HSBC Global Research

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AI: Weather forecasting

A new asset in an era of extreme weather

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ESG & Climate Change - Global

- The increased frequency and intensity of extreme weather events have stressed the importance of weather forecasting
- More unpredictable weather reduces the reliability of weather forecasting, with many negative economic and social impacts
- Artificial intelligence (AI) could raise forecast accuracy, potentially saving lives and significant climate damages

This is the first in our 'AI' series, identifying key ESG and climate topics and discussing innovative technological solutions to help address issues sustainably.

The importance of weather forecasting
Weather forecasting predicts and monitors meteorological patterns. Accurate forecasts are crucial for public safety, health and livelihoods, as well as shipping, aviation and energy production. Forecasts are becoming ever more important as we enter an era of intensified extreme weather events and record-breaking temperatures – they are vital in helping to address challenges such as food insecurity and heat-related illness.

Extreme weather is costing the economy more each decade…
Since the 1970s, economic losses related to weather, climate and water hazards have totalled USD3.6trn, representing 74% of total economic losses from reported disasters. And costs are rising: over the next five years alone we expect a further USD771bn of losses in food and water shocks alone. It is not only the intensity but the unexpectedness of extreme weather events that makes them so damaging. Reliable forecasting is essential to help communities prepare and adapt adequately, and corporates to protect assets and avoid financial damages.

…and climate change is impacting our ability to forecast, too
Studies show that as temperature increases, the accuracy of weather forecasts decreases by several hours. Events such as hurricanes may become more difficult to forecast as warming climates enable them to develop and intensify more rapidly.

The answer to this challenge may lie in AI
Studies suggest AI has the potential to increase the accuracy of existing weather forecasting systems, as well as reduce processing time and energy consumption. However, there are limitations that need to be overcome, including the ability of AI to predict future extreme events accurately using historical data. We expect the blending of these technologies to unlock the benefits of AI and improve current systems. We are optimistic about AI's potential to improve forecasting systems, possibly saving billions in damages, and better safeguarding communities worldwide.

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Amy Tyler
ESG Analyst
HSBC Bank plc

Mark McDonald
Head of Data Science and Analytics
HSBC Bank plc

James Rydge
Head, ESG Research, EMEA
HSBC Bank plc

Yaryna Kobel
Corporate Governance Analyst
HSBC Bank plc

Wai-Shin Chan, CFA
Head, Climate Change Centre; Head, ESG Research
The Hongkong and Shanghai Banking Corporation Limited

Issuer of report: HSBC Bank plc

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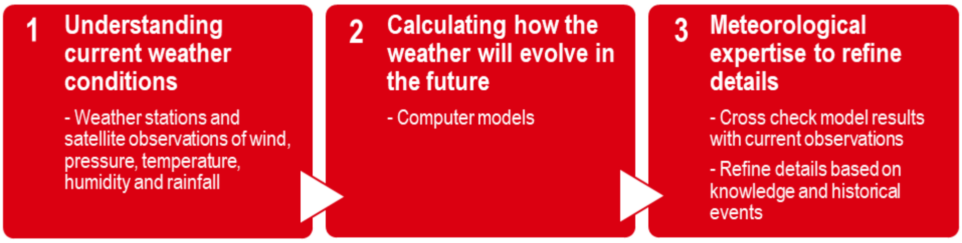
Models are continuously updated, increasing in complexity and capacity

Computer technology already plays a central role in meteorology. Today, most forecasts begin with **numerical weather prediction models (NWP)**. These are computer models that utilise weather data (e.g. wind, pressure, humidity) and predict how conditions will change in the future. As forecasts are extended further into the future, errors accumulate and accuracy reduces (Figure 2). Meteorologists then interpret and modify results using their own expertise whilst monitoring how conditions change with updated measurements and observations (Figure 1). Computer models are continuously updated and have significantly increased in complexity and capacity in recent years, with 20-30 day forecasts now possible.

A brief history of forecasting

The introduction of technology into forecasting, such as thermometers, dates back to the 1700s and has built the basis of forecasting today. It wasn't until the 1900s when forecasts started to produce reliable results, as measurement collection allowed the establishment of rudimentary weather station networks and services. The launch of meteorological satellites and sensors on military and commercial aircraft in the twentieth century further improved data collection and prediction abilities, making 5-7 day forecasts possible.

