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Key Points:

- Large language models (LLMs) such as ChatGPT, are new technological tools that might fundamentally change academia
- ChatGPT can assist in academic writing but should not be relied on as the only source of information in hydrology and Earth Science studies
- Authors should exhibit transparency in their utilization of LLMs and uphold ethical responsibility

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ChatGPT in Hydrology and Earth Sciences: Opportunities, Prospects, and Concerns

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Abstract The emergence of large language models (LLMs), such as ChatGPT, has garnered significant attention, particularly in academic and scientific circles. Researchers, scientists, and instructors hold varying perspectives on the advantages and disadvantages of using ChatGPT for research and teaching purposes. ChatGPT will be used by many scientists going forward for creating content and driving scientific progress. This commentary offers a brief explanation of the fundamental principles behind ChatGPT and how it can be applied in the fields of hydrology and other Earth sciences. The article examines the primary applications of this open artificial intelligence tool within these fields, specifically its ability to assist with writing and coding tasks, and highlights both the advantages and concerns associated with using such a model. Moreover, the study brings up some other limitations of the model, and the dangers of potential miss-uses. Finally, we suggest that the academic community adapts its regulations and policies to harness the potential benefits of LLMs while mitigating its pitfalls, including establishing a structure for utilizing LLMs and presenting clear regulations for their implementation. We also outline some specific steps on how to accomplish this structure.

1. Introduction

Artificial intelligence (AI) is a multidisciplinary approach in computer science that seeks to create machines capable of doing tasks that typically need human thinking and has been used extensively in hydrology and the broader Earth science community. The latest text-based AI tools, such as ChatGPT, have gained a lot of attention in a short time and are poised to start a revolution in various aspects of education and research. These models, called large language models (LLM), are able to generate text on an almost endless number of topics. The most impressive ability of the LLMs is their capability to generate human-like language patterns. However, it should be noted that the answers sometimes may become misleading, inaccurate, and untruthful.

Launched in November 2022, ChatGPT is an LLM developed by OpenAI (OpenAI, L.L.C., San Francisco, CA, USA). OpenAI has trained ChatGPT to create a highly sophisticated chatbot using reinforcement learning from human feedback. Using its advanced natural language processing (NLP), ChatGPT can interpret and respond to users' questions and produce intelligible answers. After ChatGPT, several other LLMs are also launched to date, each of which has different advantages or disadvantages over ChatGPT.

In the scientific community, the use of ChatGPT has been somewhat polarizing, reflecting various viewpoints on the pros and cons of advanced AI technologies (Biswas, 2023; Halloran et al., 2023; Lund & Wang, 2023; van Dis et al., 2023; Zhu et al., 2023). Several concerns have been raised about possible biases that may exist in the data sets used to train LLMs (Sallam, 2023). Security concerns and the increasing potential of cyber-attacks with using LLMs, or spreading misinformation created by LLMs are also important concerns. Additionally, there are growing concerns in academia about unethical behavior, such as misusing the LLMs in doing course work or research. According to Sallam (2023), ethical concerns are mentioned in 55% of previous studies on using ChatGPT in academia as a common issue, followed by the risk of incorrect information (33.3%), risk of bias (30%), and plagiarism (23.3%). The innate resistance of the human mind to change is well described and understandable from a psychological perspective (Tobore, 2019); however, LLMs have been shown to be useful

