



Air Quality Modelling at AUTH

*George Tsegas¹, Fotios Barmpas¹, Eleftherios Chourdakis¹,
Christos Vlachokostas¹, Evangelia Fragkou², Leonidas Ntziachristos²*

¹**Sustainability Engineering Laboratory, Aristotle University,
GR-54124 Thessaloniki, Greece**

²**Laboratory of Applied Thermodynamics, Aristotle University,
GR-54124 Thessaloniki, Greece**

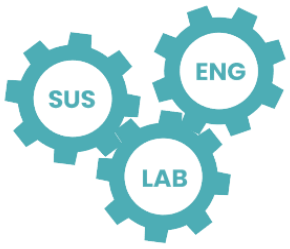




Department of Mechanical Engineering

- 7 senior researchers
- 8 PhDs
- 6 Special Courses
- Laboratory for Heat Transfer
- Combustion processes





- Air Quality assessment using atmospheric models in the Mesoscale, Urban and Neighborhood scales
- Development of novel modelling approaches
- Assessment of AQ scenarios in urban areas
- Support AQ authorities
- Novel experimental methods for air pollutant measurements
- Development and application of mesoscale meteorological models for climate downscaling






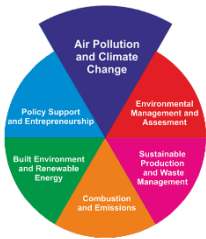
Together towards clean hard-to-electrify traffic modes

REALCHEM is an EU-funded research project on a mission to clean up transport and protect our climate. While electric power is transforming many vehicles, some sectors (like aviation, shipping, and heavy-duty vehicles, non-road mobile machinery) that are harder to electrify. That is where low-carbon fuels come in. But not all low-carbon fuels are created equal.

REALCHEM investigates how these alternative fuels perform in the real world. How clean are they, really? What do they emit into the air? And how do those emissions affect human health, air quality, and the environment?

REALCHEM brings together leading experts to answer these urgent questions. We combine existing data and cutting-edge experiments across air, sea, and land transport to:

-  Measure pollutant emissions from low-carbon fuels
-  Understand their impact on people and the planet
-  Find the best solutions for low-emission engines and cleaner air

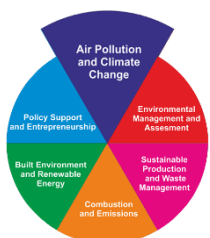


2025-27





- Increasing the resilience of the Inland Water Way infrastructures and the connected land infrastructures, under unfavorable conditions, such as extreme weather, accidents and other kinds of hazards



2022-26

- EURO-CORDEX based climate hazard downscaling → long-term statistics
- Operational Wind, Temperature and Humidity forecasting



Introduction

Scope of the PLOTO project

To increase the resilience of the Inland Water Ways (IWW) infrastructures and the connected land infrastructures, ensuring reliable network availability under unfavourable conditions, such as extreme weather, accidents and other kind of hazards. For more information: <https://ploto-project.eu/>

Aims of the study

- To combine downscaled climate change scenarios (applied to IWW infrastructures) with simulation tools and actual data
- To implement the modelling layer of an integrated support tool for effective management of IWW infrastructures at the strategic and operational levels

Modelling Methodology

Wind Downscaling	• PALM LES model (Maronga et al., 2020) with self-nesting module (Hellsten et al., 2021)
Downscaling of non-Wind Variables	• MEMO v7 non-hydrostatic mesoscale atmospheric model (Moussiopoulos et al., 2012)
Input Climatology	• EURO CORDEX Regional Climate Model (RCM) results for 2005-2100 (Kotlarski et al., 2014)
Operational Forecasting (short-term extremes)	• Operational forecasts downscaled from a regional Numerical Weather Prediction model using MEMO v7 • Real-time data assimilation from deployed sensors

Use Cases and Hazards



Use case grids for Budapest (left), Wallonia (center) and Romania (right). Fine grids for Budapest and Wallonia are presented with a different color shading.

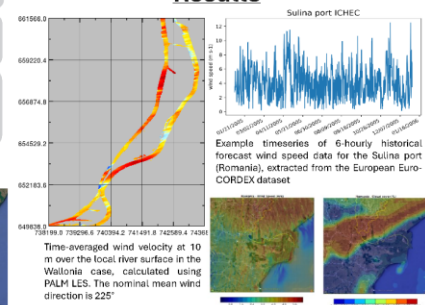
Romania (Danube-Black Sea)	High wind situations → navigational hazard for ships maneuvering near port entrances and in docking areas
	Wind is downscaled in the Sulina port. Low temperatures → icing hazard (river surface, roads, exposed structures)
	Precipitation, temperature and cloud cover are downscaled to a 250 m grid over the lower catchment area covering the St. George, main and Sulina branches.

Budapest (Port area)	High wind gusts → unsafe to load/unload conventional ships using cranes to lift containers, carriages or bulk cargo Port operators are interested both in short-term forecast as well as future trends of wind-speed exceedances as expected to change under climate scenarios.
	Intense precipitation → flash flooding potential over local assets in smaller timescales (of the order of tens of minutes)
	Icing potential is estimated based on 1 hour moving-averages of downscaled temperature.

Wallonia (Meuse river)	Persistent strong wind → wave overtopping of dikes and difficulties in boat maneuverability
	Wave overtopping is more dependent on the average wind speed while maneuvering safety depends mainly on the instantaneous or gust wind velocity.
	Downscaled precipitation → probability of local overflow and dike/dam breach events

All Use cases: 20 “representative” one-month periods between 2005 and 2100 have been selected based on climatic indicators to synthesize a **downscaled library of climate extremes**. To this end, high resolution dynamical downscaling is performed using the mesoscale model MEMO, producing detailed fields of precipitation temperature, relative humidity and cloud cover. These parameters are subsequently used as input by hydrological models to map flood hazard over future episode occurrences.

Results



Example timeseries of 6-hourly historical forecast wind speed data for the Sulina port (Romania), extracted from the European Euro-CORDEX dataset

Time-averaged wind velocity at 10 m over the local river surface in the Wallonia case, calculated using PALM LES. The nominal mean wind direction is 225°

Operational forecast of the spatial distribution of wind speed (m/s) at 2 m above ground (left), and total cloud cover (%) for the Romanian use case (right)

Conclusions

A weather- and climate-related hazard analysis was performed by downscaling output of regional-scale Climate Models and Numerical Weather Prediction models to the local scale at extremely high resolutions. Two modelling approaches were employed: PALM Large-Eddy Simulation model for wind downscaling, and an operational mesoscale system, based on the MEMO model for other meteorological parameters. Related hazards of focus in the three Use case area were identified: a) wind-induced mechanical stress on infrastructures and operations along waterways, b) precipitation for flash flood identification, and c) temperature & cloud cover for estimating water runoff and probability of ice formation.

Acknowledgements

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References

Hellsten, A., Ketelsen, K., Sühring, M., Auvinen, M., Maronga, B., Knigge, C., Barmas, F., Tsegas, G., Moussiopoulos, N., and Raasch, S. (2021). A nested multi-scale system implemented in the large-eddy simulation model PALM model system 6.0. *Geosci. Model Dev.*, 14, 3165-3214. <https://doi.org/10.5194/gmd-14-3165-2021>

Kotlarski, S., Keuler, K., Christensen, O. B., Colette, A., Déry, M., Gobiet, A., Goergen, K., Jacob, D., Luthi, D., van Meirghem, E., Nikulin, G., Schär, C., Stechmann, G., Vautard, R., Wernach-Sörgel, K., and Wulfmeyer, V. (2014). Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci. Model Dev.*, 7, 1297-1333. <https://doi.org/10.5194/gmd-7-1297-2014>

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Moussiopoulos, N., Douros I., Tsegas G., Kleanthous S. and Chourdakis E. (2012). An air quality management system for policy support in Cyprus. *Hindawi Publishing Corporation, Advances in Meteorology* 2012, doi:10.1155/2012/958280



Assimilating microclimatic data during the 2021 intense heat wave

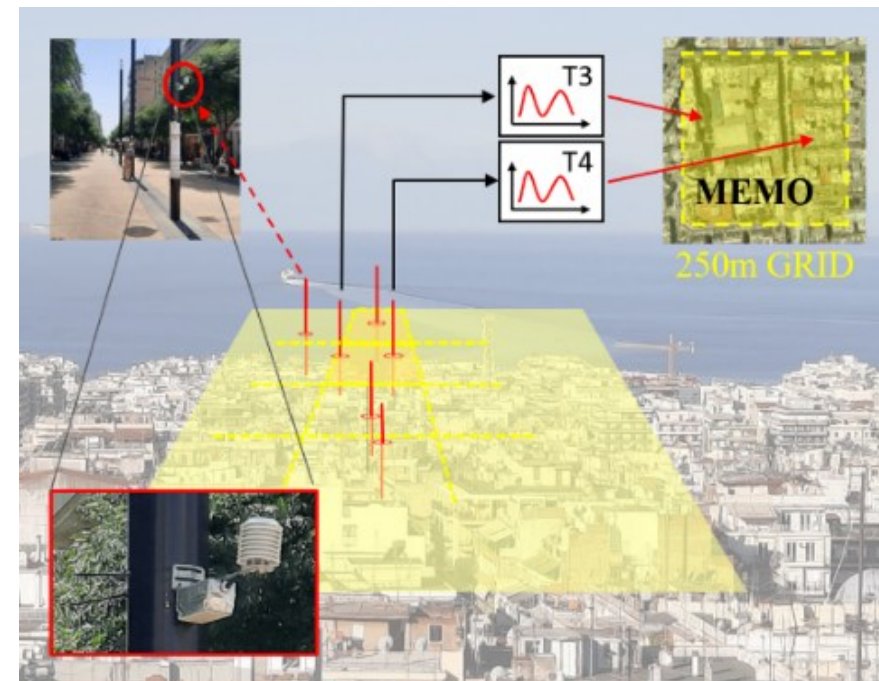


What we did:

