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CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 8

Weathering the storm: how science can contribute to improving global climate resilience through adaptation

In brief

Adapting to the impacts of climate change is essential, even if the rise in global temperatures is kept to 1.5°C. The global temperature rise felt today is already having severe impacts on societies and the environment across the world. Adaptation must be conducted in tandem with reducing greenhouse gas emissions to net zero. The two are linked. For example, carefully restoring natural ecosystems can help to sequester carbon dioxide, while failure to mitigate climate change will result in higher future adaptation costs. While mitigation has clear goals in the form of emissions reduction targets (net zero emissions by 2050), adaptation targets vary between nations and are often not based on evidence. This results in less clarity of the scale and nature of the actions required. Successful adaptation draws on a wide range of capabilities, from science-based modelling to local community knowledge, and covers many types of interventions, from engineered structures to nature-based solutions and hybrid approaches. This briefing focusses on the role of infrastructure, nature-based solutions and modelling in adapting to the impacts of climate change.

INSIGHTS

- Adaptation is necessary even under the most stringent action to reduce greenhouse gas emissions, and the cost of adaptation will increase with the level of temperature rise. A key message from research is that now is the time to raise the ambition for adaptation and significantly increase investment.
- Scientific research and expertise can help to climate-proof the estimated $94 trillion of infrastructure needed to be built in the next two decades, by targeting investment where it can reduce climate risks most reliably[1].
- Nature-based solutions (NbS) (protecting, restoring, and sustainably managing ecosystems) can protect communities and infrastructure from climate change impacts, enhance human capacity to adapt to further change, and can contribute to climate mitigation.
- Next generation climate and weather models will provide unprecedented detail on local climate impacts. These will help improve early warning systems and can be integrated into disaster preparedness and long-term adaptation. Investment in in-situ observational platforms is necessary to improve forecast initial conditions, and to provide "ground truth" for forecasts and model projections.
- Next generation models and interdisciplinary research can also play a major role in estimating the costs of adaptation across scales, which are currently not accurately quantified, as well as evaluating the efficacy of alternative adaptation strategies[2].
- Adaptation projects can deliver several co-benefits, including progress towards the Sustainable Development Goals[3]. Further research will help maximise the benefits of adaptation.
- According to the United Nations, 50% of the total share of climate finance should be spent on building resilience and adapting to the effects of a warming world[4].

1. Climate change and adaptation

Adaptation can help minimise the vulnerability of societies across the world by reducing exposure and sensitivity to climate hazards.

Adaptation is essential for minimising the impacts of climate change, even if the goals for the Paris Agreement are met. For example, even 1.5°C of warming could expose over 500 million people to life-threatening heat conditions this century, which would lead to mass displacement[5]. Currently, over 3°C of warming is anticipated by the end of the century, based on current climate mitigation pledges[6]. Impacts are already being felt, with large-scale displacement triggered by climate and weather-related hazards reported in many parts of the world[7]. Scientifically robust adaptation strategies are crucial for creating resilient communities where people can remain and prosper in their homes.

What are adaptation and resilience? Adaptation is often defined as adjustments in ecological, social, infrastructure, or economic systems in response to (or anticipation of) climatic stimuli and their impacts[8]. Essentially, it refers to the strategies and projects which will help us cope with the inevitable impacts of climate change. Adaptation strategies take different forms in different places; what is suitable in some regions will not work in others. Successful adaptation can build resilience to climate impacts. Resilience is a term used to describe the ability to cope with adverse shocks and stresses, including the capacity to anticipate and withstand, as well as respond to and recover from, climate impacts[9].

Adaptation can help minimise the vulnerability of societies across the world by reducing exposure and sensitivity to climate hazards, and enhancing the capacity of communities to proactively adapt to evolving climate risks. Efforts are already underway: the UN has reported that almost three-quarters of nations have some adaptation plans in place[8]. However, financing and implementation of adaptation strategies fall far short of what is needed to make a meaningful difference[10]. Natural and social science, as well as engineering, can play a pivotal role in the ongoing efforts to develop and implement effective, locally appropriate adaptation strategies.

Now is the time to act. Climate change is already impacting communities and the environment across the world. These impacts will worsen as climate change progresses.

1.1 Adaptation and the role of science

Adaptation embraces a wide repertoire of approaches. These approaches commonly involve infrastructure-related measures like desalination plants to provide water in coastal drought-prone areas, data gathering and modelling such as weather forecasting, and harnessing natural systems to address societal challenges like restoring and protecting mangroves so they can serve as flood defences (termed nature-based solutions). Each of these approaches draws on a combination of natural, social, and engineering science.