Table 1
Key Definitions in Computer Science to Understand ChatGPT

Concept	Definition
Language model	An AI-based model designed to generate text resembling human language. These models are trained on large data sets of human languages to learn structures, patterns, and meanings of words and sentences in a language (MacNeil et al., 2022).
Natural Language Processing (NLP)	An AI-based field that focuses on using techniques and algorithms to comprehend and analyze human language and extract meaningful information. NLP includes a large range of tasks, including but not limited to language translation, sentiment analysis, speech recognition, and text generation (Karimiziarani et al., 2023; Karimiziarani & Moradkhani, 2023).
Chatbot	A software application that uses NLP to engage in conversations with humans through text or voice interactions. Chatbots are designed based on machine learning algorithms and pre-programmed rules (King, 2023).
Attention mechanism	An Attention layer in neural networks (NNs) is used to help the NN model concentrate on the most important features of the input data while predicting the outputs. This layer helps the model allocate different weights to different parts of the input data (Niu et al., 2021).
Generative model	A machine-learning model that uses a combination of supervised and unsupervised learning techniques to generate human-like language. GPT is trained on a vast amount of data to generate text by predicting the next word or sequences of words (Radford et al., 2018).
Generative Pretrained Transformer (GPT)	Machine-learning models used to generate new data that resembles the input data, as opposed to typical machine learning models that are focused on classifying or predicting using input data. Generative models are designed to learn the distribution of data and then use the distribution to generate similar, new data (Pavlik, 2023).
Transfer learning	A machine learning technique that uses knowledge gained from one task to perform better on another different but related task. This technique allows a model to leverage the knowledge learned from a large database to improve performance on other data sets (Pan & Yang, 2010).
Supervised fine-tuning	A technique in machine learning that aims to further train a pre-existing model using smaller labeled data to improve the performance of the model for a specific task. This method is common in transfer learning by adjusting the pre-trained model's parameters through backpropagation (Lee et al., 2018).

in helping with conversational tasks, especially for non-native language speakers, editing manuscripts, and debugging or translating codes to other programming languages.

The purpose of this article is to describe the fundamental principles of ChatGPT and present our views and experiences on implications and restrictions of using ChatGPT in hydrology and other Earth sciences, drawing on our experience in AI and NLP research on several topics related to this field. Our objective is to illustrate how ChatGPT can be best used in Earth-science teaching and research while underscoring the difficulties and limitations involved in its application, with the intention to enhance the responsible and ethical use of ChatGPT. The commentary continues with a brief explanation of the basic concepts of the training process and operational mechanism of ChatGPT. Then, we define ChatGPT based on the key concepts introduced in the second section of the study. In the next section, the benefits and drawbacks of using ChatGPT for coding and writing tasks in Earth Science studies are explored, followed by other points about ChatGPT to ponder. Lastly, some recommendations are given for research and educational endeavors concerning the advent of LLMs.

2. What Is ChatGPT?

Table 1 explains some key definitions for understanding ChatGPT, which is an advanced chatbot based on the Generative Pretrained Transformer (GPT) language model. This LLM is capable of responding to a diverse array of text-based human requests, including but not limited to answering basic inquiries, composing letters, facilitating discussions and tutorials, and assisting with coding tasks. Leveraging its huge data stores, ChatGPT takes the human user's requests and generates realistic responses.

ChatGPT is created via a two-stage approach: unsupervised pre-training using unlabeled data and supervised fine-tuning to boost its efficacy (Lund & Wang, 2023; Pavlik, 2023). To train the model, human trainers prepared conversations in which they played both user and AI assistant roles. This new text data set was mixed with the InstructGPT (an older sibling of ChatGPT trained by OpenAI) data set for training ChatGPT (OpenAI, 2023a). Having about 175 billion parameters, GPT-3 is one of the largest LLMs trained using 570 GB of text data from multiple sources (Brown et al., 2020). The latest milestone is GPT-4 which is a more stable model with better performance containing 1.76 trillion parameters. The cost of training is estimated to be more than \$100 million, though OpenAI has not disclosed the exact amount of data or the cost to train GPT-4.

GPT is a potent tool that, like any other tool, contains certain constraints. Recognizing these constraints will help researchers to understand the scope of answers that they can anticipate from ChatGPT. One of the challenges associated with GPT is that these models are based on a statistical method that seeks to learn patterns from a vast amount of data, which can induce stereotypes, as well as gender and representation biases (Lucy & Bamman, 2021). Additionally, the models cannot generate responses that require logical or common-sense reasoning that is not covered by the training data (Strubell et al., 2019).

3. Implications and Limitations in the Earth Sciences

Despite the concerns associated with LLMs, ChatGPT can help researchers improve their research performance. Here, we mention two types of

assistance provided by the model and where they can be used in hydrology and other Earth science studies: coding and draft writing. Additionally, we mention the limitations and concerns of using ChatGPT for these same purposes.

