Scenario-Based and Climate-Adjusted Projections of $PM_{2.5}$ and SO_2 to 2050

Chemical Transport Modelling Evidence from Western Kazakhstan

Vitaly Salnikov | Al-Farabi Kazakh National University (KazNU)

PEEX Online Seminar

A Nexus of Industry and Climate

1

Industrial Density

High concentration of intensive oil and gas developrnent serving as primary point sources.

2

Data-Sparse Geography

Vast regions with dispersed emission sources sitting largely outside the traditional terrestrial monitoring network.

3

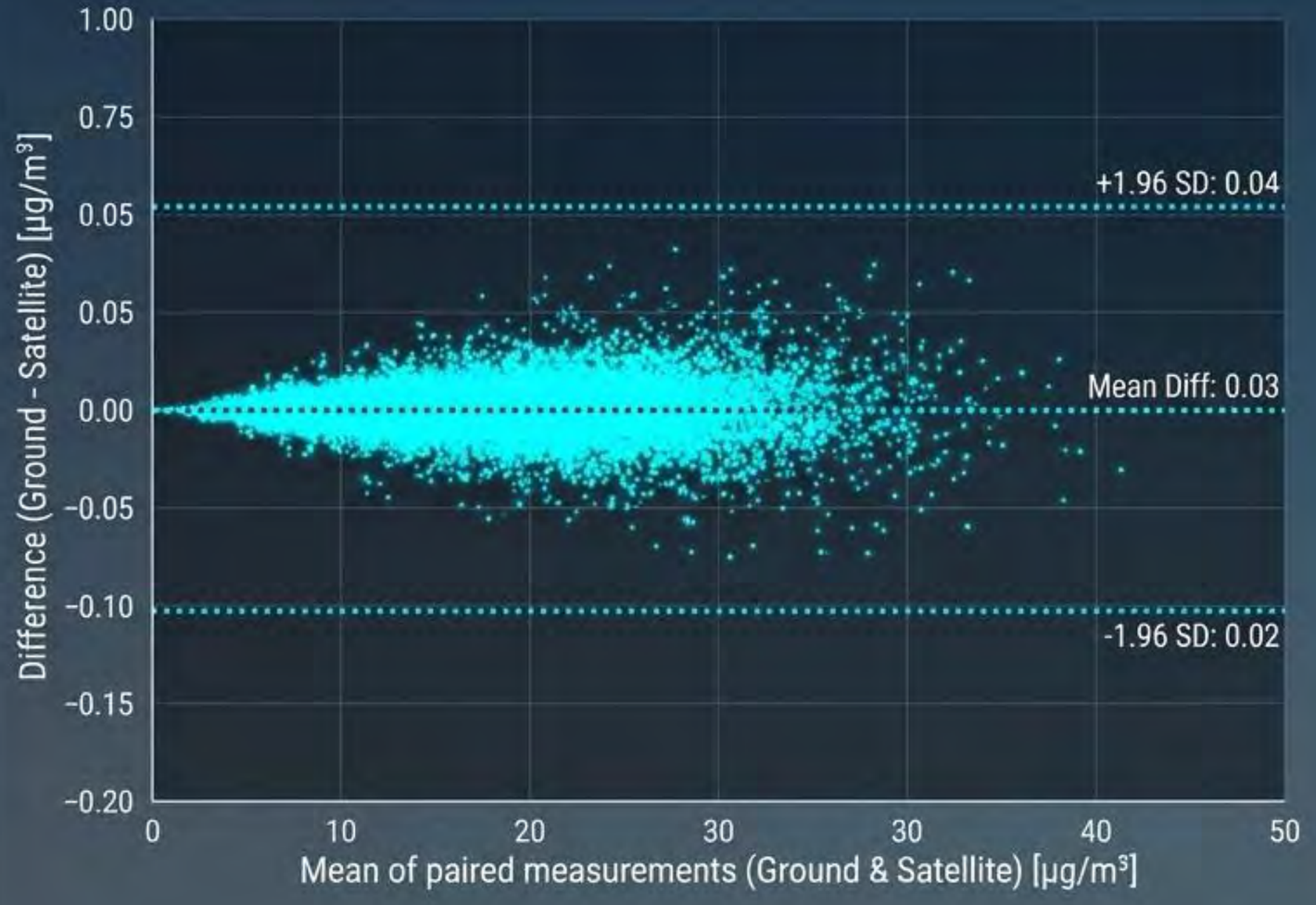
Meteorological Variability

Sharply continental climate with strong temperature inversions and wind fields driving complex, long-range pollution transport.

