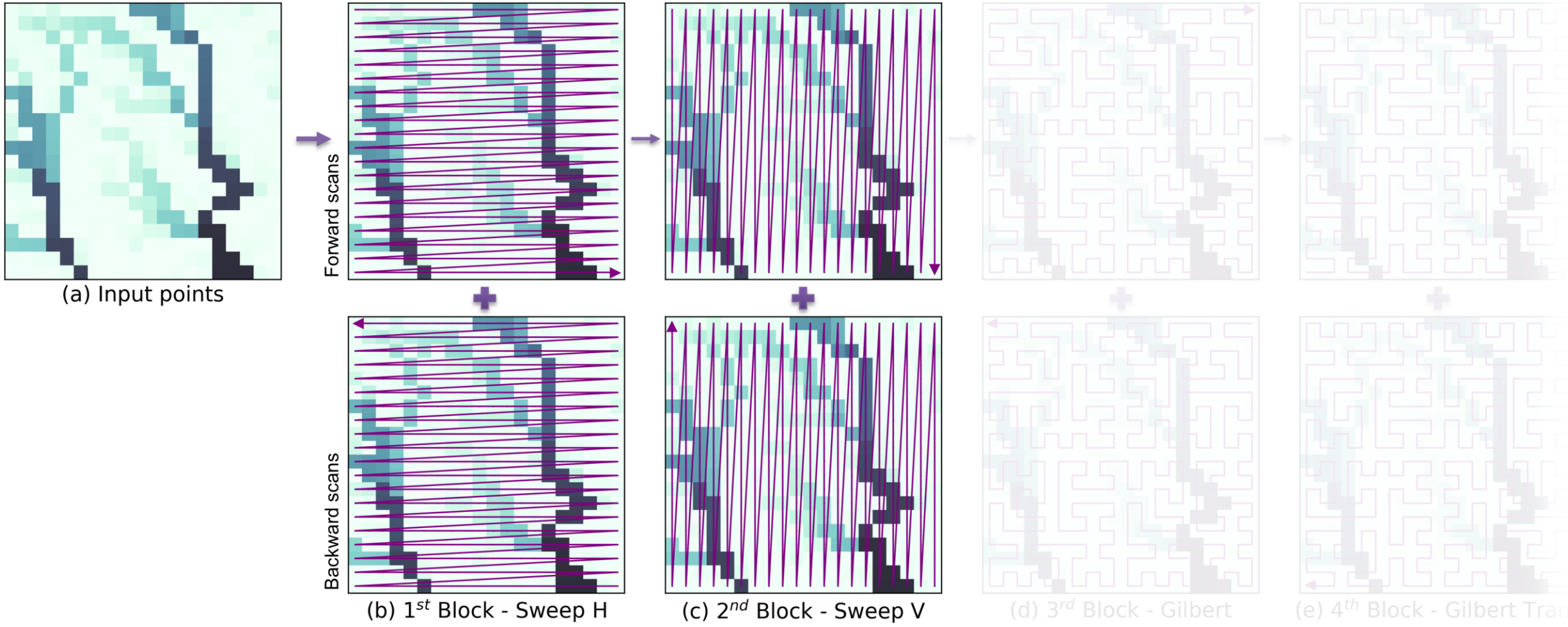

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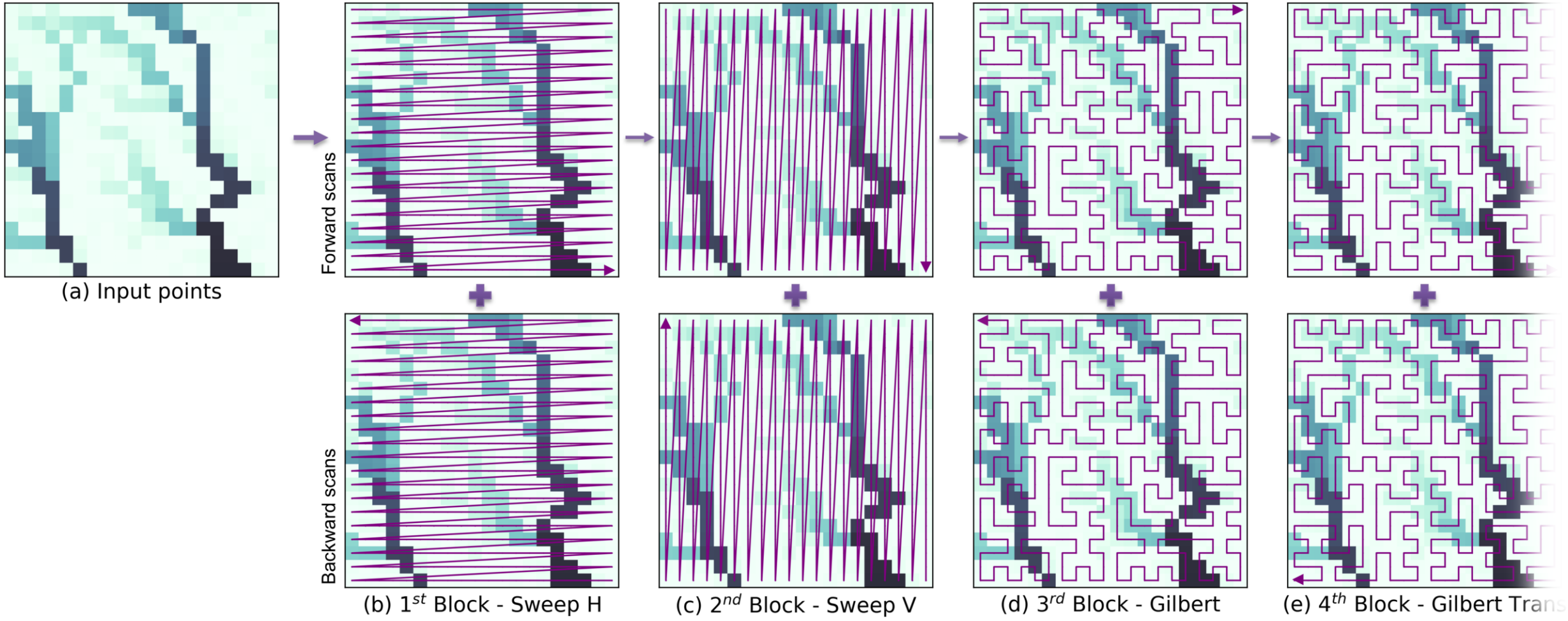

