

Observation, Simulation, and Learning for Offshore Wind Wake Dynamics

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Motivation and Introduction

Understanding offshore wind farm wakes requires integrating multiple observational and modelling approaches, as wake effects are:

- **multi-scale** and spatially heterogeneous,
- governed by **atmospheric dynamics and turbine interactions**,
- and not directly observable by a single sensing modality.

We develop a multi-source framework for wake detection and analysis:

- **Observe:** satellite-based SAR for large-scale wake detection,
- **Model:** mesoscale modelling (WRF) for physical interpretation,
- **Learn:** data-driven methods for wake impact assessment.

This enables consistent detection, physical understanding, and quantitative analysis of offshore wind farm wake effects across scales.

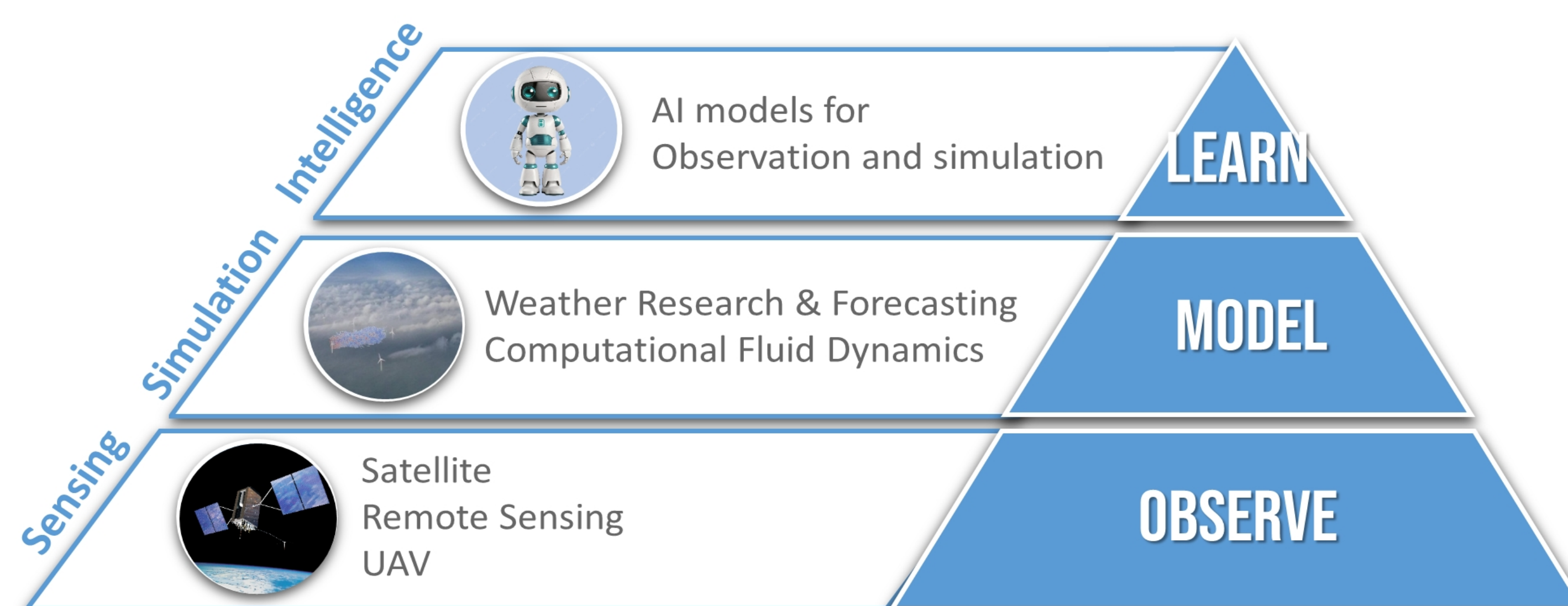


Figure 1: Integrated Framework: Observe-Model-Learn

1) Observation of Near-Surface Wake Interactions

Global-scale satellite observations indicate wind farm wakes can extend beyond **100 km**, with a systematic wind speed deficit of ~ 0.99 m/s (12.4%).