From Observation to Projection: An Integrated Approach

Bridging the gap in data-sparse regions by locking satellite observations to ground truth, then driving forward-looking chemical transport models.

Establishing Trust: Sentinel-5P Validation



Methodology

Bland-Altman analysis quantifying systematic bias and statistical agreement to calibrate regional satellite retrievals.

SO_2 Bias

0.007–0.015 µg/m³ (High spatial agreement).

NO_2 Bias

0.025–0.030 µg/m³ (Highest consistency across all pilot cities).

CO Variance

Exhibits the widest confidence intervals, driven by long atmospheric lifetimes and uniform surface distribution.

Beyond the Ground Stations: Capturing Spatial Anomalies

A Getis-Ord Gi* Hotspots

Getis-Ord Gi*: Identifies highly significant, localized pollution hotspots perfectly aligned with industrial point sources (e.g., Tengiz field, Atyrau CHPP).

B Interquartile Range (IQR) Anomalies

IQR Analysis: Exposes stable, persistently contaminated SO_2 outlier zones extending far beyond the reach of existing ground station infrastructure.

Divergent Futures: Defining the 2050 Scenarios

Decrease Scenario

Economic Focus

Deep decarbonization and economic diversification.

Emission Strategy

Aggressive Carbon Capture and Storage (CCS) integration, 50% renewable energy transition.

CO_2 Impact

-23% reduction.

Base Scenario

Economic Focus

Inertial growth following current trajectories.

Emission Strategy

Moderate, slow-paced technological adoption.

CO_2 Impact

Stabilized baseline output.

Rapid Growth

Economic Focus

Intensified hydrocarbon extraction and industrial output.

Emission Strategy

Lax regulation, prioritization of gross production.

CO_2 Impact

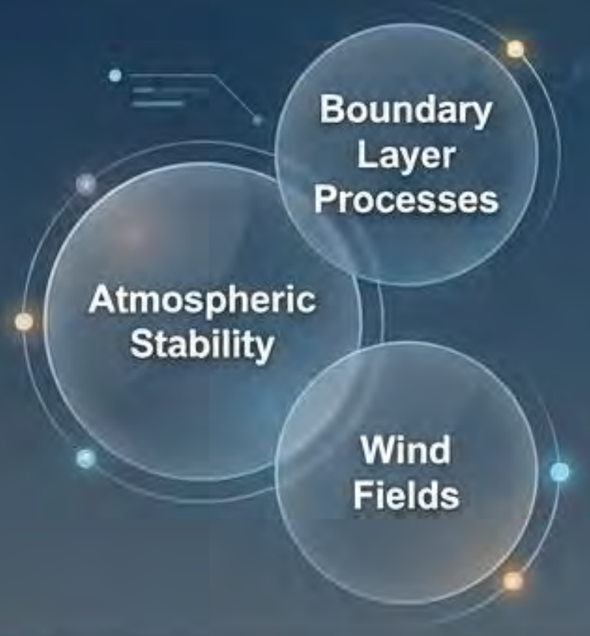
Massive industrial expansion.

Modulating Factors: The Climate-Adjusted Component

Key Takeaway: Future air quality is not purely emission-driven; it is deeply **climate-modulated**. The climate factor (CF) reaches 1.05 by 2050.

+2°C to +4°C by 2050

+5% to +10% precipitation



Temperature Penalties

+2°C to +4°C spikes exponentially alter photochemical reactions, increasing secondary aerosols and driving a 15-25% increase in PM2.5 dust in arid zones.