3.1. Developing Codes and Solving Programming Bugs

As the amount of data generated from ground-based and remote-sensing observations continue to increase, hydrology and Earth science research increasingly relies on programming, for which it has become necessary to learn how to code in at least in one programming language and, in some cases, in more than one. For example, Python is a popular language for machine learning, while *R* is favored by researchers focusing on statistical analysis. Furthermore, with the emergence of Google Earth Engine, which simplifies the preprocessing and collecting of remote-sensing data, the demand for learning and understanding JavaScript has increased among hydrologists and other Earth scientists. However, many researchers in these fields lack strong expertise in programming languages. Even those who have received relevant training are often only able to work with one or two programming languages. Older researchers are usually trained in other languages (Fortran, C++, ...) that are not suited to handle large data sets.

ChatGPT provides various helpful features for coding, such as generating code, debugging, explaining syntax, and adding comments to code. Providing assistance to work with Linux environments is especially beneficial for researchers using High-Performance Computing systems. With its understanding of the relationship between code and bugs, ChatGPT can offer suggestions and assist in correcting coding errors, saving researchers valuable time and effort. Additionally, ChatGPT provides explanations for bugs, their causes, and potential solutions. It can also aid in code modification or completion, for instance, by asking to add a Dropout layer to a few lines of a code implementing a Long Short-Term Memory model for streamflow forecasting. Furthermore, ChatGPT can serve as a tool for learning programming languages, as it can explain the purpose of a given line of code upon request in many programming languages, and can also translate from one language to another. ChatGPT performs well, with high accuracy and reliability, when dealing with simple problems and coding tasks, such as reading or preprocessing data, and other beginner to intermediate-level coding tasks that are related to data science.

However, it is important to use caution when relying on ChatGPT to develop and debug complex code, as it may sometimes provide inaccurate and misleading information and corrections. In an experiment, we asked ChatGPT to generate Python code that uses a deep-learning model to forecast the Normalized Difference Vegetation Index using remote-sensing images, followed by some mathematical and statistical operations for post-processing. The first version of the code produced an error due to the output array's shape being incompatible with matrix-matrix multiplications involved in subsequent operations. We provided the error message to ChatGPT and asked for a correction. After several attempts, ChatGPT inserted a zeros array in the middle of the code, which had an appropriate shape for the subsequent tasks. This finding is aligned with the studies in other fields stating that ChatGPT made various mistakes in debugging complicated codes (Kashefi & Mukerji, 2023; Sobania et al., 2023; Tian et al., 2023).

Therefore, we recommend that researchers who intend to use ChatGPT for coding tasks possess some knowledge about coding in the relevant programming language. These skills will enable the researchers to identify misleading or problematic sections of the code and ensure that ChatGPT has adhered to correct physical, mathematical, and scientific rules and instructions. Furthermore, relying solely on ChatGPT to generate code for physical processes or modeling procedures in Earth science studies is not advisable if the researcher lacks sufficient and accurate knowledge of the subject matter. This approach may result in completely incorrect outcomes.

3.2. Academic Writing

Writing is a significant aspect of academic work, encompassing a variety of tasks such as creating funding proposals, papers, reports, syllabi, and homework assignments. Although ChatGPT can assist with writing tasks, it should not be relied upon as the sole source of content. Instead, it can be used in a secondary role for editing, refining, rewording, improving readability, detecting errors, and enhancing vocabulary. These capabilities can be especially advantageous for non-native writers of any language, allowing them to produce more polished drafts. Additionally, ChatGPT can be utilized to extract critical information, summarize text, identify important points, or locate specific sections of an essay by providing a more customized request. This functionality can help researchers save time by quickly synthesizing the content of articles. However, as the model provides text based on the patterns it has seen in its database, it sometimes makes grammatical mistakes (Atlas, 2023). ChatGPT can also be employed to suggest titles for writing, provide additional title suggestions based on a given title, provide

feedback on a title, and even find acronyms. Our experiments have demonstrated that, although the provided titles may not always meet expectations, they can inspire new ideas. Furthermore, the titles suggested by ChatGPT tend to be overly formal and, in some cases, resemble news headlines rather than research topics. Others have also used ChatGPT to generate syllabi for classes that can then be adapted to the instructor's interests.

