Time Series Forecasting of Methane Gas in Underground Coal Mines

Zach Agioutantis & Steven Schafrik

University of Kentucky, Lexington, Kentucky, USA

Juan Díaz

Nevada Gold Mines LLC, Elko, Nevada, USA

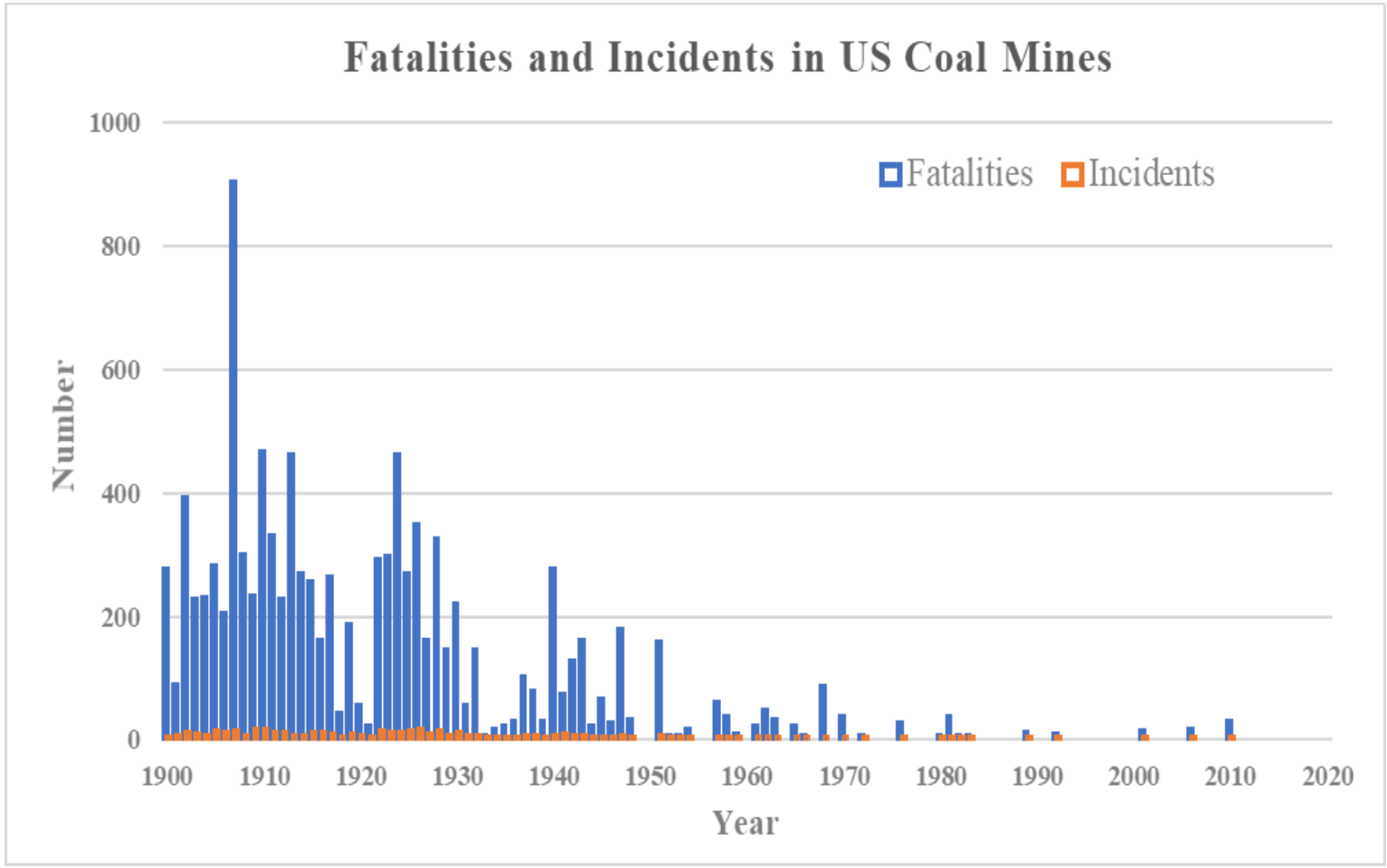
Outline

1. Introduction
2. Objectives
3. Case Studies
4. Data Management and Analysis
5. Results and Discussion
6. Conclusions and Recommendations

Fatalities and Incidents in Underground US Coal Mines since 1900

(NIOSH, 2022)

- Methane gas explosions
  - 80% of incidents
  - 90% of the fatalities
- 11,500 fatalities
- 500 accidents



Agioutantis Z., Schafrik S., Diaz J. (PEM 2023)

Methane Gas Explosions in Underground Coal Mines

- Listvyazhnaya coal mine - Russia
  - November 2021
  - 52 fatalities
- Soma coal mine - Turkey
  - May 2014
  - 300 fatalities

Objectives

- To investigate the correlation between methane gas emissions, barometric pressure, and coal production
- To develop a methane gas forecasting model(s) based on time series analysis to prevent accidents and fatalities due to methane gas explosions in underground coal mine operations.

Comparison of Coal Mine Methane Forecast Approaches

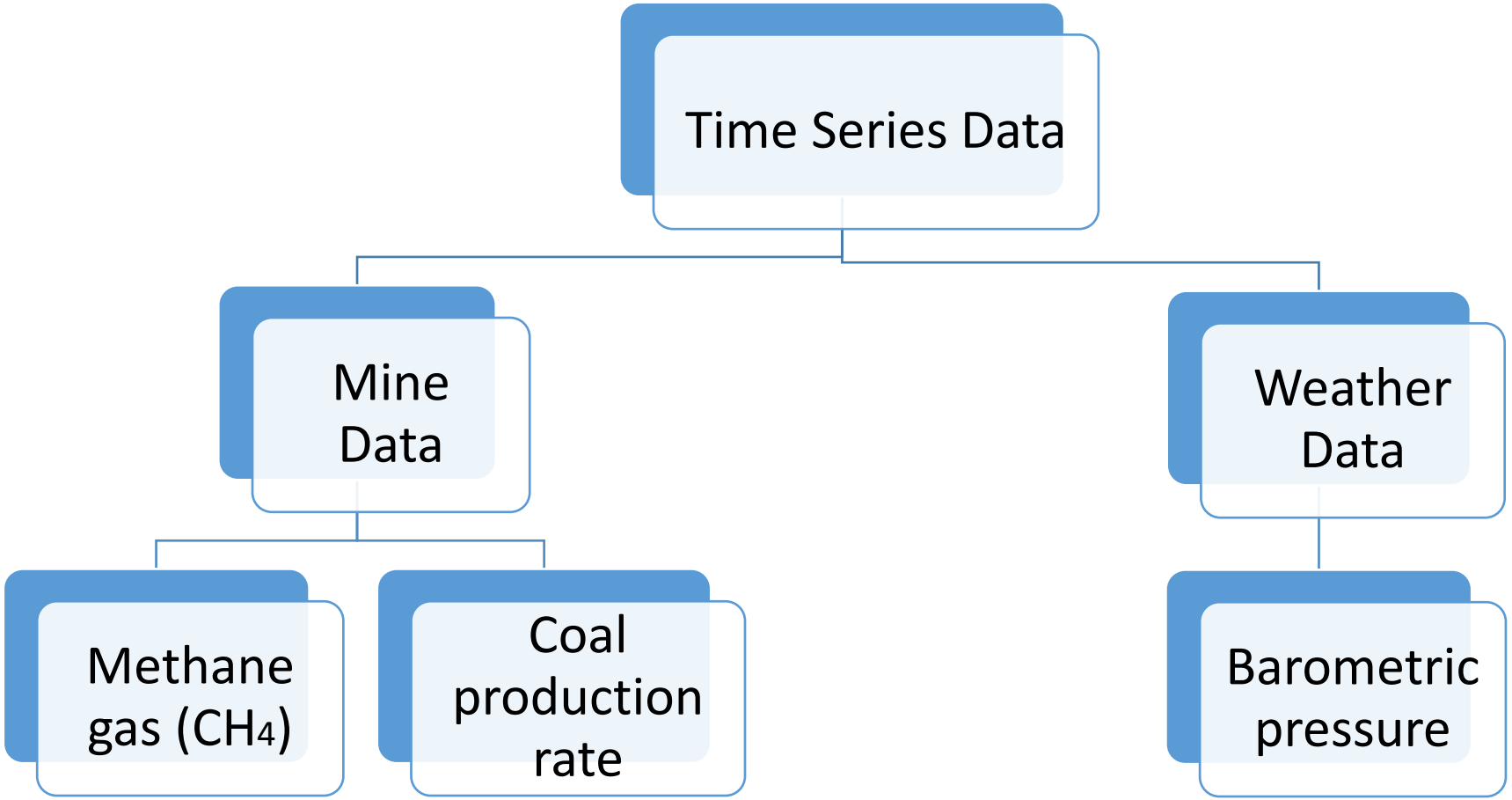
Empirical and Numerical Approaches

- Expensive
- Time-consuming
- Not broadly implemented
- Data collection is challenging
- Previous knowledge is needed

Statistical Approach

- Less expensive
- Less time-consuming
- Easily generalized
- Focuses on statistical interpretation

Collected Data



Data Sources

- Three case studies
- Mines A, B, and C
- Active mines in the Eastern US

Barometric Pressure Data

- Weather Underground (WU)
- Public weather channel
- Three weather stations

Time	Temperature	Dew Point	Humidity	Wind	Speed	Gust	Pressure	Precip. Rate.	Precip. Accum.
12:04 AM	28.4 °F	25.5 °F	88 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:09 AM	28.4 °F	25.5 °F	88 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:14 AM	28.3 °F	25.2 °F	87 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:19 AM	28.1 °F	25.2 °F	88 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:24 AM	27.9 °F	25.1 °F	88 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:29 AM	27.8 °F	25.1 °F	88 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:34 AM	27.8 °F	25.5 °F	89 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:39 AM	27.8 °F	25.5 °F	89 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:44 AM	27.6 °F	25.3 °F	89 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:49 AM	27.6 °F	25.2 °F	89 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:54 AM	27.4 °F	24.9 °F	89 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in
12:59 AM	27.0 °F	24.9 °F	90 %	ESE	0.0 mph	0.0 mph	30.21 in	0.00 in	0.00 in