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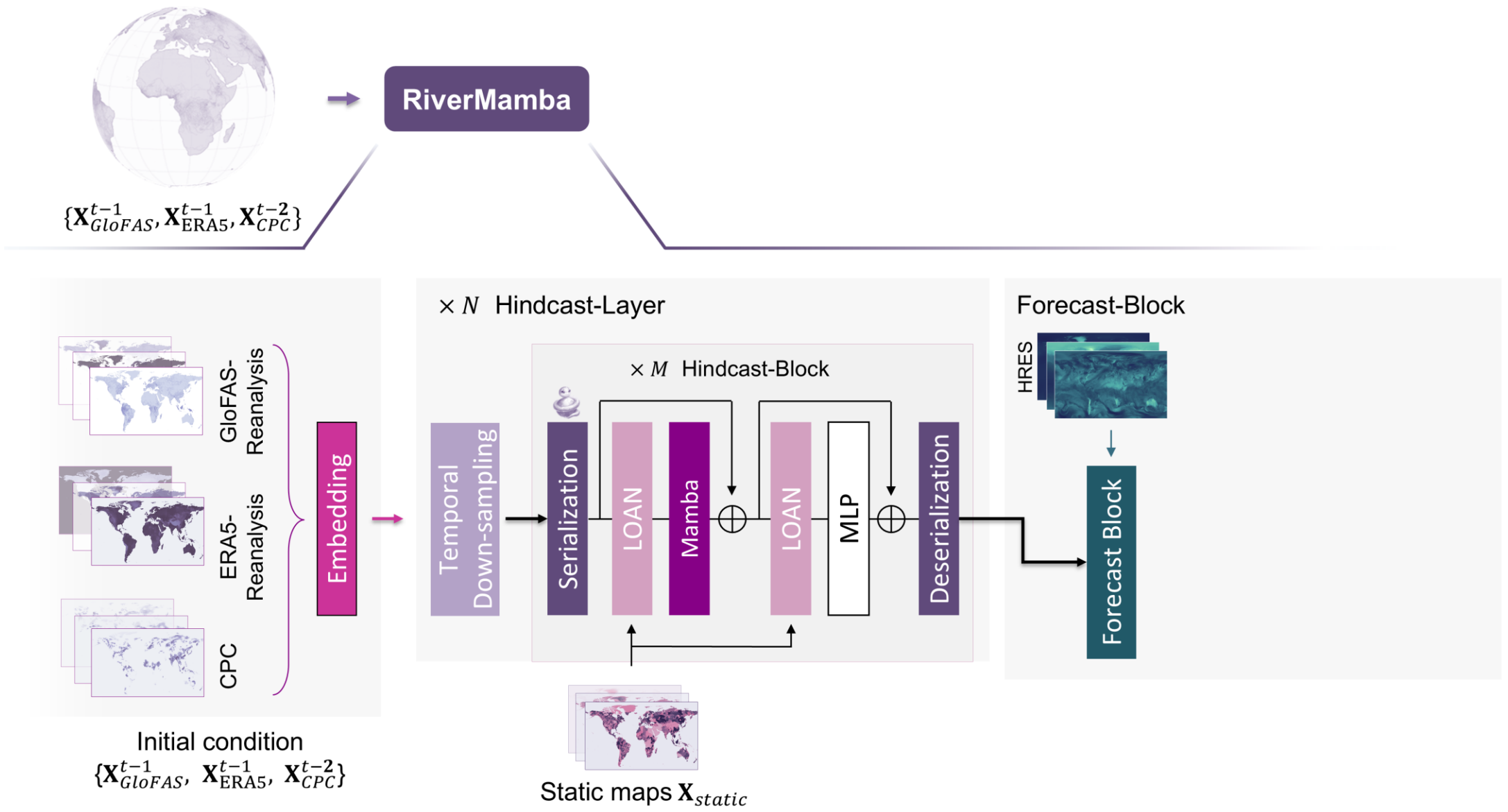
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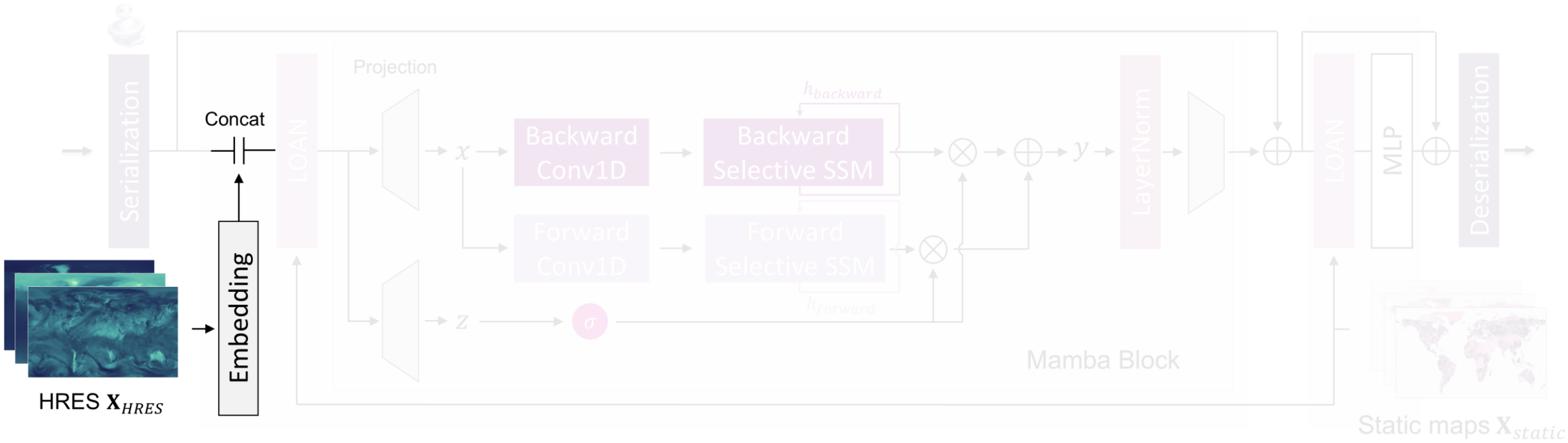
Forecast Block