- High resolution microclimatic heat mapping
- Data assimilation by a mesoscale flow model which has been used extensively as driver for dispersion calculations

Next steps:

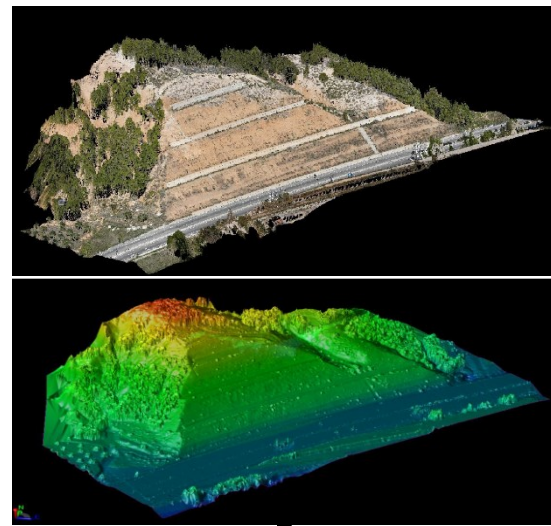
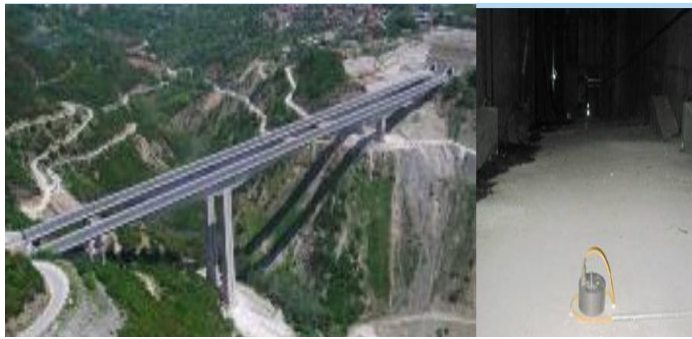
- Application and sensitivity analysis when driving a chemical dispersion model
- Synergetic effects of heat and air pollution personal exposure
- Development and calibration of a ML-based local heat-increment model



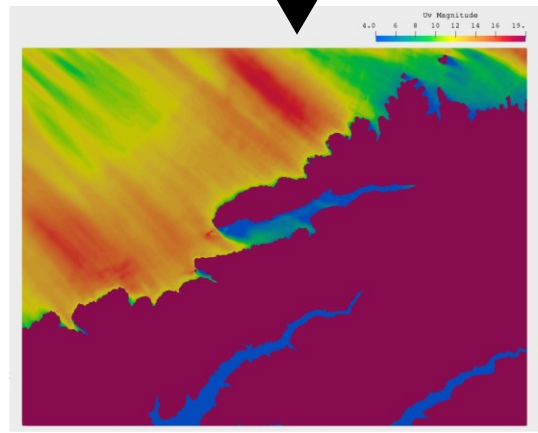


Development of a Decision Support System for Increasing the Resilience of Road Infrastructure based on Combined use of Terrestrial and Airborne Sensors and Advanced Modelling Tools - (PANOPTIS)

Morphology, on-site and remote sensing



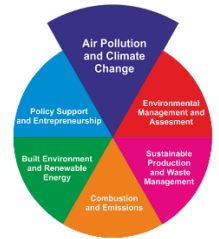
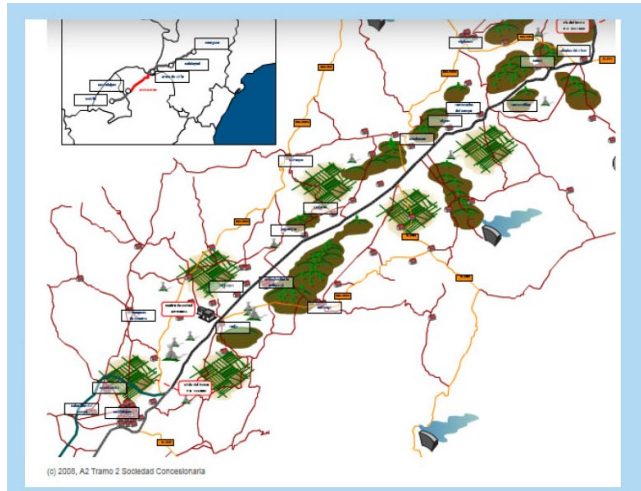
Models of high-risk areas



Dynamical downscaling of extreme events



Holistic Resilience Assessment Platform (HRAP)



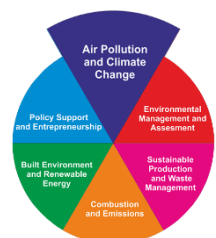
2018-21

PANOPTIS





Development of a Decision Support System for Improved Resilience & Sustainable Reconstruction of Historic Areas to Cope with Climate Change & Extreme Events Based on Novel Sensors and Modelling Tools (HYPERION)



2019-22

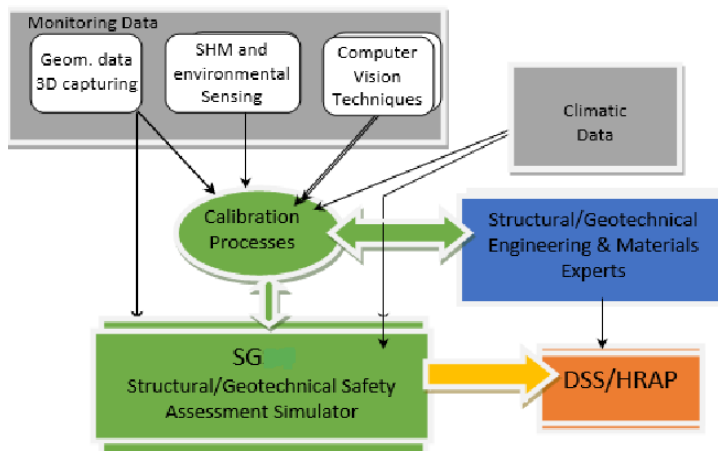


Digital modelling of historic sites\

Deployment of on-site and remote sensors

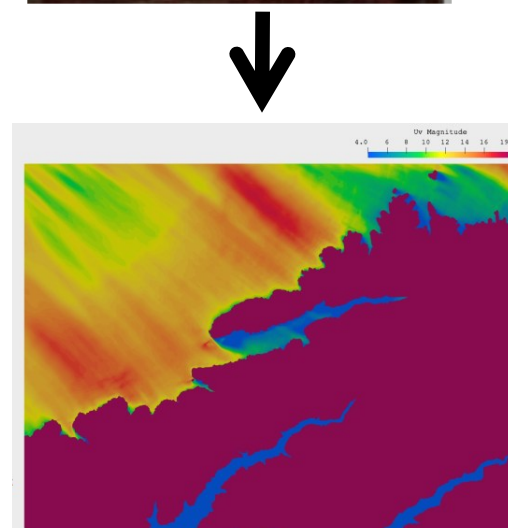


Statistics of past and future extreme events



DSS: adaptive, efficient response

Support sustainable reconstruction



Dynamical downscaling, response modelling, vulnerability assessment

Hyperion



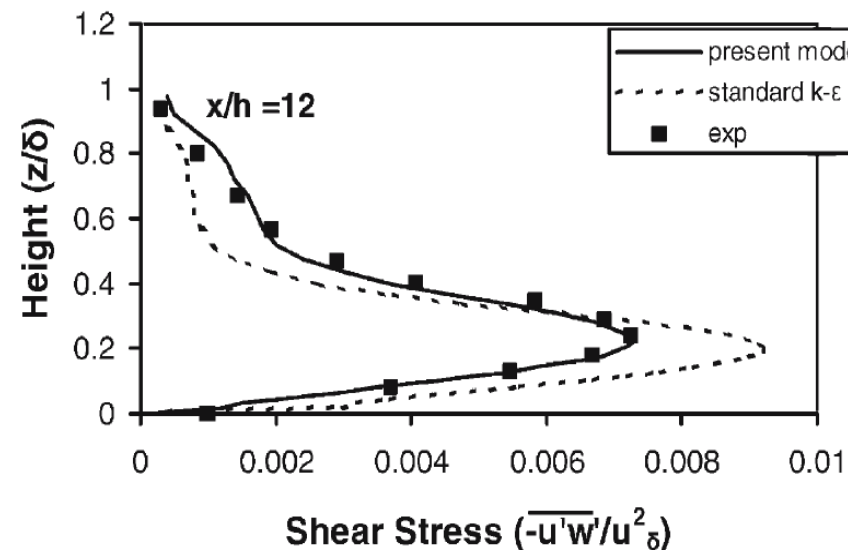
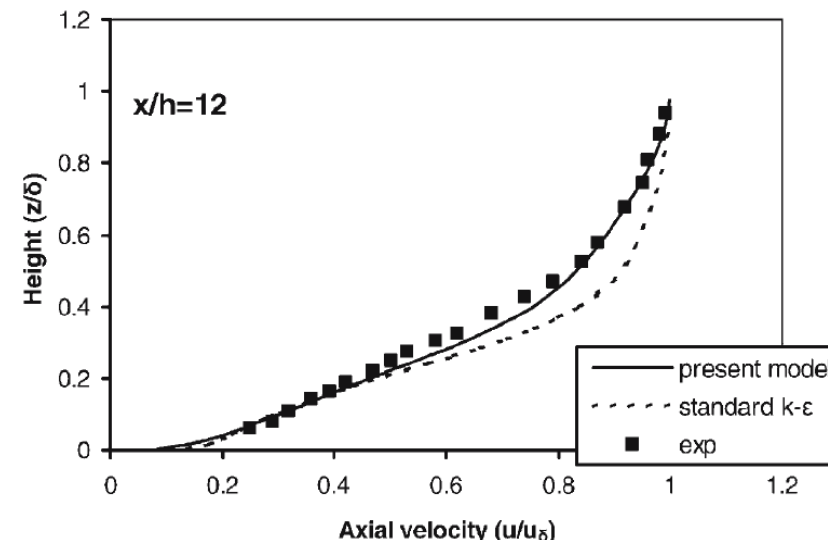