Data available from the Weather Underground stations

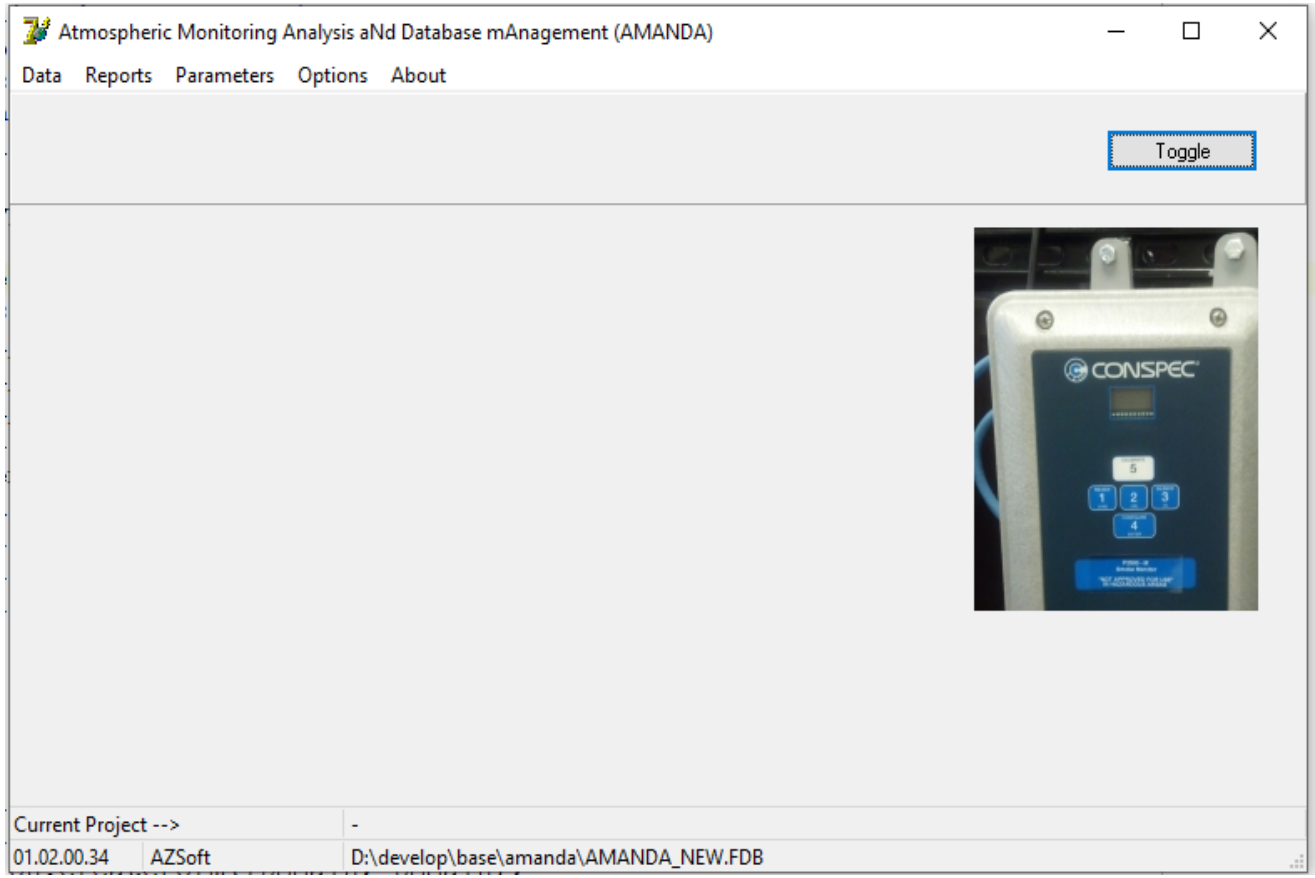
Data Summary

Source	Parameter	Approx. Frequency	Approx. Records	Data Length (years)	Units
Mine A	CH_4 conc.	Hourly	55,000	6 con.	%
	Coal Production	Daily	2,300	6 con.	Tons
Mine B	CH_4 conc.	10 sec	3 mil/year	9 non-con.	%
Mine C	CH_4 conc.	Weekly	374	7 non-con.	%
Nearest Weather Station	BP-Mine A	Hourly	55,000	6 con.	InWG
	BP-Mine B	Hourly	78,000	9 con.	InWG
	BP-Mine C	Hourly	61,000	7 con.	InWG

Data Storage and Management - AMANDA

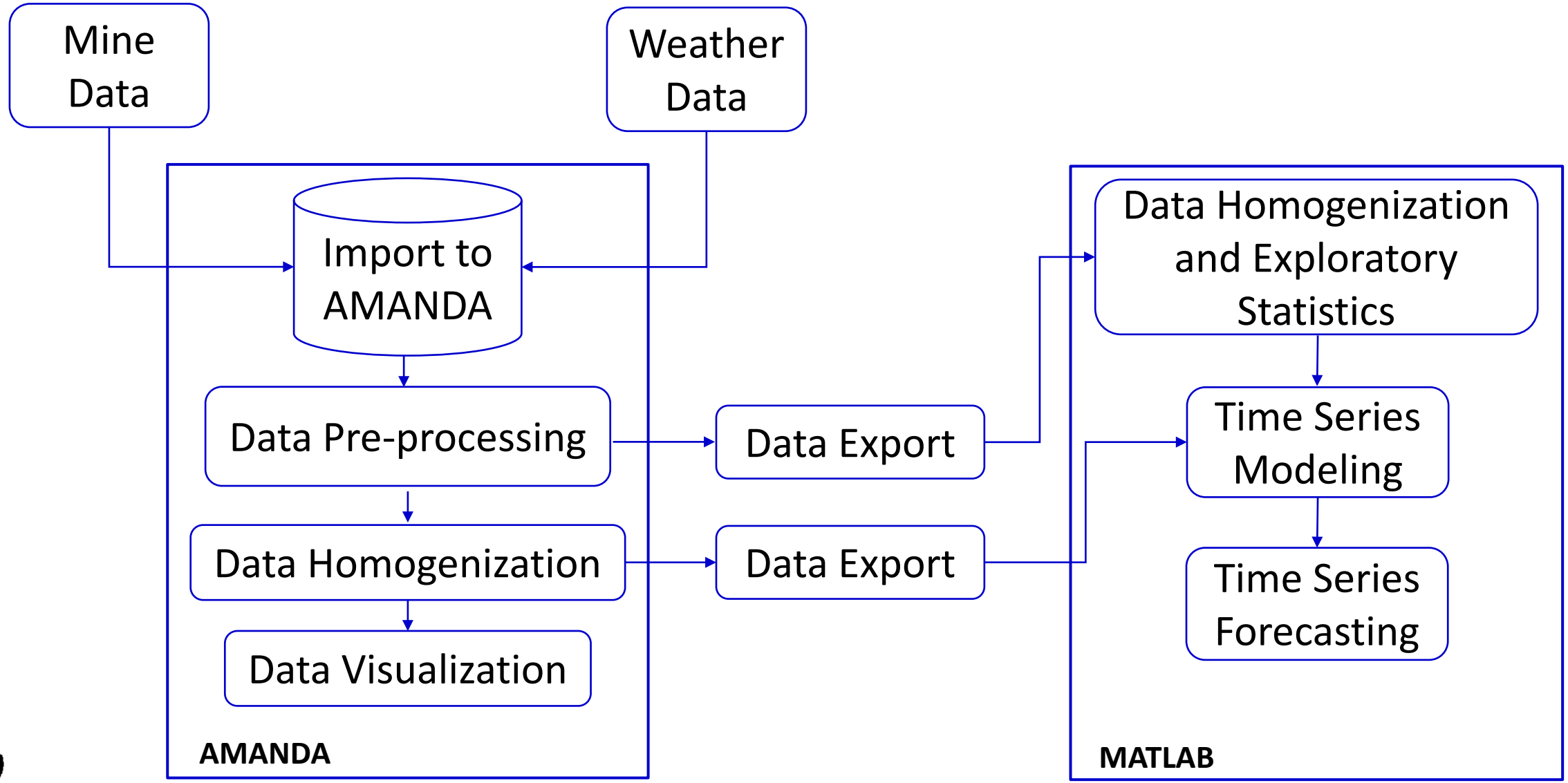
Development of a custom relational database designed to manage atmospheric data

The AMANDA (Atmospheric Monitoring Analysis and Database mAnagement) system currently holds over 200 million data records.

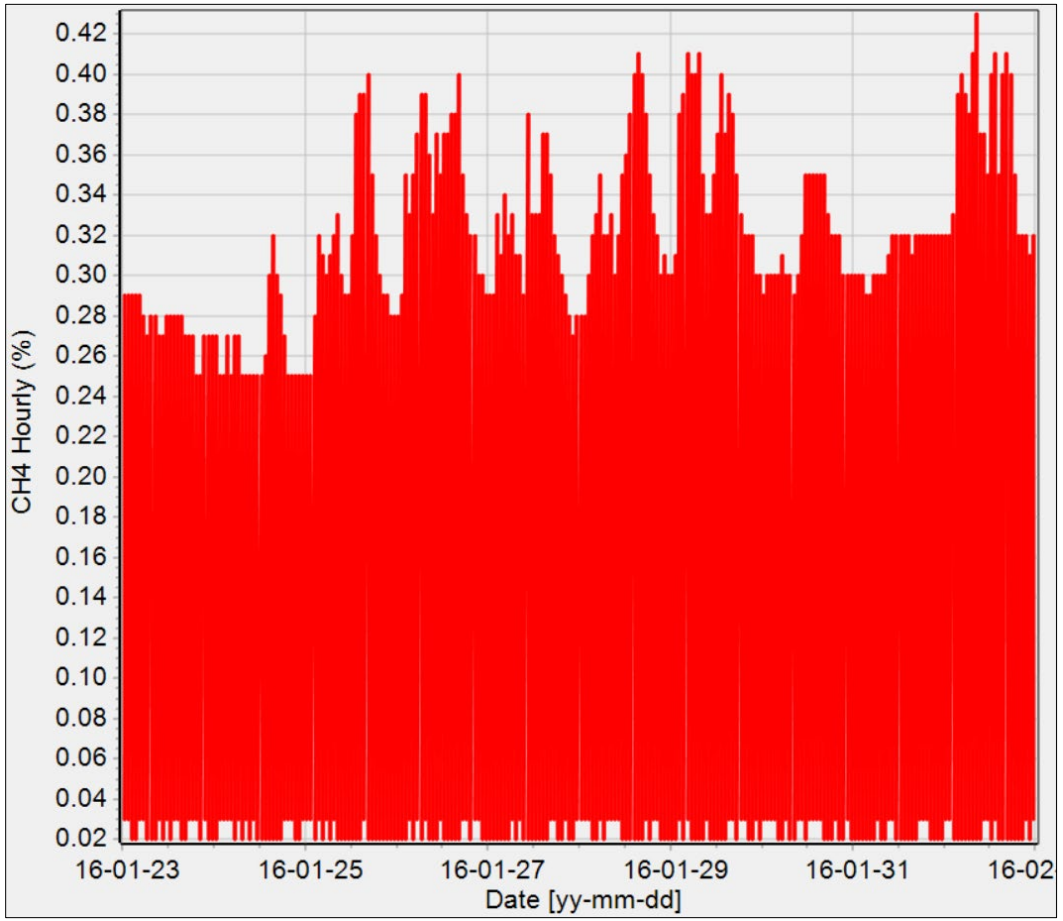


AMANDA main menu

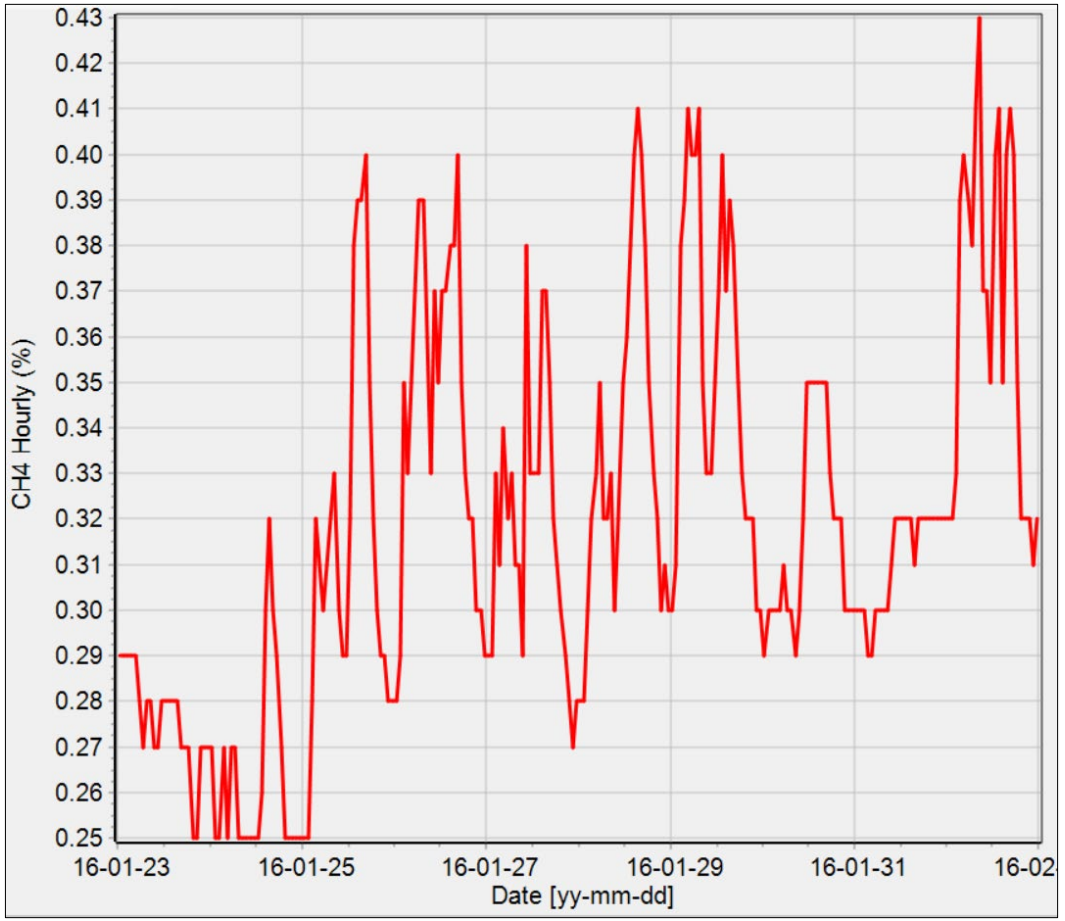
Data Management and Analysis



Data Pre-processing – Methane Gas (1/2)