These technical approaches are best integrated with broader resilience building strategies. For instance, improved forecasting of extreme weather requires robust community response plans to translate warning of risks into meaningful action. Likewise, engineered structures are increasingly being complemented by measures that improve the adaptive capacity of communities and ecosystems at a more systemic level, which can help reduce the vulnerability of communities. Examples of this include fostering agricultural resilience (by using drought resistant crops, diversifying crops and livestock, and water efficient irrigation) and making livelihoods less vulnerable through economic diversification. Interdisciplinary research can help develop appropriate adaptation systems which can be effectively integrated into communities.

Solutions that adapt to climate change can yield multiple co-benefits, including progress towards the UN Sustainable Development Goals (SDGs). Interdisciplinary research is essential to identifying the co-benefits and trade-offs of adaptation strategies to optimise design and implementation.

Research contributes to the adaptation process in many ways. This includes research on good practice, development, and implementation; weather and climate modelling to anticipate future risks, provide early warning of hazards, and assess the costs and efficacy of different adaptation strategies; tools for making decisions under uncertainty; metrics for measuring performance; and holistic assessment of co-benefits and trade-offs. Research must also integrate local knowledge to develop adaptation strategies which are both effective and appropriate.

High-profile examples of adaptation measures adopted with scientific input include Venice's MOSE flood barrier[11] and Bangladesh's programme of cyclone resilience[12]. The latter, together with improved numerical weather prediction systems, has helped reduce death tolls in Bangladesh from 300,000 in 1970's Bhola cyclone to fewer than 30 for Amphan in 2020[13]. Bangladesh has combined information systems and infrastructure with work to build adaptive capacity in the community, through education and use of volunteers[14].

Above
Khulna District of Bangladesh – flooding following Cyclone Amphan.
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2. Opportunities for progress in evidence-based adaptation

Protecting and upgrading existing infrastructure is essential for minimising disruption from climate impacts.

Interdisciplinary research has the potential to make specific and substantial contributions towards a step-change in support for adaptation. Here we provide an overview of three of the salient areas: climate-resilient infrastructure; nature-based solutions; and Earth system modelling. NbS and infrastructure can both directly limit the impacts of climate change on communities, while modelling of local conditions can underpin the design of adaption strategies, evaluate the efficacy of planned adaptation options, and can provide forewarning of climate hazards.

2.1 Climate-resilient infrastructure

Infrastructure is fundamental to how societies function. Infrastructure-based adaptation strategies will be a cornerstone of reducing societies' vulnerability to climate change. Expertise and technologies to support management and planning of climate-resilient infrastructure have developed to a point where they can significantly assist public and private sectors in their decision-making.

It is estimated that around $94 trillion of infrastructure investment is needed globally by 2040, including in energy and transport assets that will be essential for a net zero future[1]. As recommended by the Global Commission on Adaptation in 2019, resilience needs to be incorporated from the outset in planning new investments, as choices made now will lock in vulnerabilities for decades to come.

At the same time, protecting and upgrading existing infrastructure is essential to minimise disruption from climate impacts, and, in many areas, often constitutes the most feasible approach to meaningfully reducing exposure and sensitivity to climate risks. For instance, in the Netherlands, where almost a third of the land surface is below sea level, the Dutch Flood Protection Plan seeks to reduce exposure to the impacts of sea level rise through investment and upgrades to the Delta Works, the largest network of flood protection infrastructure in the world[15]. Similarly, strategies to protect energy grids in the Caribbean by selective undergrounding of energy transmission lines, strengthening above-ground poles, and distributed generation, will reduce societal sensitivity to hurricanes[16, 17].

A particular priority is to protect and upgrade infrastructure in low- and middle-income countries, which stand to experience some of the most severe climate impacts and where infrastructure disruption already costs an estimated $390 billion each year. Careful infrastructure investment in these countries can yield a net benefit of $4 of avoided future costs for every $1 invested[18]. Modelling can underpin such investment decisions, enabling better understanding of future climate risks, and assessment of the efficacy of planned infrastructure improvements in building resilience to hazards (section 2.3). It is essential that infrastructure adaptation also addresses mitigation, with new builds and upgrades designed to reduce their energy footprint.

Prioritising adaptation action involves mapping areas such as cities to show where they are vulnerable to both current and anticipated future extreme events, as well as where infrastructure is located or planned. This enables adaptation measures to be designed for existing structures and climate change to be factored into new construction. It is also critical to understand the potential cascading impacts of interacting risks, for example the flooding of an electricity substation leading to the failure of communications networks.

