UTRECHT UNIVERSITY

Department of Information and Computing Science
Department of Physical Geography

Applied Data Science master thesis

A Universal Approach to Reduce Computation Complexity: Utilize Machine Learning to Capture Dynamics of Large-Scale, High-Resolution Numerical Models

First examiner:
prof. D.J. Karssenberg

Candidate:
BSc. H.R.A. ten Eikelder

Second examiner:
MSc. O. Pomarol

Cohort:
2022-2023

June 11, 2023

Abstract

Context, 1-2 sentences of basic introduction or relevance

Background, 2-3 sentences of more detail

Problem, 1 sentence with general problem to solve

Result, start with 'here we show' 2-3 sentences in total

Consequence, 1-2 sentences of general context

Broader perspective, 2-3 sentences of the broader perspective, limit this if needed

Contents

1 Introduction **3**

2 Data **6**
2.1 Description of the data 6
2.2 Preperation of the data 6

3 Method **8**
3.1 Description of the method used 8
3.2 Feature importance 8

4 Results **9**
4.1 Overview of the results 9

5 Conclusion **10**
5.1 Discussion 10

Appendix

A Appendix title **11**

A Appendix A **12**
A.1 First appendix section 13

Bibliography **22**

1. Introduction

The overall approach to all of science is to create a hypothesis and test this hypothesis with a model, supplemented by experimental data. The classical method to modelling underlying physical patterns is by developing a mathematical theory from first principles and to parameterise the unknown variables. With the evolution in computational power many of these mathematical models have been reformulated to be approximated by numerical calculations. However, this approach has its limits when it comes to the desired accuracy and available computational power. In different fields of science many of these large-scale high resolution numerical models are in use. The computation time of these models increases with scale, resolution and complexity. These computation times can become insurmountable, even with current day supercomputer clusters. For example, fully-coupled mid-resolution global climate models take weeks to run on supercomputers [1].

There are many different approaches to solving the problem of computational complexity. One of these approaches is to apply machine learning (ML) models to take over various parts of the classical model. If the classical model is, fully or in part, coupled with the ML model this construction is called a hybrid model [2]. There are studies where ML is implemented to accelerate the classical model [3]. There are studies where ML is used to downscale spatial and temporal aspects of the models [4]–[6]. Some studies show that ML-methods can be used to improve the accuracy of the classical models [7]. A widely used application of ML support to the complex models is in parameter estimation [8], [9]. Deep learning techniques, a form of ML, are also used in Earth Sciences [10]. Integration of ML models in physics-based models also extends to applications such as:Reduced-Order Models, Inverse Modeling, Forward Solving Partial Differential Equations, Discovering Governing Equations, Data Generation, residual modelling [2].

A widely used method are Artificial Neural Networks (ANN). This method can accurately represent physics-based patterns, even non-linear patterns. This method is generally not transparent in the underlying actions of the algorithms used to generate predictions.

Rewrite The implementation of ML algorithms in support of large numerical models has gained much popularity over the last years, this has resulted in a proposal to standardised use of ML in climate simulations [11]. Other scientist have a more critical view on implementing ML models to supplement parts of a climate model. They argue that the validity of the model is reduced because the ML model does not represent the physical process it is predicting [12]. A large problem is the possibility for a ML model to predict inaccurate results that violate a law of physics. Physics guided ML is proposed as one solution to this problem [13]–[16]. The most common technique to make the ML model consistent with the laws of physics is to physics-guided loss function [17].

It has been shown that ML methods can accurately approximate the underlying equations governing the data [18], [19]. In general Physics based models lack in completeness and ML-methods are heavily dependent on how well the available data represents the true underlying pattern. These shortcomings can become a strength when the two methods are combined. When part of a complex large-scale high resolution numerical model can be substituted by a ML algorithm. In this thesis .. look at a general application of the hybrid-model structure in geophysical studies. The research will be focused on representing a complete simulation of a snow-melt-model and a forest-fire model. The models are trained on previously run simulations of the same area of interest and are tested on a new situation in that same area. The driving factors, such as wind direction, precipitation, temperature are new to the trained model. This approach has been performed in several other disciplines with neural networks [20]–[25].

The scientific results of these geophysical and climate models are input for politicians and other policy makers in their descicion making proces. Therefore there is a strong desire for a clear transparency in the model pre-

dictions. For this reason, the utilization of a random forest model is incorporated alongside the frequently employed neural network approach in this study.

