Investigation of an end-to-end neural architecture for image-based source term estimation

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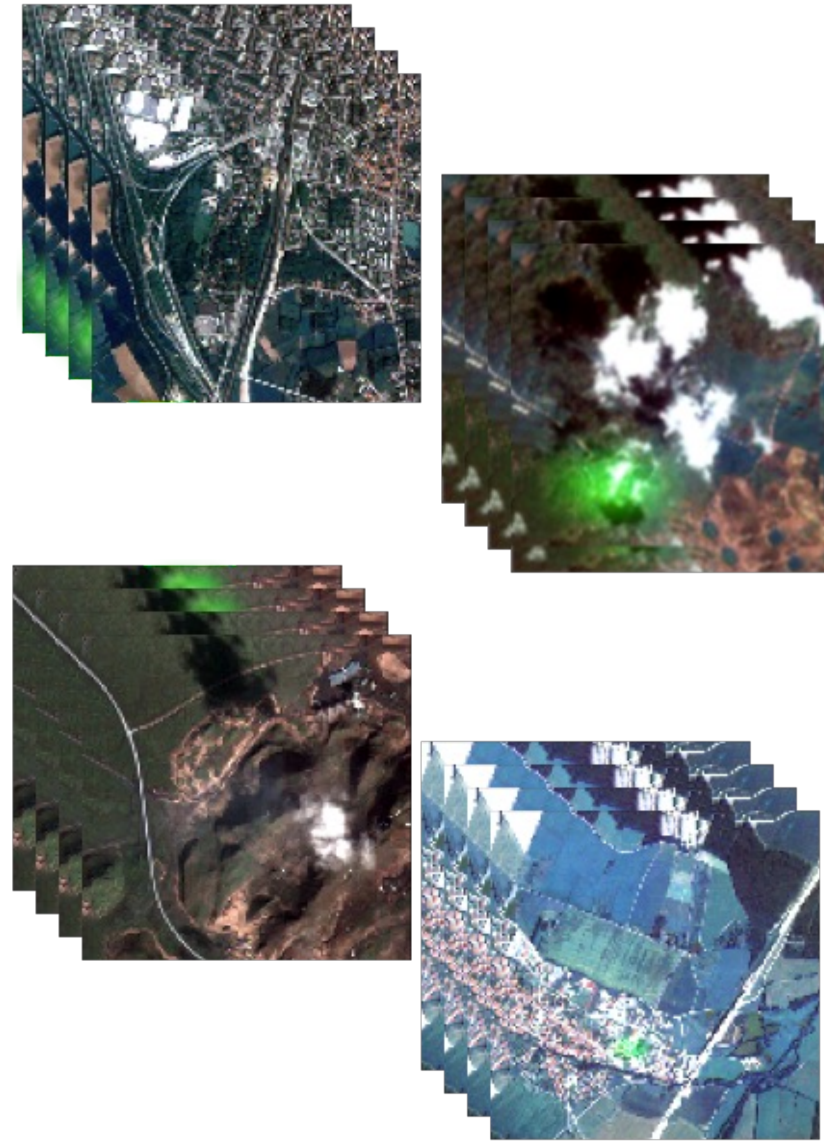
Problem definition



Problem: Increasing threat of hazardous releases: - Bhopal gas leak
- Fukushima nuclear accident
- Eyjafjallajökull volcanic eruption, …

Goal: Determine - location
- time of the release
- release mass
- meteorological data, …

Relevance: Vital for:
- Monitoring environment
- Disaster management
- Legal compliance, …

Atmospheric dispersion simulation (ADS)

