Atmospheric Plume Dispersion Modeling for Methane Quantification Under Variable Conditions

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Abstract- Atmospheric plume dispersion modeling is critical for accurately quantifying methane emissions, a potent greenhouse gas contributing significantly to global warming. This paper presents a comprehensive synthesis of theoretical principles and modeling approaches for methane plume dispersion under variable environmental conditions, emphasizing the influence of meteorological variables, terrain complexity, and temporal atmospheric dynamics. The physical processes governing plume behavior, advection, and turbulent diffusion, are examined alongside methane-specific characteristics such as buoyancy and chemical stability. Analytical Gaussian models and advanced computational fluid dynamics techniques are critically reviewed, highlighting their respective strengths and limitations in capturing dispersion in diverse settings. The study underscores how fluctuating wind patterns, atmospheric stability, temperature gradients, and surface heterogeneity shape plume transport and dilution, affecting emission quantification accuracy. It also discusses the importance of selecting appropriate models tailored to specific environmental contexts and recognizes inherent assumptions that may constrain model applicability. The paper concludes by outlining theoretical implications for improving methane quantification methodologies and proposes future directions focused on integrating high-resolution data, hybrid modeling approaches, and real-time adaptive frameworks. These insights aim to support enhanced methane monitoring strategies vital for regulatory compliance and global climate mitigation efforts.

Index Terms: Methane quantification, atmospheric plume dispersion, Gaussian models, computational fluid dynamics, meteorological variability, terrain effects

I. INTRODUCTION

1.1 Background

Atmospheric plume dispersion modeling serves as a fundamental tool in understanding how gases released into the atmosphere spread and dilute over space and time (Gifford, 1975). Among the various gases of environmental concern, methane has gained significant attention due to its potent greenhouse gas properties and increasing concentration in the atmosphere (Stockie, 2011, Britter, 1989). Methane emissions arise from multiple anthropogenic sources, including oil and gas operations, agriculture, and waste management, as well as natural sources such as wetlands and geological seepage (Williams, 2013). Understanding the dispersion patterns of methane plumes is essential for quantifying emissions accurately, especially since methane's global warming potential is approximately 28 times greater than carbon dioxide over a 100-year period (Odedeyi et al., 2020, OGUNNOWO et al., 2020).

Modeling the atmospheric behavior of methane plumes requires integrating knowledge from meteorology, fluid dynamics, and atmospheric chemistry. Dispersion patterns are influenced by a range of environmental variables such as wind speed and direction, atmospheric stability, temperature gradients, and terrain (Nielsen, 1998, Hanna et al., 1982). These factors interact to create complex patterns that determine how methane concentrations vary downwind from emission sources. Accurate plume modeling supports not only regulatory monitoring but also informs mitigation strategies by identifying emission hotspots and enabling efficient leak detection (ADEWOYIN et al., 2020a, EYINADE et al., 2020).

Recent advancements in sensor technologies and atmospheric modeling frameworks have heightened the demand for robust dispersion models capable of accommodating varying environmental conditions. As the global community intensifies efforts to curb greenhouse gas emissions, reliable methane quantification through atmospheric modeling remains crucial (Barsotti et al., 2008). The motivation behind this study is to synthesize existing theoretical frameworks and analyze the influence of environmental variability on methane plume dispersion without relying on simulations or specific case studies, thereby providing foundational insights for future applied research (Karion et al., 2019, Devaull et al., 2010).

1.2 Importance of Methane Quantification

Quantifying methane emissions accurately is paramount for addressing climate change and achieving international environmental targets. Methane is a key contributor to global warming, accounting for a significant fraction of radiative forcing since pre-industrial times. Despite its shorter atmospheric lifetime compared to carbon dioxide, methane's immediate impact on atmospheric warming is pronounced, making the timely detection and quantification of emissions critical (Nisbet et al., 2020, Balcombe et al., 2018). Regulatory agencies, environmental organizations, and industrial operators increasingly rely on methane quantification to enforce emission reduction policies and ensure compliance with environmental standards (Council et al., 2003).

Moreover, methane quantification supports the economic and operational objectives of the oil and gas industry, where unintentional leaks represent both environmental liabilities and financial losses. Detecting and quantifying these leaks enables targeted remediation efforts, improving safety and reducing the overall carbon footprint (Pekkarinen, 2020, Ganesan et al., 2019). Beyond industrial applications, methane measurements contribute to validating emission inventories at regional and global scales, providing the scientific community with reliable data for atmospheric models and climate projections (Ogunnowo, Okuh et al.).