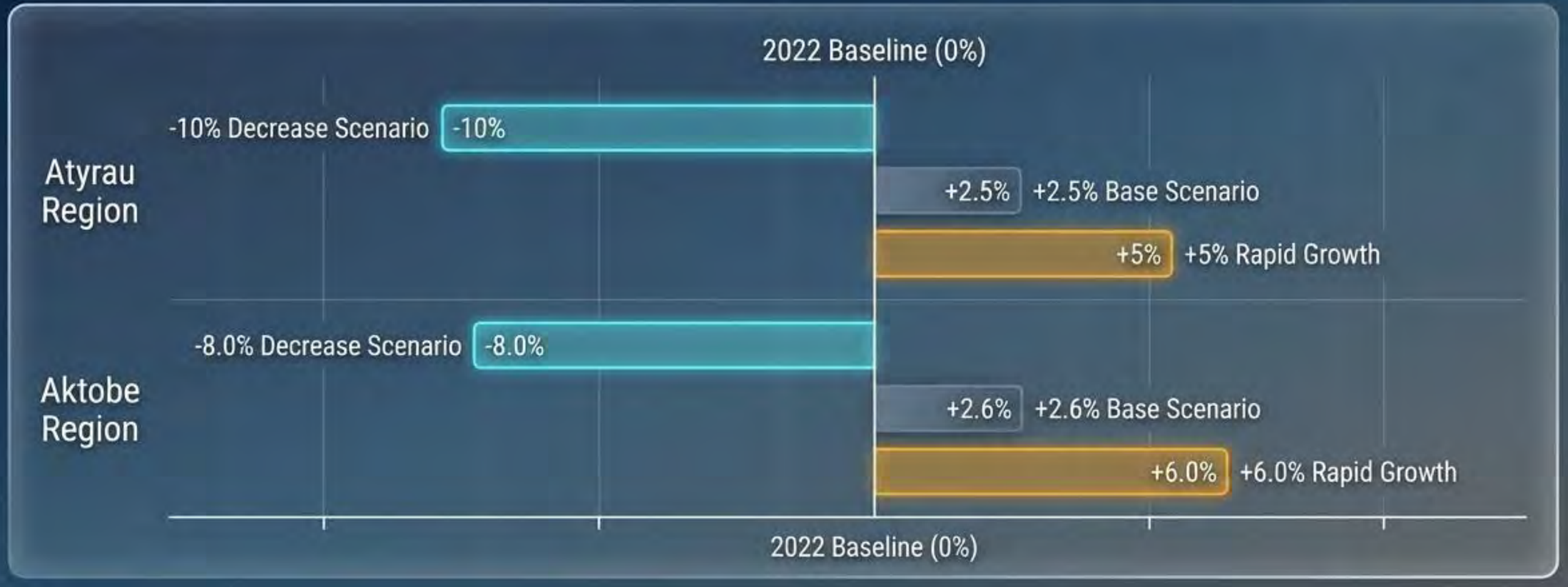
Precipitation Effects

Increased rainfall acts as a dampener, effectively reducing PM2.5 via washout in specific agricultural sub-regions.

WRF-CHIMERE: Simulating Atmospheric Composition

A high-resolution regional atmospheric model coupled with a chemical module to capture precise physical-chemical transformations of pollutants, spatial dispersion, and atmospheric decay out to 2050.