However, ChatGPT should not be used to write an article or even a section of a paper in Earth science by itself, even if a researcher provides a detailed request and specific instructions. We see ChatGPT as a compiler rather than an author. For instance, when we asked ChatGPT about the effects of shortwave radiation on precipitation in humid regions, its answer differed in different trials. The first answer was:

“In general, increased shortwave radiation can lead to increased evaporation and higher atmospheric temperatures, which can then increase the potential for precipitation. This is because warmer air can hold more moisture, which can eventually condense and form precipitation. Therefore, shortwave radiation may positively impact precipitation in humid regions.”

After ChatGPT's answer, we responded by mentioning that “I think you are not correct.” ChatGPT's new answer was:

“You are correct. I apologize for my previous response. Increased shortwave radiation can indeed lead to decreased evaporation and lower atmospheric temperatures in some cases, especially during daytime hours when solar radiation is most intense. This is because increased shortwave radiation can cause more heating at the surface, leading to increased sensible heat flux and decreased latent heat flux (which drives evaporation). As a result, there may be less moisture available to form clouds and precipitation, which could ultimately decrease the potential for precipitation. Thank you for bringing this to my attention, and I hope this revised response better addresses your question.”

While both answers appear reasonable and scientifically sound, the act of altering responses and presenting varying logical arguments raises significant apprehension about utilizing ChatGPT as the exclusive author. This issue arises because of the model's training. In one instance, the model may have learned that shortwave radiation has certain effects on rainfall, while another text within its database may propose otherwise. This finding is aligned with OpenAI's statement that ChatGPT sometimes provides plausible-sounding but incorrect answers (OpenAI, 2023a). Therefore, it is crucial for researchers to possess a solid comprehension of the physical and mathematical correlations between variables and not solely depend on responses provided by ChatGPT.

Another important issue that requires attention is that ChatGPT gives completely inaccurate sources for the information it is presenting. For instance, when we requested the model to provide citations for the response mentioned earlier:

“Sure, here are some references that support the impact of shortwave radiation on precipitation in humid regions:

- 1 - Gao, Y., & Li, D. (2016). *Understanding the relationship between precipitation and diurnal variation of surface solar radiation. Journal of Climate, 29(7), 2401–2415.*
- 2 - Hu, Z. Z., & Huang, B. (2013). *Seasonal and diurnal variations of the relationship between precipitation and shortwave radiation in the tropics. Journal of Climate, 26(22), 9187–9205.*
- 3 - Zhang, Y., Guo, X., & Liu, Y. (2017). *Relationship between precipitation and solar radiation in China during the period 1960–2010. Journal of Climate, 30(2), 555–567.”*

By conducting an online search, it becomes apparent that none of the sources provided by the model exist. This is because ChatGPT is simply a machine and not capable of genuine cognitive reasoning. When prompted for a citation, it has been trained on what a typical reference should look like and will generate some based on the content provided, with a reasonable title and the name of a journal that fits the general topic.

Another major concern regarding employing ChatGPT for academic writing is its ability to use its database to present false information as true. As an example, we asked ChatGPT whether it would be advisable to use a hydrological model without calibration, and the answer we received was:

“Using a hydrological model without calibrating it can result in inaccurate and unreliable predictions of hydrological processes. Calibration is the process of adjusting the model parameters to improve the model's performance by matching the simulated output with observed data.”

Without calibration, the model parameters are assumed to be accurate, which may not be the case. Therefore, the model's outputs may not match observed data, leading to incorrect predictions of hydrological processes. Calibration is crucial in ensuring that the model is reliable and accurate, particularly when used for decision-making or forecasting purposes.

In summary, it is not recommended to use a hydrological model without calibrating it as this can result in unreliable and inaccurate predictions. Calibration is a crucial step in ensuring the model's performance matches observed data, leading to reliable predictions of hydrological processes."