Figure 1. The process for producing current weather forecasts



Source: HSBC, Met Office

We need to understand future weather conditions and possible impacts

The importance of weather forecasting is heightened in the face of today's previously unobserved weather events and ever-changing climate conditions. **Impact-based forecasting** has developed in the face of such risks, which considers the vulnerability of people and property, identifying the impacts that may occur and allows appropriate action to be taken. This method is illustrated by a forecasting risk matrix, which maps the likelihood of the extreme weather occurring and its expected impact, with a scale of yellow to red warnings[1]. It's an important tool – yet it is estimated that less than half of countries globally report the existence of national impact-based forecasting and warning services[2].

Figure 2. Approximate accuracy of various ranges of current weather forecasts

Source: HSBC, NOAA

Only half the world has early warning systems in place…

Similarly, warning services such as the specialised **Multi-Hazard Early Warning Systems (MHEWS)** address several hazards to warn of one or more occurring, providing early warnings to save lives and livelihoods. But, it is estimated that only around half of the world currently has early warning system coverage, with developing countries especially lacking such systems yet experiencing significant vulnerabilities. It is estimated that countries with limited to moderate MHEWS coverage have a disaster-related mortality ratio that is nearly 6x higher than that in countries with substantial to comprehensive coverage[3]. Additionally, giving even 24 hours of notice before an impending event can reduce damage by 30%[4].

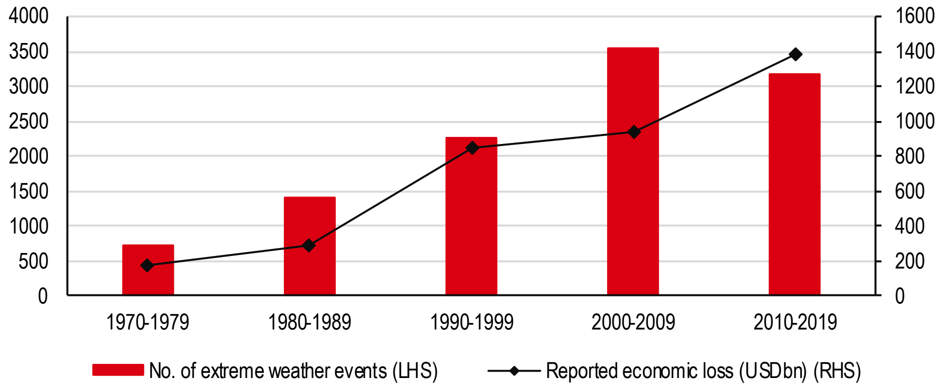
1 Met Office
2 'Global Status of Multi-Hazard Early Warning Systems: Target G', UNDRR, WMO, 2022
3 'Global Status of Multi-Hazard Early Warning Systems 2023', UNDRR, WMO, 2023
4 'Early Warning for All', United Nations

Protecting developing regions with early warning systems can prevent billions in losses each year

To ensure that vulnerable communities are protected, the UN introduced the 'Early Warnings for All Initiative', covering 30 developing countries that have been identified for support. Of these, over 75% do not produce impact-based forecasting, and over 80% do not have integrated MHEWS in place[5]. It is estimated that investing USD800m in early warning systems in developing countries could prevent losses of USD3-16bn annually[6].

Benefits of accurate weather forecasting – why is it so important to get right?
According to the World Meteorological Organization (WMO), between 1970 and 2019, 50% of all disasters were related to weather, climate and water hazards. These were responsible for 45% of all reported deaths (2.06 million) and 74% of reported economic losses in the EM-DAT (a global database on natural and technological disasters) (USD3.6trn)[7]. Since the 1970s, deaths due to such hazards have been declining, attributable to advances in early warning systems (185,000 deaths in 2010-19, compared to a peak of 667,000 in 1980-89). However, deaths by extreme temperatures have been increasing in prevalence.