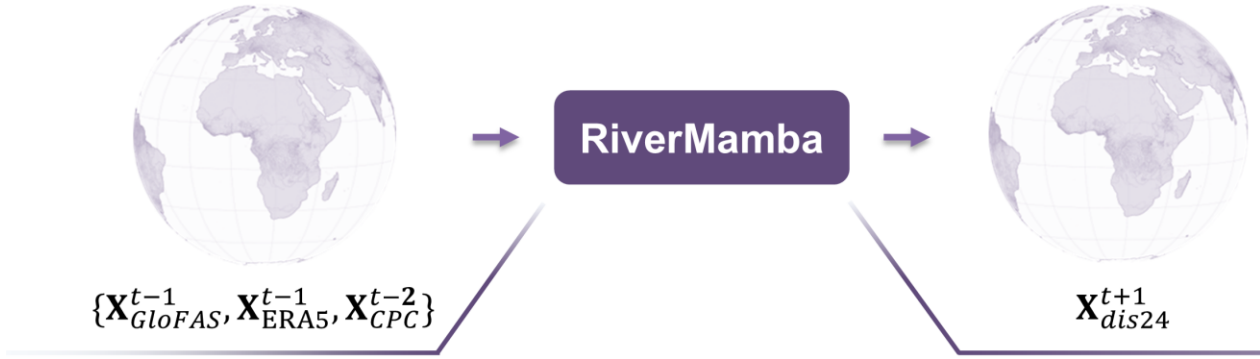
Forecast block:

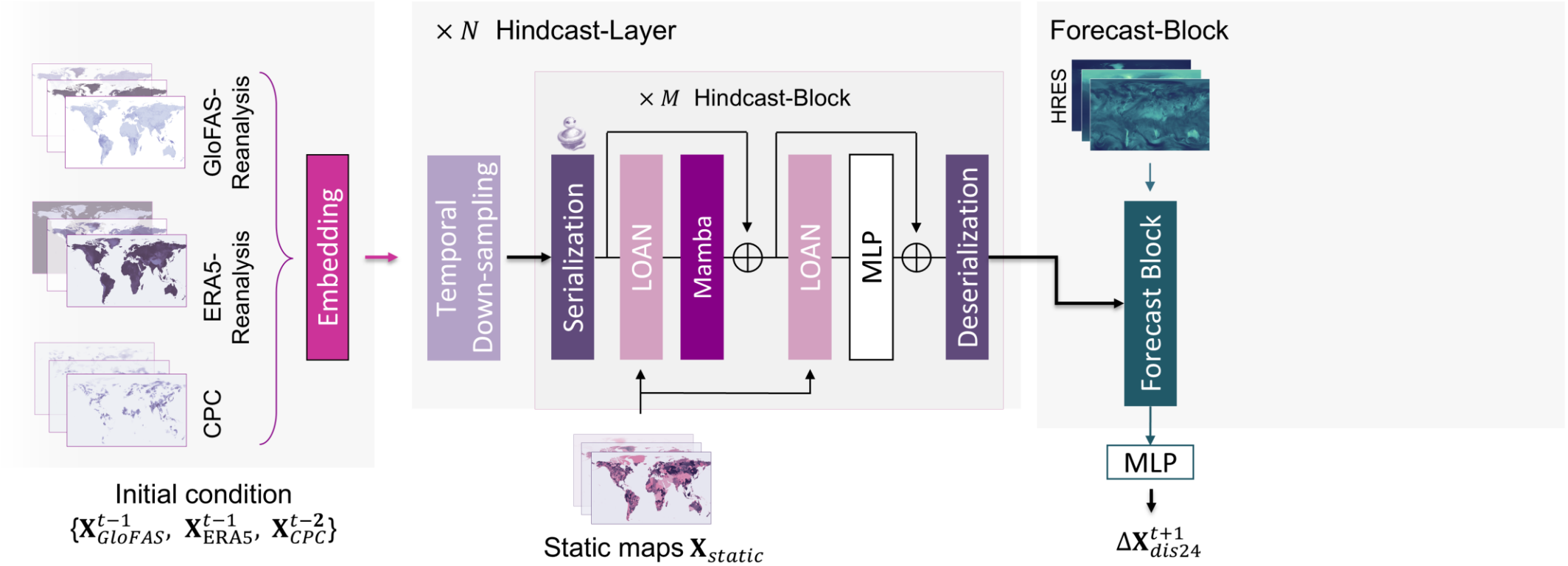


$$h'(t) = \mathbf{A}\, h(t-1) + \mathbf{B}\, x(t) \qquad \Rightarrow \qquad h_t = \overline{\mathbf{A}}\, h_{t-1} + \overline{\mathbf{B}}\, x_t$$

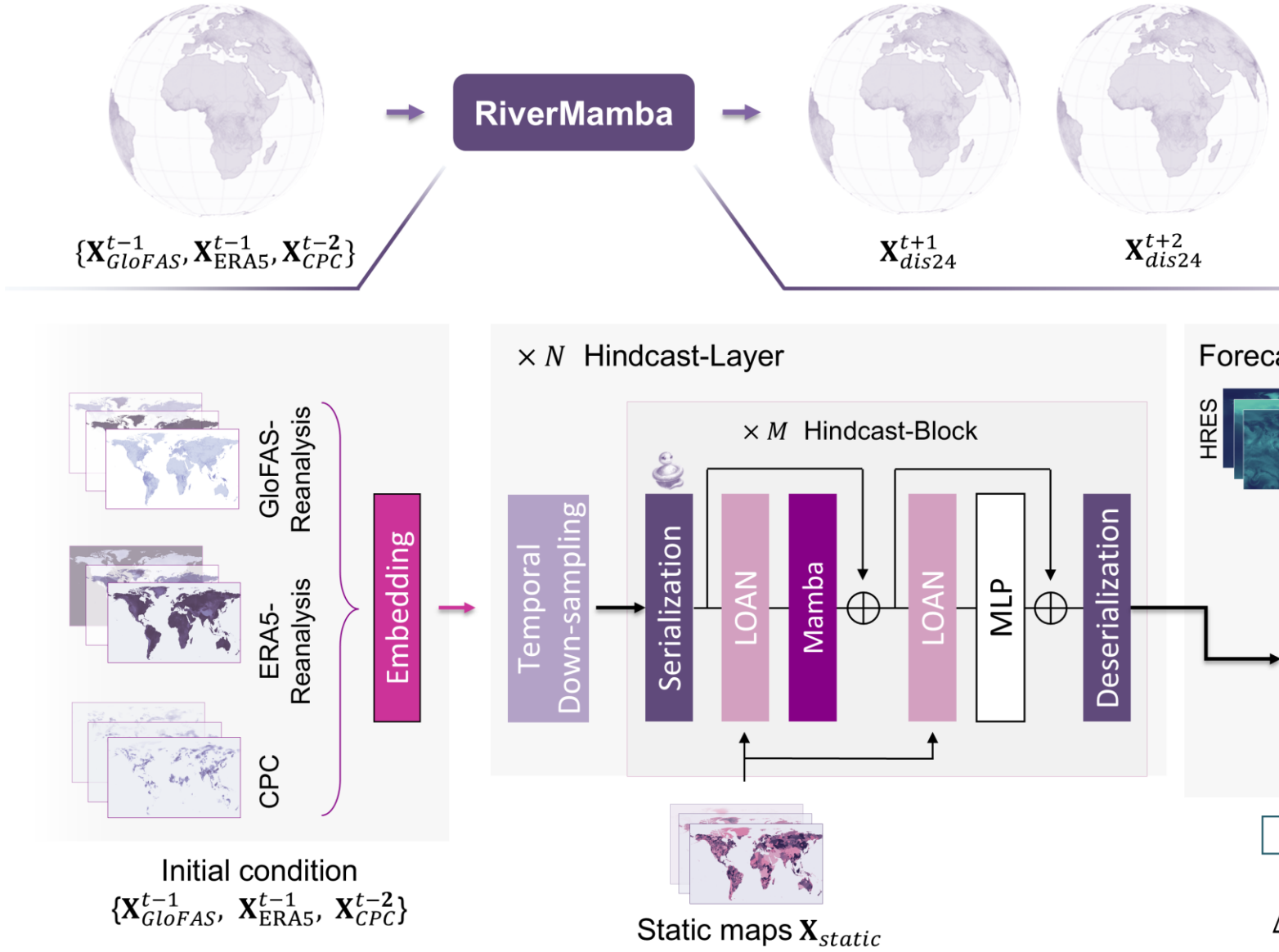
$$y(t) = \mathbf{C}\, h(t) + \mathbf{D}\, x(t) \qquad\qquad y_t = \mathbf{C}\, h_t + \mathbf{D}\, x_t$$