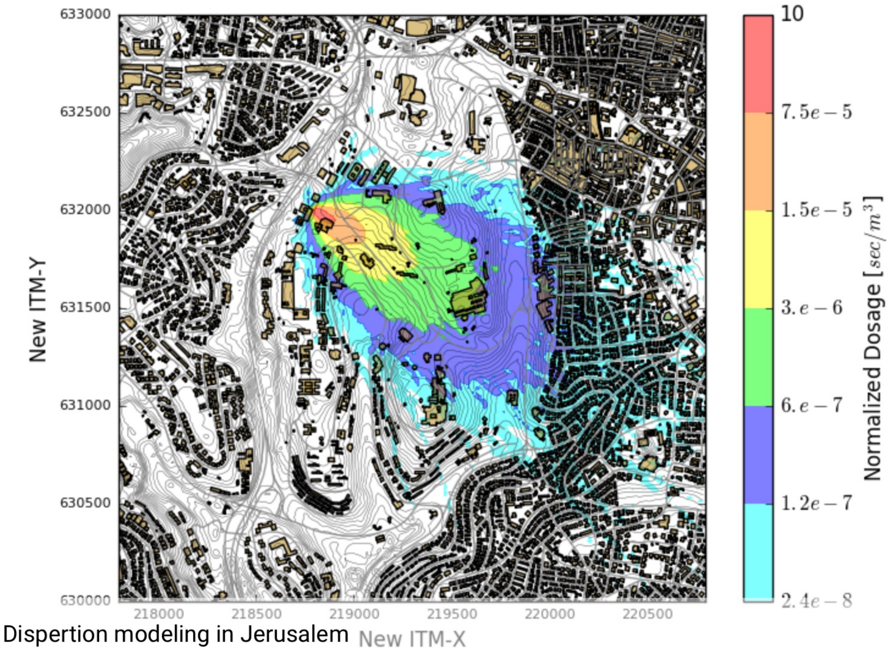
Purpose: Predict spread of contaminants for post-emergency assessment.

Popular Model: Gaussian Puff and Plume models (simple and efficient).

Forecasting Inputs:
- Meteorological data (local/global sources).
- Release strength and location.

Challenge: Determining unknown strength, location, and timing from sensor data.

Solution: Source term estimation (STE) methods.



Dispertion modeling in Jerusalem

Credit: iibr.gov.il

State of the art for STE

Aim: Optimal match between predicted and observed data.

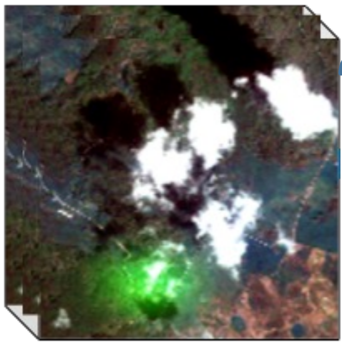
Bayesian Techniques:
- Produces estimates with confidence levels.
- Incorporates prior info through probability distributions.
- Typically computationally expensive.

Optimization methods:
- Typically faster, less computationally demanding.
- Limited need for prior info, yet benefits from its availability.
- Generates only point estimates.

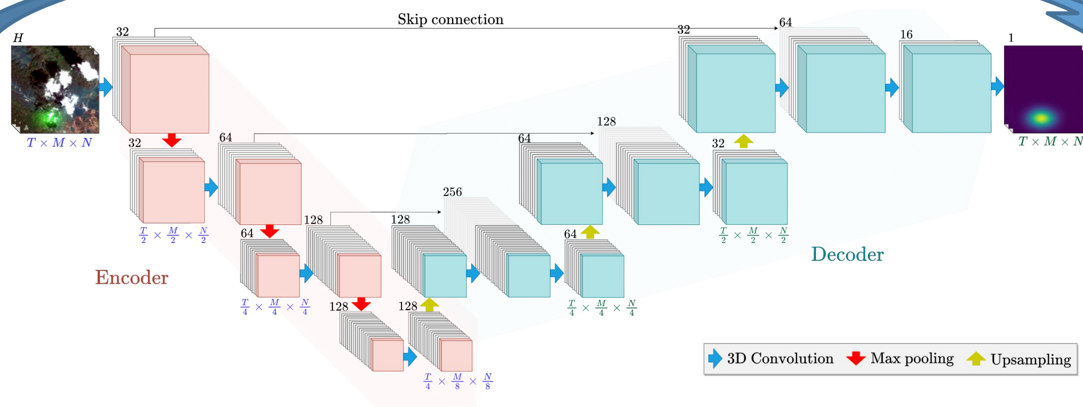
Artificial neural networks (ANNs):
- Suitable for STE's nonlinearities.
- Enhanced by large training datasets and hardware accelerators.
- Existing ANNs focus on specific parameters.
- Often lack confidence intervals.