Figure 3. Number of global extreme weather events and associated economic loss



Source: World Meteorological Organization (WMO)

Over the next five years, the expected global economic loss from the impact of extreme weather events on food and water shocks is USD771bn. This figure includes the probability of extreme events happening and makes up more than half of last decade's reported economic losses already. The estimate focuses on just food and water losses, combined with the expectation that not all economic losses are reported accurately or at all, especially in developing regions, we expect the true value of loss to be higher. Asia Pacific is highlighted as a region with particularly high loss impact expected[8].

5 'Early Warnings for All in Focus: Hazard Monitoring and Forecasting: Results of the Pillar 2 Rapid Assessment', WMO, 2023
6 'Early Warning for All', United Nations
7 'WMO atlas of mortality and economic losses from weather, climate and water extremes (1970–2019)', WMO, 2021
8 'Lloyd's new data tool highlights vulnerability of the global economy to extreme weather', Lloyd's, 11 October 2023

Figure 4. Benefits of accurate weather forecasting

Extreme weather preparation	Accurately predicting when and where extreme weather events will occur allows for greater preparation and recovery efforts – saving lives and limiting damage to livelihoods and property.
Agriculture and food security	Weather aspects such as rainfall and temperature are key for farmers for processes such as planting and ensuring the safety of cattle. This mitigates the effect of extreme weather events on their livelihoods. This has a direct impact on global food security as the ability to adapt to changing weather conditions affects efficient food production and depends upon accurate forecasts.
Transportation	Understanding future weather conditions is essential to all types of transportation, to keep passengers and crew safe and cargo secure. An aircraft's ability to monitor turbulent weather and a ship's capability to map suitable routes are vital for safety, a process that relies greatly on accurate forecasting.
Climate resilience	Climate change is increasing the intensity and severity of extreme weather events, resulting in loss of life and ever increasing economic costs (Figure 3). Developing accurate and timely forecasts for such events can help minimise the impacts by effective preparation and recovery. This subsequently increases climate resilience, which is especially important for developing regions with significant vulnerabilities to such events.
Energy production	Natural resources used for energy processes such as biofuels are particularly susceptible to weather impacts, especially when there is significant uncertainty around extreme weather events. This increases price volatility and impacts communities with often high reliance of these fuels for income. Additionally, renewable energy relies on environmental resources including wind and solar. Forecasts of these parameters are required for efficient integration into power grids to estimate power generation and integrate smart energy management. Forecasting renewable energy is critical for planning, investment and decision-making purposes to reduce uncertainty around power generation[9].
Economic benefits	Extreme weather events are costing the economy more each decade. Between 2010 and 2019, nearly USD1.4trn was reported in economic losses in total, compared to USD175bn between 1970 and 1979, with storms resulting in the greatest losses (Figure 3)[10]. Improving weather forecast accuracy allows individuals to adapt behaviour effectively, thus reducing vulnerability to the event. It is not only the intensity but the unexpectedness of an extreme weather event that drives the negative economic outcomes[11]. It is estimated that the socio-economic benefits of weather prediction amount to over USD160bn per year, however, further improvements to forecasting and early warning systems could provide an extra USD30bn per year[12].

Source: HSBC

How is climate change impacting weather forecasting?

Rising temperatures resulting in a reduced ability to predict the weather…

Climate change has long been observed to be increasing the frequency and intensity of extreme weather events[13]. However, the impact that climate change has on the way we predict future weather patterns and climate variables is less explored. According to a Stanford University study[14], rising temperatures are seen to reduce the predictability of weather in mid-latitudes[15], with cooler climates exhibiting more predictability. The study highlights how as temperature increases the accuracy of weather forecasts decreases by several hours, resulting in less time to prepare for extreme weather events, with precipitation exhibiting the most unpredictability.

Some weather events are more susceptible than others to forecasting accuracy in the face of climate change

Focusing on specific weather events, an American Meteorological Society study has found that predicting hurricanes may become more difficult due to warming climates increasing their intensity more rapidly before hitting land. The study states that there is an increased risk of poorly anticipated, high-intensity hurricane landfalls with rising temperatures and sea levels. This risks higher rates of injury and deaths unless populations can prepare to respond to hurricanes at short notice[16]. Furthermore, a study in Geophysical Research Letters found that global warming reduces the predictability of precipitation (especially in summer during warmer temperatures); however, some aspects such as pressure fields and temperature may benefit from global warming in terms of predictability[17]. Focus on preparedness for water-related disasters and water-sensitive industries such as energy is required to alleviate associated risks.