RiverMamba:

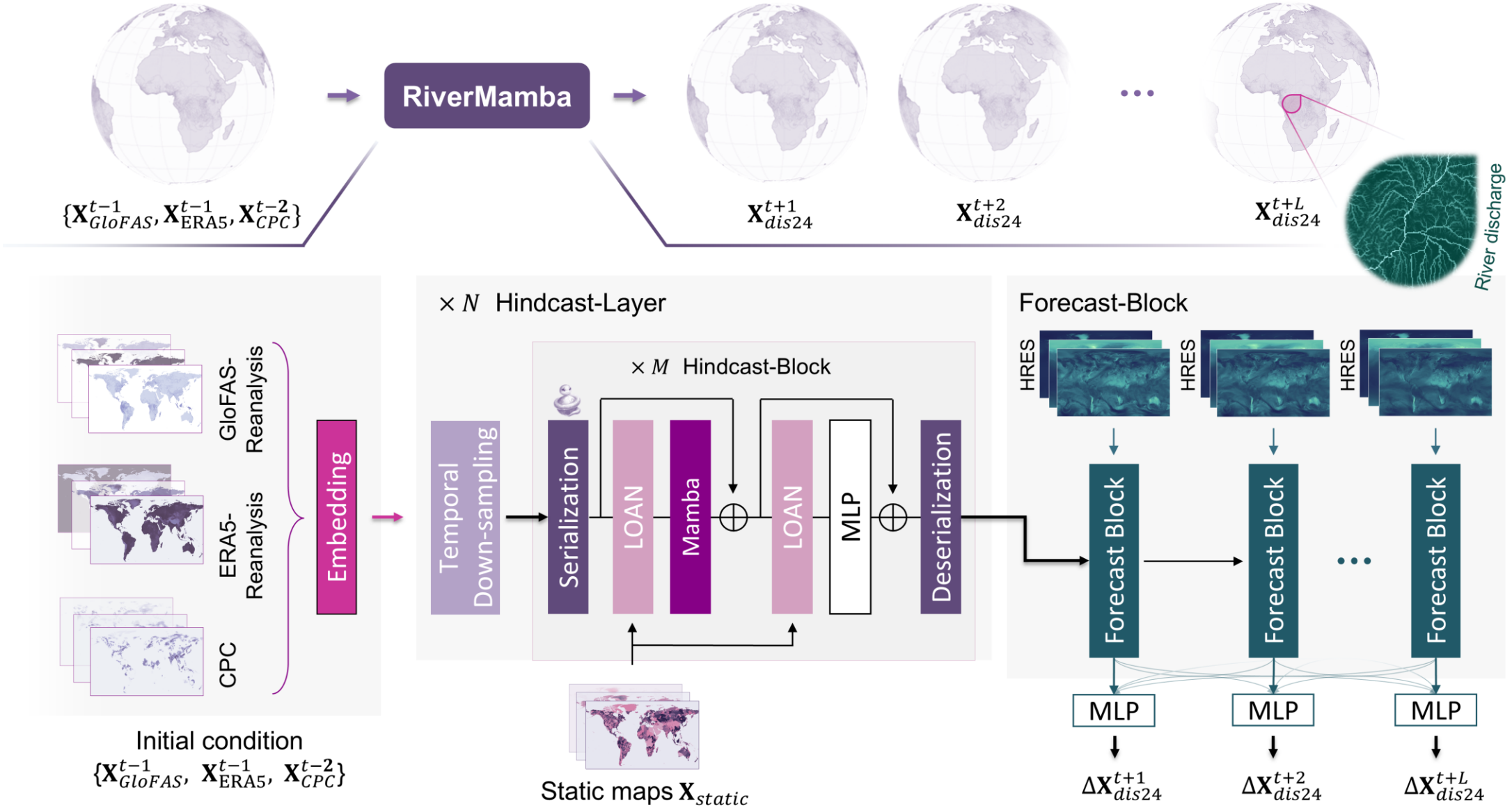

RiverMamba
$\{\mathbf{X}^{t-1}_{GloFAS}, \mathbf{X}^{t-1}_{\text{ERA5}}, \mathbf{X}^{t-2}_{CPC}\}$
$\mathbf{X}^{t+1}_{dis24}$


GloFAS-Reanalysis
ERA5-Reanalysis
CPC
Embedding
Initial condition
$\{\mathbf{X}^{t-1}_{GloFAS}, \mathbf{X}^{t-1}_{\text{ERA5}}, \mathbf{X}^{t-2}_{CPC}\}$
$\times N$ Hindcast-Layer
$\times M$ Hindcast-Block
Temporal Down-sampling
Serialization
LOAN
Mamba
LOAN
MLP
Deserialization
Static maps $\mathbf{X}_{static}$
Forecast-Block
HRES
Forecast Block
MLP
$\Delta\mathbf{X}^{t+1}_{dis24}$

RiverMamba:

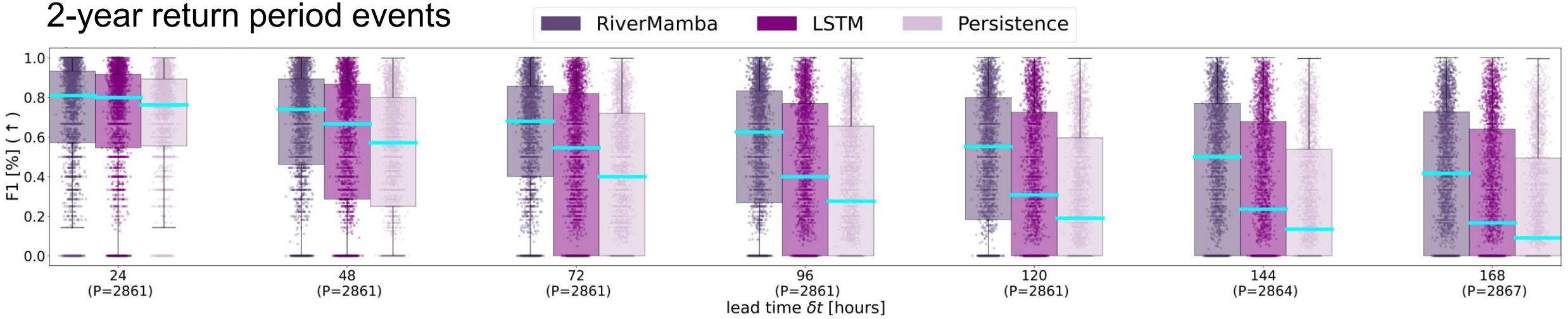

RiverMamba
$\{\mathbf{X}^{t-1}_{GloFAS}, \mathbf{X}^{t-1}_{\text{ERA5}}, \mathbf{X}^{t-2}_{CPC}\}$
$\mathbf{X}^{t+1}_{dis24}$
$\mathbf{X}^{t+2}_{dis24}$
GloFAS-Reanalysis
ERA5-Reanalysis
CPC
Embedding
Initial condition
$\{\mathbf{X}^{t-1}_{GloFAS}, \mathbf{X}^{t-1}_{\text{ERA5}}, \mathbf{X}^{t-2}_{CPC}\}$
$\times N$ Hindcast-Layer
$\times M$ Hindcast-Block
Temporal Down-sampling
Serialization
LOAN
Mamba
LOAN
MLP
Deserialization
Static maps $\mathbf{X}_{static}$
Forecast-Block
HRES
HRES
Forecast Block
Forecast Block
MLP
MLP
$\Delta\mathbf{X}^{t+1}_{dis24}$
$\Delta\mathbf{X}^{t+2}_{dis24}$

RiverMamba:

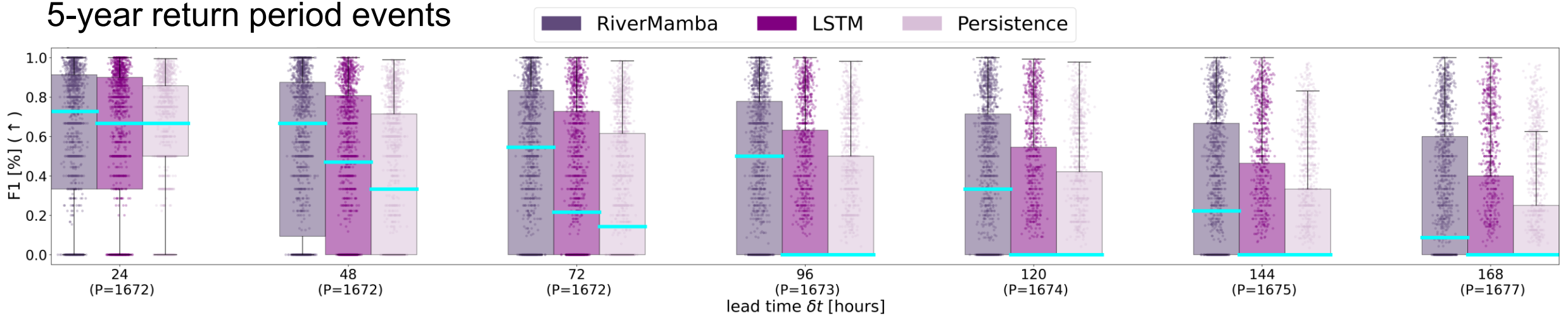

RiverMamba
$\{\mathbf{X}_{GloFAS}^{t-1}, \mathbf{X}_{\text{ERA5}}^{t-1}, \mathbf{X}_{CPC}^{t-2}\}$
$\mathbf{X}_{dis24}^{t+1}$
$\mathbf{X}_{dis24}^{t+2}$
$\mathbf{X}_{dis24}^{t+L}$
River discharge
GloFAS-Reanalysis
ERA5-Reanalysis
CPC
Embedding
Initial condition
$\{\mathbf{X}_{GloFAS}^{t-1}, \mathbf{X}_{\text{ERA5}}^{t-1}, \mathbf{X}_{CPC}^{t-2}\}$
$\times N$ Hindcast-Layer
$\times M$ Hindcast-Block
Temporal Down-sampling
Serialization
LOAN
Mamba
LOAN
MLP
Deserialization
Static maps $\mathbf{X}_{static}$
Forecast-Block
HRES
HRES
HRES
Forecast Block
Forecast Block
Forecast Block
MLP
MLP
MLP
$\Delta\mathbf{X}_{dis24}^{t+1}$
$\Delta\mathbf{X}_{dis24}^{t+2}$
$\Delta\mathbf{X}_{dis24}^{t+L}$