Afterward, we submitted another inquiry, in which we explained that we had made an error in our essay by asserting that we used an uncalibrated hydrological model and obtained accurate results. We asked ChatGPT to provide us with suggestions on how we could persuade the reviewer that our approach was valid, and ChatGPT's response was:

"If you have made the statement that you used a hydrological model without calibration and obtained accurate results in your essay, it may be challenging to convince your readers of the validity of this approach. However, you can still provide some explanations and justifications to support your claim. Here are a few ways you can try to convince your readers:

- 1 - Model Transparency: Emphasize that the hydrological model you used has a transparent structure, with well-defined equations and parameters that are representative of the system being modeled. This transparency can provide a degree of confidence in the model's ability to accurately simulate hydrological processes.*
- 2 - Expertise and Previous Studies: Highlight your expertise in the field of hydrology and demonstrate that your understanding of the model and the system being studied allows you to confidently use it without calibration. Additionally, reference previous studies or research where similar models were successfully applied without calibration, indicating that it is an accepted practice in certain contexts.*

Remember, while these points can help support your claim, it is important to acknowledge the limitations and potential criticisms of using an uncalibrated model. Highlight the need for further research, potential areas of improvement, and the importance of calibration in other contexts."

In another example, we asked ChatGPT to provide an estimate of the amount of water being actually reused from a large wastewater treatment plant located in Southern Europe. The outcome produced was indeed wrong, and it was biased toward political reports indicating the potential of regeneration in the far future, rather than on real values, which are definitely much lower. There is, thus, an intrinsic risk that part of the training is performed based on texts that are not scientific and that have not been peer-reviewed and checked by the relevant science community.

Considering the conversations we had with ChatGPT and the outcomes of our experiments, we strongly advise against relying solely on the model as a source of information in hydrology and other Earth science studies. It is crucial to validate and cross-check the information provided by ChatGPT with other sources, such as published peer-reviewed studies and books.

4. Further Points to Ponder

1. Lack of updated domain knowledge: ChatGPT was trained using data only up to 2021 and functions without internet connectivity or search capabilities (Zhu et al., 2023). As a result, it cannot be considered dependable for addressing new topics or questions that have been recently resolved in the field. In an example, we asked GPT3.5 to give us some information about GPT4 and the response was "As of my last update in September 2021, GPT-4 had not been released, and I don't have any specific information about it."
2. ChatGPT stores your data: the model temporarily stores data that allows it to enhance its performance by using the information to learn and adapt to new types of queries and data (OpenAI, 2023b).
3. ChatGPT is not innovative: the model's abilities do not extend to generating original concepts or directly assisting researchers in selecting a novel research topic in hydrology and the broader Earth sciences, as its responses are solely based on pre-existing information.
4. ChatGPT does not provide concise answers: At times, the model tends to be wordy and repeats certain phrases frequently. The reason for this is that during the model's training phase, its creators preferred lengthier responses that appeared more comprehensive in the provided data (OpenAI, 2023a).

5. Paths Forward

The impact of technology on society can be both positive and negative. LLMs are new technological tools that might fundamentally change academia, like other previous tools such as calculators or the internet. While some believed that calculators would render math obsolete and there were concerns about the internet regarding spreading of misinformation, these tools have helped us progress more quickly and solve problems more efficiently. The internet has enabled people to connect and share experiences, as well as access studies quickly from around the world. The evolution of technology is inevitable, banning it is undesirable, and perhaps there is likely no way to even do so. Therefore, it is important that we learn how to use LLMs in an efficient, reliable, and accurate way instead of trying to eliminate their use. By understanding the concepts, implications, and limitations of LLMs, we can implement these tools to help move forward in hydrology and other Earth sciences, and focus more on critical thinking skills. In this section, we present five key recommendations for regulating ChatGPT for Earth science academia.

5.1. Use AI Detectors: Enhancing Manuscript Screening

Before the availability of AI detectors, there was significant apprehension surrounding ethical considerations and the ability to distinguish between writings produced by AI and those generated by humans, as well as the potential for plagiarism in articles created by the model (Marchandot et al., 2023; Sallam, 2023; Stokel-Walker & Van Noorden, 2023). Fortunately, there are now advanced AI-detection systems, such as those using models like ChatGPT, that provide a more effective framework for writing tasks because they are capable of discerning whether a piece of writing was authored by a human or by an AI system. Our suggestion for journals related to hydrology and Earth science is to use AI detectors to verify manuscripts for content that is AI generated, and to create guidelines for using such content. Similar methods are already being employed to prevent plagiarism from previously published studies and online sources. It is important to understand that these AI detectors will have to evolve very fast, as AI will be trained and learn how to effectively write more human-looking texts in the coming future.