Proposal

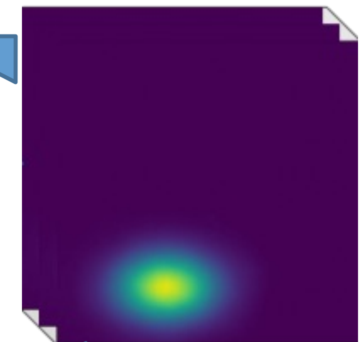
Time-series of hyperspectral satellite images



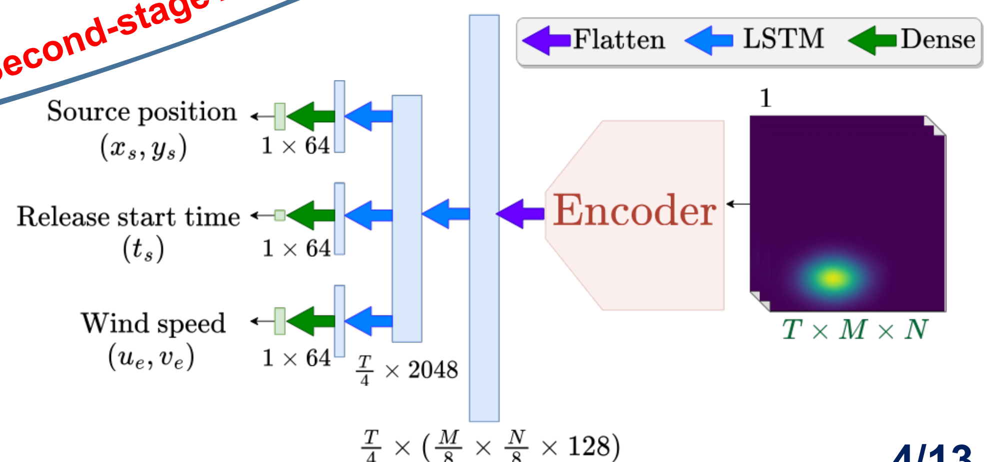
First-stage ANN



3D concentration map



Second-stage ANN

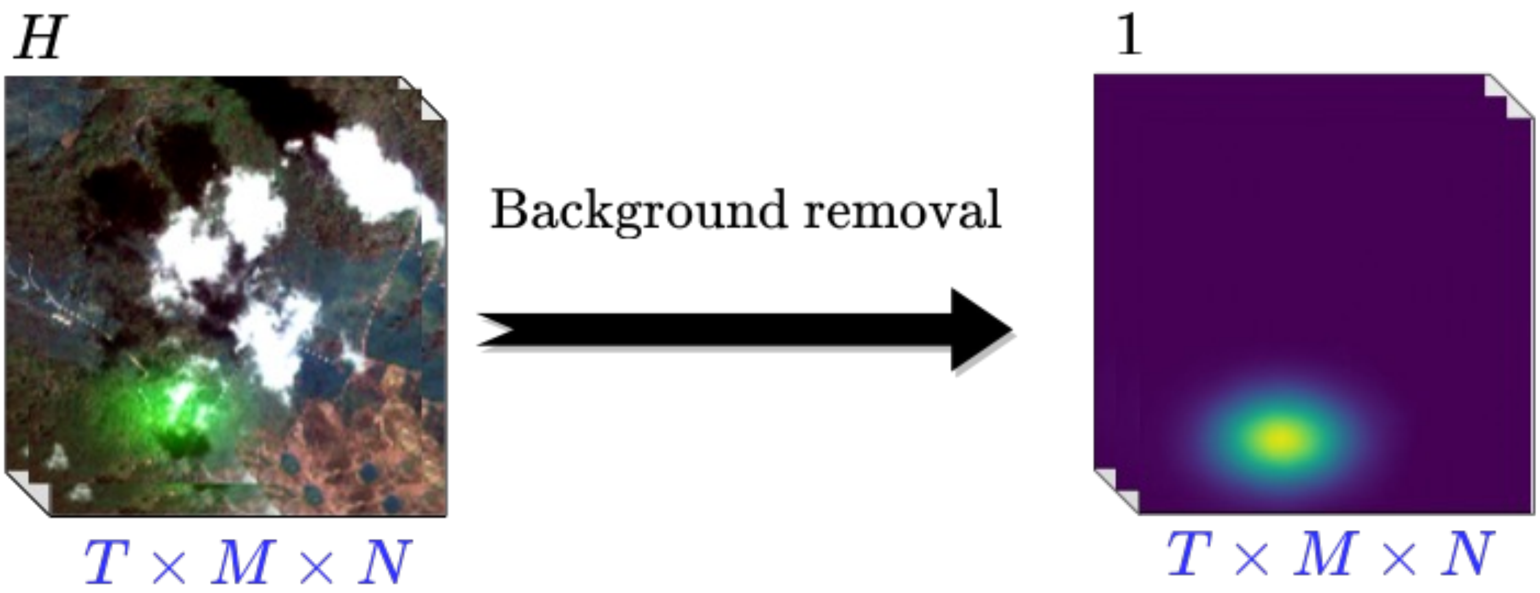


Source term parameters

- The starting time of the emission t_s
- Position of the emission source (x_s, y_s)
- The wind speed components (u_e, v_e)