An improved turbulence closure scheme for windfarm applications

- Reynolds Averaged Navier–Stokes modelling of the Atmospheric Boundary Layer (ABL) typically uses the $k-\epsilon$ turbulence closure model.
- Although successful for local-scale problems in neutral conditions, it is deficient for multiscale flows.
- A new approach based on the inverse-length scale ζ is developed aiming to improve reliability and applicability over several spatial scales.
- Applications of the $k-\zeta$ model in 1-D neutral ABL problems fully support its validity for those types of flow.
- In a 2-D square section simulation, agreement with the experimental data, is improved compared to $k-\epsilon$ especially for shear stresses.



2023-25





- Two-way Mesoscale-Microscale coupling in urban areas
- High-resolution assessment of shipping emissions mitigation scenarios





Two-way coupled Mesoscale-Microscale modelling – Motivation

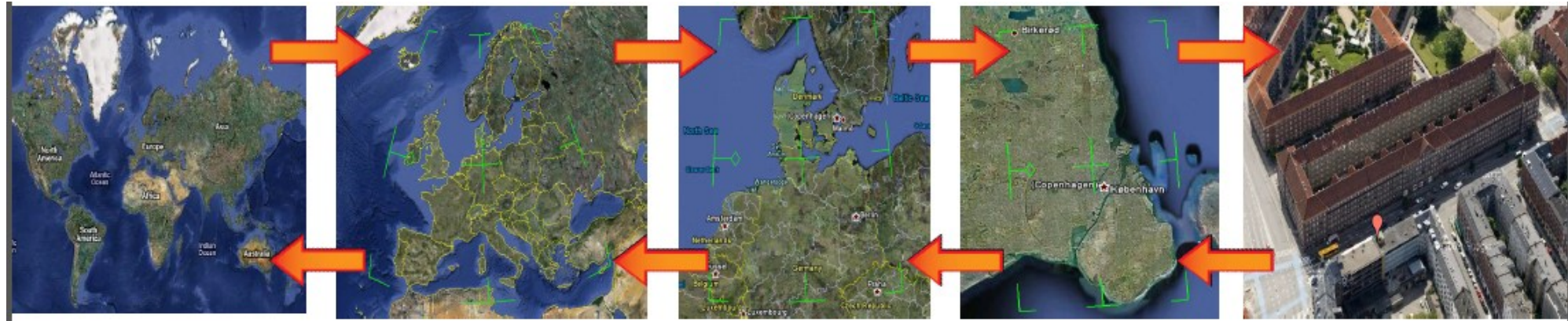


Different scales, different modelling considerations:

- Land use characteristics and scenarios
- Anthropogenic heat fluxes
- Emission inventories and scenarios
- Dynamical down- and upscaling

Approaches for coupling between scales:

- Level 1 – Spatial: One way
(Global \rightarrow Regional \rightarrow Urban \rightarrow Street)
- **Level 2 – Spatial: Two way**
(Global \leftrightarrow **Regional** \leftrightarrow **Urban** \leftrightarrow **Street**)
- Level 3 – Time integration: Timescale and direction; Direct and Inverse modelling



Two way Nesting, Zooming, Nudging, Parameterizations,
Urban increment methodology (Chourdakis et al., 2012)



Two-way coupled Mesoscale-Microscale modelling – Methodology



Three - step approach

1st step:

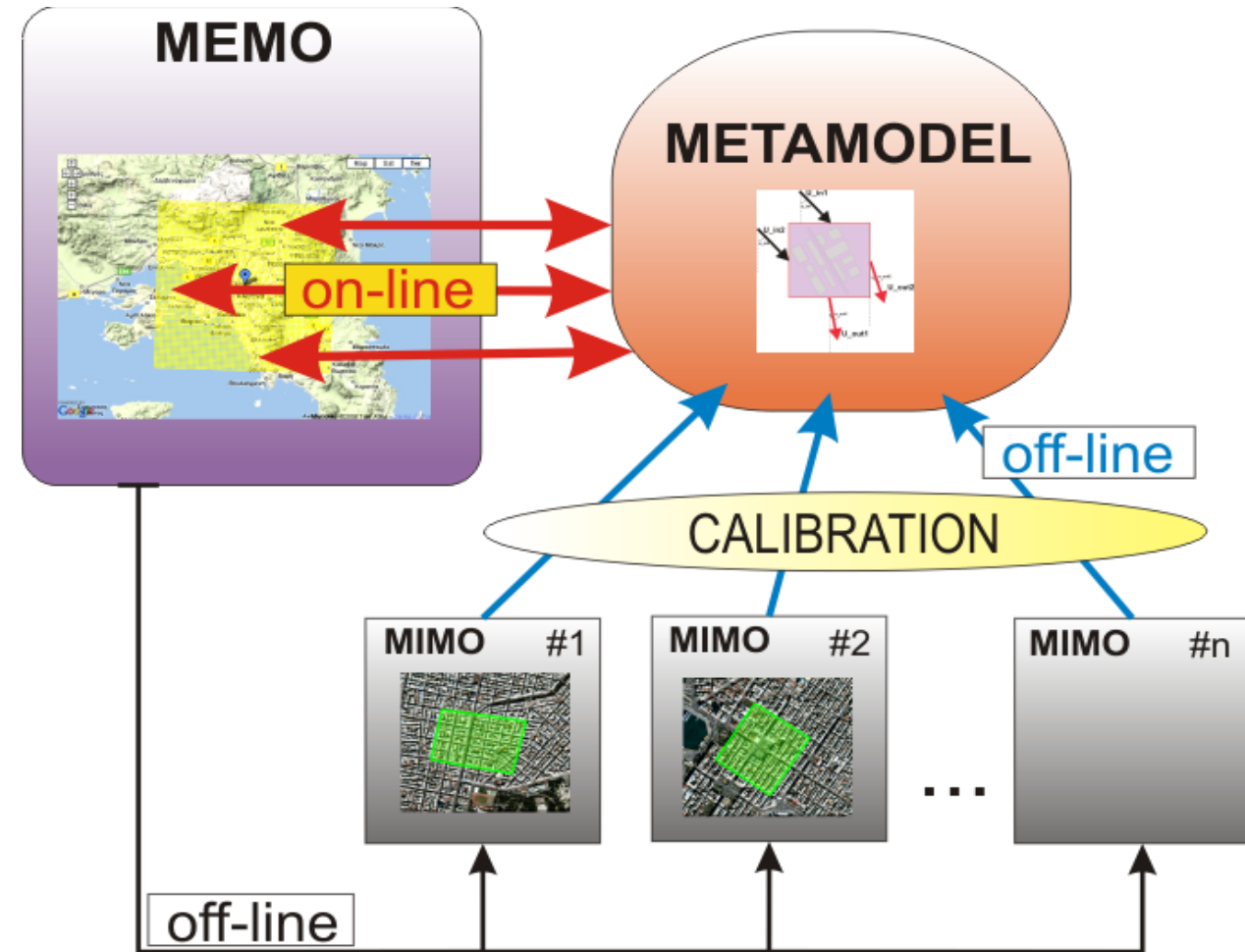
Boundary Conditions calculated from an initial MEMO run are used for multiple MIMO cases (off-line process).

2nd step:

The response of each microscale domain is used as calibration input for an interpolating metamodel.

3rd step:

The calibrated metamodel is fast enough to be used in on-line coupling with MEMO.



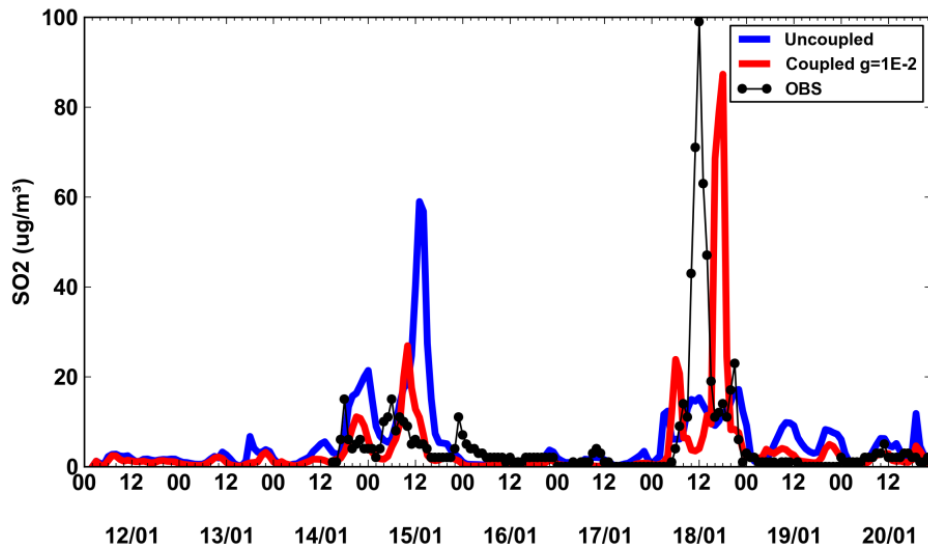


Two-way coupled Mesoscale-Microscale modelling – Dispersion calculations (MARS-aero)