The challenge lies in the spatial and temporal variability of methane sources and the dynamic nature of atmospheric conditions, which complicate the measurement and interpretation of methane concentrations. Traditional bottom-up inventories based on activity data often underestimate actual emissions, underscoring the need for top-down quantification approaches supported by atmospheric dispersion models (Okuh et al., Adewoyin et al., 2020b). This underscores the importance of refining dispersion models that can accurately translate concentration measurements into emission estimates, thereby strengthening methane mitigation strategies worldwide.

1.3 Objectives and Contributions

This paper aims to present a comprehensive overview of atmospheric plume dispersion modeling focused on methane quantification under variable environmental conditions. Without incorporating simulation results or specific case studies, the study concentrates on synthesizing theoretical concepts and examining how meteorological and terrain factors influence methane dispersion patterns. The objective is to provide a robust conceptual foundation that can inform future empirical research and technological development in methane monitoring.

Key contributions include a systematic review of physical principles underlying plume behavior, a critical evaluation of prevalent modeling approaches, and an analysis of how variable atmospheric conditions impact the accuracy and reliability of methane quantification. By emphasizing the interaction between environmental variability and dispersion mechanisms, the study highlights important considerations for model selection and application in diverse settings.
Additionally, the paper aims to bridge gaps between atmospheric science theory and practical methane

emission assessment, fostering interdisciplinary understanding. The insights derived are intended to guide researchers, policymakers, and industry practitioners in refining their approaches to methane monitoring and reduction. Ultimately, this work lays the groundwork for advancing atmospheric dispersion modeling frameworks tailored to the complexities of methane emissions, thereby contributing to global environmental sustainability efforts.

II. FUNDAMENTALS OF ATMOSPHERIC PLUME DISPERSION

2.1 Physical Principles of Plume Dispersion

Atmospheric plume dispersion describes the transport and spreading of gases emitted from a localized source into the surrounding air. At its core, dispersion results from the combined effects of advection and diffusion (Council et al., 2010, Sciences et al., 2018). Advection is the process by which a plume is carried by the mean wind flow, transporting the gas downwind from the emission point. Diffusion, on the other hand, involves the random turbulent mixing of gas molecules within the atmosphere, which causes the plume to spread laterally and vertically, diluting its concentration over distance (Gbabo et al., Gbabo et al.).

The dispersion process can be modeled using conservation equations derived from fluid dynamics and atmospheric physics. The advection-diffusion equation governs the behavior of the concentration field of the plume, accounting for wind velocity, turbulent diffusion coefficients, and source characteristics. The balance between transport by wind and spreading due to turbulence determines the shape and extent of the plume. Stable atmospheric conditions with limited turbulence tend to produce narrow, elongated plumes, while unstable, turbulent conditions promote rapid dispersion and dilution (Jonas et al., 2019, Fuglestvedt et al., 2003).

Fundamental plume models often assume steady-state conditions and idealized atmospheric behavior to allow analytical solutions. For example, Gaussian plume models simplify the dispersion process by representing concentration distributions as normal distributions in horizontal and vertical directions. Despite their simplicity, these models capture the essential physics of plume dispersion and provide valuable estimates of downwind concentrations, serving as a foundation for more advanced modeling techniques (Shindell et al., 2017, Le Fevre, 2017).

2.2 Atmospheric Factors Affecting Dispersion

Dispersion of atmospheric plumes is heavily influenced by meteorological factors that vary spatially and temporally. Wind speed and direction are primary drivers of plume transport, controlling the advection of emitted gases. Higher wind speeds increase the transport rate and often enhance dispersion by generating mechanical turbulence, whereas calm conditions may result in limited plume spread and higher concentrations near the source (Fisher, 2002, Bei et al., 2013).

Atmospheric stability, determined by the vertical temperature gradient, significantly affects turbulent mixing. Stable conditions, characterized by temperature inversions or weak vertical temperature gradients, suppress turbulence and limit vertical mixing, resulting in plumes that remain concentrated and close to the ground. Conversely, unstable conditions promote convective turbulence, causing enhanced vertical and lateral mixing that dilutes the plume more rapidly (Venkatram et al., 2005).