Computer models used for weather forecasting today use atmospheric physics and current weather observations, therefore, it is argued that climate change shouldn't impact the accuracy of weather forecasts. However, the predictability of weather events may be impacted. This is illustrated by the previously discussed studies, as when weather events intensify or change rapidly, predictability naturally diminishes[18].

9 'Weather Forecasting for Renewable Energy System: A Review', R. Meenal, et al., Archives of Computational Methods in Engineering, 2022
10 'WMO atlas of mortality and economic losses from weather, climate and water extremes (1970–2019)', WMO, 2021
11 'The Economic benefits of weather forecasting', World Bank, 12 September 2023
12 'The value of Surface-Based Meteorological Observation Data: Costs and benefits of the Global Basic Observing Network', Systematic Observations Financing Facility (SOFF), October 2020
13 'How is climate linked to extreme weather?', Met Office
14 'Climate of chaos: Stanford researchers show why heat may make weather less predictable', Stanford University, 14 December 2021
15 Mid-latitude: Part of the northern or southern hemisphere between 30°-60° latitude.
16 'Will global warming make hurricane forecasting more difficult?', K. Emanuel, American Meteorological Society, March 2017
17 'How Global Warming Changes the Difficulty of Synoptic Weather Forecasting', S. Scher, G. Messori, Geophysical Research Letters, 2019
18 'Will climate change make weather forecasting less accurate?', MIT, 30 January 2023

Is AI the answer?

Recent developments in technology, specifically **artificial intelligence (AI)**, have brought new attention to weather forecasting, for which the NWP models has remained the primary process for many decades. AI and machine learning are now being applied to forecasting, not only using numerical models and atmospheric physics but incorporating historical data as well.

AI models outperforming conventional forecasting systems

Recent studies have found accuracy benefits in AI application. Google DeepMind's GraphCast AI model has significantly outperformed conventional forecasting methods for predicting weather in 90% of the 1,380 verification targets used in the current European Centre for Medium-range Weather Forecasts (ECMWF) product[19]. The study in *Science* highlights how the model brings advancements in efficiency and accuracy of weather forecasting and supports better extreme event prediction. Additionally, a study in *Nature* found that Huawei's Pangu-Weather AI model obtained stronger results on reanalysis data when compared to the ECMWF's NWP forecasting system, noting that the model worked well when forecasting extreme weather events[20].

Figure 5. Latest developments in AI application to weather forecasting

Company	Details
Google DeepMind United States	The GraphCast AI model uses machine learning with over 40 years of global ECMWF data, to produce a 10-day forecast in less than a minute.
IBM & NASA United States	In a collaboration with NASA, IBM announced development of geospatial mapping with AI technology for weather and climate prediction. Modelled on 40 years' worth of weather observations, it is hoped the technology can also assist in climate change research.
Microsoft United States	ClimaX is a Deep Learning (DL) model for weather and climate science, that can be trained using physics-informed climate simulation datasets.
Nvidia United States	FourCastNet is a data-driven Deep Learning (DL) weather forecasting model with accuracy comparable to current NWP models and predications produced in seconds. The model is trained on ECMWF data.
Huawei Mainland China	Pangu-Weather is an AI model for global weather forecasting, which has been used by the ECMWF to successfully predict recent extreme weather events.

Source: Financial Times, TechRadar. Microsoft, Nvidia, Huawei.

Reducing time and energy requirements to produce the same results…

One major advantage of utilising AI in forecasting is the time it takes to produce results – reducing from hours to seconds. This makes updating forecasts fast and effective for short-term events that may unfold before a traditional model could process the result. This is critical as extreme weather events are intensifying and approaching regions more rapidly; research suggest we should expect to see more of this pattern as temperatures rise[21]. As well as time efficiency, AI modelling is a less energy-intensive process than current methods, therefore, improving energy efficiency and reducing cost and emissions – it is estimated that the GraphCast model could be 1,000x cheaper in regards to energy consumption[22]. Therefore, as well as AI assisting in forecasting weather to maximise energy production via renewable energy sources, it can help reduce energy consumption from the weather forecasting process itself.