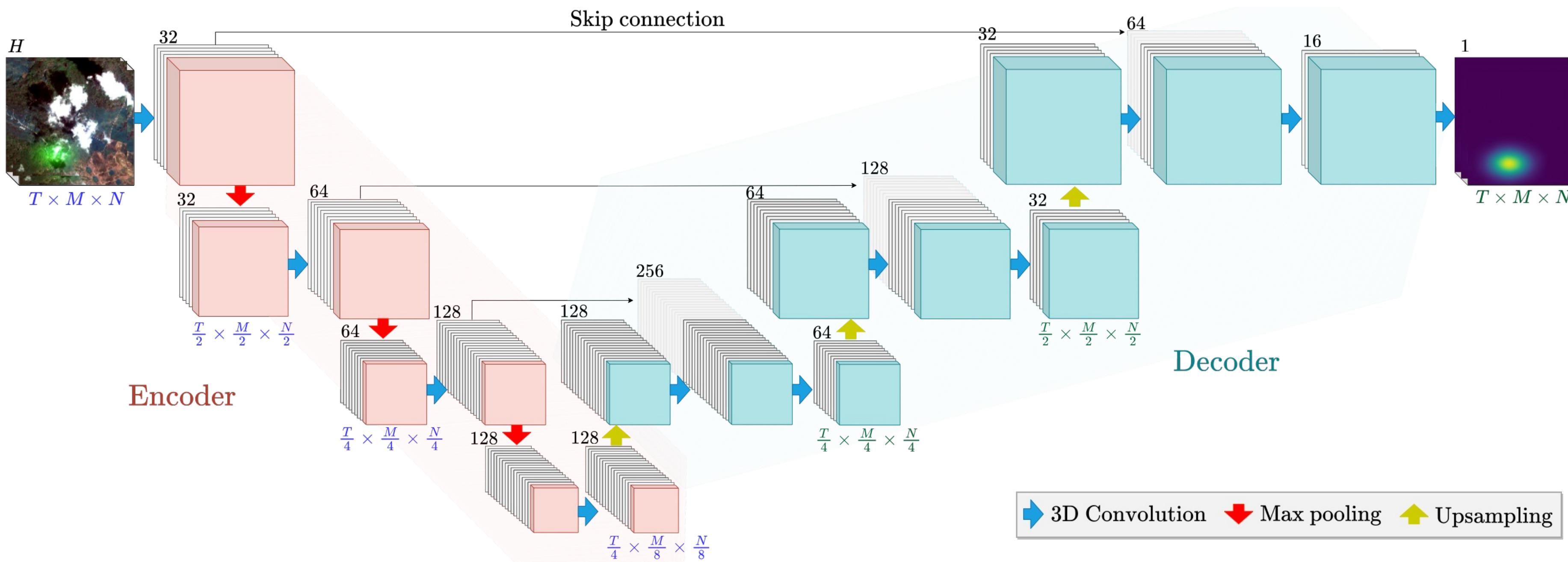
First-stage ANN: Background removal

- Extracts the 3D concentration map from the time-series multi/hyperspectral satellite images.



First-stage ANN: Architecture

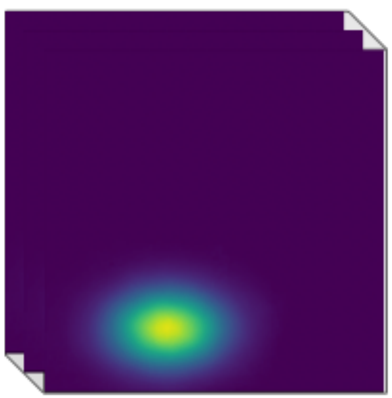
❖ **3D U-net architecture**: This design integrates