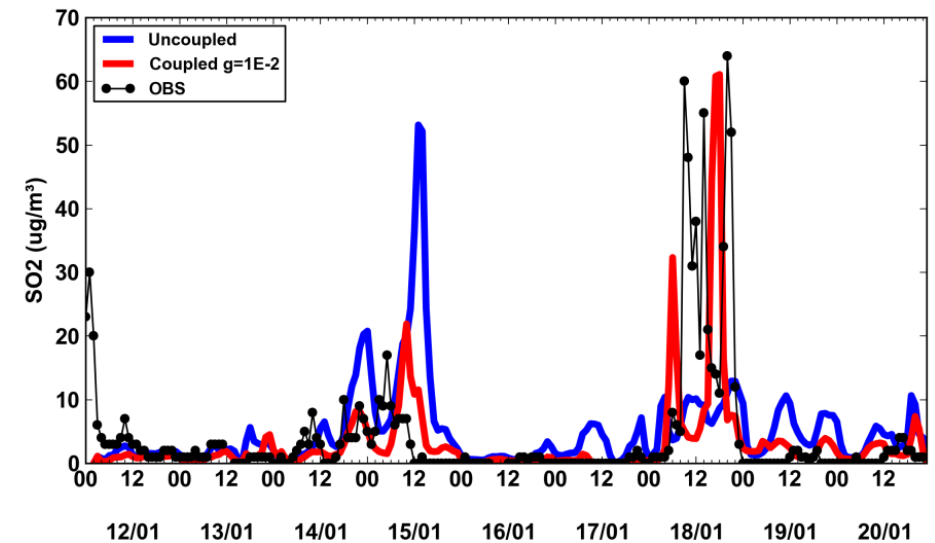


MARS-aero driven by coupled MEMO-MIMO vs ordinary roughness approach

Station: FR04014 / Paris_12e



Station: FR04146 / Ivry-sur-Seine



- Prediction of background peaks is significantly improved
- Traffic-related peaks however are not resolved

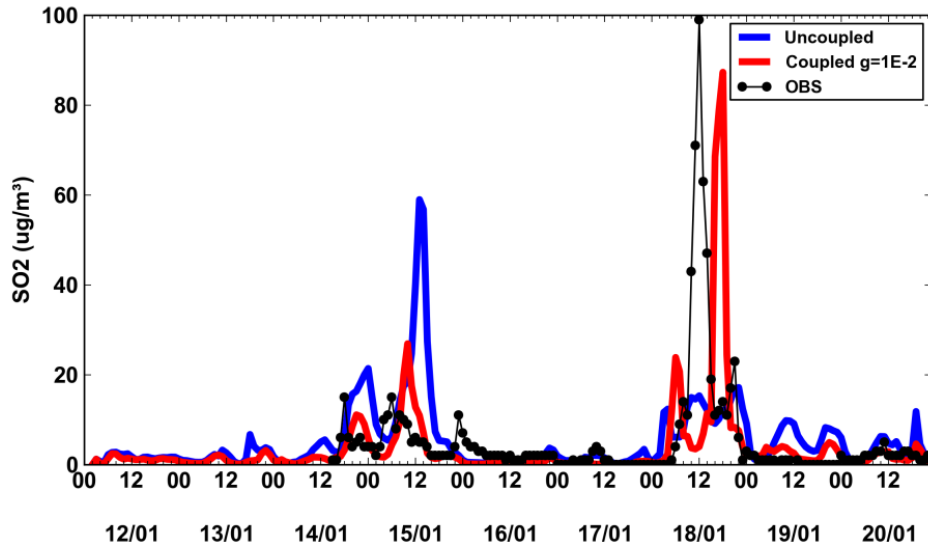


Two-way coupled Mesoscale-Microscale modelling – Dispersion calculations (MARS-aero)

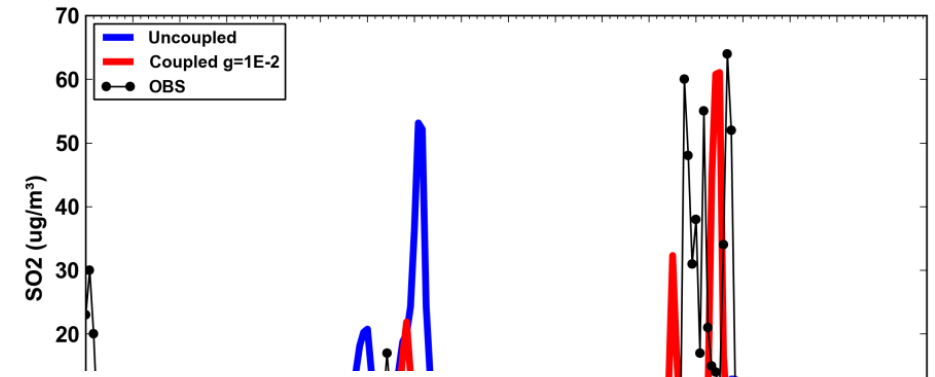


MARS-aero driven by coupled MEMO-MIMO vs ordinary roughness approach

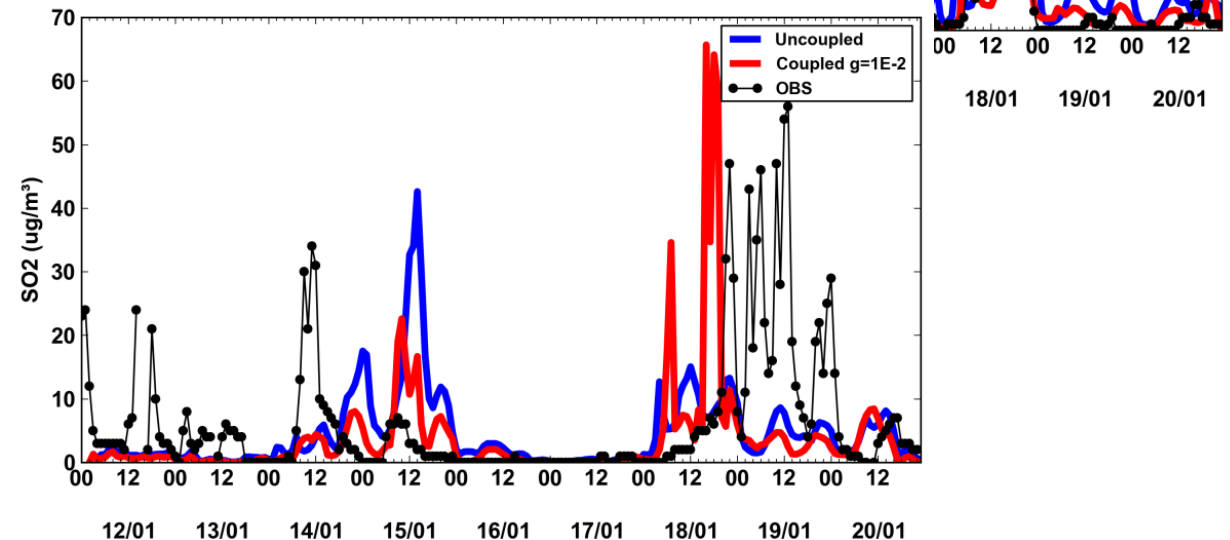
Station: FR04014 / Paris_12e



Station: FR04146 / Ivry-sur-Seine



Station: FR04053 / Bd_Peripherique_Aute



- Prediction of background peaks is significantly improved
- Traffic-related peaks however are not resolved



