Modeling of Atmospheric Pollution Due to Marine Traffic in Marseille

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Aix Marseille Université

Centrale Méditerranée

irphé Institut de Recherche sur les Phénomènes Hors Equilibre

CNRS

AtmoSud Inspirer un air meilleur

Objectives

Build a model to predict air pollution based on detailed ship traffic data

- What is the contribution of ships to air pollution in Marseille and its surroundings ?
- How ship pollution is influenced by local meteorological conditions ?
- How Machine Learning can be used for operational purpose ?

Introduction

Atmospheric Pollution

WHO air quality guidelines (AQGs)

Pollutant	Averaging period	AQG
PM_{10}	1 day	45 $\mu g.m^{-3}$
	calendar year	15 $\mu g.m^{-3}$
$PM_{2.5}$	1 day	15 $\mu g.m^{-3}$
	calendar year	5 $\mu g.m^{-3}$
O_3	Maximum daily 8-h mean	100 $\mu g.m^{-3}$
	peak season	60 $\mu g.m^{-3}$
NO_2	1 hour	200 $\mu g.m^{-3}$
	1 day	25 $\mu g.m^{-3}$
	calendar year	10 $\mu g.m^{-3}$
SO_2	10 minutes	500 $\mu g.m^{-3}$
	1 day	40 $\mu g.m^{-3}$
CO	1 hour	30 $mg.m^{-3}$
	Maximum daily 8-hour mean	10 $mg.m^{-3}$
	1 day	4 $mg.m^{-3}$
BaP	calendar year	-
C_6H_6	calendar year	-
Pb	calendar year	0.5 $\mu g.m^{-3}$
As	calendar year	-
Cd	calendar year	5 $ng.m^{-3}$
Ni	calendar year	-

- *Particulate Matter*

  $PM_{2.5}$ = 253 000 premature deaths in 2020 in Europe[1]

- *Gas-phase Species*

  O_3 = 22 000 premature deaths in 2020 in Europe[1]

  NO_2 = 52 000 premature deaths in 2020 in Europe[1]

[1] *European Environmental Agency (EEA), 2022*

Port of Marseille-Fos

Tankers

Cruise Ships

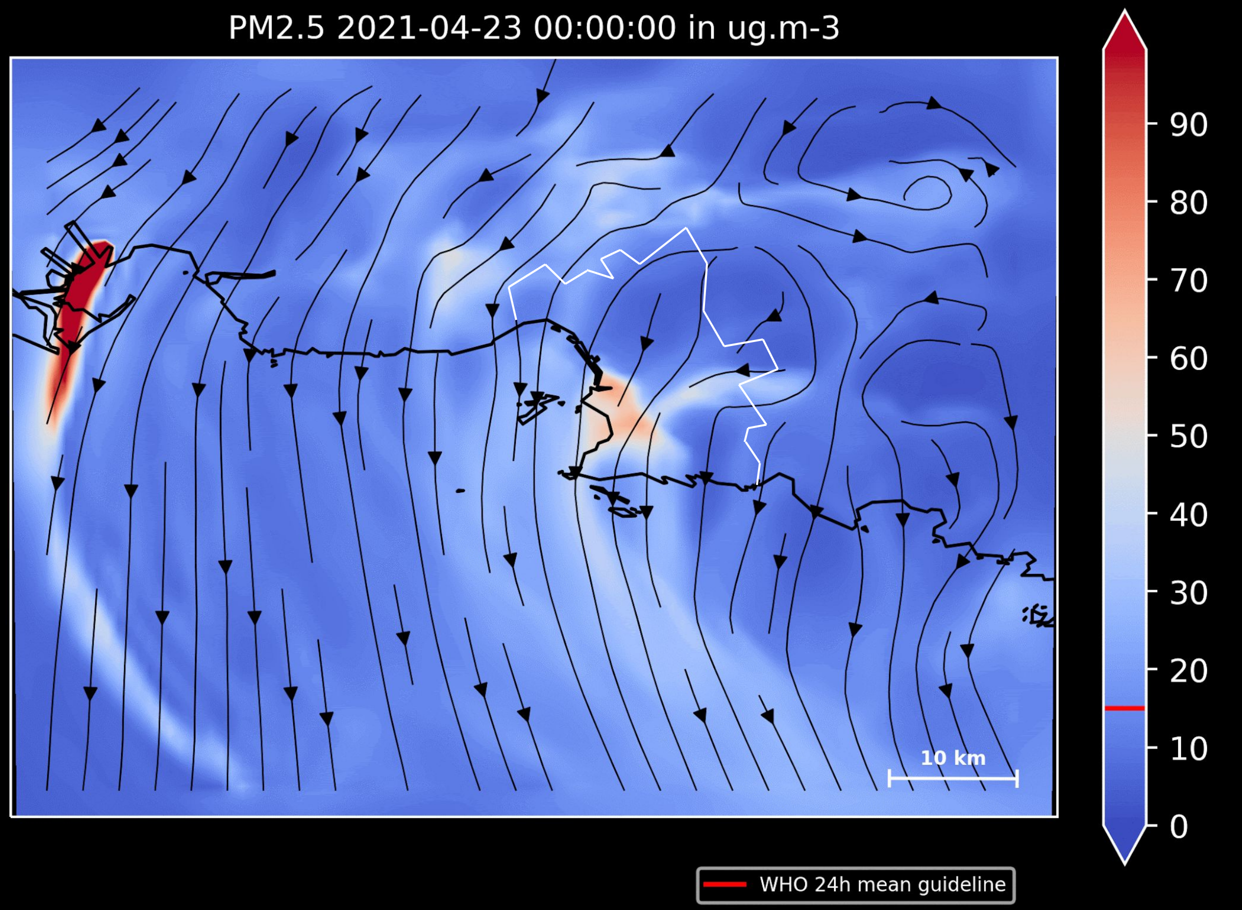
Containers / Cargo

WEST BASIN

EAST BASIN

Ferries

Numerical Set-Up



Chevet et al. (2024) - Modeling of air pollution due to marine traffic in Marseille