Other factors, such as atmospheric moisture, solar radiation, and cloud cover, indirectly impact dispersion by influencing temperature profiles and turbulence generation. Surface roughness and terrain complexity also modify wind flow patterns and turbulence intensity. For example, urban environments or forested areas create mechanical turbulence that alters dispersion characteristics compared to flat, open terrain. Understanding the interplay of these atmospheric factors is critical for accurate plume modeling under variable environmental conditions (Yee et al., 1993).

2.3 Methane Characteristics Relevant to Dispersion

Methane's physical and chemical properties play an important role in its atmospheric dispersion behavior. As a colorless, odorless gas lighter than air, methane has a molecular weight of approximately 16 g/mol, which is less than that of ambient air (~29 g/mol) (Alakalabi, 2020). This buoyancy effect influences the vertical movement of methane plumes, often causing them to rise above the emission source initially before mixing with the surrounding air. The degree of buoyancy-driven rise depends on the temperature and velocity of the emitted methane relative to ambient air (Williams, 2013).

Methane is chemically stable under typical atmospheric conditions, with an atmospheric lifetime of about 9 to 12 years. This stability means methane generally disperses without rapid chemical transformation in the near field, allowing dispersion models to treat it as a conservative tracer over short distances and time scales. However, longer-term chemical interactions, particularly oxidation by hydroxyl radicals, occur on a global scale, affecting atmospheric methane budgets, but are beyond the scope of plume dispersion modeling (Atkins, 2003, Lundegard, 1964).

Additionally, methane's low solubility in water vapor and absence of reactive components simplify its atmospheric behavior compared to reactive gases. This makes dispersion primarily a function of physical transport and mixing processes. Understanding these characteristics allows modelers to focus on transport dynamics without needing to incorporate complex chemical transformations, thereby improving model efficiency and interpretability for quantification purposes (Ahmed, 2004).

III. MODELING APPROACHES FOR METHANE PLUME DISPERSION

3.1 Gaussian and Analytical Models

Gaussian plume models have long been the cornerstone of atmospheric dispersion modeling due to their relative simplicity and analytical tractability. These models assume that pollutant concentrations downwind from a point source follow a normal (Gaussian) distribution in both the vertical and horizontal directions. By applying the advection-diffusion equation under steady-state conditions, Gaussian models estimate concentration profiles as functions of wind speed, atmospheric stability, emission rate, and distance from the source. This framework enables rapid calculations and has been widely adopted in regulatory frameworks and preliminary emission assessments (Vasudevan et al., 2009, Homicz, 2002).

Despite their utility, Gaussian models rely on several simplifying assumptions, such as steady, uniform wind conditions and flat terrain, which limit their applicability in complex or highly variable environments. They often assume continuous emission sources and constant meteorological parameters and neglect chemical transformations. However, for methane, given its relatively inert behavior over short distances, Gaussian models provide reasonable first-order approximations for emission quantification, especially in open terrain with stable meteorological conditions (Camps-Valls et al., 2016).

Analytical models beyond Gaussian formulations include plume rise corrections and multiple source interactions, which refine dispersion estimates. These models are valuable for gaining insights into dispersion behavior and performing sensitivity analyses. Nevertheless, their limitations become apparent when atmospheric conditions are highly non-uniform or terrain complexity is significant, necessitating more sophisticated approaches for accurate plume representation.

3.2 Computational Fluid Dynamics and Advanced Models

Computational Fluid Dynamics (CFD) represents a class of numerical modeling approaches that solve the fundamental Navier-Stokes equations governing fluid motion, enabling detailed simulation of plume dispersion in complex atmospheric and terrain conditions. Unlike Gaussian models, CFD incorporates spatial and temporal variations in wind fields, turbulence structures, thermal stratification, and surface heterogeneity. This results in highly resolved concentration fields capable of capturing local effects such as channeling through urban canyons or plume trapping within valleys (Hirsch, 2007, Pozrikidis, 2009).

Advanced models may also integrate Large Eddy Simulation (LES) or Reynolds-Averaged Navier-Stokes (RANS) turbulence closures to resolve turbulent mixing processes critical for accurate dispersion prediction. These models can accommodate transient emissions and rapidly changing meteorological conditions, making them valuable for operational leak detection and emergency response planning. However, the computational cost and data requirements for CFD modeling are considerably higher, limiting their routine application to detailed studies or high-priority scenarios (Zikanov, 2019).