Recent years have seen rapid advances in resilience-related data, including cutting-edge flood risk modelling[19]; global infrastructure databases such as OpenStreetMap[20]; and specialist communities such as the Global Flood Partnership[21]. In one example, scientists from the University of Oxford and the World Bank combined big data analysis of more than 50 million km of transport network data with global climate hazard data to pinpoint risks to transport networks everywhere on Earth[22].

This type of analysis is helping governments and development organisations to target adaptation action.

2.2 Nature-based solutions

Nature-based solutions (NbS) involve working with nature to address societal challenges. They include protecting, restoring, and sustainably managing natural ecosystems such as forests, wetland and coastal habitats, sustainable management of agricultural lands, as well as harnessing natural processes in cities. Policymakers are increasingly adopting NbS following growing recognition of their capacity to deliver multiple policy benefits[23].

NbS can build resilience at local scales, rooted in local knowledge and expertise as well as interdisciplinary research[24]. For instance, in urban areas, increasing green spaces reduces the urban heat island effect, can improve drainage to minimise flood risk, and benefits human wellbeing, while some species of shrub have been found to reduce particulate air pollution[25, 26]. Similarly, in Bangladesh and US States along the Gulf of Mexico, restored oyster beds were found to improve coastal protection by dampening wave height, reducing erosion, enabling expansion of coastal ecosystems, protecting biodiversity as well as supporting local livelihoods[27]. Such strategies can minimise direct exposure to climate hazards, but also have the potential to reduce sensitivity to climate shocks by helping to diversify livelihoods (which can provide financial and nutritional security), and through building the adaptive capacity of communities to face rapid change[28].

NbS can be used in conjunction with infrastructure as a hybrid approach to adaption. For instance, in Java, EcoShape (a consortium of businesses, researchers and NGOs focussed on blending hydraulic engineering and nature) is working with the government to restore eroding mangrove coasts using a unique combination of engineering and water management in a community-oriented approach. The project is building permeable bamboo dams that dampen waves and increase elevation by trapping sediment, as well as rehabilitating aquaculture ponds to improve biodiversity, bolster fish stocks, and provide alternative income sources[29]. Similarly, in the United States, hybrid mixes of hard, soft, and green infrastructure to protect

Below:
Red mangrove forest in shallow tropical waters.
© apomares.

Nature-based solutions can build resilience at local scales, rooted in local knowledge and expertise as well as interdisciplinary research.

against flooding and storm surges have been proposed in Hoboken New Jersey, as part of the 'Rebuild by Design' programme following Hurricane Sandy[30].

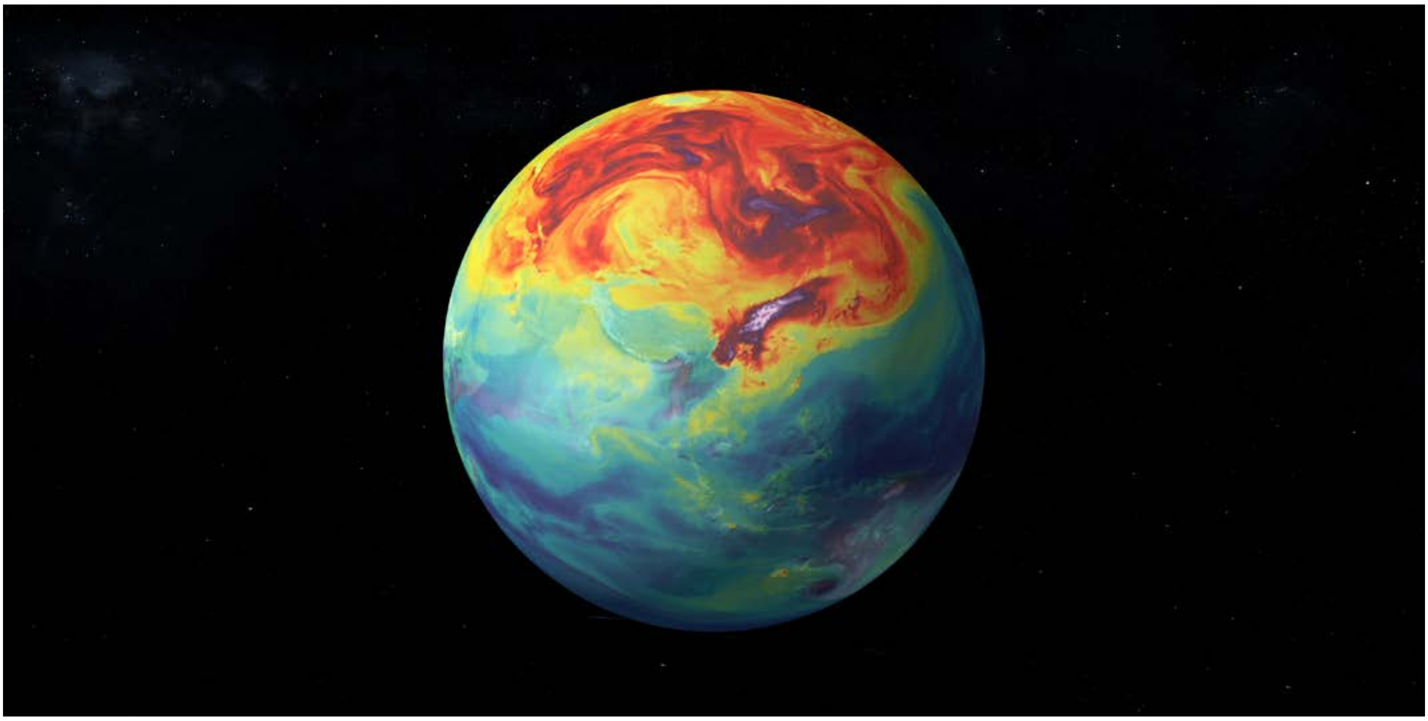
NbS can offer multiple co-benefits, including to livelihoods, local economies, biodiversity, and in helping to meet a range of SDGs. They can also contribute to climate change mitigation. However, unlocking such co-benefits and avoiding trade-offs requires careful design and implementation. At their core, NbS must be designed, implemented and managed by (or with) local communities, to both harness and protect local ecosystems to meet local needs. The long-term efficacy of such strategies depends on appropriate management, governance, and empowerment of communities[31] (see briefing 9: *Climate change and land*).