both an encoder and a decoder, connected by skip connections.



Second-stage ANN: STE

- Estimates the source term parameters from the extracted 3D concentration map.

1



$T \times M \times N$

Source term estimation →

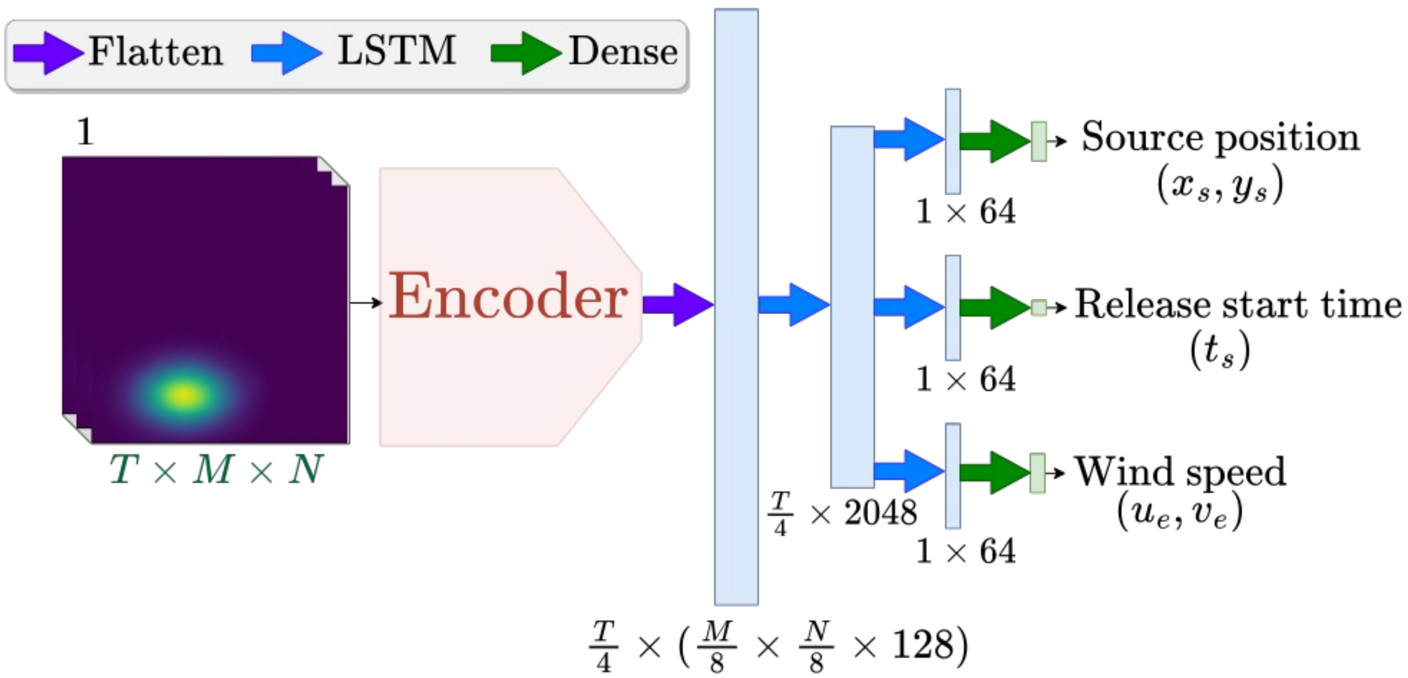
Source position (x_s, y_s)