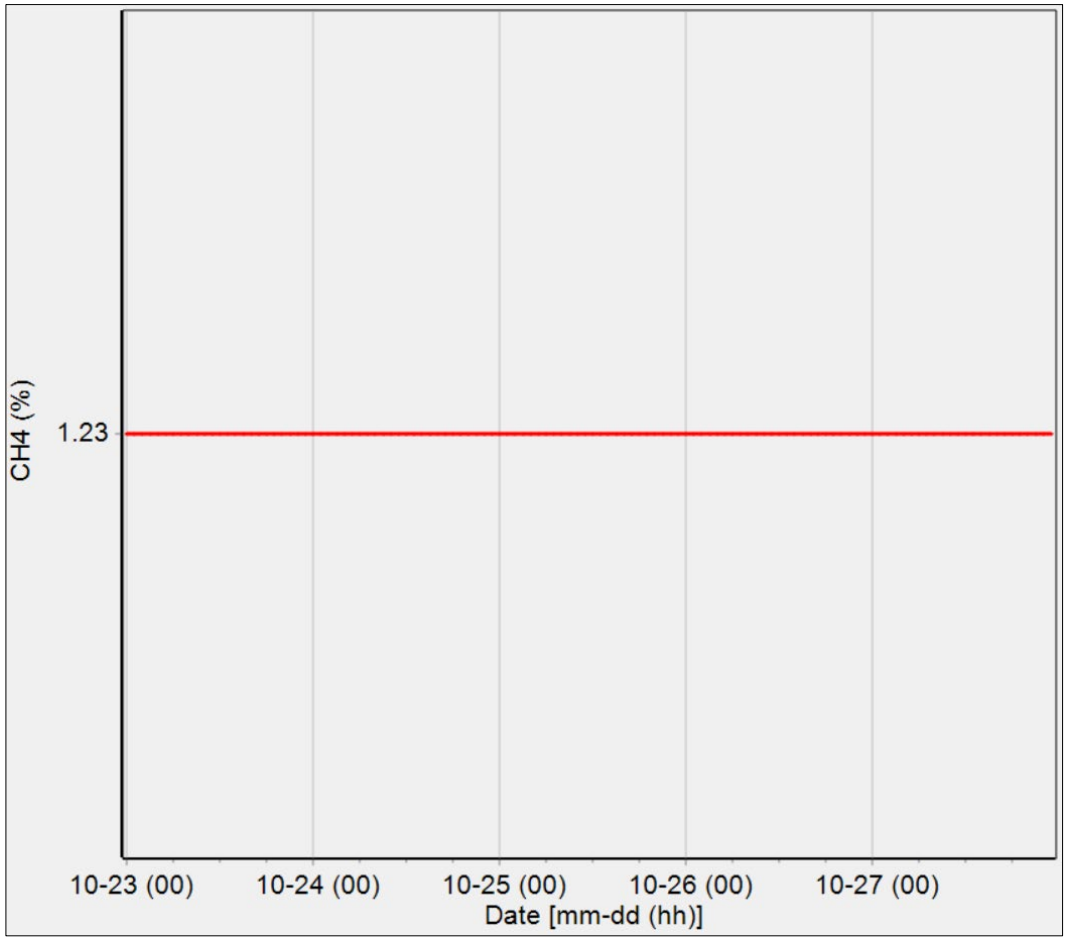


Raw CH_4 data from Mine A (before filtering)

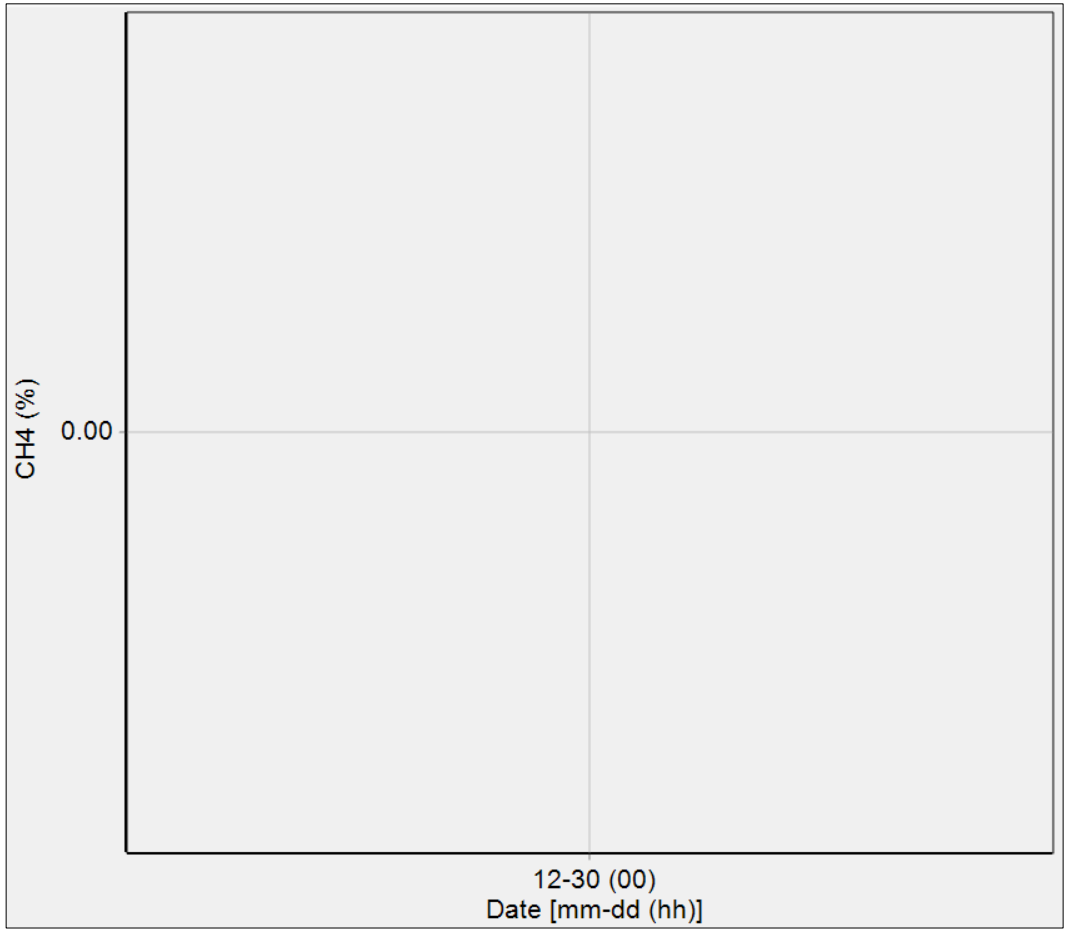


CH_4 data from Mine A (after filtering)

Data Pre-processing – Methane Gas (2/2)