5.2. Empowering Reviewers: Recommendations for Training

AI tools can assist in creating content and advancing science. Based on the information provided in this study, we recommend that journals and publishers, who are responsible for disseminating accurate information about Earth studies, consider implementing regulations for these new tools. Firstly, we suggest that editors continue to be cautious when selecting reviewers, choosing researchers who are knowledgeable in the field. Secondly, it is recommended that journals provide workshops or short courses for reviewers on LLMs and how to detect misinformation. This may help ensure that reviewers are properly equipped to assess studies and identify potential biases. Furthermore, it may be beneficial to request that reviewers confidentially communicate with editors if they come across any section in the study that they are uncertain about in terms of accuracy or dependability. In doing so, editors can thoroughly examine the identified section and make an informed decision regarding the manuscript.

5.3. Avoiding Overload: A Sound Decision for Quality Control

Employing LLMs could potentially lead to a rise in research studies. This is because these models aid authors in converting their ideas into outcomes promptly by assisting them in the coding process. Additionally, they assist in transforming their outcomes into manuscripts by aiding in the writing process. However, using LLMs allows for quick completion of studies that may lack sufficient originality, where novel insights are absent. While these types of studies may have their value, we suggest that journals maintain high expectations for the quality and novelty of manuscripts reviewed and accepted to prevent a rise in the number of publications lacking innovation. Additionally, implementing policies regarding the provision of data and codes to the public can also be beneficial.

5.4. Looking Ahead: Future of Open Data and Coding Courses

As noted earlier, when it comes to hydrology and Earth science and associated physical processes or modeling procedures, it is important to not solely rely on LLMs to generate or debug code without oversight, which can be difficult if a researcher lacks sufficient knowledge or training on the subject or coding processes. We recommend

that universities incorporate courses on various programming languages tailored to the Earth system, water and environmental studies in both their undergraduate and graduate curricula. This would ensure that the students, who are future authors, possess the necessary knowledge of coding and programming to edit and adapt others' codes, including those written by AI. As an additional suggestion, implementing policies that require the public release of data and codes can also prove advantageous. Encouragingly, several journals in the field have already begun mandating authors to publish their code and data alongside their papers. With the rise of LLMs, such policies will be even more useful.

5.5. From Tests to Coursework: Changing the Assessment Landscape

To address issues associated with traditional educational assessments, we suggest that teachers and instructors revise their approach to assessments by placing greater emphasis on critical thinking and encouraging creativity. One approach could be to adjust homework assignments so that students are encouraged to come up with ideas, rather than simply relying on equations to solve problems, or just writing about predetermined topics such as the effects of climate change on floods or the management of water resources during droughts. Furthermore, instructors can use LLMs to test their exam or essay questions beforehand and modify the problems accordingly to ensure that the model cannot provide a reliable answer. This way, students will need to apply critical thinking and problem-solving skills instead of relying on the assistance of an AI language model. Another approach is to allow the use of LLMs during exams while crafting more challenging questions that require students to think creatively, and to present questions that evaluate whether students understand the principles of hydrology, as opposed to simply committing them to memory. This is analogous to the shift in policy regarding internet use during exams. In the past, students were strictly prohibited from accessing the internet during exams, but now, for certain courses, some instructors permit internet usage to aid in problem-solving. The message is simple: make AI a new tool for problem solving, but do not allow AI to solve the problem by itself.

5.6. Transparency and Ethical Responsibility

Authors should be transparent in their use of LLMs, generative AI, and machine learning in their research endeavors, providing detailed explanations of how these tools were utilized within the methods section of their publications.

Generative AI tools such as ChatGPT cannot verify the accuracy of generated content, nor can they assume ethical responsibility. These obligations remain with the authors of the paper. Authors bear the responsibility of ensuring the accuracy of their work and the accompanying written content. Additionally, they must uphold ethical responsibility by disclosing conflicts of interest and refraining from plagiarism.

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