This report describes the research in the applicability of ML emulated simulations to reduce computational complexity. The chosen areas of interest and data structures are described. A description of the methods used in this research regarding feature selection, hyperparameter tuning and performance evaluation is followed by the results. All is followed by a discussion which includes a critical look at the results and methods used but is restricted to fundamental evaluations of the use of ML in physics-based modelling. In the appendix code snippets can be found, the research will continue and the progress can be followed on the following github repository: https://github.com/RicktenE/Utilize-Machine-Learning-to-Capture-Dynamics-of-Large-Scale-High-Resolution-Numerical-Models

2. Data

2.1 Description of the data

Data exploration results
Nice examples of specifics found
Use appendices for full data exploration results

2.2 Preperation of the data

Data preparation used during analysis
Only discussed the relevant parts
Ethical and legal consideration of the data

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bi-

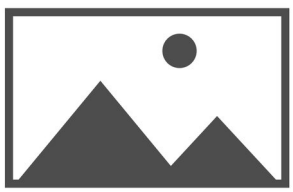

Figure 2.1: Caption

bendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

3. Method

3.1 Description of the method used

Translation of RQ to data science question
Motivated selection of method used
Motivated settings of method used

previous time point (Markovian property) and on the input variables [29,30,31]. This approach is considered the most reliable when dealing with models based on differential equations because it embeds the dynamics of the process. However, the performance of this method is poor if the simulated process has a large degree of stochasticity.

3.2 Feature importance

3.2.1 Game of Life

3.2.2 Forest Fire

3.2.3 Snow melt model

4. Results

4.1 Overview of the results

Keep it brief

Use appendices for full analysis if needed

5. Conclusion

Answer the data science question
Answer the research question

5.1 Discussion

Describe and discuss implications
Discuss ethical implications and considerations

Appendices

A. Appendix title

A. Appendix A

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bi-

bendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetuer.

A.1 First appendix section

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis

eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Nulla malesuada porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis. Donec nonummy pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem. Sed lacinia nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus. Nullam cursus pulvinar lectus. Donec et mi. Nam vulputate metus eu enim. Vestibulum pellentesque felis eu massa.

Quisque ullamcorper placerat ipsum. Cras nibh. Morbi vel justo vitae lacus tincidunt ultrices. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. In hac habitasse platea dictumst. Integer tempus convallis augue. Etiam facilisis. Nunc elementum fermentum wisi. Aenean placerat. Ut imperdiet, enim sed gravida sollicitudin, felis odio placerat quam, ac pulvinar elit purus eget enim. Nunc vitae tortor. Proin tempus nibh sit amet nisl. Vivamus quis tortor vitae risus porta vehicula.

Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo

lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetuer.

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetuer at, consectetuer sed, eleifend ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui.

Morbi luctus, wisi viverra faucibus pretium, nibh est placerat odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetuer a, feu-

giat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetuer. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetuer odio sem sed wisi.

Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetuer eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetuer tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.

Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus. Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor.

Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Ae-

nean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam congue neque id dolor.

Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa.

Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem

id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

Bibliography

[1] K. Kochanski, D. Rolnick, P. Donti, and L. Kaack, "Climate change+ ai: Tackling climate change with machine learning," in *AGU Fall Meeting Abstracts*, vol. 2019, 2019, GC33A–04.

[2] J. Willard, X. Jia, S. Xu, M. Steinbach, and V. Kumar, "Integrating physics-based modeling with machine learning: A survey," *arXiv preprint arXiv:2003.04919*, vol. 1, no. 1, pp. 1–34, 2020.

[3] D. Kochkov, J. A. Smith, A. Alieva, Q. Wang, M. P. Brenner, and S. Hoyer, "Machine learning–accelerated computational fluid dynamics," *Proceedings of the National Academy of Sciences*, vol. 118, no. 21, e2101784118, 2021.

[4] A. A. Kajbaf, M. Bensi, and K. L. Brubaker, "Temporal downscaling of precipitation from climate model projections using machine learning," *Stochastic Environmental Research and Risk Assessment*, vol. 36, no. 8, pp. 2173–2194, 2022.

[5] S. Rasp, M. S. Pritchard, and P. Gentine, "Deep learning to represent subgrid processes in climate models," *Proceedings of the National Academy of Sciences*, vol. 115, no. 39, pp. 9684–9689, 2018.

[6] K. Chattrairat, W. Wongseree, and A. Leelasantitham, "Comparisons of machine learning methods of statistical downscaling method: Case studies of daily climate anomalies in thailand," *Journal of Web Engineering*, pp. 1397–1424, 2021.