Two-way coupled Mesoscale-Microscale modelling

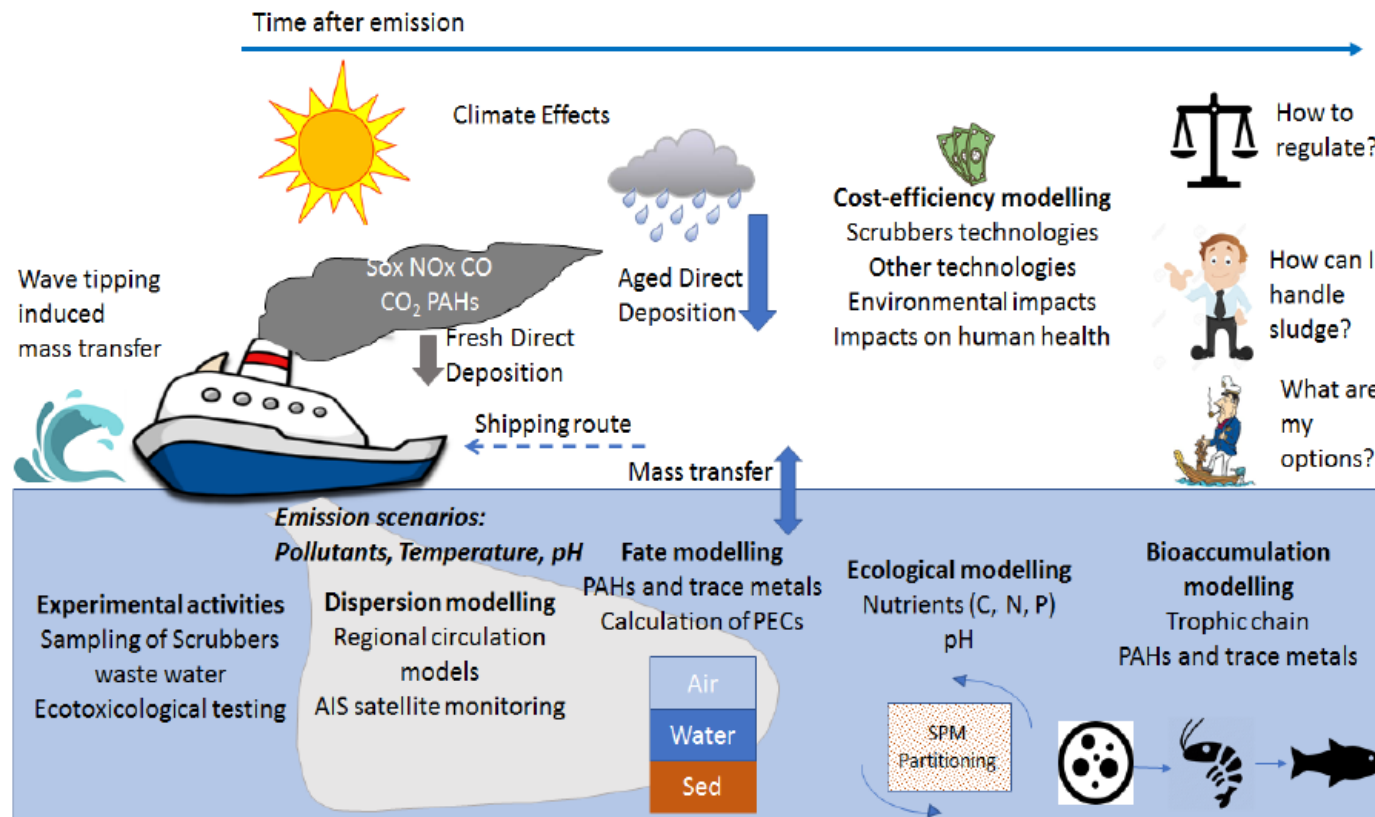
- The approach works and does not induce instabilities.
- In most cases, fields are improved compared to roughness approach.
- However, very small difference in low-density urban fabric
- Need to improve classification → development of ML model for morphology identification
- Currently testing more advanced surrogate model implementations.

The EMERGE project



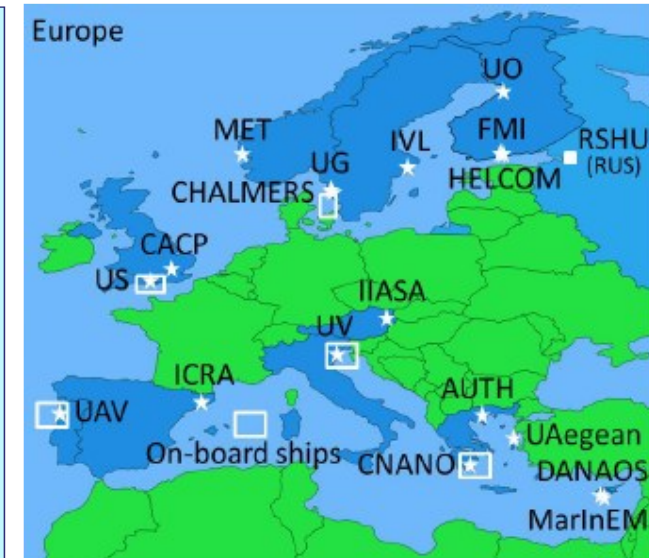
- Comprehensively quantify and evaluate the effects of a range of potential emission reduction solutions for shipping in Europe.

- Develop more effective strategies and measures to reduce the environmental impacts of shipping.
- Emphasis on the impact of emissions and discharge effluent related to the use of scrubbers



Wide scope, includes impacts on

- marine environments, ecology, plants, animals, bioaccumulation, etc.
- Atmosphere and health
- Climate
- Cost-benefit analyses



Pressures: emissions scenarios for the Mediterranean region



Scenario number	Ship traffic development	Number of scrubber installations	SCRs in use	Low sulphur required	Ambition to reduce GHG emissions	Alternative fuel
1	High growth	High	NECA	SECA	No ambition	
2	High growth	High	NECA	SECA	No ambition	
3	High growth	High	Everywhere	Everywhere	No ambition	
4	Low growth	High	NECA	SECA	No ambition	LNG
5	Low growth	No scrubbers	None	SECA	50% reduction	Methanol
6	High growth	High	NECA	SECA	50% reduction	Methanol
7	High growth	Low	None	SECA	50% reduction	Methanol
8	High growth	No scrubbers	None	SECA	50% reduction	LNG & Methanol

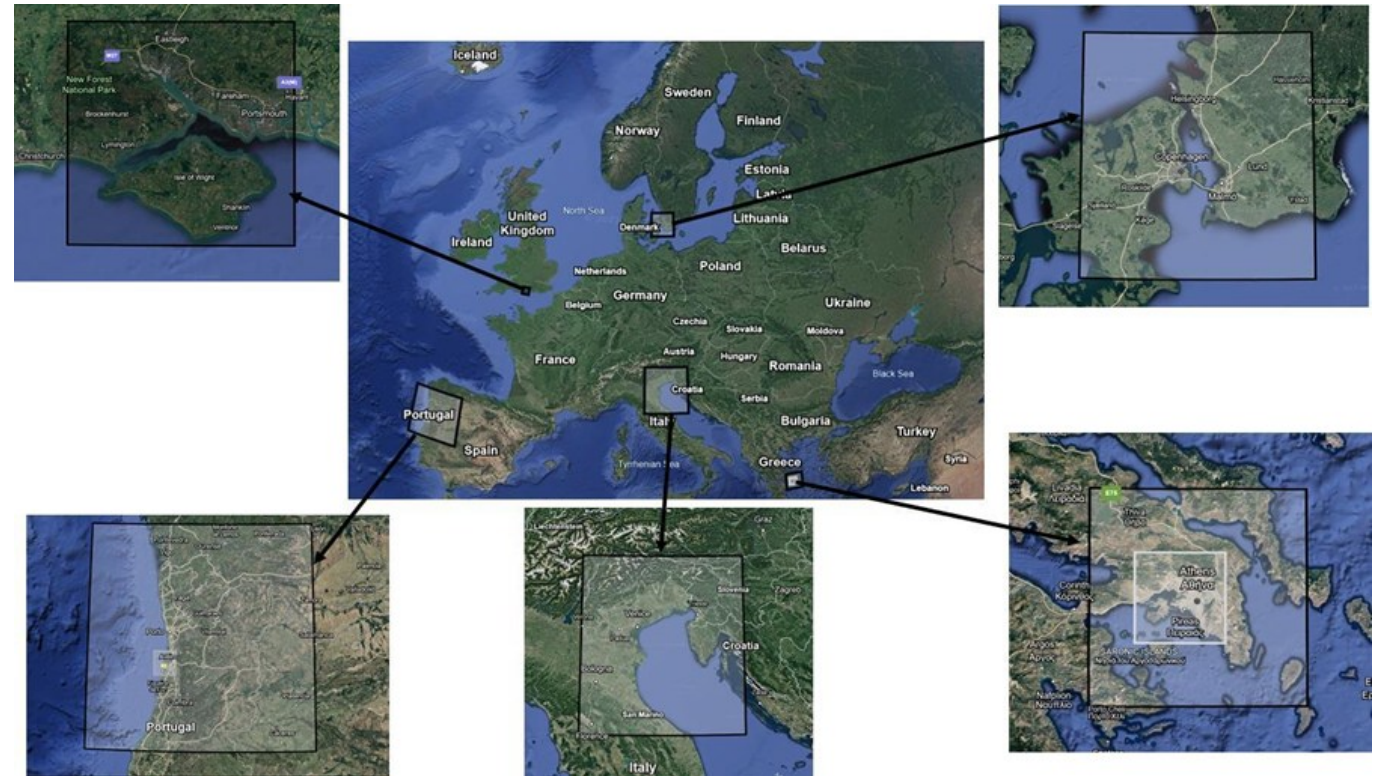
Table 3. 1 Number of ships with closed-loop and open-loop scrubbers in the Mediterranean Sea in EMERGE baseline year 2018 and scenarios for 2030 and 2050.

Scenario	Number of ships with open-loop scrubbers	Number of ships with closed-loop scrubbers	Number of ships with hybrid scrubbers	Number of ships with unknown type of scrubbers
2018	856	26	299	142
2030 Scenario 3	6163	0	0	0
2030 Scenario 3b	0	6163	0	0
2030 Scenario 8	0	0	0	0
2050 Scenario 3	23556	0	0	0
2050 Scenario 3b	0	23556	0	0
2050 Scenario 8	0	0	0	0

Assessing the effect of maritime emissions on the air quality of a Mediterranean port