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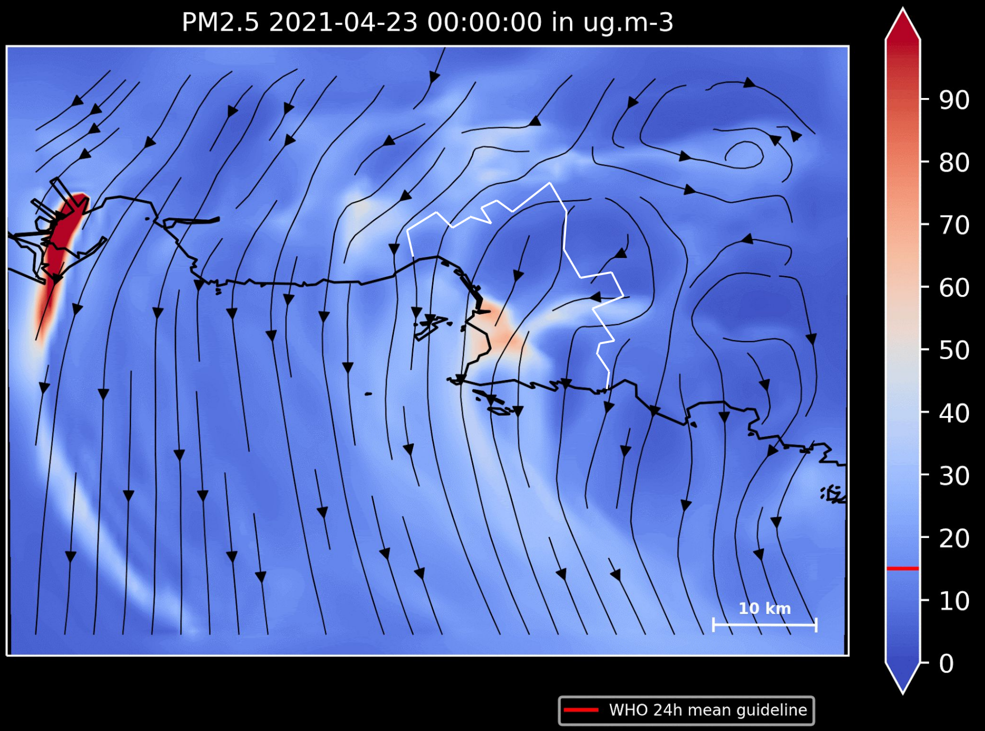

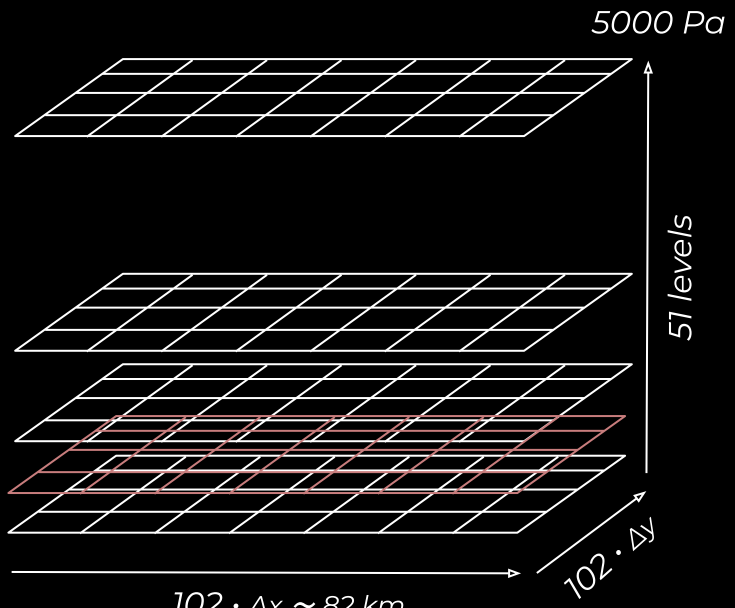

$\Delta x = \Delta y = 800$ m

WRF-CHEM
(Weather Research and Forecasting + Chemistry)

NCAR = National Center for Atmospheric Research

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Non-hydrostatic compressible Euler equations (Flux-form)

- *Continuity Equation*

$$\partial_t \mu_d + (\nabla.\mathbf{V}) = 0$$

- *Momentum Equation*

$$\partial_t U + (\nabla.\mathbf{V}u) + \mu_d \alpha \partial_x p + (\alpha/\alpha_d)\partial_\eta p \partial_x \phi = F_U$$

$$\partial_t V + (\nabla.\mathbf{V}v) + \mu_d \alpha \partial_y p + (\alpha/\alpha_d)\partial_\eta p \partial_y \phi = F_V$$

$$\partial_t W + (\nabla.\mathbf{V}w) - g(\partial_\eta p - \mu_d) = F_W$$

- *Thermodynamic Equation*

$$\partial_t \Theta + (\nabla.\mathbf{V}\theta) = F_\Theta$$

- *Humidity and Geopotential*

$$\partial_t Q_m + (\nabla.\mathbf{V}q_m) = F_{Q_m}$$

$$\partial_t \phi + [(\mathbf{V}.\nabla\phi) - gW]/\mu_d = 0$$

- *State and mass volume equation*

$$p = p_0(R_d \theta_m / p_0 \alpha_d)^\gamma$$

$$\partial_\eta \phi = -\alpha_d \mu_d$$

Where : $\mathbf{V} = \mu_d \mathbf{v}$ $\quad \phi = gz$

$\alpha = 1/\rho$ $\quad \mu_d = p_{dhs} - p_{dht}$

WRF-CHEM

Non-hydrostatic compressible Euler equations (Flux-form)