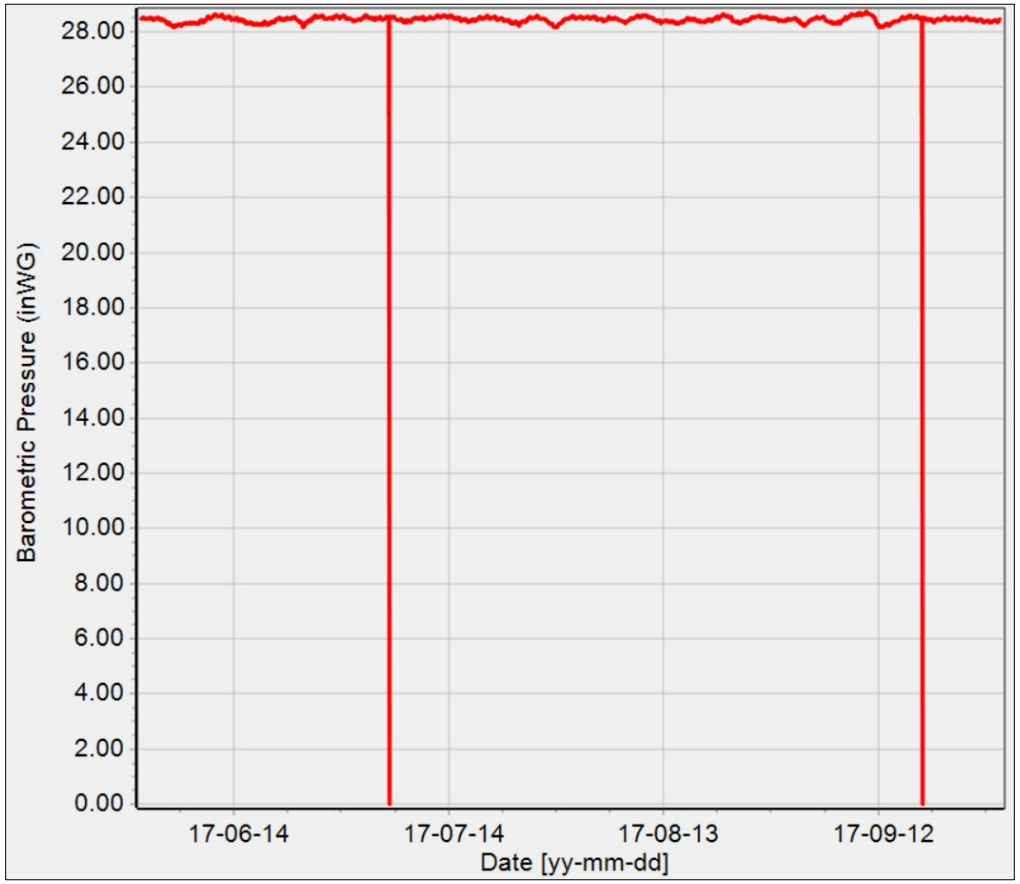


Unreliable CH_4 data

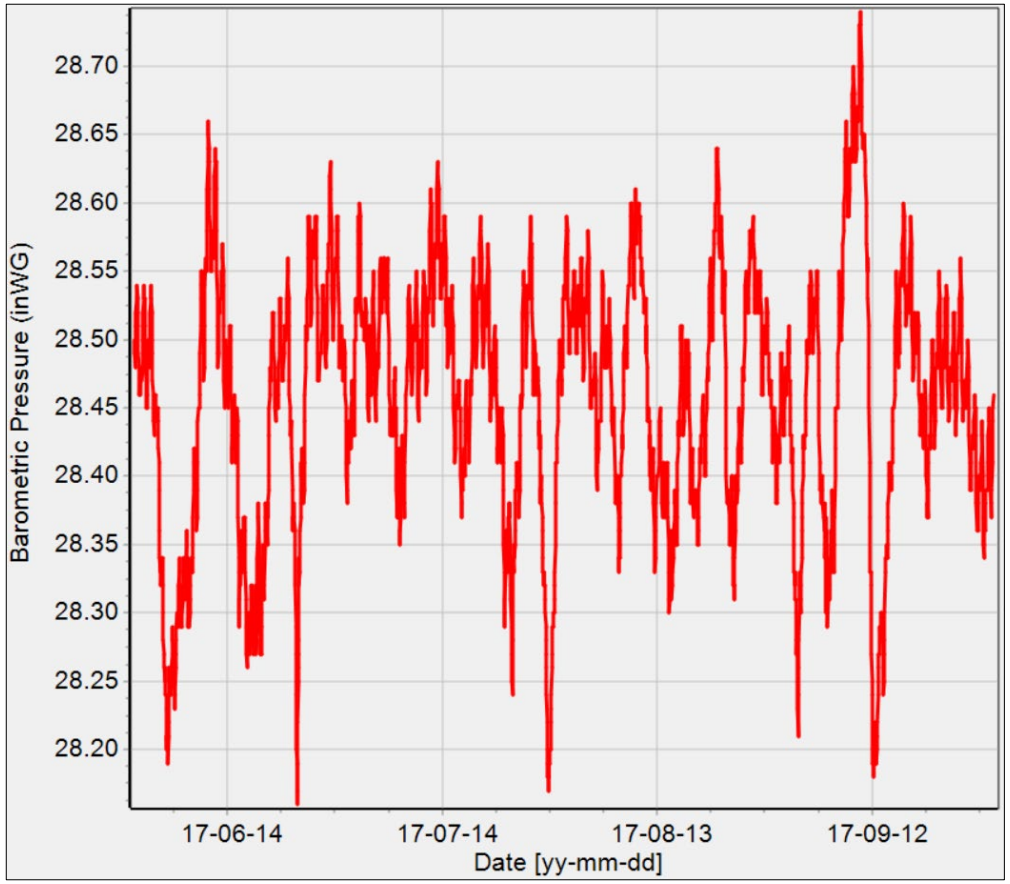


Missing CH_4 data

Data Pre-processing – Barometric Pressure

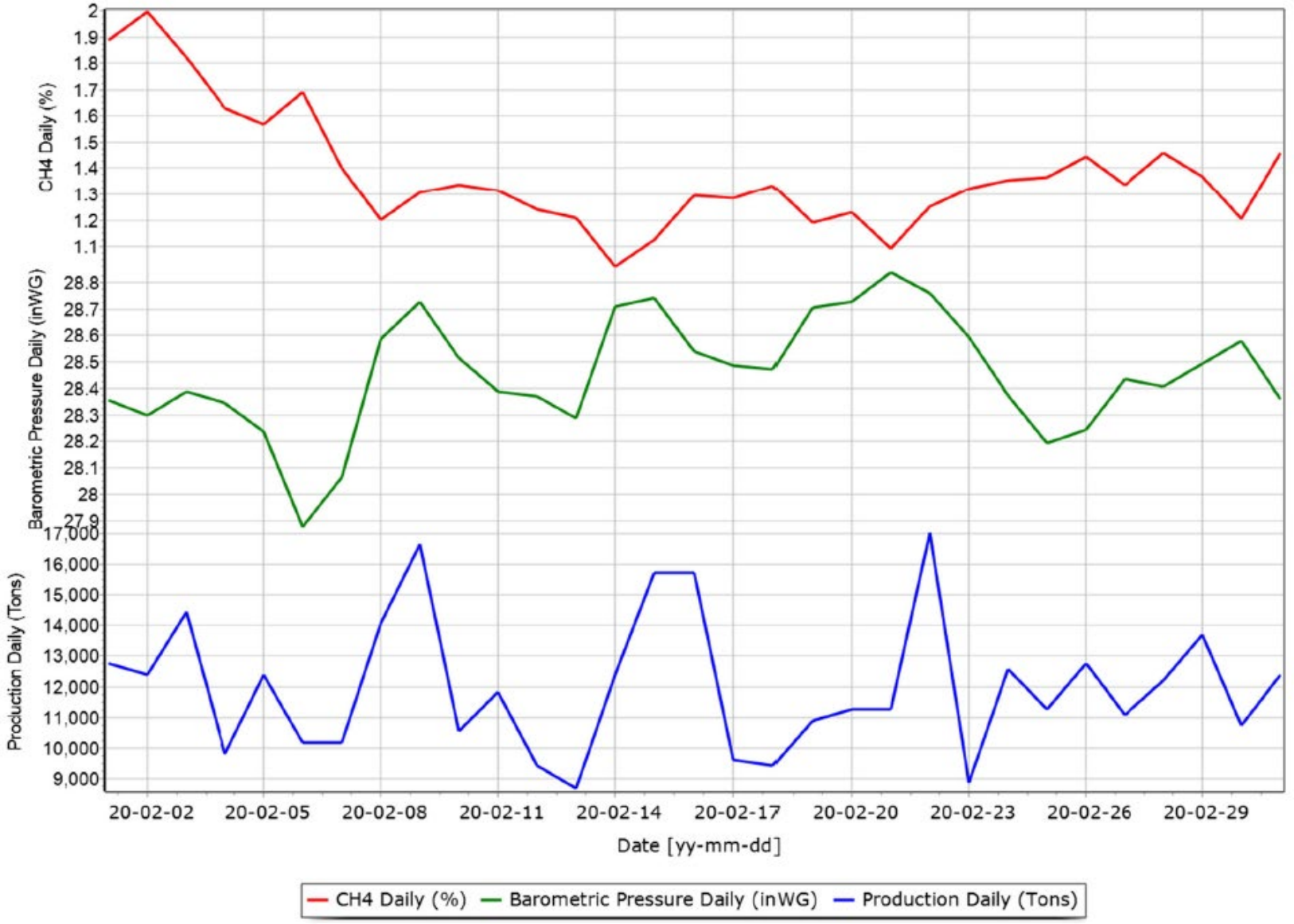


Barometric pressure data (before filtering)

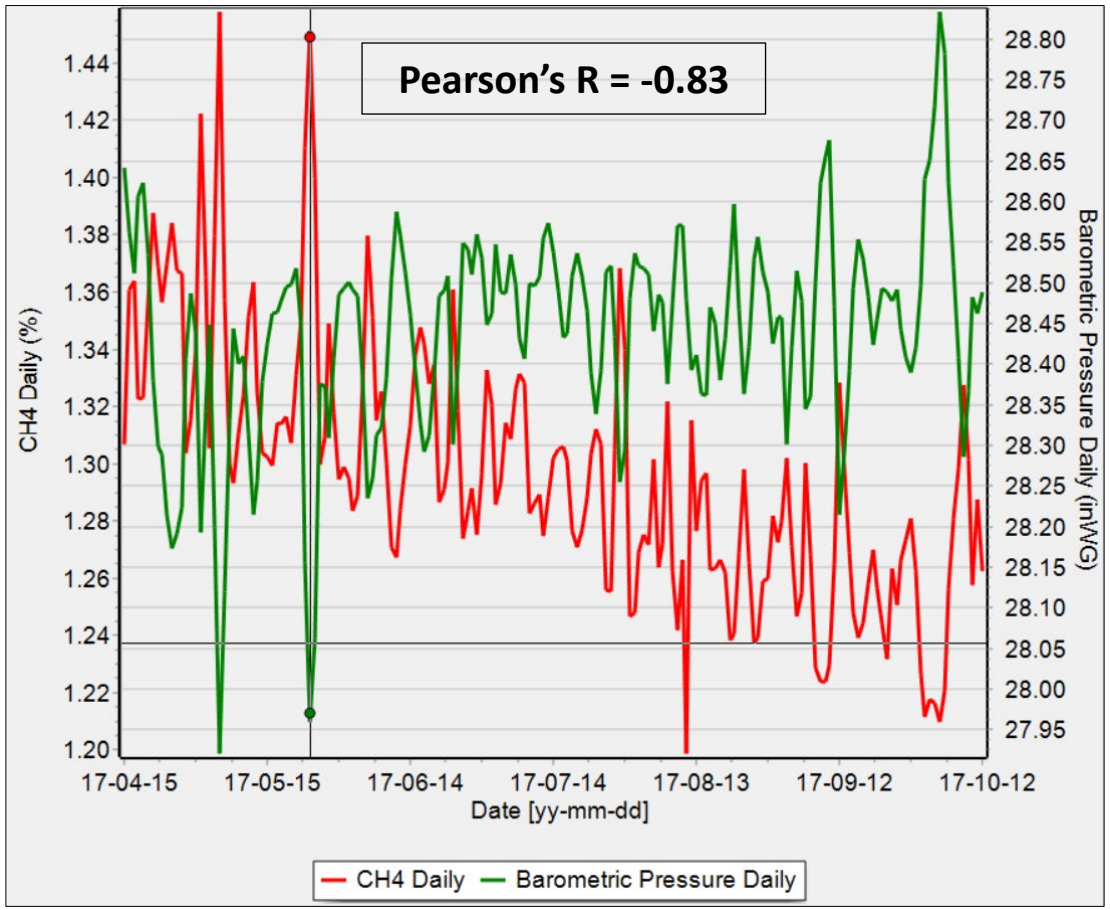


Barometric pressure data (after filtering)