Hybrid approaches combine the efficiency of Gaussian models with local corrections derived from CFD or observational data, offering balanced solutions for methane quantification under variable conditions. Such integrated frameworks improve model adaptability and accuracy, though they demand multidisciplinary expertise for effective implementation (Ashgriz and Mostaghimi, 2002).

3.3 Model Assumptions and Limitations

Every atmospheric dispersion model rests on a foundation of assumptions that inherently constrain its accuracy and applicability. Simplifying assumptions about steady-state conditions, homogeneity of atmospheric turbulence, and neglect of chemical reactions are common but can introduce uncertainties in real-world applications. For methane, treating it as a passive tracer is reasonable in short-range dispersion but neglects longer-term photochemical interactions that are important at larger scales.

Models often assume flat and uniform terrain, which fails to capture the complexities introduced by hills, vegetation, and urban infrastructure. Such terrain heterogeneity affects wind flow patterns and turbulence intensity, thereby altering plume dispersion in ways not represented by simple models. Likewise, steady wind direction and speed assumptions are challenged by fluctuating meteorological conditions, which require dynamic or ensemble modeling approaches to capture variability adequately.

Limitations also arise from uncertainties in emission source characteristics, such as the exact release rate, temperature, and velocity of methane. These factors influence plume rise and initial dispersion behavior. Moreover, model validation is constrained by the scarcity of high-resolution observational data, particularly for intermittent or fugitive methane emissions. Recognizing and accounting for these limitations is essential for interpreting model outputs responsibly and guiding improvements in atmospheric dispersion modeling methodologies (Rees-White et al., 2019, García et al., 2016).

IV. INFLUENCE OF VARIABLE ENVIRONMENTAL CONDITIONS

4.1 Meteorological Variables (Wind, Stability, Temperature)

Meteorological variables such as wind speed, atmospheric stability, and temperature are primary determinants of how methane plumes disperse in the atmosphere. Wind acts as the principal transport mechanism, carrying the methane away from its emission source. The velocity and direction of wind influence not only the plume’s trajectory but also its dilution rate. Strong winds generally enhance lateral and vertical mixing, promoting dispersion and lowering methane concentrations near the source. Conversely, low wind speeds tend to produce higher localized concentrations due to limited transport and reduced turbulent mixing (Müller, 1992, Fisher, 2002).

Atmospheric stability, which depends largely on temperature gradients, governs the intensity of turbulence that facilitates mixing. Stable conditions, often associated with temperature inversions, suppress vertical mixing and confine plumes closer to the ground (Stull, 1993, Sun et al., 2015). This can lead to elevated methane concentrations over longer distances downwind. In contrast, unstable atmospheric layers generate convective turbulence, which rapidly dilutes plumes through vertical and horizontal dispersion. Temperature differences between the plume and ambient air also affect buoyancy, influencing the initial rise and spread of methane emissions (Koehn et al., 2013).

Together, these meteorological variables exhibit complex interactions that vary over time and space. Accurate plume dispersion modeling requires careful characterization of these factors to capture the dynamic environment in which methane is transported. Without considering meteorological variability, quantification efforts risk significant errors, limiting their usefulness for regulatory or mitigation purposes (Osibanjo, 2016).

4.2 Terrain and Surface Effects

Terrain features and surface characteristics profoundly affect the dispersion of methane plumes by altering local airflow patterns and turbulence. Flat and open landscapes typically allow relatively straightforward plume transport dominated by prevailing winds and atmospheric turbulence. However, complex terrain such as hills, valleys, and urban structures creates heterogeneous wind fields characterized by eddies, channeling, and stagnation zones that can trap or redirect plumes unpredictably (Egan, 1975, Meixner and Eugster, 1999).

Surface roughness, including vegetation, buildings, and other obstacles, generates mechanical turbulence that enhances mixing near the ground. This effect can either increase plume dilution or cause irregular dispersion patterns depending on the scale and arrangement of roughness elements. For example, forests induce strong turbulence that promotes vertical mixing, whereas urban canyons can confine plumes within narrow corridors, increasing local methane concentrations (Williams, 2013).

