GC Insights: Communicating long-term changes in local climate risk using a physically plausible causal chain

Ed Hawkins[1], Nigel Arnell[2], Jamie Hannaford[3] and Rowan Sutton[1]

[1] National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, UK

[2] Department of Meteorology, University of Reading, Reading, UK

[3] Centre for Ecology and Hydrology, Wallingford, UK

Correspondence to: Ed Hawkins (ed.hawkins@ncas.ac.uk)

Abstract. Directly linking greenhouse gas emissions or global warming to experiences of local climatic changes is a potentially important communication tool. Using observations we develop a physically plausible 'causal chain' visualisation to demonstrate the connections between global carbon dioxide emissions and local climate events. We highlight how increased flood risk in one river basin in the UK could be discussed with people directly affected by recent floods.

It is unequivocal that human activities are warming the climate (IPCC, 2021). This type of global assessment is critical for those needing to make decisions on mitigating against the risks of ongoing climatic changes but is potentially less relevant when communicating to individuals about how climate change may directly affect them.

The effects of climate change will often feel most 'real' during an extreme event, such as a flood or heatwave, especially when significant harm is caused. The process of linking an individual extreme weather event to climate change – event attribution – is now a commonly used and effective tool, often communicated to decision-makers, media and the public in near-real-time (e.g. van Oldenborgh et al., 2021). There is some evidence that attribution of weather events that are experienced personally can generate climate change concern and changed decision, but this effect may be limited, especially if the attribution conflicts with an individual's prior beliefs (Sambrook et al. 2021).

Here we focus on communicating long-term trends in local climate risks. In this case, it might be people's experience that certain types of extreme event are becoming more frequent, or that the consequences are getting worse, for example. We develop a new visual approach using a 'causal chain' (e.g. Niemeijer & de Groot, 2008) as a potential communication tool to highlight how global carbon dioxide emissions, which may feel rather abstract to any individual, affect climate risks that matter to people. To ensure relevance and improve understanding we consider it is essential for the causal chain to be based on observations and well understood physical principles rather than, for example, the output of complex climate models. Although we are using the general term 'risk' for communication purposes, we mainly focus on the hazard component; changes in exposure and vulnerability are also relevant but are not emphasised here.

Widespread recent flood impacts have led to increasing concerns over changing UK flood regimes in a warming world (e.g. Hannaford et al. 2021 and references therein). We therefore consider flood risk in one UK river basin as the end-point of the causal chain, but this visual approach could be developed more generally for other types of climate risk and in other countries. The UK is fortunate to have lengthy observation-based datasets of several relevant climate variables available for open use (Hollis et al. 2019).

Figure 1 shows simple observation-based timeseries of climate-related changes using the full extent of the available records. Cumulative anthropogenic global carbon dioxide emissions since 1750 have exceeded 2500 GtCO2 (grey), around 70% of which are due to burning fossil fuels (Friedlingstein et al. 2023). These emissions, along with those of other greenhouse gases and anthropogenic factors, have caused global temperatures to increase by around 1.2°C since the era before widespread industrialisation (orange; Morice et al. 2021). The best estimate is that human activities have caused all the observed warming, and that global warming will stop when we reach net-zero anthropogenic carbon dioxide emissions, i.e. when cumulative emissions stop increasing (IPCC, 2021).

Global warming is experienced in the UK as a slightly larger change in mean temperature (1.4°C since 1884; red); land areas warm faster than ocean areas (Byrne & O'Gorman, 2018). There is a corresponding increase in near-surface specific humidity (+7.7% since 1960; green) as a warmer atmosphere can hold more moisture due to the Clausius-Clapeyron relationship. In turn, this increase in atmospheric water content leads to more intense rainfall (+14% since 1891; blue) – when it rains, it rains more (e.g. King et al. 2023). This observed increase in UK rainfall intensity occurs in all seasons but is larger in winter than in summer (not shown).

The dashed black lines show the regression of a smoothed version of the global temperature series onto the other observed timeseries. Note particularly that the signature of the ups and downs of global temperature are also visible in the local, noisier timeseries over the UK. For example, there is a slight cooling of UK temperatures, and small reductions in rainfall intensity, during the 1950s-1960s when global temperatures also slightly cool. This suggests that variations in global temperature are being directly experienced in the UK; it is notable that the rainfall intensity data is entirely independent from the global temperature data.