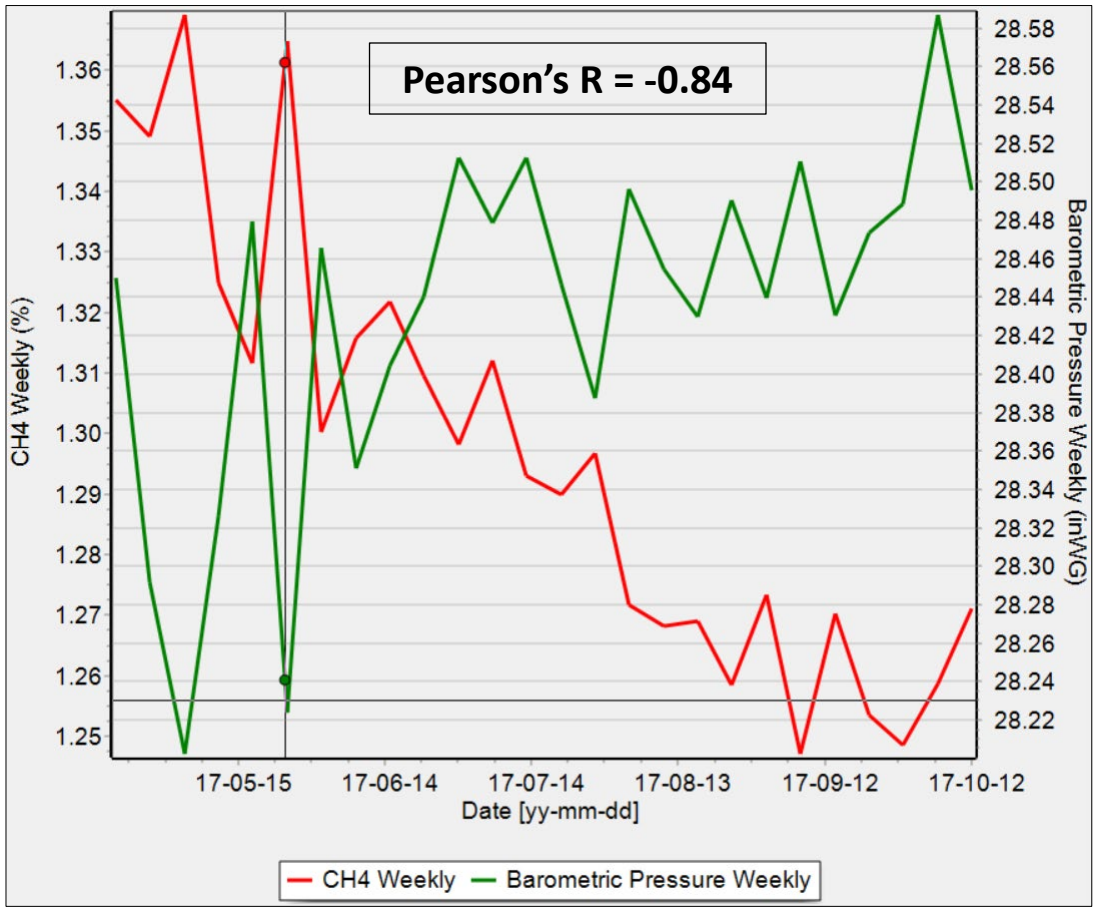
Typical time-series data



Cross-correlation Estimation – CH_4 vs. BP

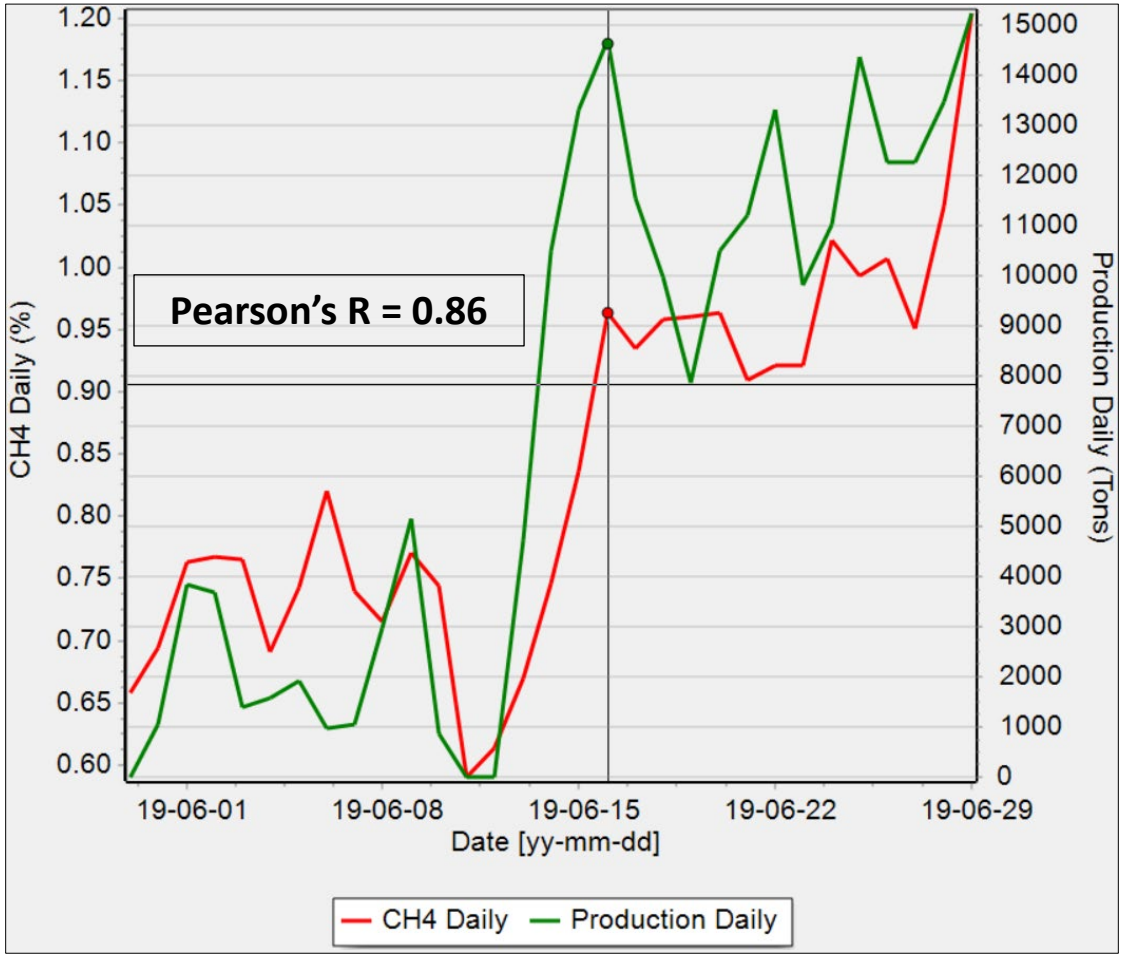


Pearson correlation for daily averages

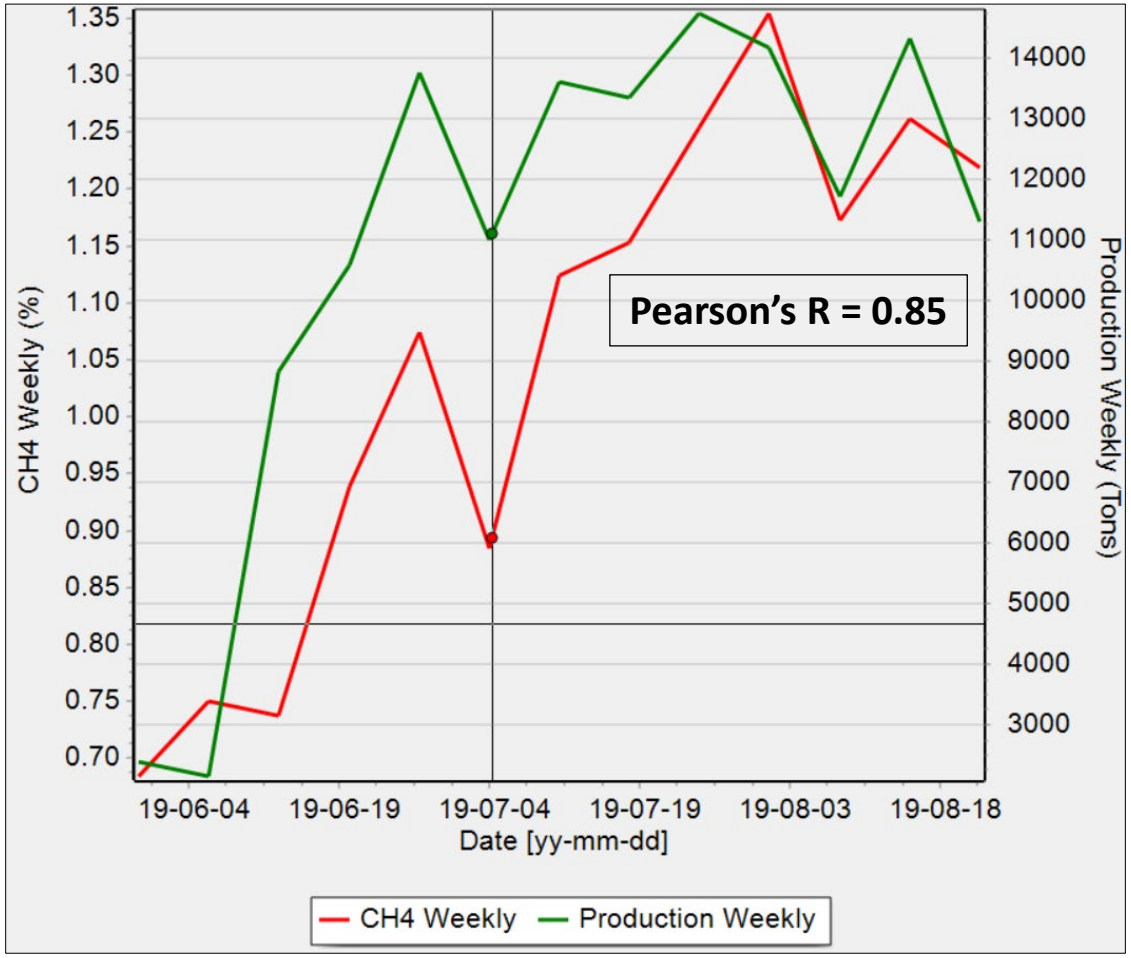


Pearson correlation for weekly averages

Cross-correlation Estimation – CH_4 vs. Coal Prod. Rate

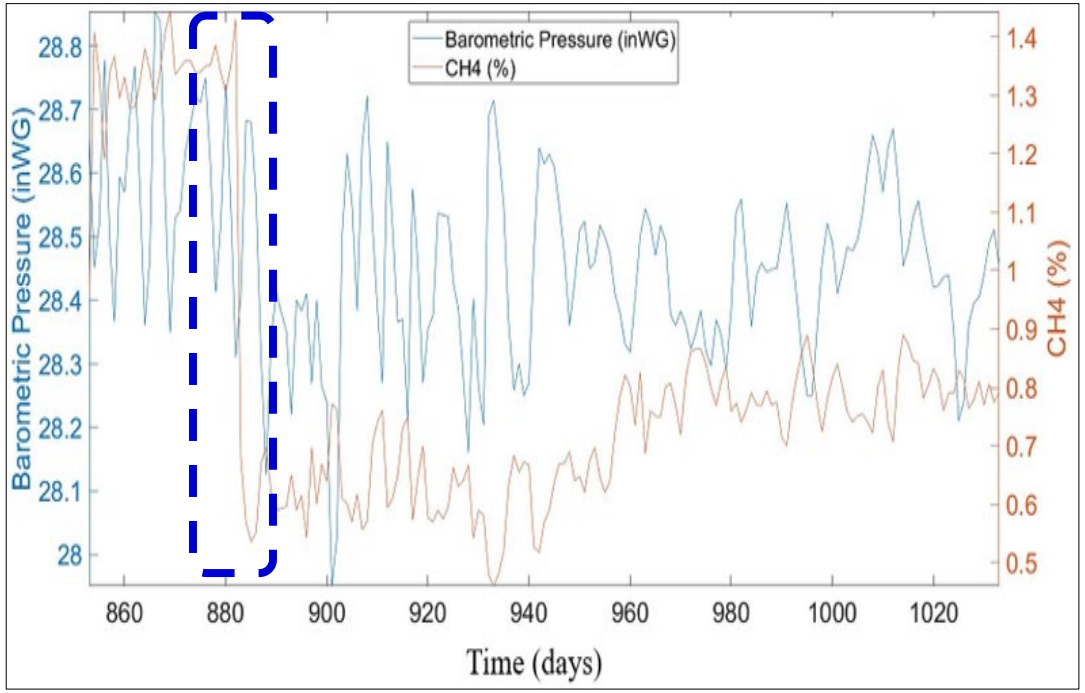


Pearson correlation for daily averages

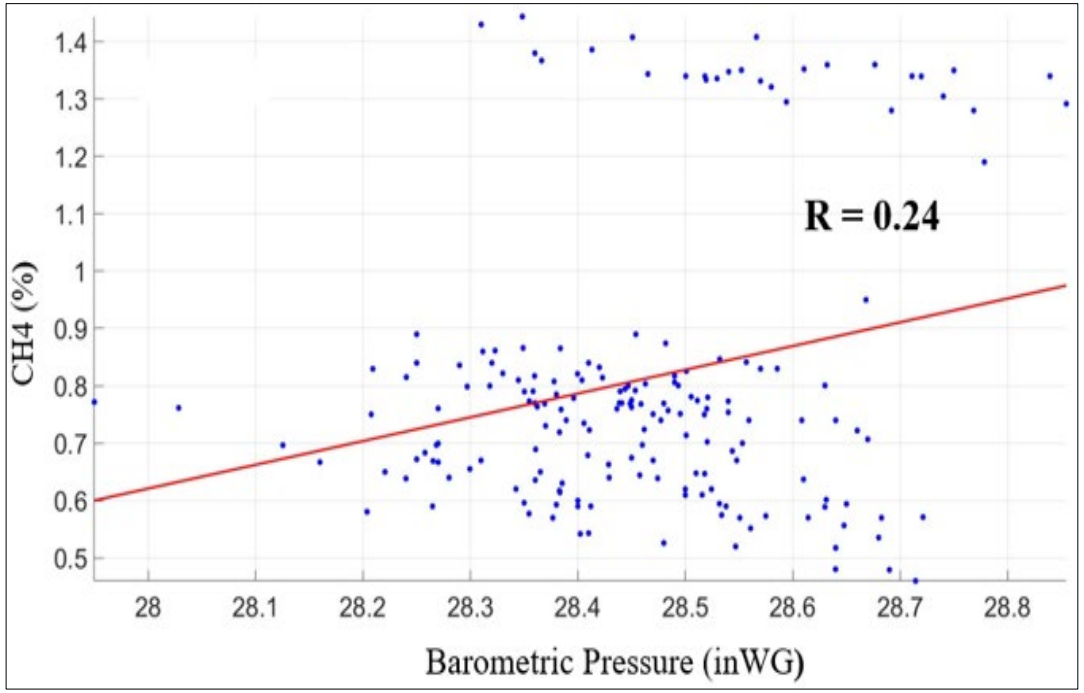


Pearson correlation for weekly averages

Correlation Estimation (Bad)