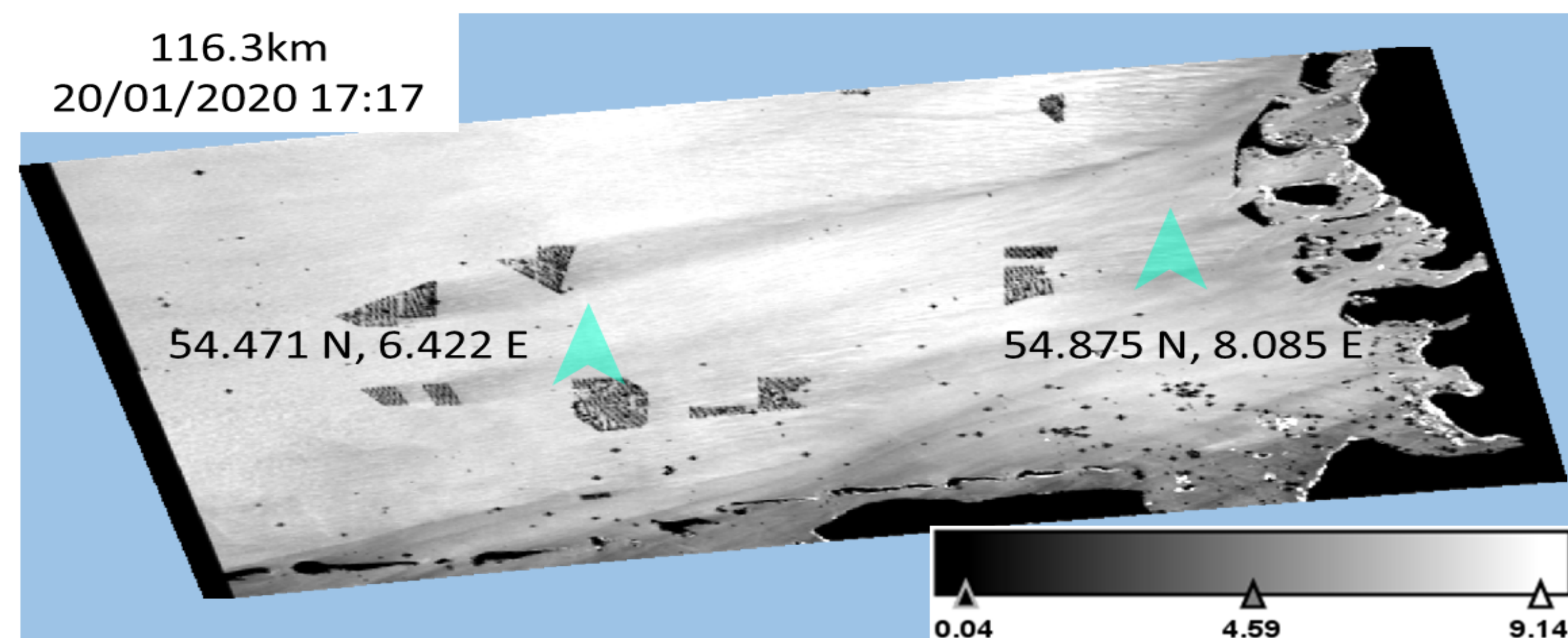


Figure 2: SAR image showing long-range wake effects (>100 km).