Although rainfall intensity could be the end-point in this causal chain, we take a further step to relate the causes of global warming to local impacts and risks by considering the effects on a single river basin. In this example, the annual maximum peak flow for the Ribble river has increased by 44% over the past 50 years (black; NRFA, 2023). If you live near the Ribble, this is of direct relevance to your own personal flood risk; this river basin experienced severe floods affecting hundreds of homes in the 1980-1981, 2015-2016 and 2019-2020 'water years' (October to September) when the peak flows were largest.
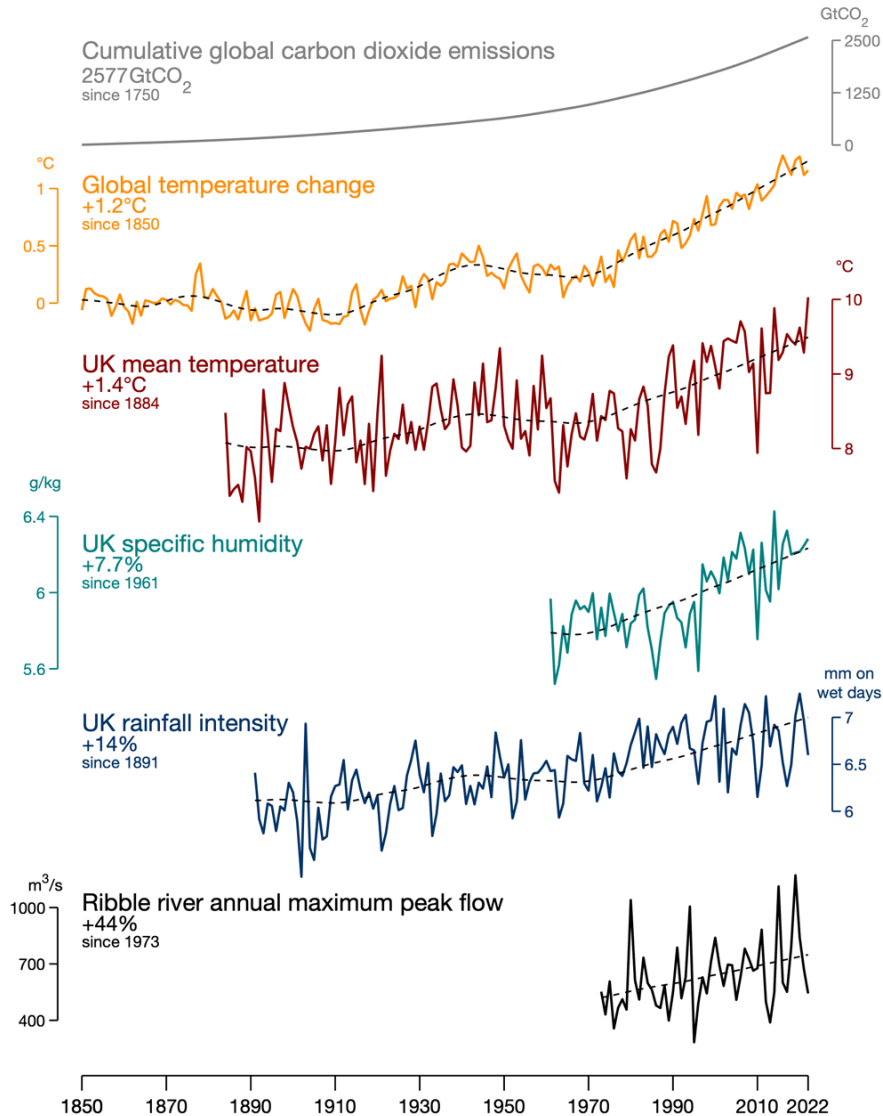
Figure 1: An observation-based causal chain from global carbon dioxide emissions to peak flow in the Ribble river.
Cumulative anthropogenic global carbon dioxide emissions (grey; Friedlingstein et al. 2023) are causing global temperatures to increase (orange, with 41-year loess smoothed version in dashed black; Morice et al. 2021). Global warming is experienced locally as warmer UK temperatures (red), increased specific humidity (green), with corresponding increases in rainfall intensity (blue); all based on data from Hollis et al. (2019). Annual maximum peak flow on the Ribble river has increased in the last 50 years (black; NRFA 2023). Black dashed lines show regressions onto the smoothed global temperature timeseries.