2.3 Earth system modelling

Earth system modelling can underpin adaptation efforts in three distinct ways: through climate risk assessment (quantifying the probability of hazard occurrence and the potential impacts); by providing early warning of imminent hazards to enable rapid response; and by evaluating the efficacy of alternative adaptation strategies to inform design and implementation. The usefulness of these pillars in supporting adaptation strategies depends on the accuracy of these models, and on the ability to represent and estimate uncertainties in predictions and projections. Models must be complemented by real-world observational data from in-situ measurements and remote sensing: these provide both the initial conditions for early warning systems, and the 'ground truth' needed to assess the reliability and skill of forecasts and projections.

A shortcoming of current-generation climate models is an inability to accurately represent extremes of weather and climate due to inadequate spatial resolution. Improving the spatial resolution of such models (which incorporate information on ocean, land, and atmospheric processes) to around 1 km (from current resolutions of 10 km or more) will significantly improve their reliability and probabilistic skill, as they will allow the laws of physics to be applied at much finer scales[32, 33]. Higher-resolution modelling will be possible on next-generation exascale computers dedicated to weather and climate modelling, capable of 10^{18} (or one billion billion) calculations per second[34] (see briefing 1: *Next generation climate models*). High-resolution climate models are now taking shape in initiatives like the EU's

Below:
Visualisation of carbon dioxide emissions over Earth. © janiecbros.



Destination Earth project[35] which aims to develop an ultra-high resolution digital model of the planet, conjoining physical processes and socio-economic data (see briefing 2: *Computing for net zero*).

An Earth-system approach to modelling, incorporating more detailed ocean, atmosphere, biosphere, terrestrial, and biogeochemical processes, can further improve climate risk assessments and prediction of imminent hazards and their impacts. Machine learning and artificial intelligence methods could prove valuable for representing Earth-system processes in climate models in a computationally efficient way[36]. AI is also valuable to enable downscaling of model outputs to beyond the 1 km scale[32].

Reliable estimates of uncertainty in model predictions are vital in decision making. Ensemble approaches, in which a climate model is run multiple times, perturbing uncertain initial conditions and model processes with random noise, are central to the quantification of uncertainty[37]. For example, probabilistic triggers based on such ensembles are increasingly being used by disaster relief agencies to inform precautionary action (see Box 1).

Work to improve the reliability and accuracy of models must be done collaboratively at a global scale; the laws of physics are the same all around the world. On top of this, data must be shared globally. Building systems for data sharing and international collaboration will not only improve ground-truthing of model outputs but also support countries which do not have the capacity to undertake their own risk modelling.