PM2.5 to 2050: Driven by Dust and Industry



Key Insight

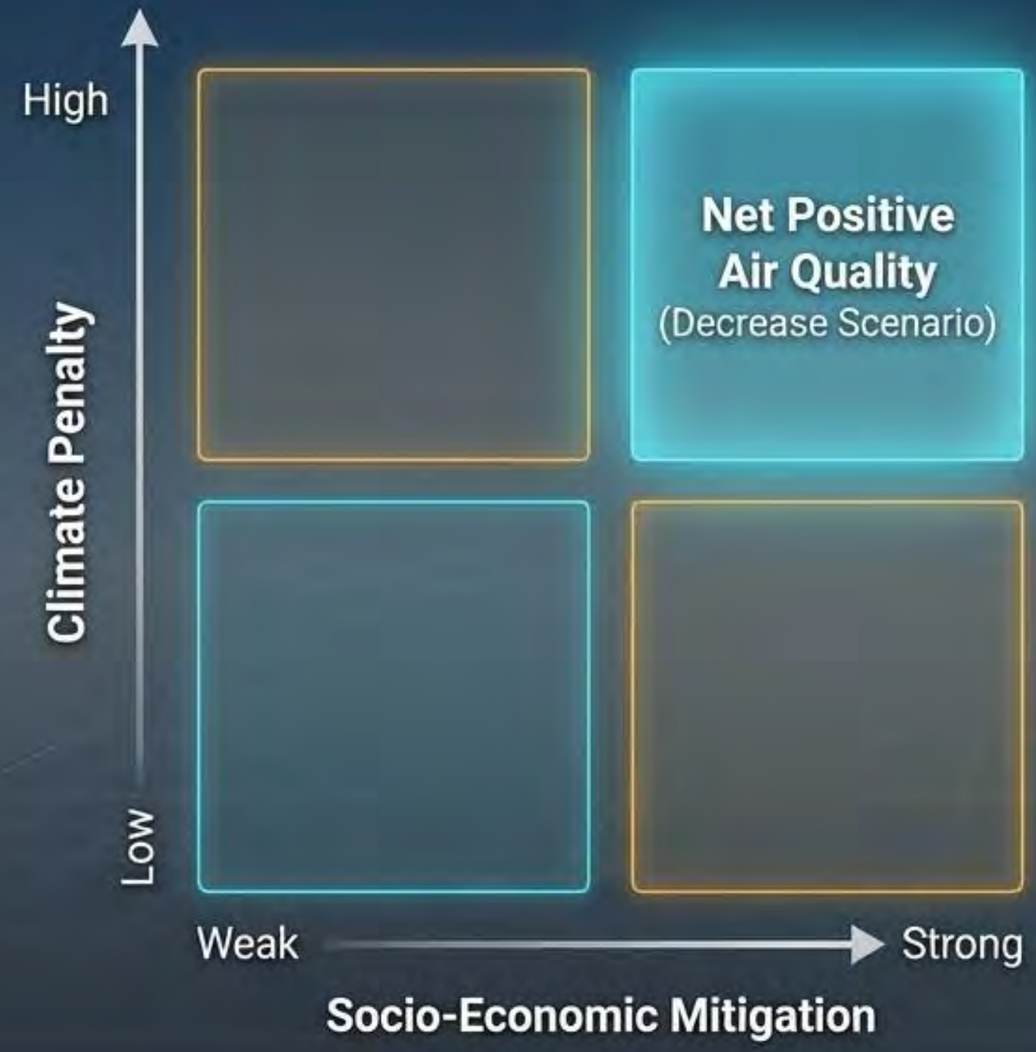
The Decrease scenario achieves up to a 10% reduction in Atyrau, overcoming the severe climate penalty (temperature-driven dust increases) only through aggressive industrial mitigation.

SO_2 to 2050: The Impact of Decarbonization

Key Insight

SO_2 is intensely sensitive to socio-economic pathways. Atyrau projects a massive 20% reduction under the Decrease scenario, validating the localized effectiveness of decarbonizing the energy and refining sectors.

Synthesis: Navigating the 2050 Horizon



The Baseline Reality

Satellite validation (Bland-Altman) guarantees our starting point is accurate, bypassing the limitations of sparse ground networks.

The Atmospheric Friction

Climate adjustments (+Temperature, +Precipitation) will actively fight against air quality improvements, acting as a multiplier on PM2.5.

The Required Trajectory

WRF-CHIMERE proves that only the aggressive Decrease scenario can outpace the climate penalty and yield definitive air quality improvements by 2050.


Shaping the Future of
Central Asian Air Quality
Validated Observations • Integrated Modeling • Actionable Scenarios
Thank you for your attention.
Floor open for questions regarding WRF-CHIMERE
parametrizations, satellite validations, or regional trajectories.
Vitaly Salnikov | Al-Farabi Kazakh National University (KazNU)