[7] N. D. Brenowitz, B. Henn, J. McGibbon, *et al.*, "Machine learning climate model dynamics: Offline versus online performance," *arXiv preprint arXiv:2011.03081*, 2020.

[8] K. Dagon, B. M. Sanderson, R. A. Fisher, and D. M. Lawrence, "A machine learning approach to emulation and biophysical parameter estimation with<? xmltex\break?> the community land model, version 5," *Advances in Statistical Climatology, Meteorology and Oceanography*, vol. 6, no. 2, pp. 223–244, 2020.

[9] P. A. O'Gorman and J. G. Dwyer, "Using machine learning to parameterize moist convection: Potential for modeling of climate, climate change, and extreme events," *Journal of Advances in Modeling Earth Systems*, vol. 10, no. 10, pp. 2548–2563, 2018.

[10] G. Camps-Valls, D. Tuia, X. X. Zhu, and M. Reichstein, *Deep learning for the Earth Sciences: A comprehensive approach to remote sensing, climate science and geosciences*. John Wiley & Sons, 2021.

[11] X. Wang, W. Xue, Y. Han, and G. Yang, "Efficient climate simulation via machine learning method," *arXiv preprint arXiv:2209.08151*, 2022.

[12] S. Kawamleh, "Can machines learn how clouds work? the epistemic implications of machine learning methods in climate science," *Philosophy of Science*, vol. 88, no. 5, pp. 1008–1020, 2021.

[13] X. Jia, J. Willard, A. Karpatne, *et al.*, "Physics-guided machine learning for scientific discovery: An application in simulating lake temperature profiles," *ACM/IMS Transactions on Data Science*, vol. 2, no. 3, pp. 1–26, 2021.

[14] X. Jia, J. Willard, A. Karpatne, *et al.*, "Physics guided rnns for modeling dynamical systems: A case study in simulating lake temperature profiles," in *Proceedings of the 2019 SIAM International Conference on Data Mining*, SIAM, 2019, pp. 558–566.

[15] A. Daw, R. Q. Thomas, C. C. Carey, J. S. Read, A. P. Appling, and A. Karpatne, "Physics-guided architecture (pga) of neural networks for quantifying uncertainty in lake temperature modeling," in *Proceedings of the 2020 siam international conference on data mining*, SIAM, 2020, pp. 532–540.

[16] A. Daw, A. Karpatne, W. Watkins, J. Read, and V. Kumar, "Physics-guided neural networks (pgnn): An application in lake temperature modeling," *arXiv preprint arXiv:1710.11431*, 2017.

[17] A. Karpatne, G. Atluri, J. H. Faghmous, *et al.*, "Theory-guided data science: A new paradigm for scientific discovery from data," *IEEE Transactions on knowledge and data engineering*, vol. 29, no. 10, pp. 2318–2331, 2017.

[18] F. Regazzoni, L. Dede, and A. Quarteroni, "Machine learning for fast and reliable solution of time-dependent differential equations," *Journal of Computational physics*, vol. 397, p. 108 852, 2019.

[19] T. Qin, K. Wu, and D. Xiu, "Data driven governing equations approximation using deep neural networks," *Journal of Computational Physics*, vol. 395, pp. 620–635, 2019.

[20] J. H. Faghmous and V. Kumar, "A big data guide to understanding climate change: The case for theory-guided data science," *Big data*, vol. 2, no. 3, pp. 155–163, 2014.

[21] V. M. Krasnopolsky and M. S. Fox-Rabinovitz, "Complex hybrid models combining deterministic and machine learning components for numerical climate modeling and weather prediction," *Neural Networks*, vol. 19, no. 2, pp. 122–134, 2006.

[22] L. J. Slater, L. Arnal, M.-A. Boucher, *et al.*, "Hybrid forecasting: Blending climate predictions with ai models," *Hydrology and Earth System Sciences*, vol. 27, no. 9, pp. 1865–1889, 2023.

[23] P. Parisouj, H. Mohebzadeh, and T. Lee, "Employing machine learning algorithms for streamflow prediction: A case study of four river basins with different climatic zones in the united states," *Water Resources Management*, vol. 34, pp. 4113–4131, 2020.

[24] P. Stolfi and F. Castiglione, "Emulating complex simulations by machine learning methods," *BMC bioinformatics*, vol. 22, no. 14, pp. 1–14, 2021.

[25] S. Scher, "Toward data-driven weather and climate forecasting: Approximating a simple general circulation model with deep learning," *Geophysical Research Letters*, vol. 45, no. 22, pp. 12–616, 2018.