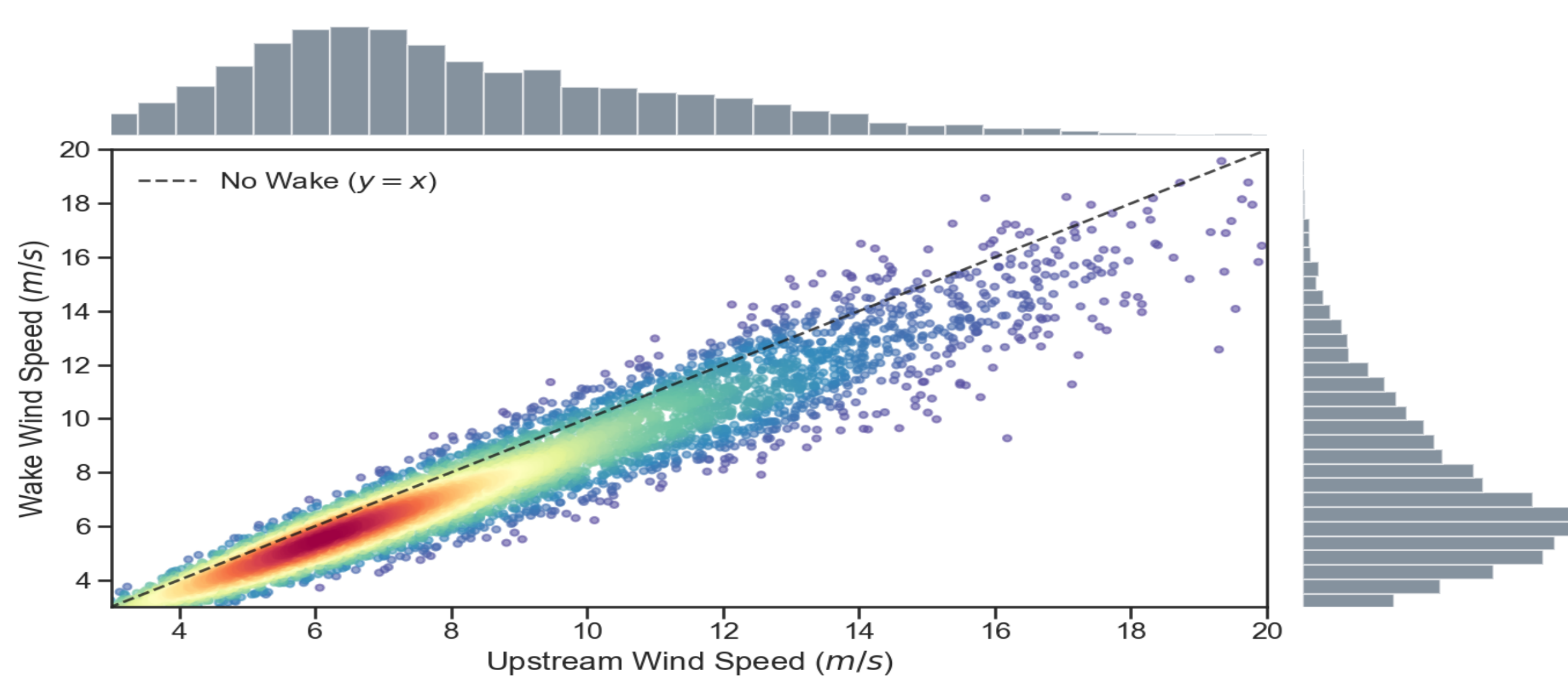


Figure 3: Statistical relationship between upstream and wake wind speeds.

2) AI-Enhanced Wake Dynamics Modelling

Physics-based models are **accurate** but **expensive**, while simplified models are **efficient** but **limited**. We develop AI models to bridge this gap for **fast** and **scalable** wake dynamics prediction.