BOX 1

Impact-based forecasting

Advanced climate and weather models are increasingly being combined with other models and data (such as health and economic models and demographic data) in the field of 'Impact-based forecasting', which, for example, does not simply state that there will be heavy rain in a general area, but flooding within 30 metres of a particular river leading to an estimated amount of displacement[44]. This helps to target humanitarian responses to where they are needed. One initiative in this area is the development of Forecast-Based Financing, whereby humanitarian funding for action in a location is agreed in advance and triggered when a given probability threshold is passed[45]. For example, on 4 July 2020, the European Commission's Global Flood Awareness System predicted a high-probability of severe flooding in Bangladesh, which triggered the UN Central Emergency Response Fund (CERF) to release $5.2 million for assistance including cash, livestock feed, storage drums and hygiene kits. This was the first time that funds had been allocated before the peak floods occurred. Ultimately 200,000 people were able to benefit from this anticipatory action[46]. The efficacy of these approaches depends on integration of different models and data, quantification of uncertainty, and collaboration with local governments and aid agencies.

Improving the spatial resolution of climate models to around 1 km will significantly improve their reliability and probabilistic skill.

3. Priorities for research and development

Substantial opportunities exist for infrastructure and NbS-related adaptation to build climate resilience, and for modelling to provide far greater insight into climate risks to better inform adaptation strategies. These opportunities will only be fully realised through further research and development.

One way to realise the full potential of modelling technology for climate and weather forecasting could be the creation of a dedicated international exascale computing facility, a “CERN for climate change”, where countries of the world pool human and computing resources to achieve what no single country can alone[33] (see briefing 1: *Next generation climate models*). In order to understand the extremes of climate that lie ahead, it would be beneficial that we develop a digital twin of the Earth and its systems, which is indistinguishable from the real climate system on weather scales. Such innovations need to be allied to action on the ground to ensure that forecasts are properly communicated and acted upon.

Nature-based solutions have demonstrable benefits in reducing climate impacts, but there remains a need to explore the timeframes and spatial scales over which they bring broader socioeconomic and ecological benefits[38]. Furthermore, it is important to better understand and plan for the resilience of NbS ecosystems to the impacts of climate change. There is also a lack of evidence on the effectiveness of NbS in developing countries; a strengthened evidence base is critical to build resilience for vulnerable communities worldwide. Finally, exploring the many ways NbS and engineered structures can work together can help design novel adaptation approaches at the local scale.

The science of risk assessment of infrastructure systems is now mature enough to bring expertise together into a global geospatial computational facility which maps out risks and visualises adaptation responses. Worldwide access to such a facility will provide decision makers in governments, utility operators, investors and insurers with the information they need to climate-proof their infrastructure systems.

Research can also play a substantial part in renewed efforts to understand the costs required for adaptation solutions and provide a basis for investment. For instance, modelling can help predict the cost of future climate impacts, and, in tandem with experts in infrastructure and NbS, can help evaluate different adaption options. However, understanding the necessary investment is challenging, as finance needs for adaptation are difficult to quantify. Many countries struggle to estimate their vulnerabilities and local adaptation needs[39]. Furthermore, estimates of necessary investment involve a diverse range of adaptation activities at many scales all around the world, some of which are ‘mainstreamed’ into other budgets, such as for infrastructure investment. Finally, while mitigation now has a clear target of net zero emissions, there is no definitive target for the ‘right’ amount of adaptation action, and hence no reference point against which to estimate the cost.

There is wide agreement that current spending on adaptation is too little. In 2018, adaptation-specific projects accounted for only around 20% of the nearly $80 billion of climate finance mobilised for developing countries[40]. To help meet global adaptation needs, especially in low-income countries, it has been proposed that investment equivalent to 25 – 100% of current mitigation spending by donors and multilateral banks be directed towards adaptation strategies[4, 41].

It is essential to bring the expertise and experience of researchers, organisations, communities, and governments together to identify vulnerabilities and research needs, as well as to design, cost, and implement effective adaptation strategies. Co-ordination of initiatives, stakeholders and research activities can also harness co-benefits and minimise trade-offs from adaptation measures, and better align adaptation and mitigation strategies[42]. For example, careful design of river restoration projects can minimise flood risks and improve agricultural output, while also sequestering carbon[43].

There is wide agreement that current spending on adaptation is too little.

4. Conclusion

Adaptation must become a central element of our response to climate change, with clear targets and research goals, to help ensure people worldwide are protected from the impacts climate change will bring. Resilience thinking must be brought into the design of future infrastructure and NbS adaptation strategies, supported both by interdisciplinary research across scales and advanced modelling. To protect the most vulnerable communities, investment in upgrading existing infrastructure, identifying appropriate NbS and hybrid systems, and advancing and integrating modelling is needed across the world. The areas addressed in this briefing are not independent of one another; advanced modelling, engineering and NbS can be designed and applied in mutual complementarity. Co-ordination, collaboration, and interdisciplinary research is essential to maximising the many benefits of adaptation strategies worldwide.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

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