Understanding terrain and surface influences is critical for accurate dispersion modeling, especially in regions where methane emissions coincide with varied topography. Models that assume uniform flat terrain risk underestimating concentration peaks or failing to predict plume behavior accurately. Incorporating high-resolution terrain data and surface parameters into dispersion frameworks improves the reliability of methane quantification under real-world conditions.

4.3 Temporal Variability and Atmospheric Dynamics

Atmospheric conditions are inherently variable over time scales ranging from seconds to seasons, making temporal variability a crucial factor in methane plume dispersion. Short-term fluctuations in wind direction and speed can cause rapid shifts in plume trajectories, affecting instantaneous concentration measurements. Diurnal cycles influence atmospheric stability through solar heating, with typically more unstable conditions during daytime enhancing plume mixing compared to more stable nocturnal layers (Taylor et al., 2018).

Seasonal and longer-term meteorological changes also affect dispersion patterns. For instance, colder months often feature more frequent temperature inversions, which suppress vertical mixing and increase ground-level methane concentrations. Conversely, warmer periods with stronger convection promote plume dilution. Additionally, weather events such as frontal passages and storms can disrupt typical dispersion regimes, causing complex transient behaviors in methane concentration fields.

These temporal dynamics necessitate dispersion models capable of incorporating time-dependent meteorological inputs. Static or time-averaged conditions are often insufficient to capture the true variability of plume behavior. Accurate methane quantification demands models that can accommodate dynamic atmospheric processes, improving the representativeness of emission estimates and supporting effective monitoring and mitigation strategies (Giovannini et al., 2020).

CONCLUSION

5.1 Summary of Key Insights

This study has examined the fundamental principles and modeling approaches related to atmospheric plume dispersion for methane quantification under variable environmental conditions. It has highlighted that the interplay of physical processes, such as advection and turbulent diffusion, governs how methane spreads in the atmosphere. The review of modeling techniques, from classical Gaussian models to advanced computational methods, underscores a trade-off between simplicity and accuracy depending on the complexity of environmental conditions.

Meteorological factors, including wind, stability, and temperature, along with terrain and temporal variability, significantly influence dispersion behavior. These factors create spatially and temporally dynamic concentration fields that must be carefully accounted for in dispersion modeling frameworks. Methane's physical characteristics, notably its buoyancy and chemical stability, simplify certain aspects of modeling but do not eliminate the challenges posed by environmental heterogeneity.

By synthesizing these insights, this work reinforces the importance of selecting appropriate models and accurately characterizing environmental variables to improve methane emission quantification. Such efforts are vital for enhancing the reliability of emission inventories and supporting global climate mitigation initiatives focused on reducing methane's atmospheric impact.

5.2Theoretical Implications for Methane Quantification

The analysis presented here contributes to the theoretical understanding of methane plume dispersion by elucidating how environmental variability modulates transport and dilution processes. It emphasizes that no single modeling approach universally applies across all scenarios; rather, model selection must consider the scale, terrain, and meteorological context. This perspective advances the theory of atmospheric dispersion by integrating methane-specific properties with environmental complexity.

Furthermore, this work highlights the necessity of treating methane as a dynamic tracer influenced by both physical transport and variable atmospheric forcing. Recognizing the limitations of common assumptions, such as steady-state conditions and flat terrain, guides researchers toward developing more robust models that incorporate transient and heterogeneous factors. These theoretical considerations foster improved interpretation of observational data and emission estimates. Ultimately, the framework outlined here supports a more nuanced approach to methane quantification, bridging the gap between idealized models and real-world applications. It encourages interdisciplinary collaboration among atmospheric scientists, engineers, and policymakers to refine theoretical constructs and translate them into effective monitoring tools.

5.3 Future Directions

Advancing methane plume dispersion modeling requires integrating high-resolution meteorological data and detailed terrain representation to capture environmental variability more precisely. Developing hybrid models that leverage the efficiency of analytical approaches and the accuracy of numerical simulations offers promising pathways to balance computational feasibility with modeling fidelity.

Incorporating real-time atmospheric measurements and leveraging machine learning techniques to adjust model parameters dynamically can enhance adaptability to changing conditions. Such innovations would improve the responsiveness of methane monitoring systems and support timely leak detection and mitigation. Expanding observational networks and validating models against diverse environmental settings will strengthen confidence in dispersion-based quantification.