75 One potential implication of this causal chain is that global emissions of carbon dioxide directly increase the risk of flooding from the Ribble river, but there is no formal attribution for that conclusion. However, we note that the links in this causal chain are well studied. The increase in global temperature due to cumulative carbon dioxide emissions has been quantified (IPCC, 2021), and UK temperature rise has been attributed to anthropogenic factors and global warming (Karoly & Stott, 2006; Hawkins et al. 2020). Increases in specific humidity have been attributed to human influences globally (Willett et al. 2007),

80 and the physical reasons why warming will cause increases in humidity and rainfall intensity are well established (Pfahl et al. 2017), including the Clausius-Clapeyron relationship. A human influence on the risk of specific UK flood events has also been demonstrated (Pall et al. 2011; Schaller et al. 2016; Otto et al. 2018; Kew et al. 2024).

But, what about the final link in the chain? There is a robust increase in peak river flows in many UK regions (Hannaford et

85 al. 2021, Slater et al. 2021) and, all else being equal, more intense rainfall will lead to more runoff, higher peak flows and increased flood risk. However, for any particular river basin, this final link in the chain is highly complex due to the role of catchments in modulating changes in rainfall variability; all else is rarely equal (Hannaford, 2015). The complexities can include the role of antecedent conditions and evaporation, and catchment storage in groundwater or soils that could dampen extreme rainfall increases. Similarly, direct anthropogenic modifications, such as reservoirs, river engineering or floodplain

90 development can directly influence flood hazard but may additionally influence exposure and vulnerability. As such, there is often a highly non-linear relationship between trends in extreme rainfall and river flooding, and trends in the former do not always lead to similar responses in the latter (Do et al., 2020).

In our chosen example, the Ribble is a 'benchmark' catchment (Harrigan et al. 2018) as it is largely free of major disturbances

95 and is relatively responsive to rainfall variability given the wetness of the setting, upland terrain and impermeable geology. Hence, the above complexities are likely to be minimised, and there is reasonable confidence in the link between extreme rainfall and flow responses, although there is a possible role for other local factors such as land use change.

These relatively simple connections between global carbon dioxide emissions, increases in global average temperature and

100 severe impacts on people could be a useful communication tool to develop further. We suggest that talking through the links in this causal chain may be useful for local decision makers and the millions of people living with increased flood risk in the UK, such as those in the Ribble valley, to understand how climate change may directly affect them and inform decisions on adaptation. The efficacy of the graphical tool created will be tested in future.

105 Long observation-based records are extremely useful for communicating that the climate has changed and how this is already affecting people. The extension of this approach to other climate-related hazards such as heatwaves, droughts, storm surges, or wildfires may also be useful, along with expanding to other locations or countries, dependent on data availability. Further work could also develop more complex causal networks or storylines for some of the links in the chain (Niemeijer & de Groot,

2008; Shepherd et al. 2018). However, as with river flows, it will undoubtedly be the last link, towards the impact, that will bring the most complexity.

Competing interests

Ed Hawkins is an Editor for Geoscience Communication.

Data availability

The timeseries shown are available at
https://github.com/ed-hawkins/data-for-papers/tree/main/causal-chain

Acknowledgements

EH and RS are supported by the UK National Centre for Atmospheric Science. This publication has emanated from research conducted with the financial support from a Co-Centre award number 22/CC/11103. The Co-Centre award is managed by Science Foundation Ireland (SFI), Northern Ireland's Department of Agriculture, Environment and Rural Affairs (DAERA) and UK Research and Innovation (UKRI), and is supported via UK's International Science Partnerships Fund (ISPF), and the Irish Government's Shared Island initiative.