…but what about the use of historical data in a changing climate?

Ultimately, we are experiencing a changing climate which requires the ability of forecasting models to apply and adjust. Current AI models are typically trained on data from the last 40 years. Though the climate has been changing over this period, decades to come will likely experience much greater variation in extreme weather events. This risks reliability under a changing climate as models are not trained on the possible future extremes we expect to experience. One solution is **physics-informed machine-learning**. This provides the opportunity for the model to be trained on less data than before and introduces physical laws into the parameters in which it operates, helping to increase accuracy and viability. Models that incorporate physical laws are more likely to be robust under a changing climate[23]. Additionally, incorporating large volumes of historical weather data can allow the model to recognise and learn weather patterns, integrating these into predictions[24].

19 'Learning skillful medium-range global weather forecasting', R. Lam, et al., Science, 2023
20 'Accurate medium-range global weather forecasting with 3D neural networks', K. Bi, et al., Nature, 2023
21 'Will climate change make weather forecasting less accurate?', MIT, 30 January 2023
22 'AI outperforms conventional weather forecasting methods for first time', Financial Times,14 November 2023
23 'FourCastNet: A Global Data-driven High-resolution Weather Model using Adaptive Fourier Neural Operators', J. Pathak, 2022
24 'Climate Change Could Stump AI Weather Prediction', Scientific American, 12 July 2023

A costly process, mainly left to private institutions currently…

Developing an AI weather forecasting model requires significant volumes of data and training time and is, therefore, a costly process. With the additional cost of integrating physics principles to increase accuracy, the process requires significant funding and is currently mainly developed on the private level. Although we have seen some national forecasting agencies looking to AI to improve forecasts, they are the exception rather than the rule, for now. For example, the UK Met Office recently announced a partnership with the Alan Turing Institute, to develop AI models to help forecast extreme weather events and protect national infrastructure. The project aims to incorporate AI techniques into the Met Office's existing forecasting infrastructure once accuracy has been tested against NWP forecasts[25].

AI could be an effective tool for developing regions to establish accurate forecasting easily

What this means for developing regions

Of all deaths due to weather, climate and water hazards, 91% occur in developing regions, which accounted for 71% of such disasters between 1970 and 2019[26]. These regions face significant challenges in weather forecasting, across resource availability, measurement data, knowledge gaps and language differences whereby translation capabilities are vital for early warning systems. Collaboration and communication across global partners will be key to support regions which are expected to be significantly impacted by climate change and exhibit vulnerabilities to extreme weather events. Technological developments such as AI are promising for developing regions due to their efficiency, reduced energy consumption and resource requirements. However, translating that promise into reality will rely on improving the reliability of such models and ensuring those regions that need them most have access.

Conclusion

We expect AI to be carefully integrated into current physics-based NWP forecasting models, supplementing and enhancing them. It offers potential savings in both time and energy, as well as proving to be equally or more accurate than current NWP methods[27]. Physics-based NWP models reflect a wealth of accumulated expertise that could help to train and refine AI models. Meteorologists' expertise will also remain vital in interpreting and communicating results. And for sure there are, for now, some limitations to what AI can achieve – not least the question of how well systems trained on historical data can anticipate future events, when climate change is reshaping weather patterns.

In all, though, we are optimistic about AI's potential to improve weather forecasting. On a corporate level, it could help communities and companies to better prepare for extreme events, potentially avoiding billions of dollars in damages. It could also, we think, be a particularly useful asset for developing countries, allowing for cheaper and quicker early warnings. Nowhere is this more important than in regions expected to see some of the harshest results of climate change, and where preparation is essential to protect lives and livelihoods.

25 'AI to take weather forecasting by storm', Met Office, 31 October 2023
26 'WMO atlas of mortality and economic losses from weather, climate and water extremes (1970–2019)', WMO, 2021
27 'Huawei Cloud Pangu-Weather Model Now Available on European Weather Agency Website', Huawei, 03 August 2023

Disclosure appendix

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