→ ***Finite Difference 5th order - Runge-Kutta 3rd order -** Δt = 5 s*

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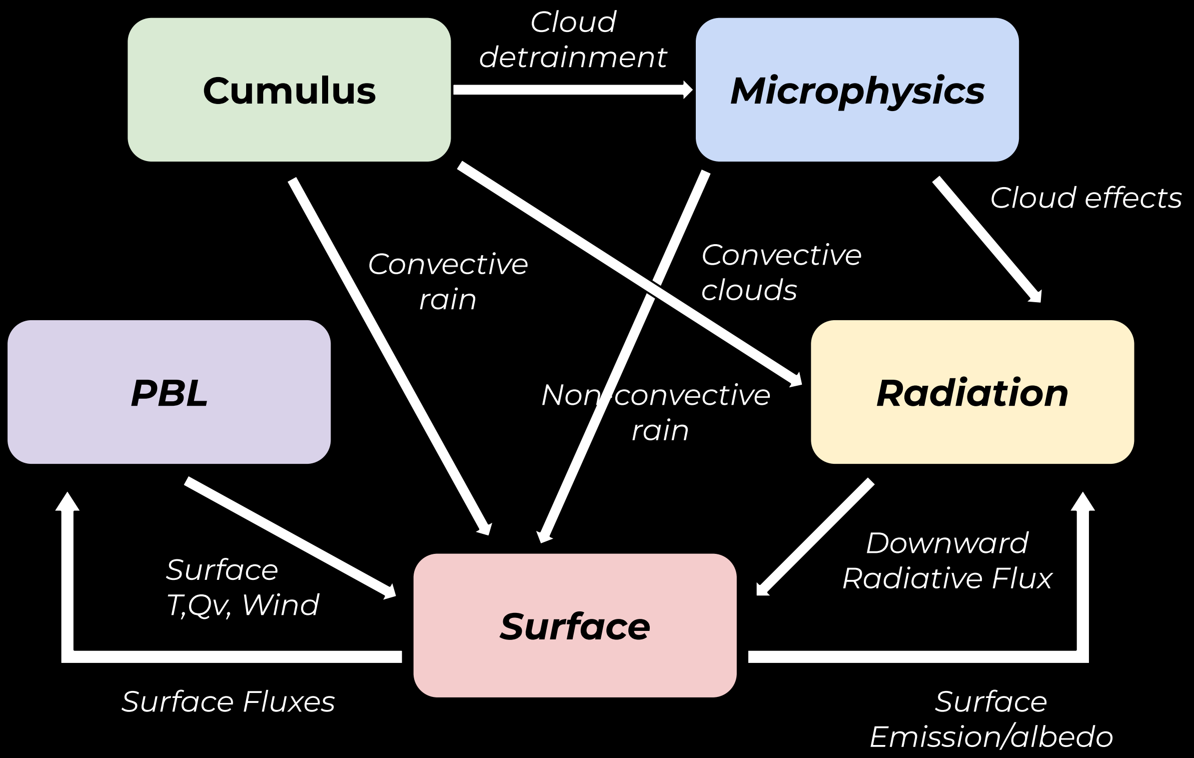
WRF-CHEM


Cumulus
Cloud detrainment
Microphysics
Cloud effects
Convective rain
Convective clouds
PBL
Non-convective rain
Radiation
Downward Radiative Flux
Surface T,Qv, Wind
Surface
Surface Fluxes
Surface Emission/albedo

WRF-CHEM

Chemistry + *Aerosols*

MOZART

(Model for OZone And Related chemical Tracers)

- *85 gas-phase species*
- *157 chemical reactions*
- *37 photochemical reactions*

MOSAIC

(Model for Simulating Aerosol Interactions and Chemistry)

- *4 aerosol size sections (bins)*
  - bin_1 = [39 - 156] nm
  - bin_2 = [156 - 625] nm
  - bin_3 = [0.625 - 2.5] μm
  - bin_4 = [2.5 - 10] μm