Correlation between CH_4 and BP



Scatter plot between CH_4 and BP

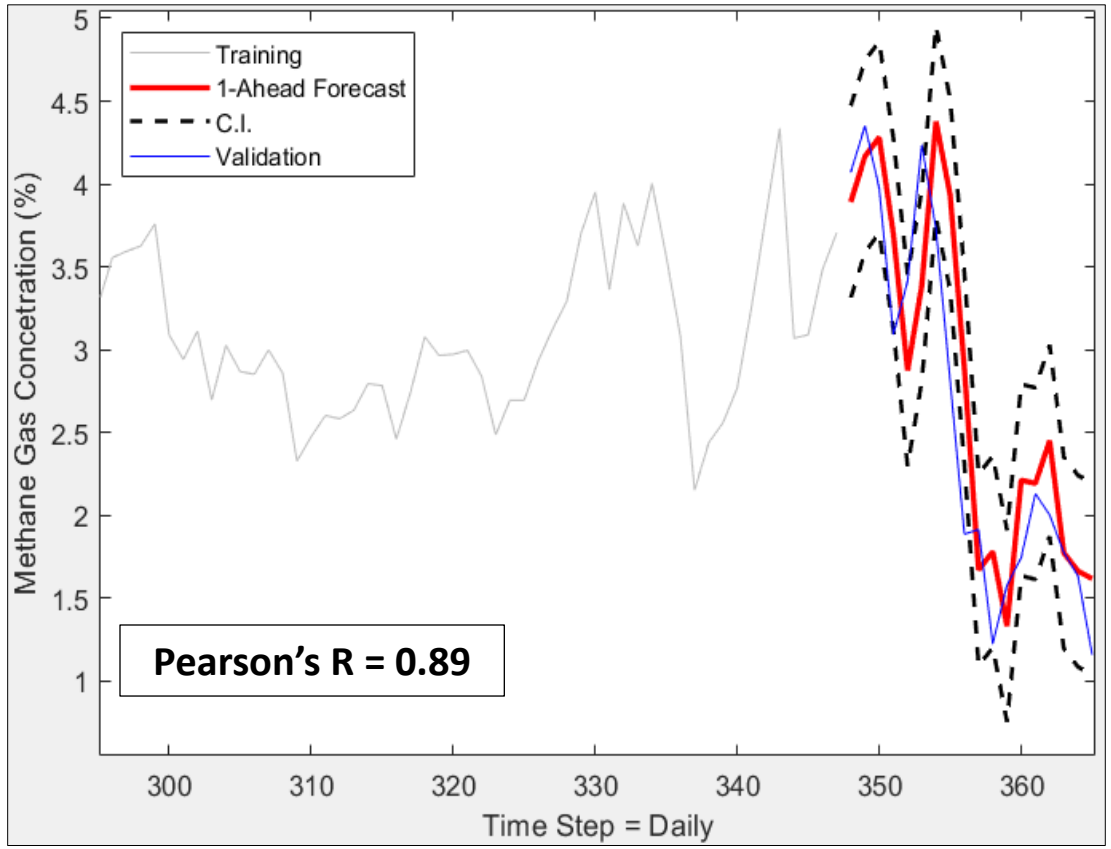
Summary of Cross-Correlation Results

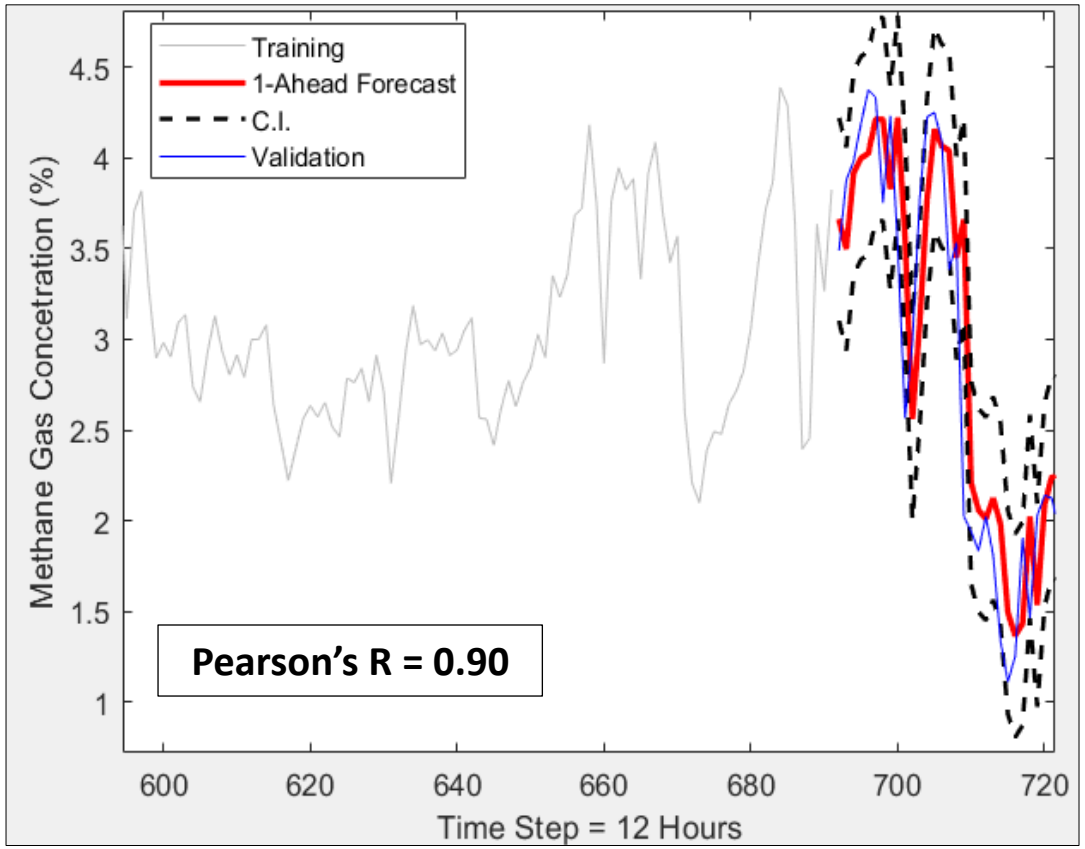
- There is a negative correlation between CH4 and BP
- There is a positive correlation between CH4 and Coal Production Rate

Autocorrelation

- Methane gas time series may exhibit *autocorrelation* -- the correlation of a time series and its lagged version over time
- Autocorrelation was examined using the ARIMA model (AutoRegressive Integrated Moving Average)

Univariate Forecasting Approach – ARIMA

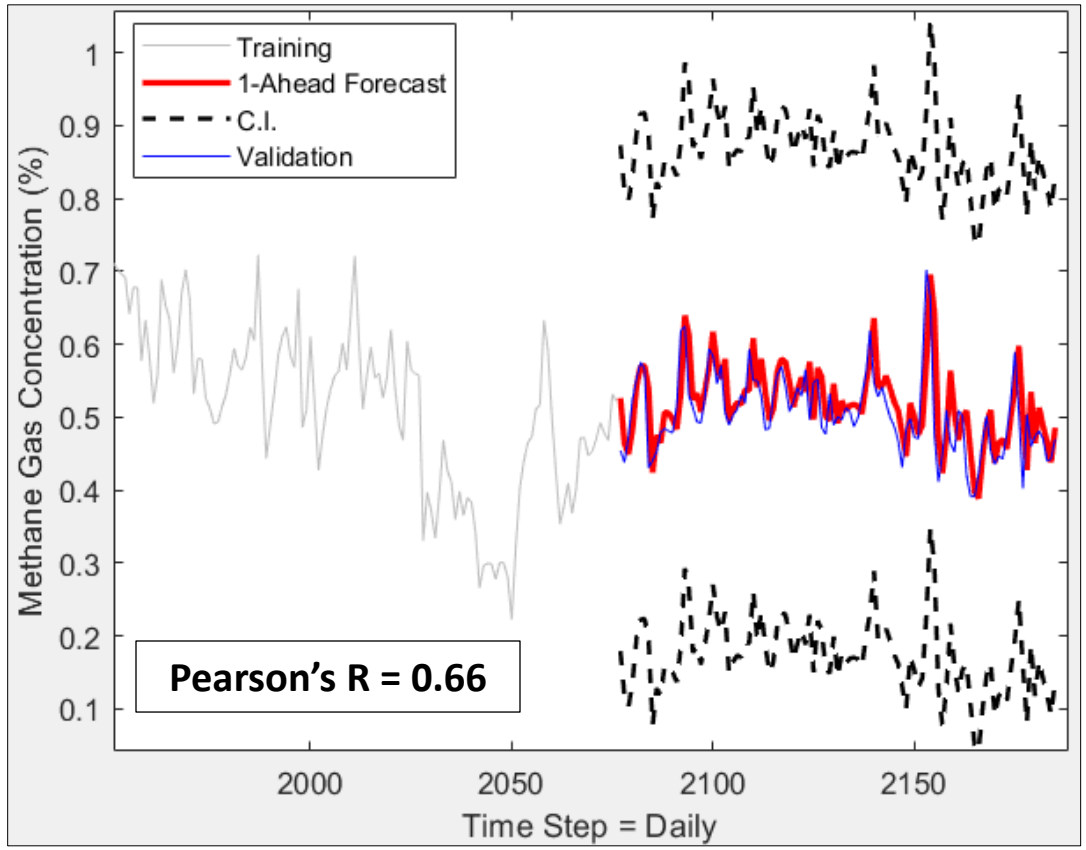




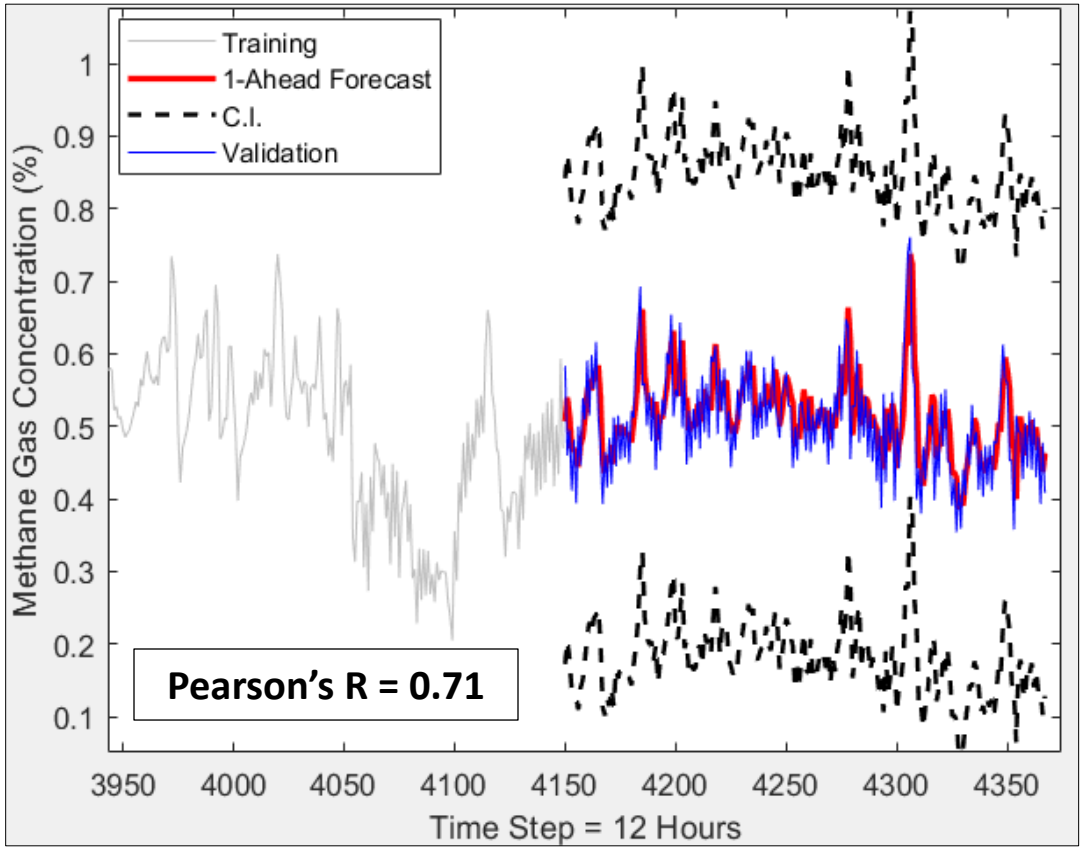
CH_4 concentration forecasts for dataset 1 - using daily average values