Evaluation on GloFAS-reanalysis river discharge (2021-2024):

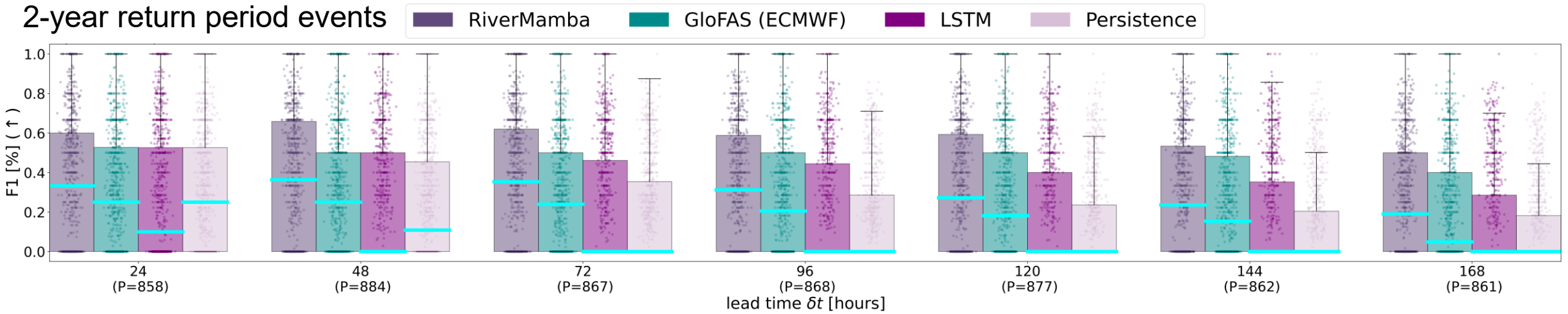
2-year return period events



5-year return period events

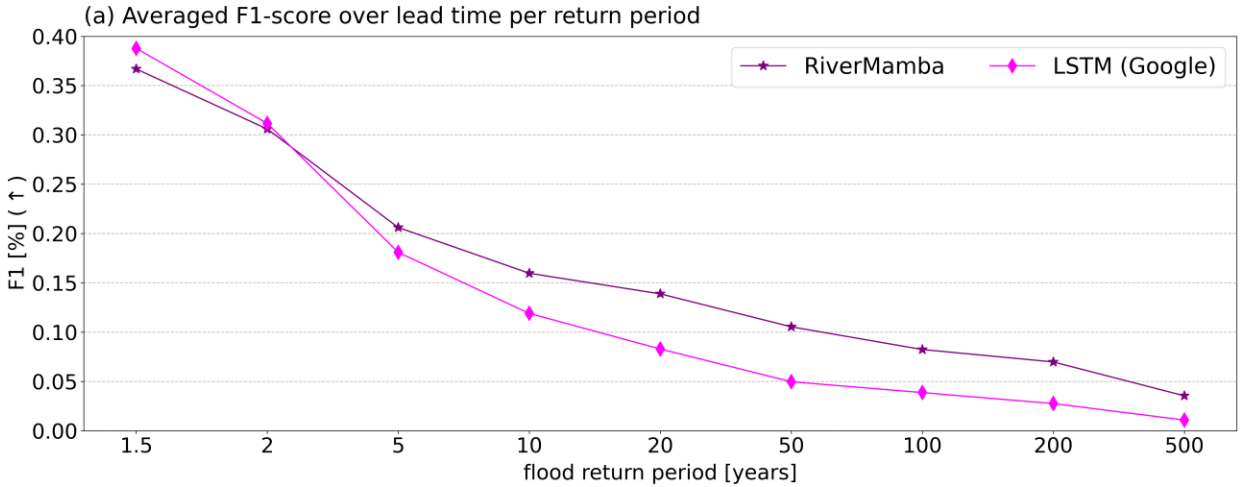


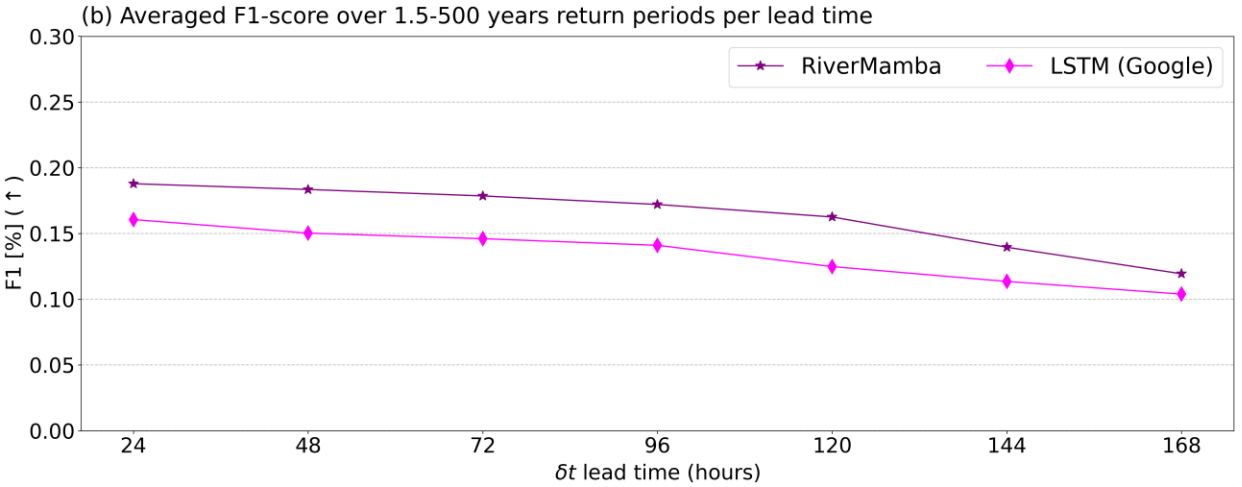
Evaluation on observational GRDC river discharge (2021-2023):