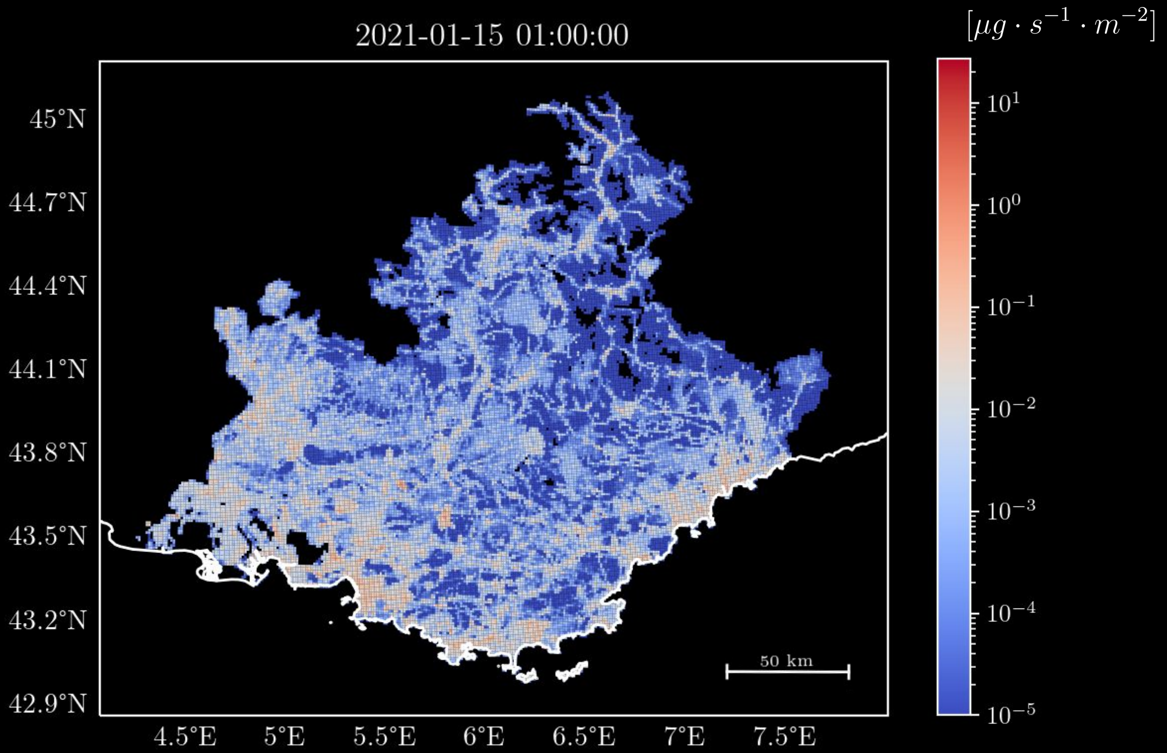
Chemical inputs

Background Emission

From ATMOSUD: CIGALE
Δx = 9.1e-3° = 1 km

$$E_h = E_a \times C_m \times C_d \times C_h$$

Crippa et al. (2020)



$PM_{2.5}$ background emissions at ground level (log scale).
Data from CIGALE (2019)

Chemical inputs

Ship Emission

From GPMM and AtmoSud

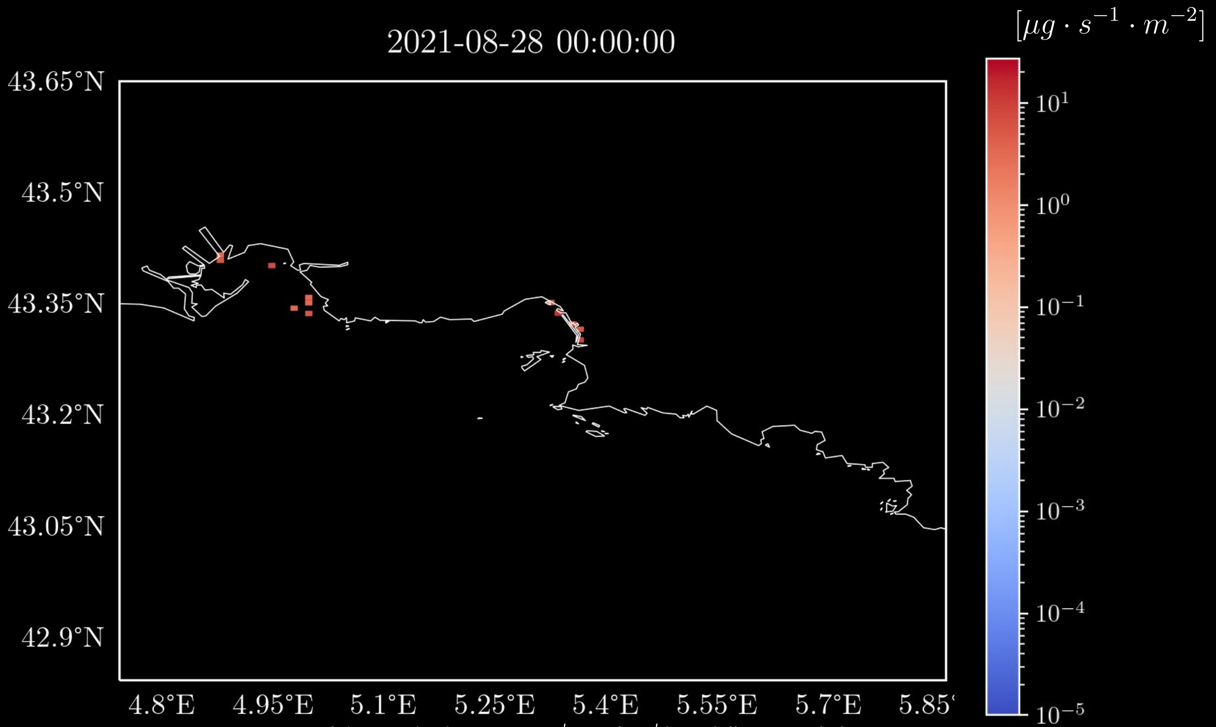
$$E = \sum_p P \times LF_p \times EF_p$$

P : *Nominal Power*

LF : *Load Factor*

EF : *Emission Factor*

EMEP (2019)
(European Environmental Agency)



$PM_{2.5}$ ship emissions at 2^{nd} and 3^{rd} level (log scale).
Data from GPMM (2021)

Numerical set up

Meteo

From NCEP: GDAS/FNL
Δx = 0.25° = 27 km;

Chemistry

From NCAR: WACCM
Δx = 0.23° = 25 km;

Background Emission

From ATMOSUD: CIGALE
Δx = 9.1e-3° = 1 km

Ship Emission

From GPMM and AtmoSud

→ **WRF-CHEM** →

Meteo

Δx = 7.2e-3° = 800 m

Pollution

Δx = 7.2e-3° = 800 m

Ship Contribution

Real Case Study

"Zero-Out" method : $$[C_{ship}]_{\%} = \left[\frac{C_{bg+ship} - C_{bg}}{C_{bg+ship}}\right]_{\%}$$