Objective of the study

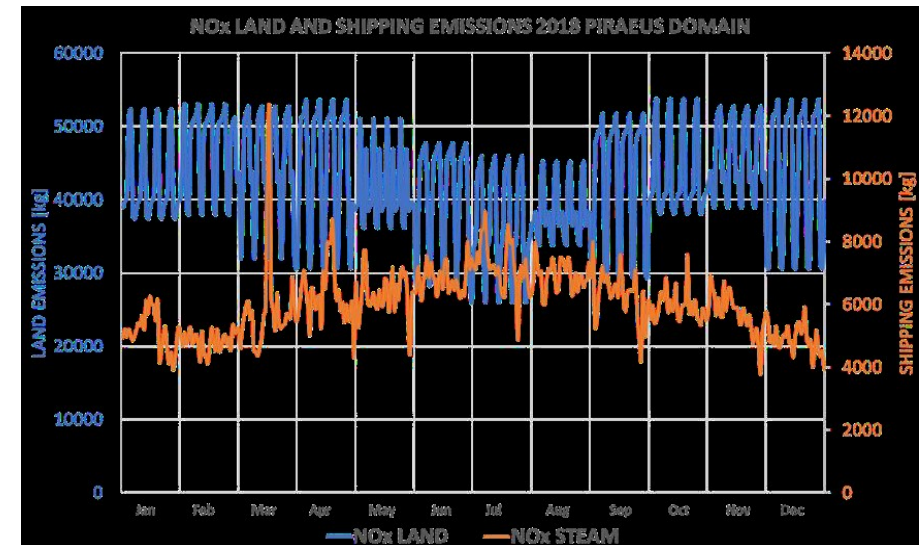
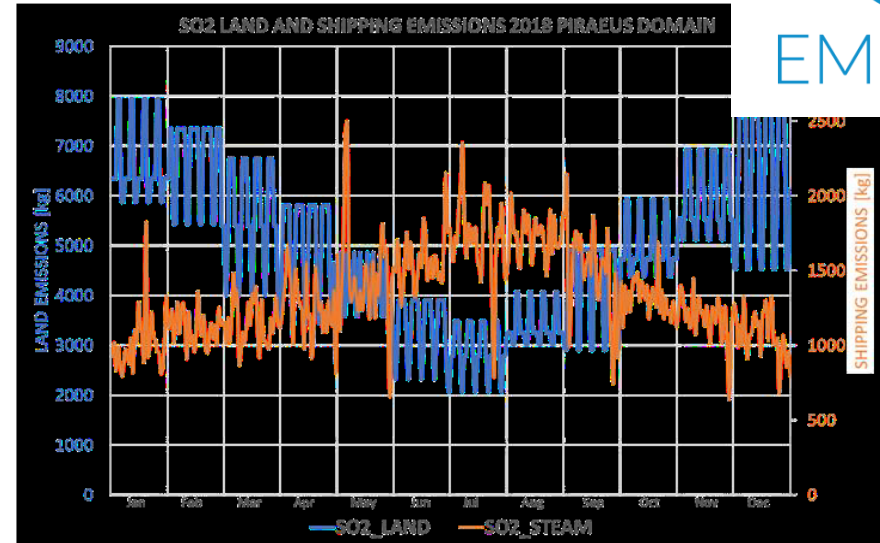
- Assess the state of air quality in the Mediterranean port city of Piraeus, Greece.
- Quantify the contribution of shipping emissions on current air pollutant levels in urban areas around the port.
- Evaluate the efficiency of two different mitigation strategies to reduce shipping related air pollution by 2050.



The five selected geographical case studies of the EMERGE project, representing vulnerable environments.

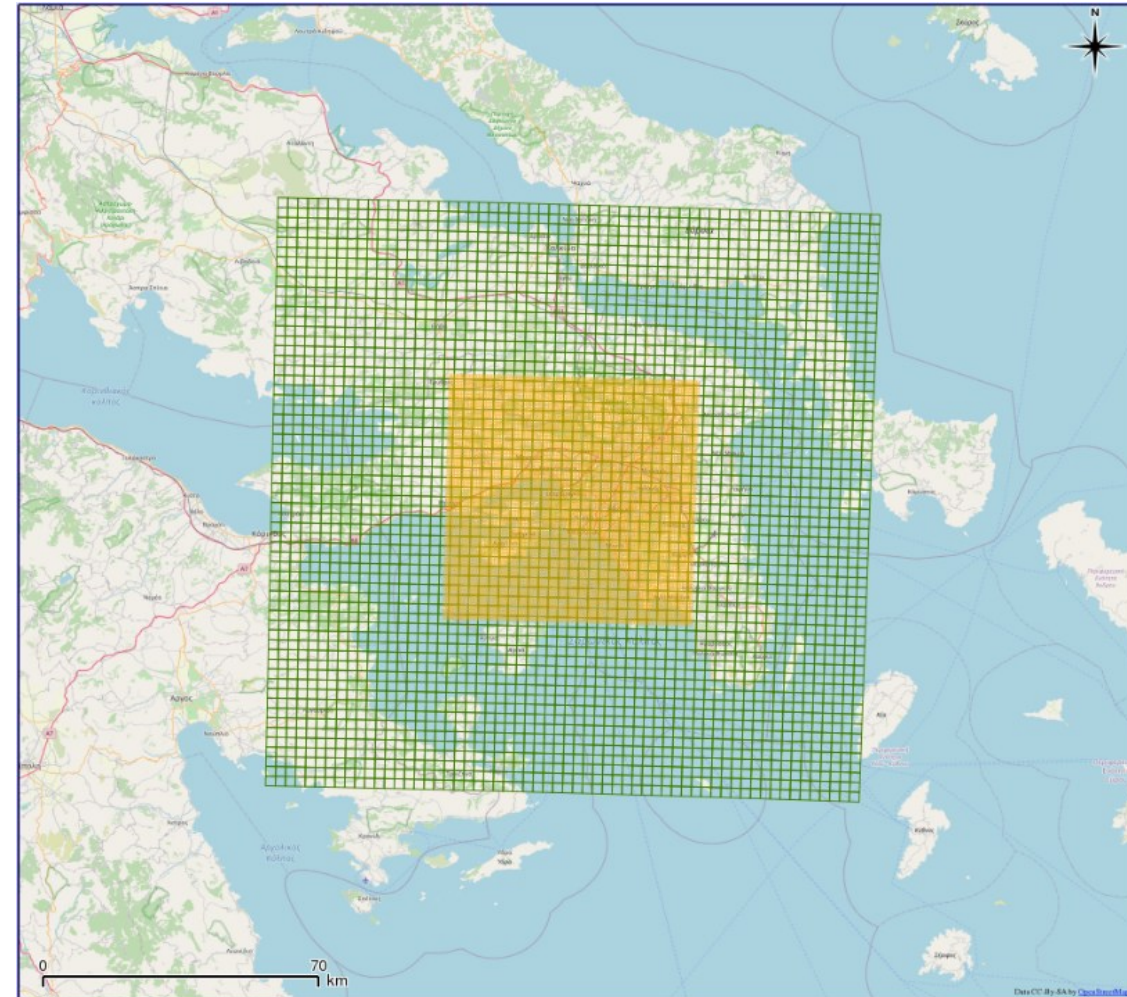
Pressures – Calculation of emissions in Piraeus

- Hourly-resolved shipping emissions for 2018 and the 2050 scenarios were calculated using the STEAM model, based on AIS data and load-dependent updated EFs, considering emissions control technologies, such as scrubbers and SCR.
- CAMRS-REG v2.2 was used for reproducing spatial distribution of land emissions over the Attica region, while total emitted mass of pollutants for 2018 was derived from the EMEP model and EIONET Portal.
- Land emission temporal profiles were obtained from GNFR temporal factors based on a source classification.



State - Methodology for assessing air quality in the Piraeus region

- The mesoscale meteorological model **MEMO** and the chemistry-transport model **MARS-aero** were employed to simulate dispersion of pollutants.
- An inner computational grid with a high resolution of **500 m** focused on the main port and anchorage areas, including the dense urban areas of Piraeus and southern Athens.
- **Zero-out** based source apportionment was used for determining the shipping contribution.



State - Methodology for assessing air quality in the Piraeus region

Four locations:

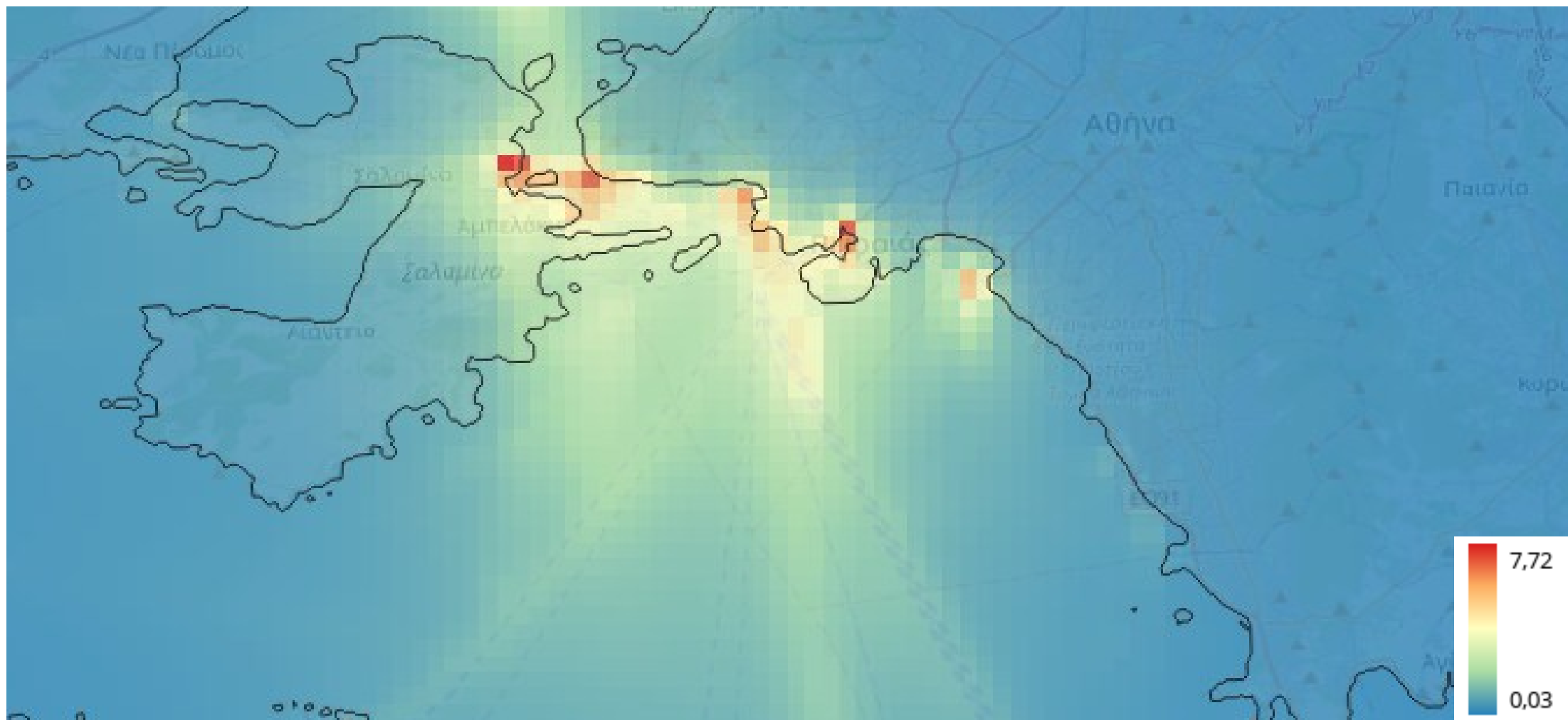
- Drapetsona,
- Chatzikiriakio
- Perama
- Piraeus centre