Further research should also explore the coupling of dispersion models with chemical transport and atmospheric chemistry frameworks to address longer-term methane dynamics. This holistic approach would extend model applicability beyond immediate plume behavior to broader atmospheric methane budgets. Ultimately, continued refinement and interdisciplinary collaboration will be critical to realizing accurate, reliable methane quantification essential for climate action and environmental stewardship.

REFERENCES

[1] ADEWOYIN, M. A., OGUNNOWO, E. O., FIEMOTONGHA, J. E., IGUNMA, T. O. &

ADELEKE, A. K. 2020a. Advances in Thermofluid Simulation for Heat Transfer Optimization in Compact Mechanical Devices.

[2] ADEWOYIN, M. A., OGUNNOWO, E. O., FIEMOTONGHA, J. E., IGUNMA, T. O. & ADELEKE, A. K. 2020b. A Conceptual Framework for Dynamic Mechanical Analysis in High-Performance Material Selection.

[3] AHMED, F. 2004. *Design of Catalysts for the Abatement or Decomposition of Anthropogenic Carbon Dioxide Methane and Nitrous Oxide*, University of Surrey (United Kingdom).

[4] ALAKALABI, A. 2020. *Dispersion of heavy petroleum gases in the atmosphere.* University of Central Lancashire.

[5] ASHGRIZ, N. & MOSTAGHIMI, J. 2002. An introduction to computational fluid dynamics. *Fluid flow handbook,* 1, 1-49.

[6] ATKINS, P. W. 2003. *Atkins' molecules*, Cambridge University Press.

[7] BALCOMBE, P., SPEIRS, J. F., BRANDON, N. P. & HAWKES, A. D. 2018. Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts,* 20, 1323-1339.

[8] BARSOTTI, S., NERI, A. & SCIRE, J. 2008. The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach and physical formulation. *Journal of Geophysical Research: Solid Earth,* 113.

[9] BEI, N., LI, G., ZAVALA, M., BARRERA, H., TORRES, R., GRUTTER, M., GUTIÉRREZ, W., GARCÍA, M., RUIZ-SUAREZ, L. G. & ORTINEZ, A. 2013. Meteorological overview and plume transport patterns during Cal-Mex 2010. *Atmospheric Environment,* 70, 477-489.

[10] BRITTER, R. E. 1989. Atmospheric dispersion of dense gases. *Annual review of fluid mechanics,* 21, 317-344.

[11] CAMPS-VALLS, G., VERRELST, J., MUNOZ-MARI, J., LAPARRA, V., MATEO-JIMENEZ, F. & GOMEZ-DANS, J. 2016. A survey on Gaussian processes for earth-observation data analysis: A comprehensive investigation. *IEEE Geoscience and Remote Sensing Magazine,* 4, 58-78.

[12] COUNCIL, N. R., EARTH, D. O., STUDIES, L., SCIENCES, B. O. A. & EMISSIONS, C. O. M. F. E. G. G. 2010. *Verifying greenhouse gas emissions: methods to support international climate agreements*, National Academies Press.

[13] COUNCIL, N. R., EARTH, D. O., STUDIES, L., SCIENCES, B. O. A. & RELEASES, C. O. T. A. D. O. H. M. 2003. *Tracking and predicting the atmospheric dispersion of hazardous material releases: Implications for homeland security*, National academies press.

[14] DEVAULL, G. E., KING, J. A., LANTZY, R. J. & FONTAINE, D. J. 2010. *Understanding atmospheric dispersion of accidental releases*, John Wiley & Sons.

[15] EGAN, B. A. 1975. Turbulent diffusion in complex terrain. *Lectures on air pollution and environmental impact analyses.* Springer.

[16] EYINADE, W., EZEILO, O. J. & OGUNDEJI, I. A. 2020. A Treasury Management Model for Predicting Liquidity Risk in Dynamic Emerging Market Energy Sectors.

[17] FISHER, B. 2002. Meteorological factors influencing the occurrence of air pollution episodes involving chimney plumes. *Meteorological Applications,* 9, 199-210.

[18] FUGLESTVEDT, J. S., BERNTSEN, T. K., GODAL, O., SAUSEN, R., SHINE, K. P. & SKODVIN, T. 2003. Metrics of climate change: Assessing radiative forcing and emission indices. *Climatic Change,* 58, 267-331.