GloFAS (ECMWF): Harrigan et al., “Daily ensemble river discharge reforecasts and real-time forecasts from the operational Global Flood Awareness System”, Hydrol. Earth Syst. Sci., (2023).

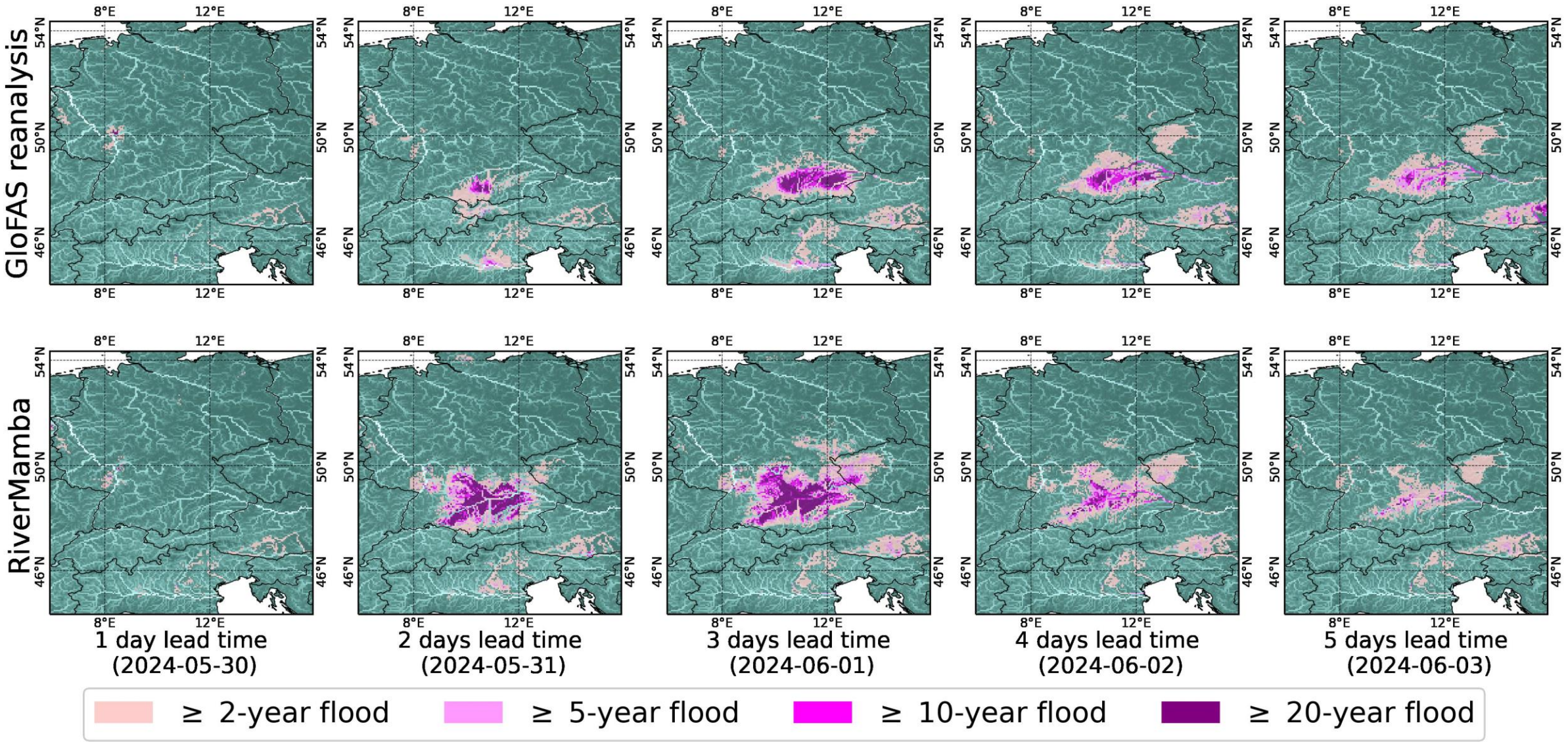
Comparison to ungauged Google reforecast (2014-2021):





LSTM (Google): Nearing et al., “Global prediction of extreme floods in ungauged watersheds”, Nature (2024).

Germany floods 2024



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CRC 1502 DETECT

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Thank you for your Attention

https://hakamshams.github.io/RiverMamba/

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