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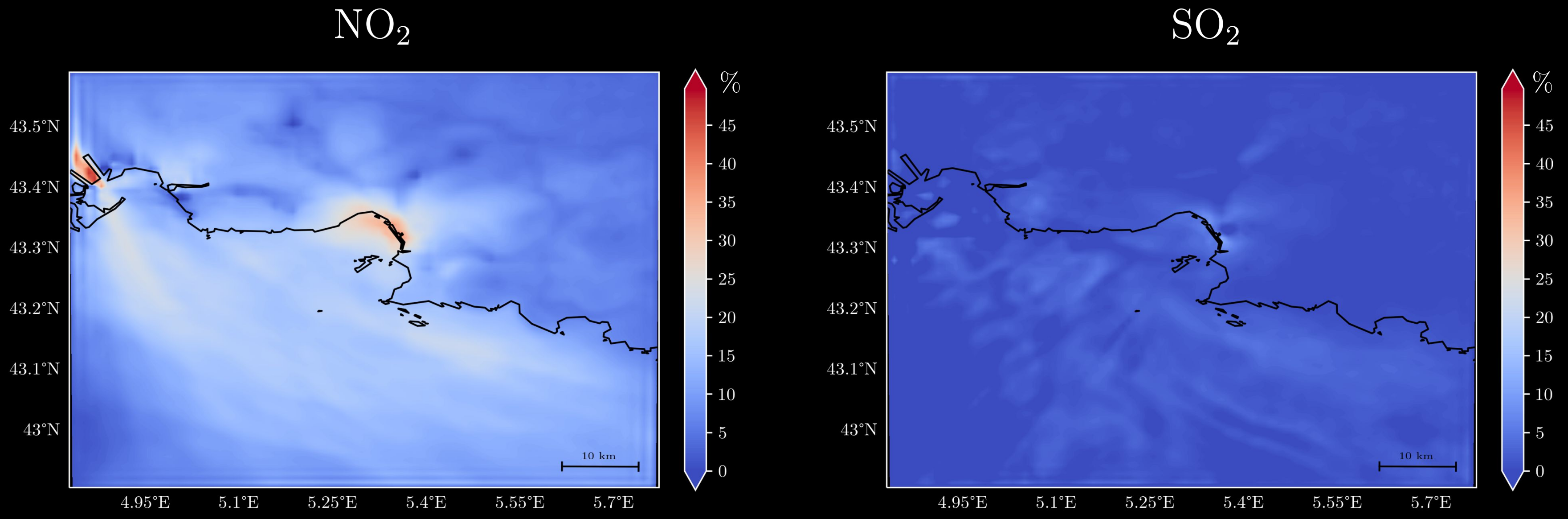

Time-averaged NO_2 and SO_2 ship contribution for June 2021 at 8m above ground level.

Real Case Study

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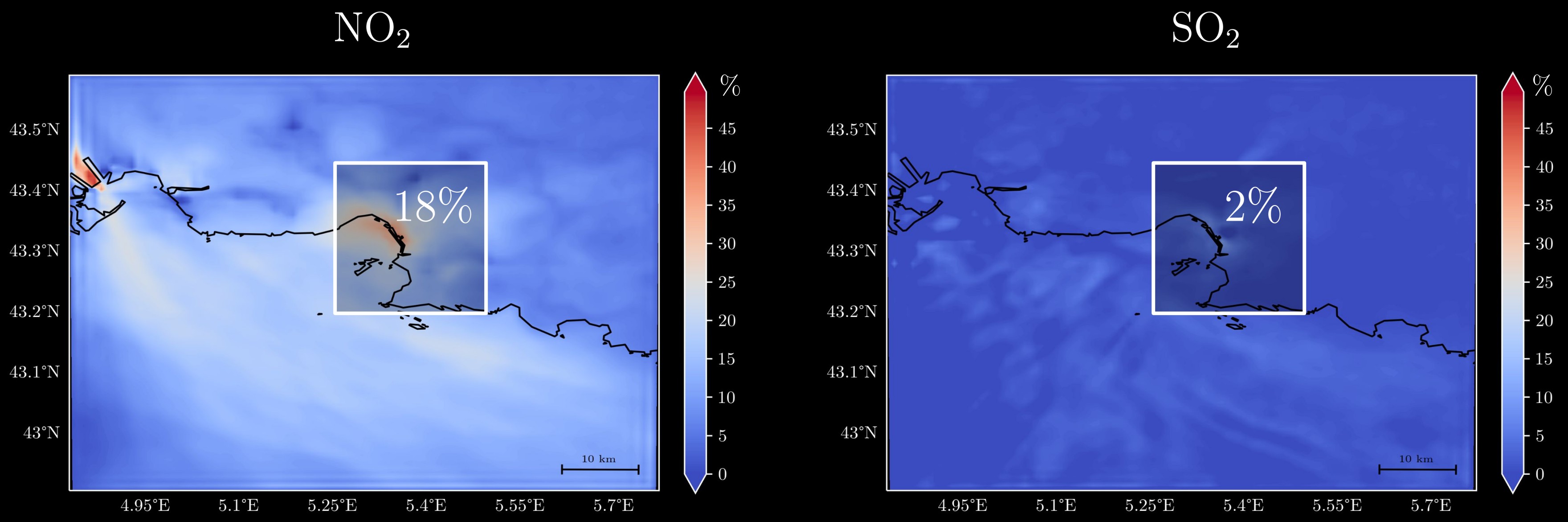