CH_4 concentration forecasts for dataset 3 - using 12-hour average values

Univariate Forecasting Approach – ARIMA



CH_4 concentration forecasts for dataset 2 - using daily average values



CH_4 concentration forecasts for dataset 4 - using 12-hour average values

ARIMA Forecasting Summary

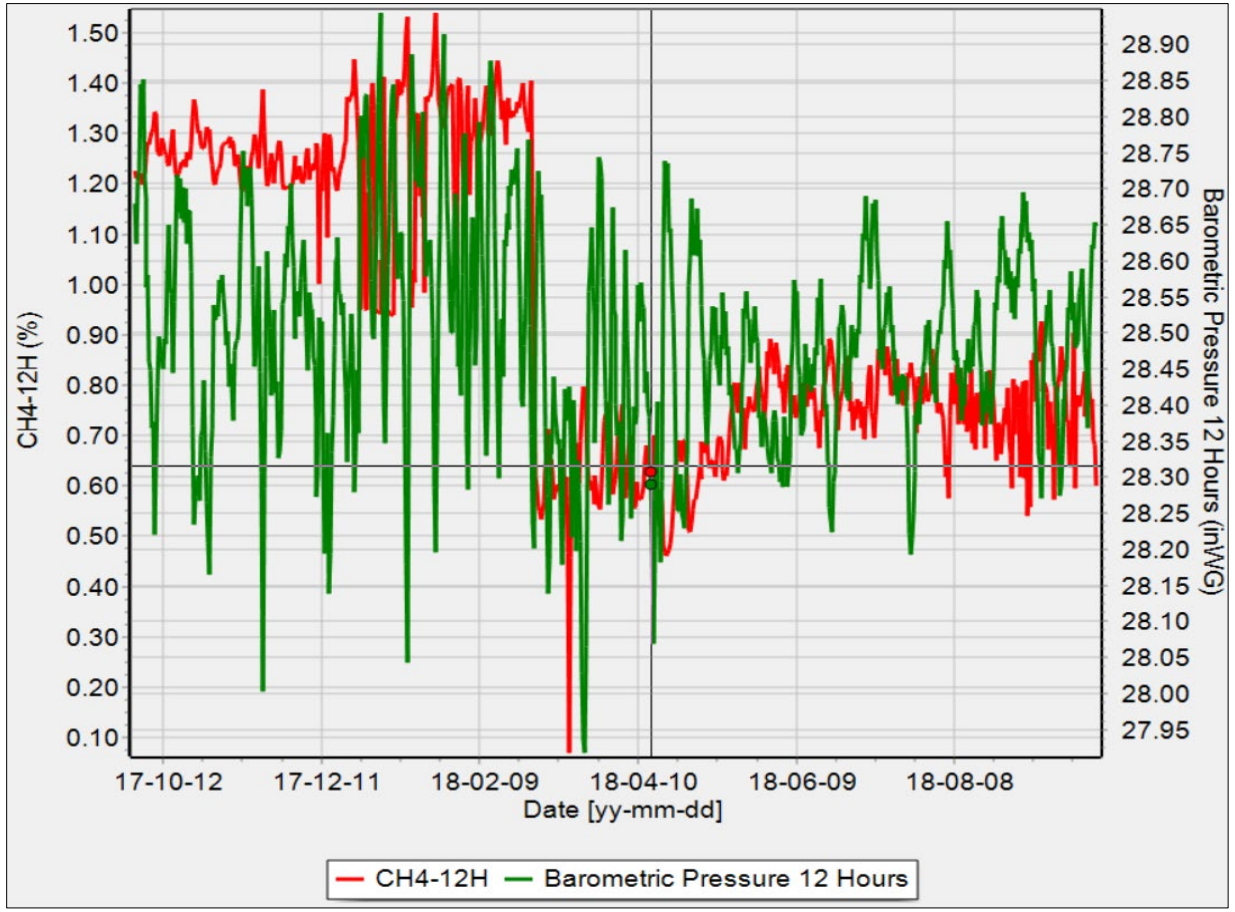
	Time step	Training data		Validation data		Best ARIMA (p,d,q) model	Correlation coefficient (R)	RMSE	ME	MAE
		Length (days)	Sample size	Length (days)	Sample size					
Forecast 1	Daily average	365	365	18	18	(4,1,4)	0.89	0.54	−0.19	0.44
Forecast 2	Daily average	2200	2200	109	109	(3,1,4)	0.65	0.05	0.00	0.03
Forecast 3	12-h average	365	730	18	37	(4,1,4)	0.90	0.47	−0.11	0.35
Forecast 4	12-h average	2200	4380	109	219	(4,1,4)	0.71	0.05	0.00	0.04

Discussion I

- The ARIMA model can accurately predict methane gas concentrations
- The forecast matches the direction of the validation data
- The linear correlation between the forecast and the validation data was significant and positive
- The observed values of methane gas levels were captured by the 95% confidence interval

Discussion II

- The linear correlation between the forecast and the validation data was weak in some cases
- 12-hour average value time series yields better results than daily average values time series in most cases (higher linear correlation, lower RMSE)

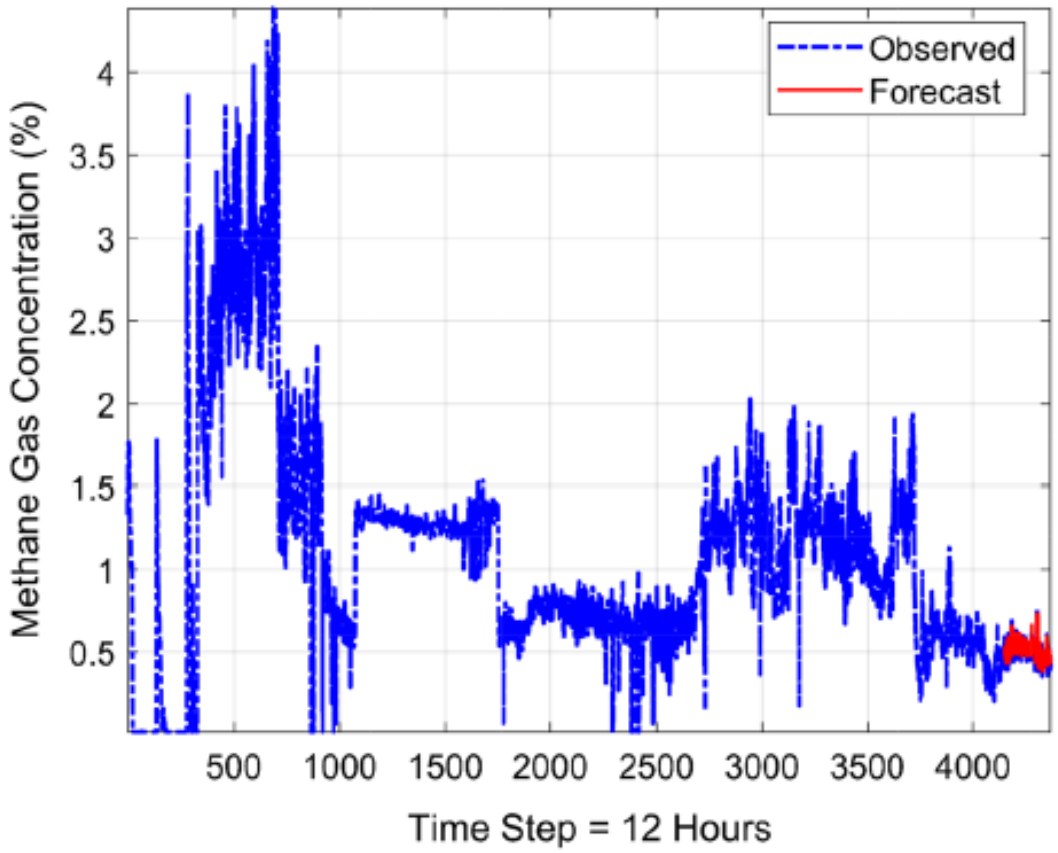


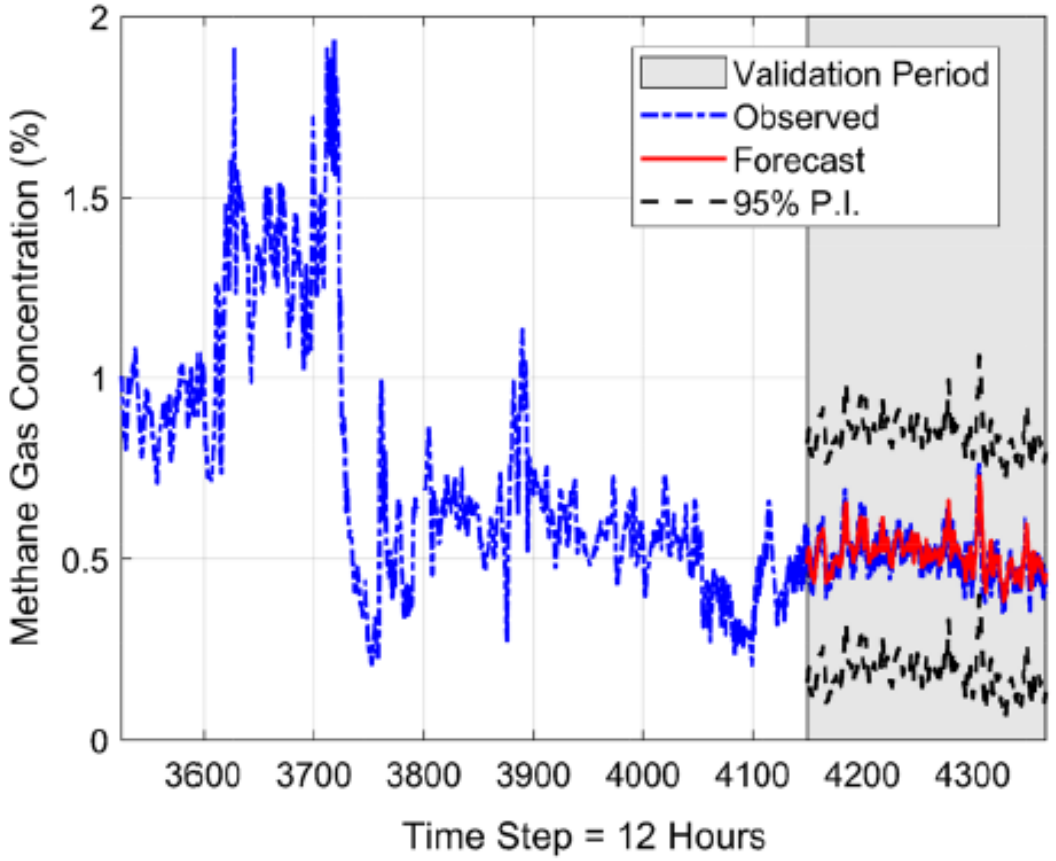
Methane gas and barometric pressure time series included in dataset 6