References

Byrne, M. and O'Gorman, P. (2018), Trends in continental temperature and humidity directly linked to ocean warming, PNAS, 115 (19) 4863-4868, doi: 10.1073/pnas.1722312115

Do, H. X., Mei, Y., & Gronewold, A. D. (2020), To what extent are changes in flood magnitude related to changes in precipitation extremes? Geophysical Research Letters, 47, e2020GL088684. doi: 10.1029/2020GL088684

Friedlingstein, P., et al (2023), Global Carbon Budget 2023, Earth System Science Data, 15, 5301-5369, 2023, doi: 10.5194/essd-15-5301-2023

Hannaford, J. (2015). Climate-driven changes in UK river flows: A review of the evidence. Progress in Physical Geography: Earth and Environment, 39(1), 29-48. doi: 10.1177/0309133314536755

Hannaford, J., Mastrantonas, N., Vesuviano, G., Turner, S. (2021) An updated national-scale assessment of trends in UK peak river flow data: how robust are observed increases in flooding? Hydrology Research 52 (3): 699–718. doi: 10.2166/nh.2021.156

Harrigan, S., Hannaford, J., Muchan, K., Marsh, T.J. (2018) Designation and trend analysis of the updated UK Benchmark Network of river flow stations: the UKBN2 dataset. Hydrology Research, 49 (2): 552–567. doi: 10.2166/nh.2017.058

Hollis, D., McCarthy, M.P., Kendon, M., Legg, T., Simpson, I. (2019) HadUK-Grid - A new UK dataset of gridded climate observations. Geoscience Data Journal, 6, 151, doi: 10.1002/gdj3.78

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi: 10.1017/9781009157896.001

Karoly, D.J. and Stott, P.A. (2006), Anthropogenic warming of central England temperature. Atmosph. Sci. Lett., 7: 81-85. doi: 10.1002/asl.136

Kew, S.F. et al. (2024) Autumn and Winter storms over UK and Ireland are becoming wetter due to climate change. doi: 10.25561/111577

King, A.D., Reid, K.J. & Saunders, K.R. (2023) Communicating the link between climate change and extreme rain events. Nat. Geosci. 16, 552–554. doi: 10.1038/s41561-023-01223-1

Morice, C.P., J.J. Kennedy, N.A. Rayner, et al. (2021) An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. Journal of Geophysical Research (Atmospheres) doi: 10.1029/2019JD032361

Niemeijer, D., de Groot, R.S. (2008) Framing environmental indicators: moving from causal chains to causal networks. Environ Dev Sustain 10, 89–106, doi: 10.1007/s10668-006-9040-9

NRFA (2023), National River Flow Archive peak flow data for Samlesbury, https://nrfa.ceh.ac.uk/data/station/peakflow/71001 and updates https://environment.data.gov.uk/hydrology/station/6e4d9ef9-131a-4712-895e-52a05dc290e9 (accessed 7th January 2024)

Otto, F. et al. (2018) Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond—a real-time event attribution revisited. Environ. Res. Lett. 13, 024006. doi: 10.1088/1748-9326/aa9663

Pall, P., Aina, T., Stone, D. et al. (2011) Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature 470, 382–385. doi: 10.1038/nature09762

Pfahl, S., O'Gorman, P. & Fischer, E. (2017) Understanding the regional pattern of projected future changes in extreme precipitation. Nature Clim Change 7, 423–427. doi: 10.1038/nclimate3287

Sambrook, K., Konstantinidis, E., Russell, S. and Okan, Y. (2021) The Role of Personal Experience and Prior Beliefs in Shaping Climate Change Perceptions: A Narrative Review. Front. Psychol. 12:669911. doi: 10.3389/fpsyg.2021.669911

Schaller, N., Kay, A., Lamb, R. et al. (2016) Human influence on climate in the 2014 southern England winter floods and their impacts. Nature Clim Change 6, 627–634. doi: 10.1038/nclimate2927

Shepherd, T. G. et al. (2018) Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Clim Change, 151, 555–571, doi: 10.1007/S10584-018-2317-9

Slater, L. J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., Kelder, T., Kowal, K., Lees, T., Matthews, T., Murphy, C., and Wilby, R. L. (2021) Nonstationary weather and water extremes: a review of methods for their detection, attribution, and management, Hydrol. Earth Syst. Sci., 25, 3897–3935, doi: 10.5194/hess-25-3897-2021

van Oldenborgh, G. J., van der Wiel, K., Kew, S., et al. (2021) Pathways and pitfalls in extreme event attribution, Clim Change, 166, 1–27. doi: 10.1007/S10584-021-03071-7

Willett, K., Gillett, N., Jones, P. et al. (2007) Attribution of observed surface humidity changes to human influence. Nature 449, 710–712, doi: 10.1038/nature06207