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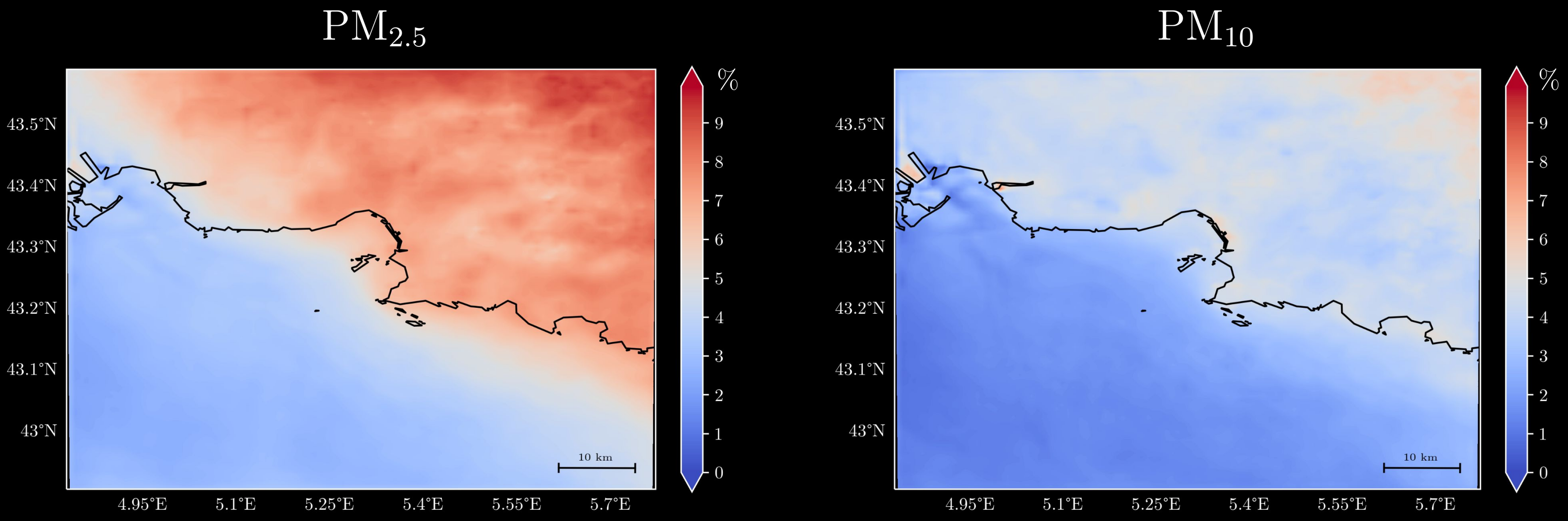

Time-averaged $PM_{2.5}$ and PM_{10} ship contribution for June 2021 at 8m above ground level.

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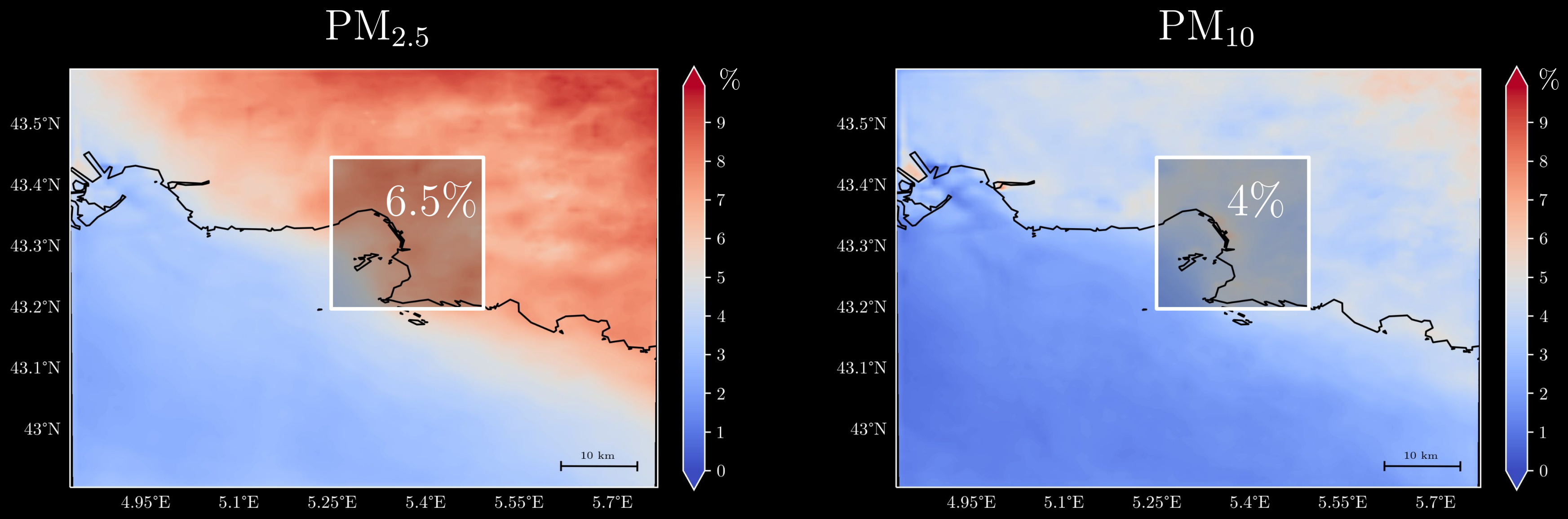
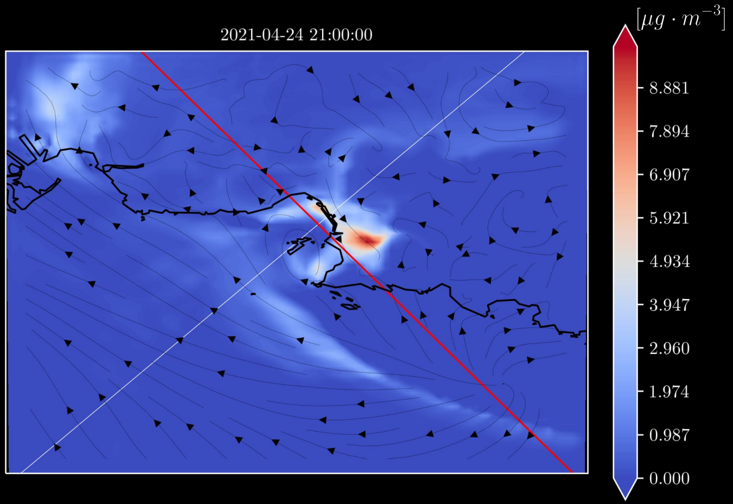
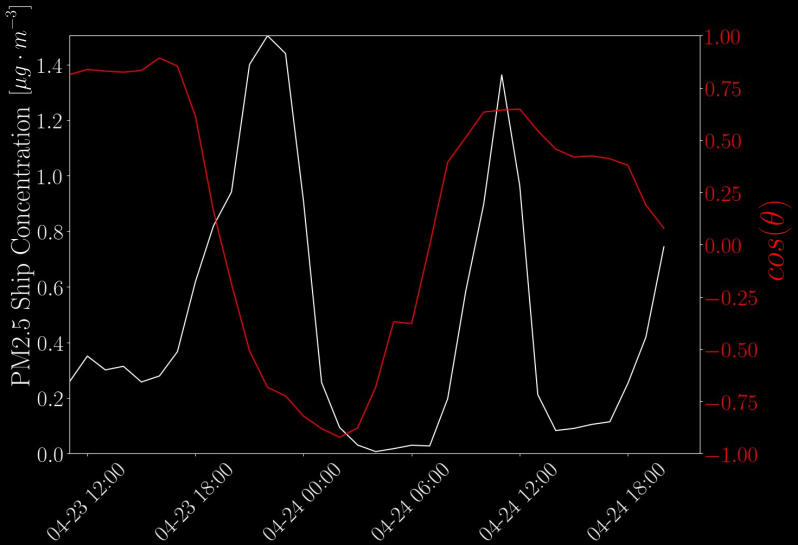