Forecasting using auxiliary or explanatory variables

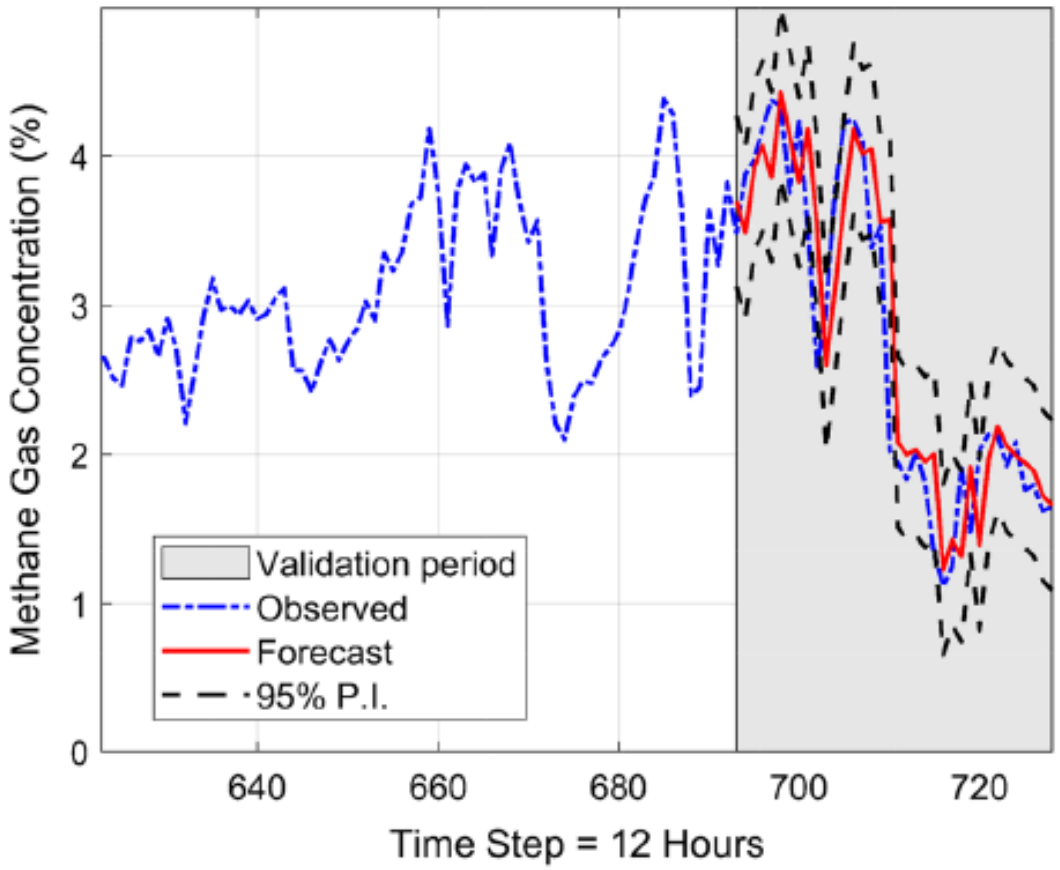
- Forecasting was examined
  - using the VAR(p) (multivariate Vector Autoregressive) model
  - using the ARIMAX model (AutoRegressive Integrated Moving Average with Explanatory (exogenous) Variable)

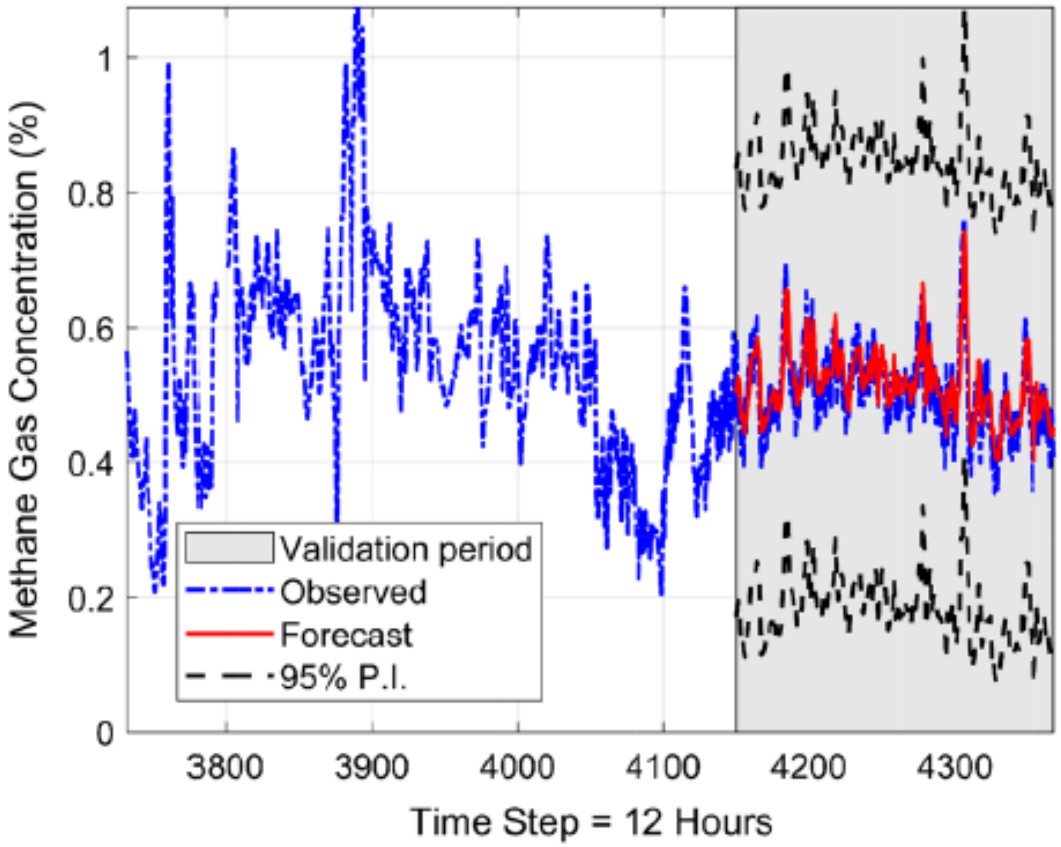
VAR(p) 1-step ahead for dataset 4 (CH4 & BP)





ARIMAX 1-step ahead for dataset 3&4 (CH4 & BP)



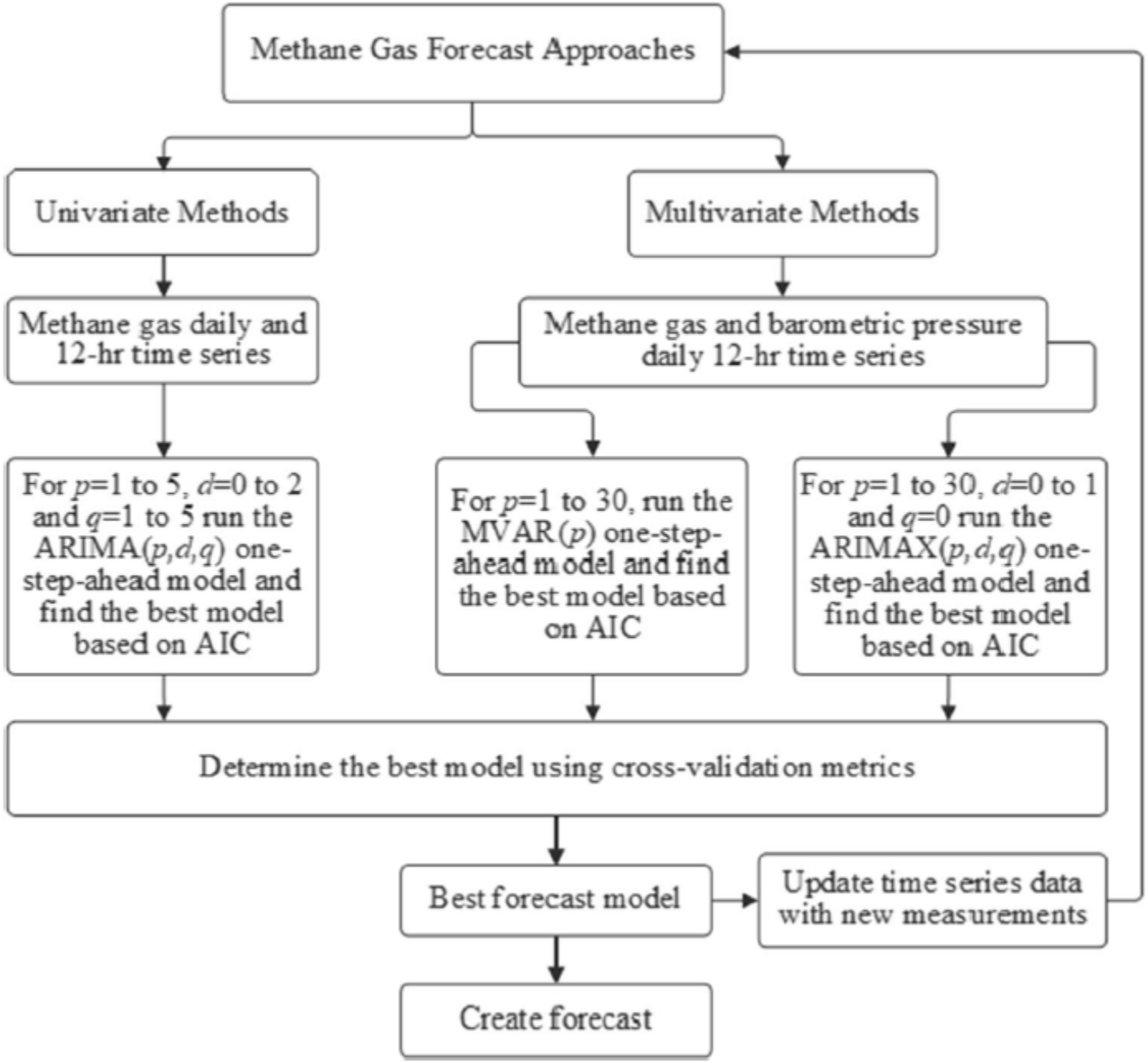


ARIMAX forecasting summary

	Time step	Training data		Validation data		p^*	R	RMSE	ME	MAE
		Length (days)	Sample size	Length (days)	Sample size					
Dataset 1	24-hour	365	365	18	18	28	0.87	0.58	−0.20	0.49
Dataset 2	24-hour	2200	2200	109	109	23	0.65	0.05	−0.01	0.03
Dataset 3	12-hour	365	730	18	37	8	0.91	0.46	−0.07	0.33
Dataset 4	12-hour	2200	4380	109	219	29	0.68	0.05	−0.01	0.04

VAR(p) forecasting summary

	Time step	Training data		Validation data		p^*	R	RMSE	ME	MAE
		Length (days)	Sample size	Length (days)	Sample size					
Dataset 1	24-hour	365	365	18	18	2	0.89	0.50	−0.11	0.44
Dataset 2	24-hour	2200	2200	109	109	13	0.66	0.05	−0.01	0.04
Dataset 3	12-hour	365	730	18	37	8	0.91	0.46	−0.06	0.32
Dataset 4	12-hour	2200	4380	109	219	30	0.66	0.05	−0.01	0.04


Methane Gas Forecast Approaches
Univariate Methods
Multivariate Methods
Methane gas daily and 12-hr time series
Methane gas and barometric pressure daily 12-hr time series
For p=1 to 5, d=0 to 2 and q=1 to 5 run the ARIMA(p,d,q) one-step-ahead model and find the best model based on AIC
For p=1 to 30, run the MVAR(p) one-step-ahead model and find the best model based on AIC
For p=1 to 30, d=0 to 1 and q=0 run the ARIMAX(p,d,q) one-step-ahead model and find the best model based on AIC
Determine the best model using cross-validation metrics
Best forecast model
Update time series data with new measurements
Create forecast

Conclusions

- The ARIMA, VAR(p), ARIMAX 1-step-ahead methane gas forecasting method presented can reliably predict methane gas concentration.
- Autocorrelation trends can be improved by using one or more explanatory (auxiliary) variables
- The performance of the forecasting model needs to be further assessed with different datasets and operating conditions.

Acknowledgments

- This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (Alpha Foundation), contract number AFCTG20-103. The views, opinions, and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the Alpha Foundation, its Directors, and staff.