Release start time (t_s)

Wind speeds (u_e, v_e)

Second-stage ANN: Architecture

- A deterministic ANN with an encoder-like structure for parameter estimation.



Two-stage ANN Training

Sequential Training:

1. Train first-stage ANN.
2. Train second-stage ANN with frozen first-stage.

Training Details:

- Duration: 100 epochs.
- Optimizer: Adam.
- Learning Rate: 10^{-3}.
- Batch Size: 30.

Loss Function: Mean Squared Error (MSE).

- First branch: MSE between true and predicted concentration cloud.
- Second branch: MSE between true and predicted source term parameters.

Simulations

Data Collection:
- Source: Pleiades ESA archive.
- Total Images: 3200 (from 320 high-resolution satellite images).
- Image Dimensions: 128x128x3.

Gas Release Simulation:
- Method: Gaussian puff model:

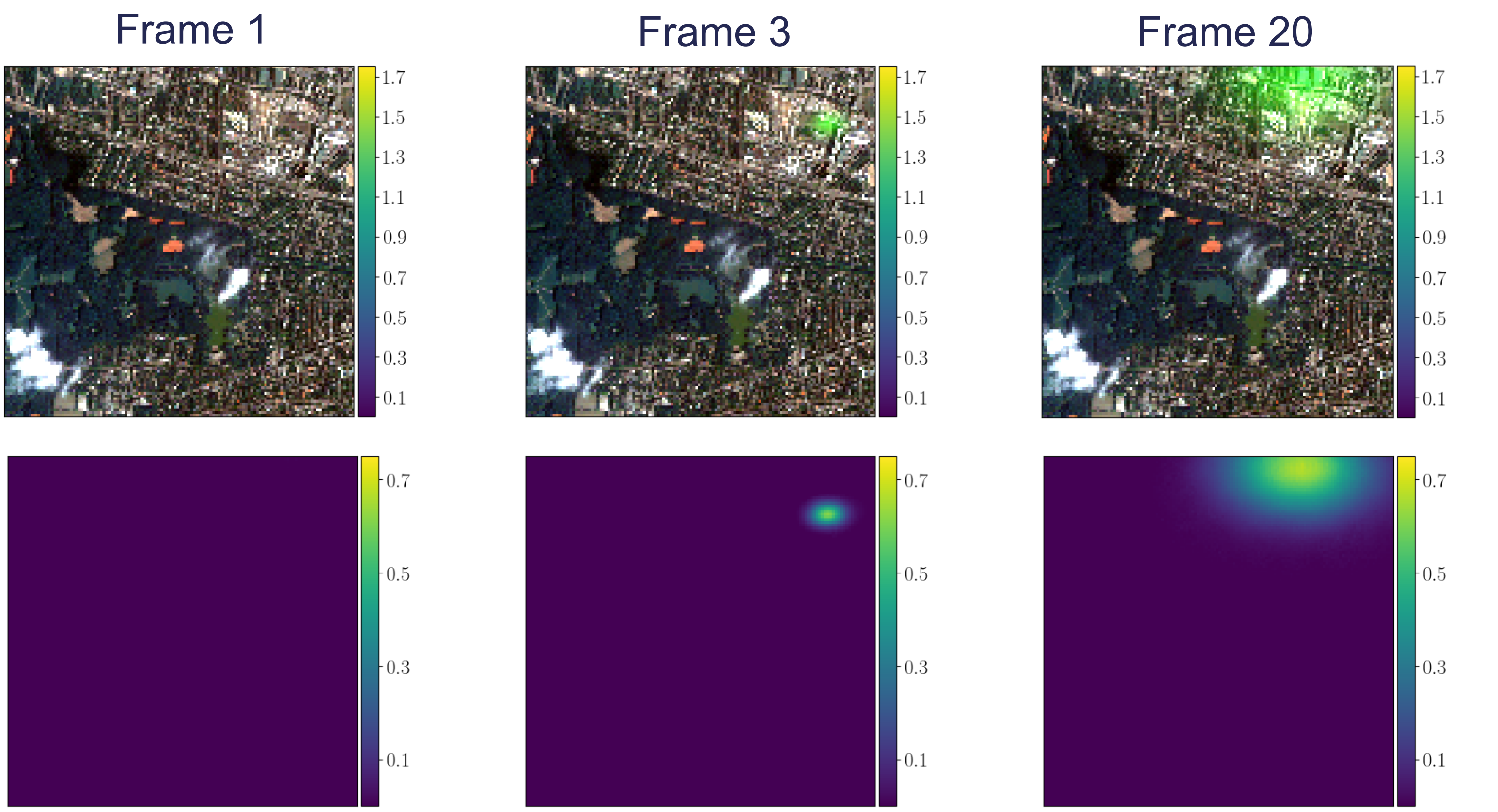
$$c(x,y,t) = \frac{q_s}{4\pi\sqrt{\sigma_x\sigma_y}}\exp\left[-\frac{0.25}{(t-t_s)}\left(\frac{\left(x-x_s-u_e(t-t_s)\right)^2}{\sigma_x}+\frac{\left(y-y_s-v_e(t-t_s)\right)^2}{\sigma_y}\right)\right]$$

- Resultant Data: 4D cubes of 20x128x128x3 (20 time frames).

Dataset Sizes:
- Training: 3000x20x128x128x3.
- Testing: 200x20x128x128x3.

First-stage ANN: Results

❖ Estimated concentration maps maps over time (second row) obtained from the corresponding satellite images (first row) using the 3D U-net. Displayed from left to right are the results for frames 1, 3, and 20.



MSE = 1×10^{-6}

Second-stage ANN: Results

- Average MSE results between the predicted emission parameters, obtained using the second-stage ANN, and the true values for the testing dataset comprising 200 emission scenarios.

source term parameter	MSE
x_s	1.16 ± 2.04 (pixels)
y_s	0.99 ± 1.67 (pixels)
t_s	0.09 ± 0.15 (frames)
u_e	0.4 ± 1.52 (pixels)
v_e	0.42 ± 1.65 (pixels)

Conclusions & Future Work

Findings:

- Introduced a two-stage ANN pipeline for STE using multispectral satellite imagery.
- Addressed STE's non-linearity.
- Offers rapid and precise hazard release estimation.

Future Directions:

- Need for comparison with other STE methods.
- Conduct an uncertainty analysis.
- Refine architecture: Explore VAE integration.
- Enhance real-world applicability: Address irregular timings and faint cloud detection.
- Re-evaluate training: Consider end-to-end training or single network approach.

Thank you for your attention!