Time-averaged $PM_{2.5}$ and PM_{10} ship contribution for June 2021 at 8m above ground level.

Sea-Land Breeze Mechanism



$PM_{2.5}$ ship-emitted concentration for 2021-04-23 at 8m above ground level.



Time series of $PM_{2.5}$ ship-emitted average concentration over Marseille for 2021-04-23.
Time series of average scalar product between sea-land breeze vector and wind direction over Marseille

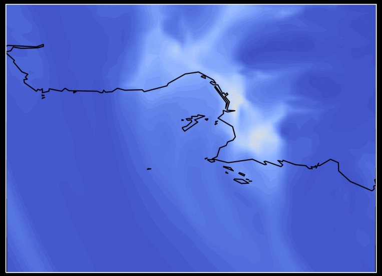
Chevet et al. (2024) - Modeling of air pollution due to marine traffic in Marseille

Machine Learning

Machine / Deep Learning

Objective : *Build a supervised hybrid Deep Learning model*

Dataset



PM2.5 concentration for 2021 from WRF-CHEM

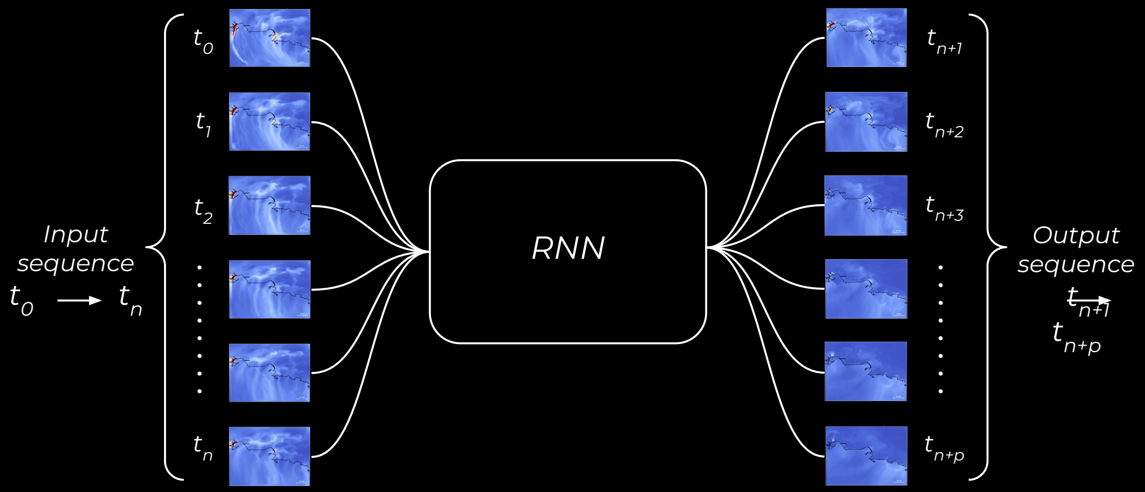
- *Spatial Dimension :*

  64 x 64 = 4096

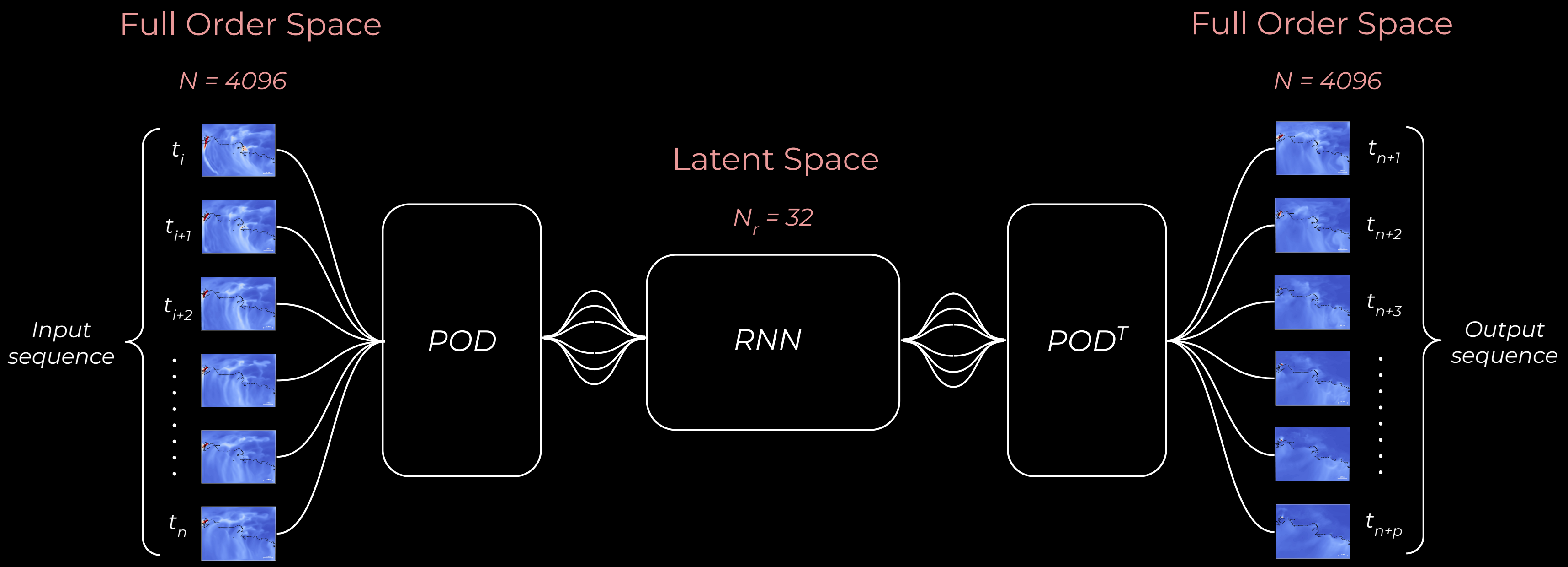
- *Temporal Dimension :*

  7107 snapshots ~ 10 months

RNN
(Recurrent Neural Network)

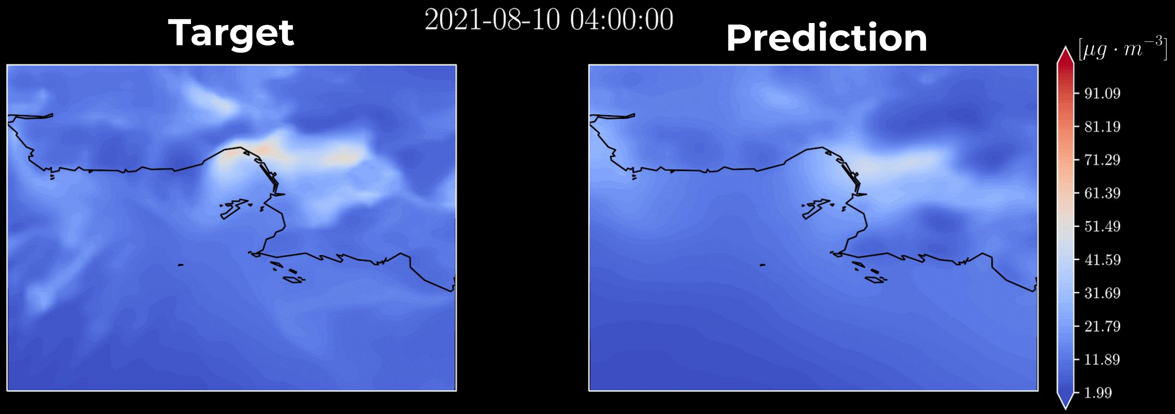


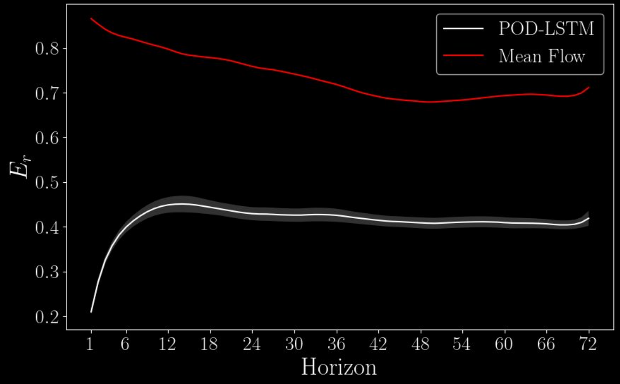
POD-RNN



Full Order Space
N = 4096
Input sequence
t_i
t_{i+1}
t_{i+2}
t_n
POD
Latent Space
$N_r = 32$
RNN
POD^T
Full Order Space
N = 4096
t_{n+1}
t_{n+2}
t_{n+3}
t_{n+p}
Output sequence

Multivariate POD-RNN





$$E_r = \frac{\left\| S - \hat{S} \right\|}{\|S\| + \varepsilon}$$

Conclusion

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➢ Built a numerical setup based on hourly ship traffic data

- **What is the contribution of ships to air pollution in Marseille and its surroundings ?**

- **How ship pollution is influenced by local meteorological conditions ?**

- **How Machine Learning can be used for operational purpose ?**

Conclusion

- Built a numerical setup based on hourly ship traffic data

  - **What is the contribution of ships to air pollution in Marseille and its surroundings ?**

    - **Quantitative results :** $PM_{2.5} \rightarrow$ 6.5 % ; $PM_{10} \rightarrow$ 4 % ; $SO_2 \rightarrow$ 2 % ; $NO_2 \rightarrow$ 18 %

  - **How ship pollution is influenced by local meteorological conditions ?**

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  ➢ **Sea-land breeze dynamics contribute to pollutant accumulation**

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- **How Machine Learning can be used for operational purpose ?**

  ➢ **Development of a POD-RNN model for operational purpose : Univariate and Multivariate**

Questions