[19] GANESAN, A. L., SCHWIETZKE, S., POULTER, B., ARNOLD, T., LAN, X., RIGBY, M., VOGEL, F. R., VAN DER WERF, G. R., JANSSENS-MAENHOUT, G. & BOESCH, H. 2019. Advancing scientific understanding of the global methane budget in support of the Paris Agreement. *Global Biogeochemical Cycles,* 33, 1475-1512.

[20] GARCÍA, M. Á., SÁNCHEZ, M. L., PÉREZ, I. A., OZORES, M. I. & PARDO, N. 2016.

Influence of atmospheric stability and transport on CH4 concentrations in northern Spain. *Science of the Total Environment,* 550, 157-166.

[21] GBABO, E. Y., OKENWA, O. K. & CHIMA, P. E. Constructing AI-Enabled Compliance Automation Models for Real-Time Regulatory Reporting in Energy Systems.

[22] GBABO, E. Y., OKENWA, O. K. & CHIMA, P. E. Integrating CDM Regulations into Role-Based Compliance Models for Energy Infrastructure Projects.

[23] GIFFORD, F. 1975. Atmospheric dispersion models for environmental pollution applications. *Lectures on air pollution and environmental impact analyses.* Springer.

[24] GIOVANNINI, L., FERRERO, E., KARL, T., ROTACH, M. W., STAQUET, C., TRINI CASTELLI, S. & ZARDI, D. 2020. Atmospheric pollutant dispersion over complex terrain: Challenges and needs for improving air quality measurements and modeling. *Atmosphere,* 11, 646.

[25] HANNA, S. R., BRIGGS, G. A. & HOSKER JR, R. P. 1982. Handbook on atmospheric diffusion. National Oceanic and Atmospheric Administration, Oak Ridge, TN (USA ….

[26] HIRSCH, C. 2007. *Numerical computation of internal and external flows: The fundamentals of computational fluid dynamics*, Elsevier.

[27] HOMICZ, G. F. 2002. Three-dimensional wind field modeling: a review.

[28] JONAS, M., BUN, R., NAHORSKI, Z., MARLAND, G., GUSTI, M. & DANYLO, O. 2019. Quantifying greenhouse gas emissions. *Mitigation and Adaptation Strategies for Global Change,* 24, 839-852.

[29] KARION, A., LAUVAUX, T., LOPEZ COTO, I., SWEENEY, C., MUELLER, K., GOURDJI, S., ANGEVINE, W., BARKLEY, Z., DENG, A. & ANDREWS, A. 2019. Intercomparison of atmospheric trace gas dispersion models: Barnett Shale case study. *Atmospheric chemistry and physics,* 19, 2561-2576.

[30] KOEHN, A. C., LEYTEM, A. B. & BJORNEBERG, D. L. 2013. Comparison of atmospheric stability methods for calculating ammonia and methane emission rates with WindTrax. *Transactions of the ASABE,* 56, 763-768.

[31] LE FEVRE, C. 2017. Methane Emissions: from blind spot to spotlight.

[32] LUNDEGARD, P. D. 1964. Methane. *Environmental forensics.* Elsevier.

[33] MEIXNER, F. X. & EUGSTER, W. 1999. Effects of landscape pattern and topography on emissions and transport. *Integrating hydrology, ecosystem dinamics, and biogeochemistry in complex landscapes. Wiley and Sons, New York*, 147-175.

[34] MÜLLER, J. F. 1992. Geographical distribution and seasonal variation of surface emissions and deposition velocities of atmospheric trace gases. *Journal of Geophysical Research: Atmospheres,* 97, 3787-3804.

[35] NIELSEN, M. 1998. Dense gas dispersion in the atmosphere.

[36] NISBET, E., FISHER, R., LOWRY, D., FRANCE, J., ALLEN, G., BAKKALOGLU, S., BRODERICK, T., CAIN, M., COLEMAN, M. & FERNANDEZ, J. 2020. Methane mitigation: methods to reduce emissions, on the path to the Paris agreement. *Reviews of Geophysics,* 58, e2019RG000675.

[37] ODEDEYI, P. B., ABOU-EL-HOSSEIN, K., OYEKUNLE, F. & ADELEKE, A. K. 2020. Effects of machining parameters on Tool wear progression in End milling of AISI 316. *Progress in Canadian Mechanical Engineering,* 3.