Selection based on:

- Shipping plume intrusion
- Population density
- Proximity to measuring stations

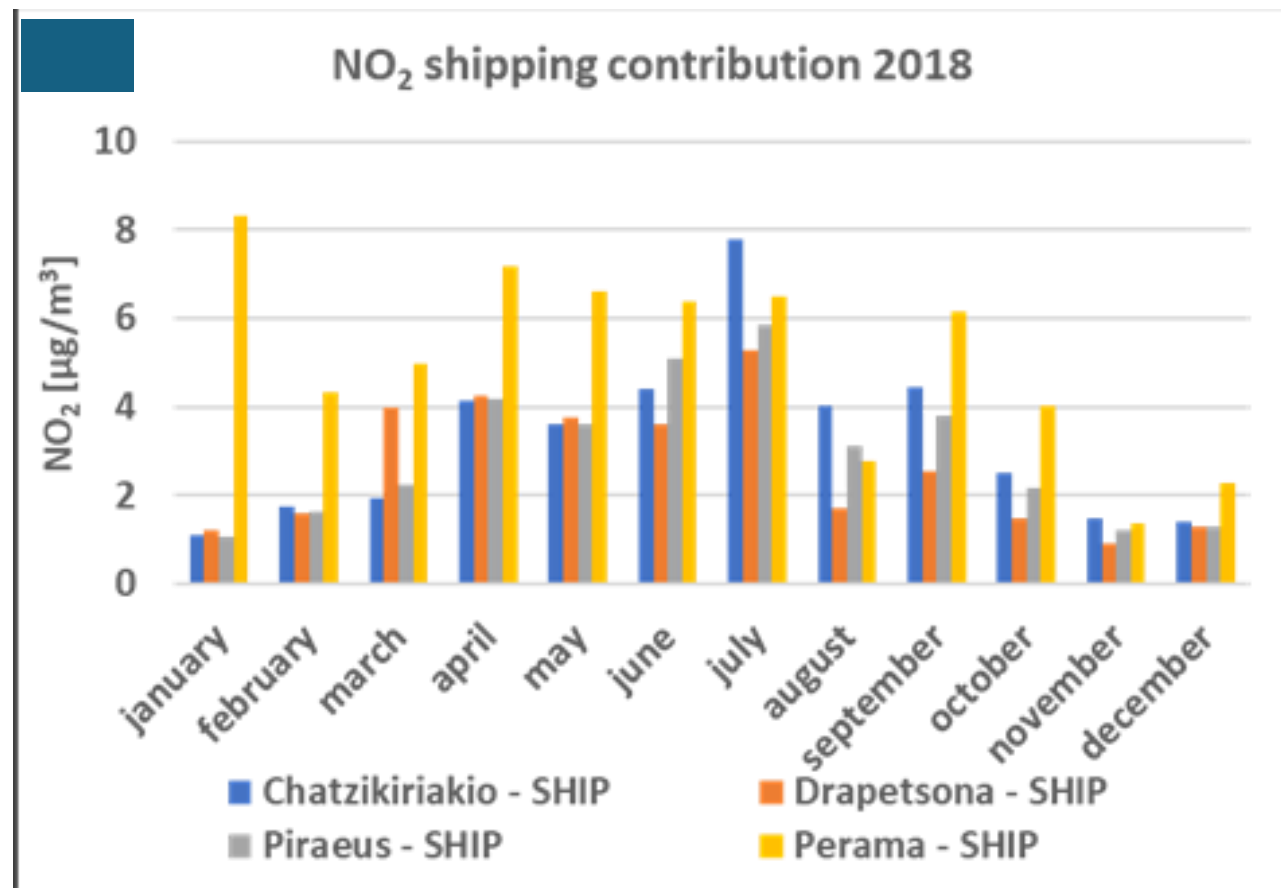


State – Concentrations in hot-spots



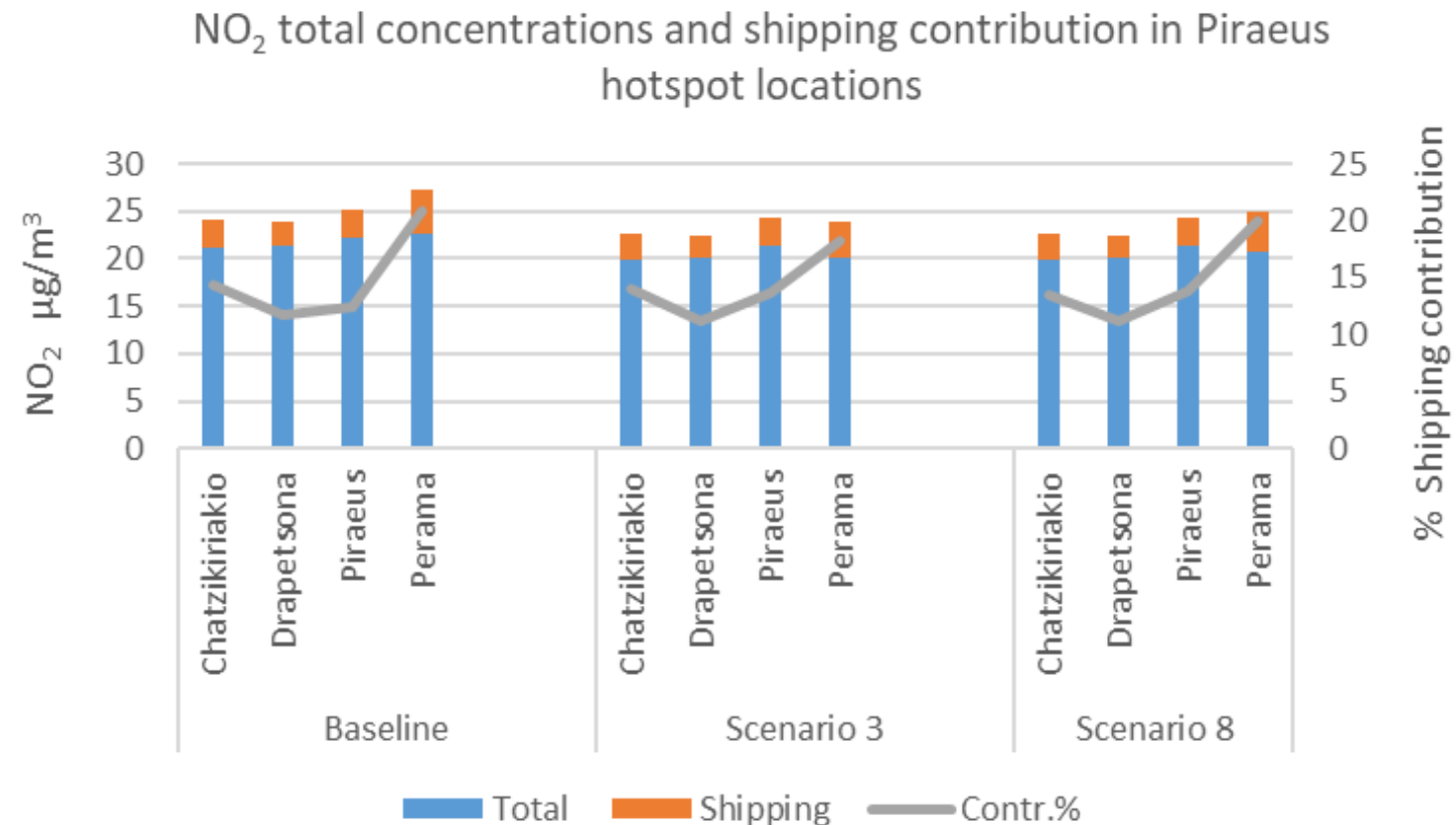
State – Concentrations in hot-spots

- The shipping contribution appears higher during the summer months, with the characteristic July peak in the case of Chatzikiriakio, which is located near the cruise ship terminal.
- In Perama, shipping contribution reaches its highest value in January, due to increased shipyard activities.