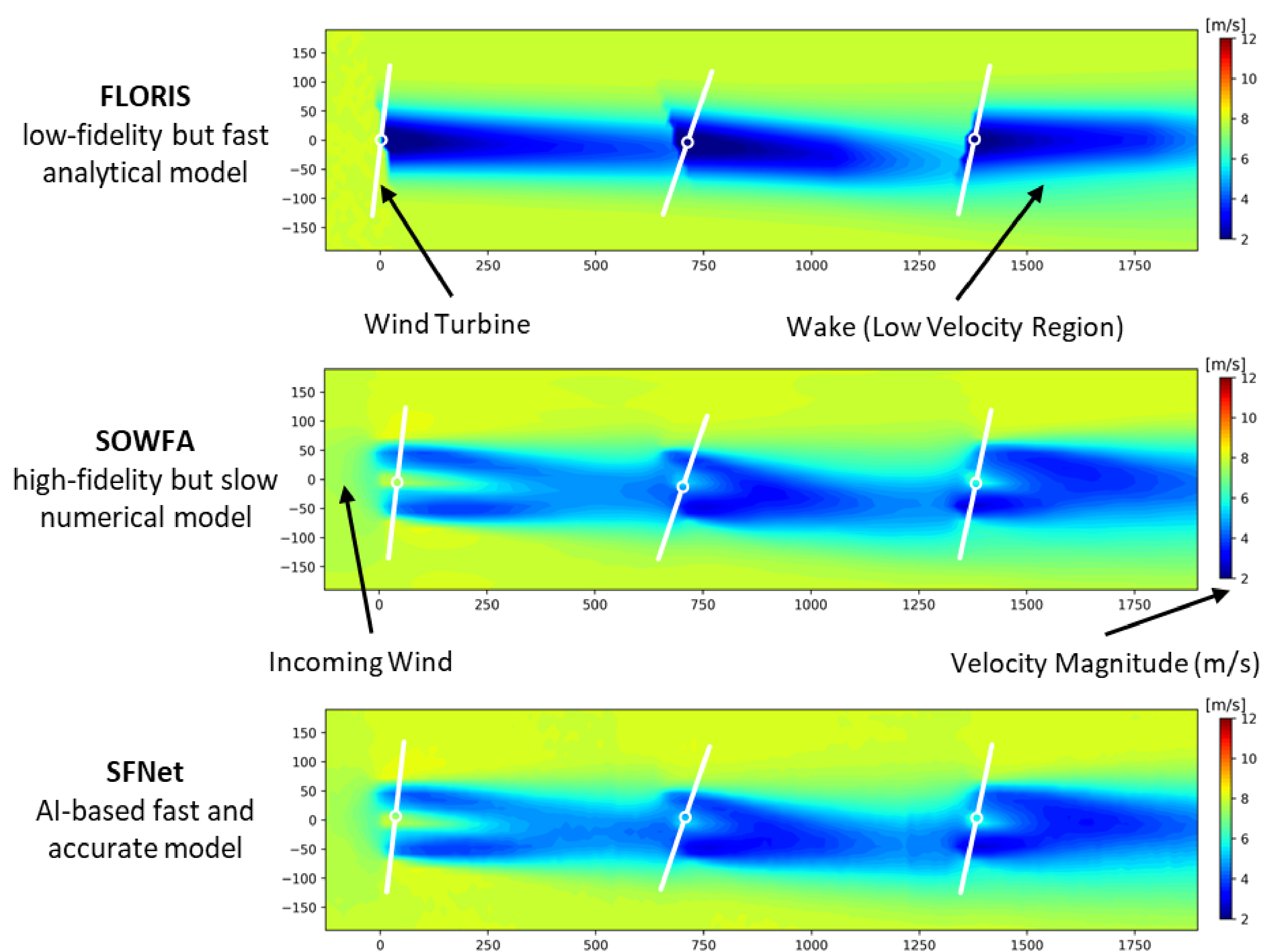


Figure 4: AI-based models capture complex wake structures with accuracy comparable to physics-based simulation, while enabling significantly faster prediction and bridging the gap between CFD and low-fidelity models.

3) Bridging Satellite Observation and WRF Simulation for Offshore Wind Wakes

Satellite observations reveal large-scale wake effects from offshore wind farms, but lack physical interpretability. Using the WRF model, we show that turbine parameterization is essential to reproduce these wake structures. This observation-simulation consistency confirms that wake effects are physically driven and can be captured at the mesoscale, enabling system-level impact assessment.

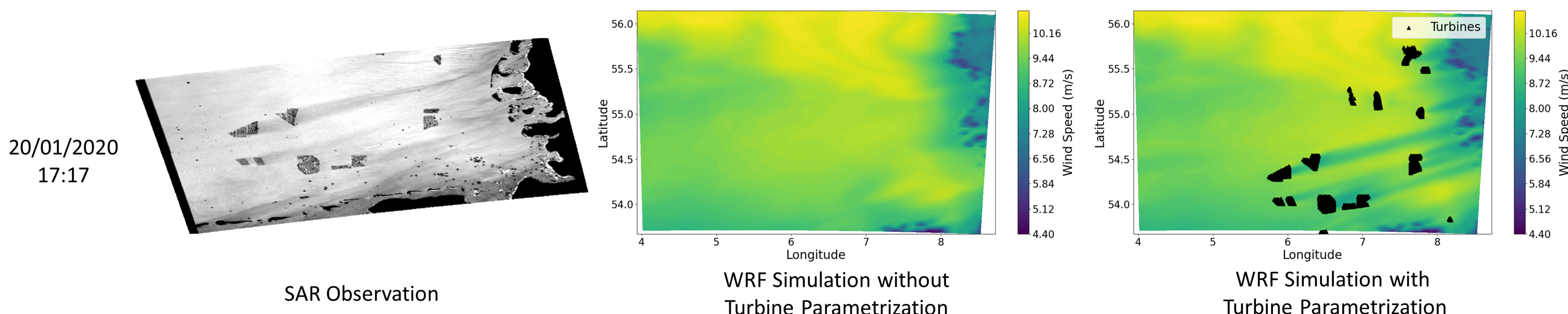


Figure 5: Consistency between satellite observation and mesoscale simulation. Left: SAR-derived wind field showing wake signatures downstream of offshore wind farms. Middle: WRF simulation without turbine parameterization fails to capture wake structures. Right: WRF simulation with turbine parameterization reproduces wake patterns consistent with observations.