[38] OGUNNOWO, E. O. A Conceptual Framework for Digital Twin Deployment in Real-Time Monitoring of Mechanical Systems.

[39] OGUNNOWO, E. O., ADEWOYIN, M. A., FIEMOTONGHA, J. E., IGUNMA, T. O. & ADELEKE, A. K. 2020. Systematic Review of Non-Destructive Testing Methods for Predictive Failure Analysis in Mechanical Systems.

[40] OKUH, C. O., NWULU, E. O., OGU, E., IFECHUKWUDE, P., EGBUMOKEI, I. N. D. & DIGITEMIE, W. N. Creating a Sustainability-Focused Digital Transformation Model for Improved Environmental and Operational Outcomes in Energy Operations.

[41] OKUH, C. O., NWULU, E. O., OGU, E., IFECHUKWUDE, P., EGBUMOKEI, I. N. D. & DIGITEMIE, W. N. An Integrated Lean Six Sigma Model for Cost Optimization in Multinational Energy Operations.

[42] OSIBANJO, O. O. 2016. *Investigation of the influence of temperature inversions and turbulence on land-atmosphere interactions for rolling terrain*, University of Nevada, Reno.

[43] PEKKARINEN, V. 2020. Going beyond CO2: Strengthening action on global methane emissions under the UN climate regime. *Review of European, Comparative & International Environmental Law,* 29, 464-478.

[44] POZRIKIDIS, C. 2009. *Fluid dynamics: theory, computation, and numerical simulation*, Springer Science & Business Media.

[45] REES-WHITE, T., MØNSTER, J., BEAVEN, R. & SCHEUTZ, C. 2019. Measuring methane emissions from a UK landfill using the tracer dispersion method and the influence of operational and environmental factors. *Waste management,* 87, 870-882.

[46] SCIENCES, N. A. O., MEDICINE, EARTH, D. O., STUDIES, L., STUDIES, B. O. E., ENERGY, B. O., SYSTEMS, E., SCIENCES, B. O. E., SCIENCES, B. O. A. & STATES, C. O. A. M. E. I. T. U. 2018. *Improving characterization of anthropogenic methane emissions in the United States*, National Academies Press.

[47] SHINDELL, D., FUGLESTVEDT, J. & COLLINS, W. 2017. The social cost of methane: theory and applications. *Faraday Discussions,* 200, 429-451.

[48] STOCKIE, J. M. 2011. The mathematics of atmospheric dispersion modeling. *Siam Review,* 53, 349-372.

[49] STULL, R. B. 1993. Review of non-local mixing in turbulent atmospheres: Transilient turbulence theory. *Boundary-Layer Meteorology,* 62, 21-96.

[50] SUN, J., NAPPO, C. J., MAHRT, L., BELUŠIĆ, D., GRISOGONO, B., STAUFFER, D. R., PULIDO, M., STAQUET, C., JIANG, Q. & POUQUET, A. 2015. Review of wave-turbulence interactions in the stable atmospheric boundary layer. *Reviews of geophysics,* 53, 956-993.

[51] TAYLOR, D. M., CHOW, F. K., DELKASH, M. & IMHOFF, P. T. 2018. Atmospheric modeling to assess wind dependence in tracer dilution method measurements of landfill methane emissions. *Waste Management,* 73, 197-209.

[52] VASUDEVAN, S., RAMOS, F., NETTLETON, E. & DURRANT-WHYTE, H. 2009. Gaussian process modeling of large-scale terrain. *Journal of Field Robotics,* 26, 812-840.

[53] VENKATRAM, A., ISAKOV, V., PANKRATZ, D. & YUAN, J. 2005. Relating plume spread to meteorology in urban areas. *Atmospheric Environment,* 39, 371-380.

[54] WILLIAMS, M. L. 2013. Atmospheric dispersal of pollutants and the modelling of air pollution.

[55] YEE, E., KOSTENIUK, P., CHANDLER, G., BILTOFT, C. & BOWERS, J. 1993. Statistical characteristics of concentration fluctuations in dispersing plumes in the atmospheric surface layer. *Boundary-Layer Meteorology,* 65, 69-109.

[56] ZIKANOV, O. 2019. *Essential computational fluid dynamics*, John Wiley & Sons.