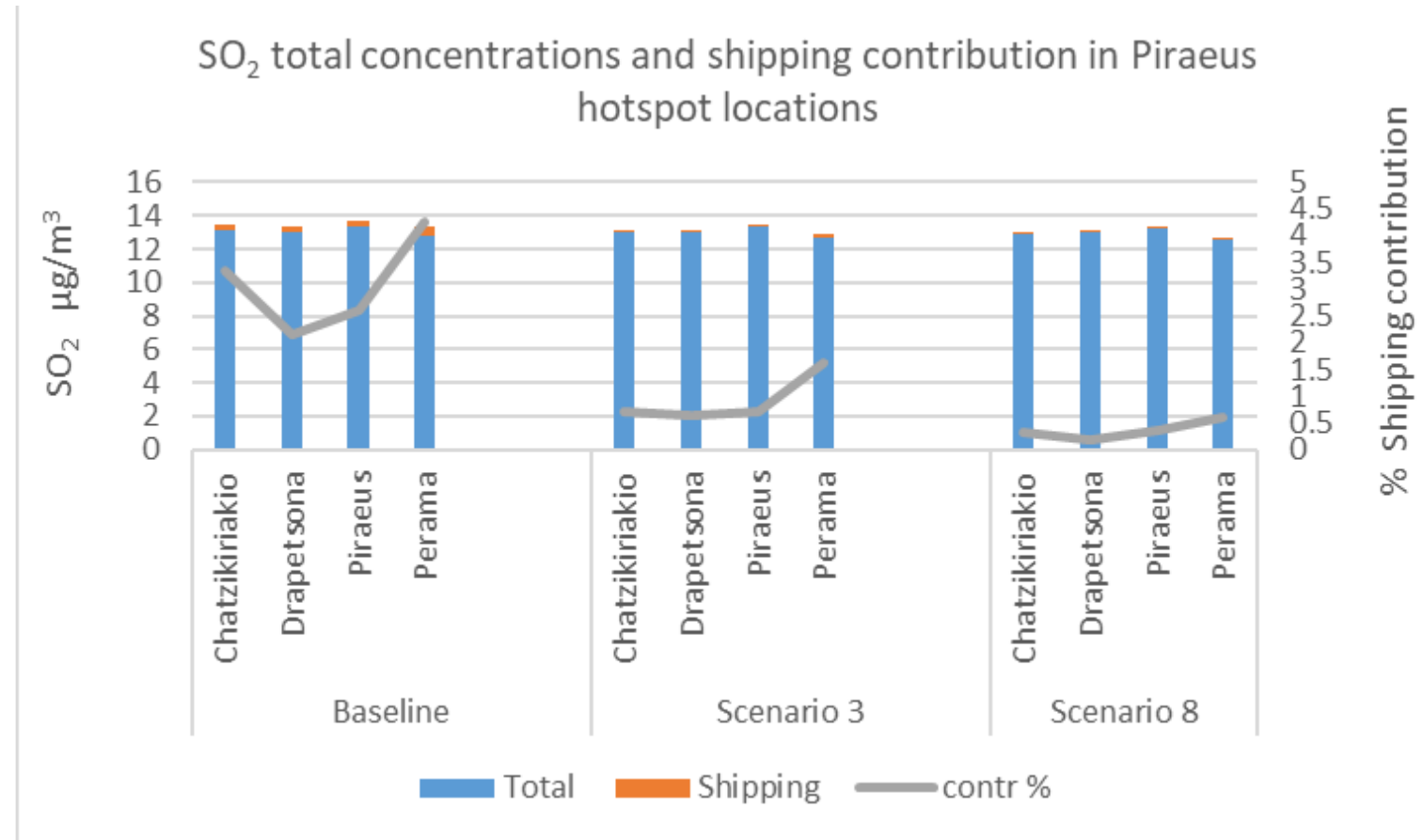
State – NO₂

- For the baseline scenario, highest observed concentrations in Perama (shipyard activities, naval base) and Piraeus (road traffic-affected).
- Shipping contribution to total concentrations also varies significantly between locations, from 21% in Perama to 12% in Drapetsona.
- Introduction of NECA (Scenario 3) causes a notable reduction of shipping contribution in the Perama location (reaching 13%), while the introduction of alternative fuels (Scenario 8) plays a more important role in the cruise-ship-affected Chatzikiriakio (6%).



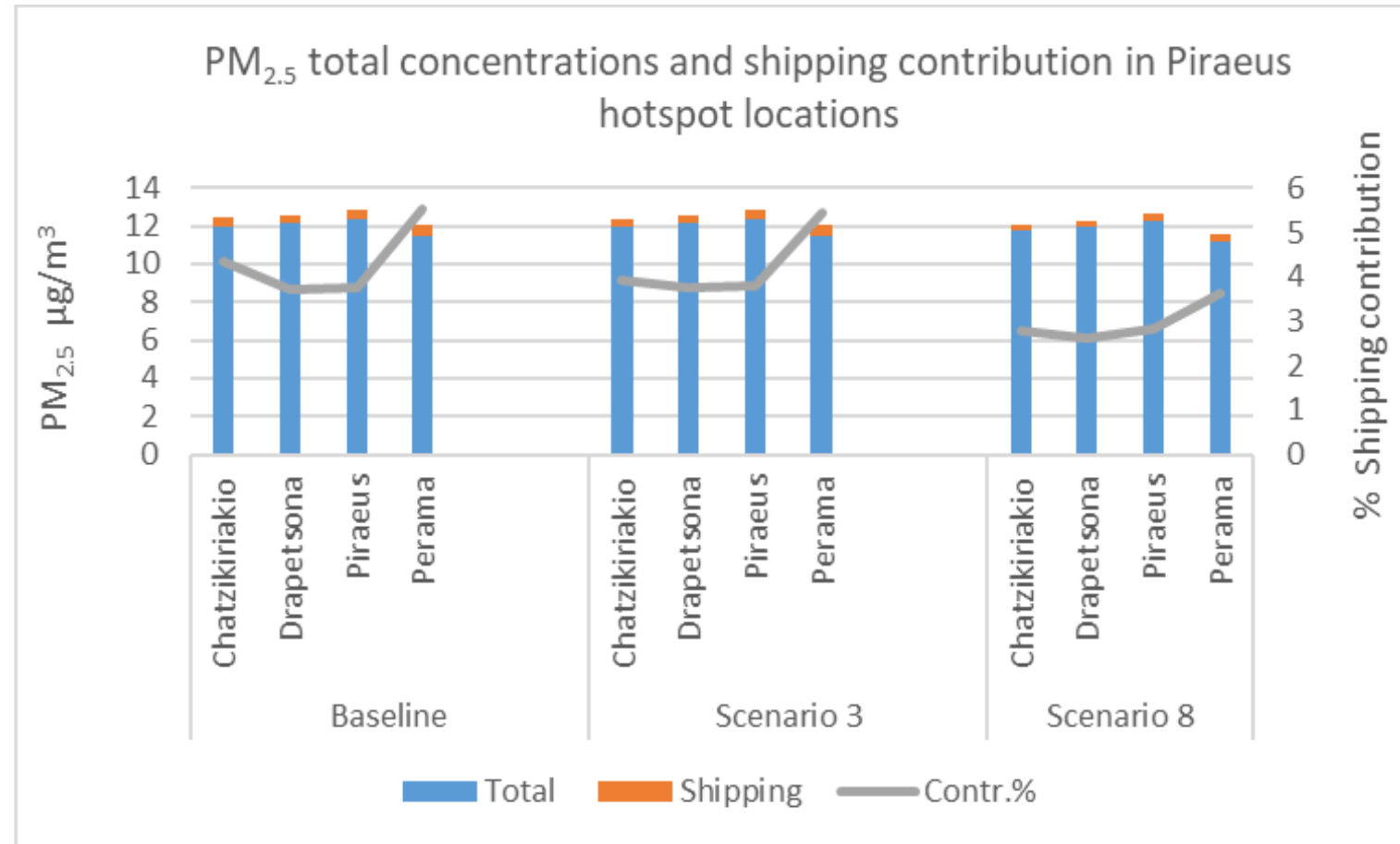
State – SO₂

- Due to the dominant influence of land-based stationary SO₂ sources, the shipping contribution ranges from 2.2% to 4.3%.
- The introduction of alternative fuels is more efficient in reducing SO₂ shipping contribution (89% average across the four locations) compared to the high scrubber Scenario 3 (71% average across the four locations).
- For both scenarios, slightly lower reductions are achieved in Perama compared to the other three hotspot locations.

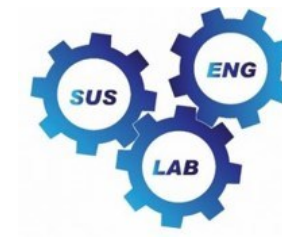


State – PM_{2.5}

- PM_{2.5} shipping contribution remains low ranging between 4% and 6%, mainly due to the presence of strong nearby land sources. Perama is the most affected location
- Scenario 3 induces a reduction of 10% for Chatzikiriakio near the cruise ship terminal, but much smaller reductions of the order of 0-1.4% in the other three areas.
- The introduction of alternative fuels under scenario 8 is causing a larger reduction of PM_{2.5} concentrations in all four hotspots, ranging from 25% in Piraeus to 36% in Chatzikiriakio.



Conclusions



- Research on air quality modelling and assessment at SEL/AUTH and LAT/AUTH is focusing on **multiscale approaches**, **high-resolution** urban modelling and detailed **emission inventories**.
- Approaches **combining process-based** atmospheric modelling and **surrogate models** are actively developed and evaluated.
- Microscale and mesoscale models **can now be coupled** and provide a robust **alternative** to roughness-based approaches → MEMICO, PLOTO
- The **shipping sector** has emerged as a major focus of air quality research, in view of **new technical solutions and regulations** → SCIPPER, EMERGE
- Newly-developed **emission factors for shipping** necessitate a combined top-down and bottom-up approach for shipping emissions, particularly for **emerging pollutants** → REALCHEM

