

The Role of Digital Technologies in Responding to the Grand Challenges of the Natural Environment: The Windermere Accord

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Bigger Picture. Digital technology is having a major impact on many areas of society and there is equal opportunity for impact on science in addressing grand scientific challenges. This is particularly true in the environmental sciences as we seek to understand the complexities of the natural environment under climate change. This perspective reports on the outcomes from a summit in this area, attended by 42 researchers selected as leading experts operating at the interface between digital technology and the environmental sciences. The key output of this workshop was the Windermere Accord, a collective statement around what is required to achieve a transformative effect through digital technology based around 4 key pillars of investigation, namely: using technology to tame uncertainty; growing advocates and champions to enable, empower and influence; embracing a new open and transparent style of science; enabling integration and sophisticated treatment of feedbacks in complex environmental systems. These pillars all feed into decision-making processes and are supported by a growing community. Looking forward, the accord also identified a pathway with particular emphasis on building an international, cross-disciplinary community to address the key challenges and achieve the real opportunities around digital technology and the environment.

1 Introduction

Digital technology is having a major impact on many areas of society, stimulating innovations in areas as diverse as smart cities, healthcare, energy (smart grid) and logistics. For this paper, we define digital technology as “the branch of scientific or engineering knowledge that deals with the creation and practical use of digital or computerised devices, methods, systems, etc.”¹. Digital technology also has the potential to revolutionise the way we carry out science, and in addressing grand scientific challenges. This is certainly true in the environmental sciences where new tools can both deepen our understanding of the natural environment and help determine well-founded mitigation and adaptation strategies and policies in the face of environmental change.

This short paper reports on the findings of a summit examining the “Role of Digital Technology in responding to the Grand Challenges of Environmental Change”. This summit was held in the Lake District, UK on 10th-12th October, 2018, and represented a unique cross-disciplinary gathering bringing together leading researchers working at the interface between digital technology and environmental science with a view of exploring the potential contributions of digital technology in addressing the pressing issues around the natural environment. The summit used a process of creative facilitation to encourage the necessary cross-disciplinary conversation and to achieve our goals.

The paper discusses in particular the shared vision in the form of a framework and roadmap produced at the event, which we collectively refer to as the *Windermere Accord*, and issues a call to build the international community necessary to achieve this vision. The paper starts with background and context for the event and the organisation of the summit and methods employed in reaching our consensus, leading up to a description of the accord. We also include a retrospective on how things have developed since.

2 Summit: background and context

2.1 Digital technology

Digital technology is a fast moving field that, as mentioned in the introduction, is having a profound impact on the way we live. We focus on several areas of innovation that have the most potential to be transformative on the environmental sciences:

1. The ability to *acquire unprecedented amounts of environmental data* – utilising technologies such as remote sensing, cheap and ubiquitous sensing devices and, more generally, the Internet of Things, citizen science, and additional data mined from the web²;
2. The ability to *store and process big data* through the massive and elastic/on demand resources offered by *cloud computing*³;
3. The ability to *make sense* of this big data and extract meaningful patterns through breakthroughs in *data science and Artificial Intelligence (AI)*, thus generating new scientific knowledge particularly when combined with process understanding from the environmental sciences^{2,4,5};
4. The ability to *visualise, present and interact* with this data and its subsequent analyses to support communication to different stakeholder groups, and hence support informed *decision-making*.

We note as well that this supports a *chain of innovation* impacting on all aspects of the scientific process from data acquisition, through storage and processing and subsequent analyses, to communicating and collaborating over the results. We also note that, alongside the profound positive impact of such technologies, there is also a significant risk that they can have negative impacts on society including through their greenhouse gas emissions⁶ and it was important to acknowledge this and take it into account in the summit.

2.2 Grand challenges of environmental science

The environmental sciences are also going through an important transition towards a scientific discourse that is responding to:

1. The unprecedented amounts of *environmental data* related to different environmental facets, at different locations and scales²;
2. The need to move towards a more *open, cross-disciplinary and collaborative style of science*⁷ as demanded by the grand challenges of the natural environment, e.g. addressing food security, climate change, clean air/water, etc;
3. The need to embrace *FAIR Principles* (Findable, Accessible, Interoperable and Reusable) in managing and accessing environmental data^{8,9};
4. The need for a more *holistic approach* based on systems thinking to address the complexities of environmental ecosystems and their interactions;
5. The subsequent need to *integrate data and models* to answer scientific questions around (complex) ecosystems.

2.3 A digital environment

It is interesting to note that there is a strong relationship between the changing nature of the environmental sciences and the areas of digital innovation identified in section 2.1. Because of this, there is significant interest in what some observers call a 'digital

environment', i.e. is seeking ways in which digital technology can support a deeper understanding of the natural environment. In the UK, UK Research & Innovation (UKRI) has recently announced an ambitious cross-research council Strategic Priority Fund that aims at 'Constructing a Digital Environment' (CDE)¹⁰. In their call document, they state:

"By harnessing [...] advances in technology [...], there is an opportunity to create a digitally enabled environment [that] will deliver the capacity to improve the understanding and modelling of longer term environmental change and the prediction of events."

Similarly, Microsoft have recently launched a \$50m programme, AI for Earth, looking at the potential transformative power of AI/data science coupled with cloud technology can help to society to step towards more sustainable solutions in for key areas, namely climate, water, agriculture and biodiversity¹¹. Google have launched a sustainability mission building environmental sustainability "into everything they do"¹². There are also various other small to medium sized communities emerging on around this theme, e.g. in Climate Informatics¹³, the ICT for Sustainability (ICT4S) community and conference series¹⁴, Sustainability Informatics¹⁵, IS-GEO¹⁶, or Modeling for Sustainability¹⁷.

Although efforts are somewhat fragmented, all agree that the digital environment is fundamentally a cross-disciplinary area of study requiring collaboration between environmental scientists, computer scientists, data scientists, social scientists and creative disciplines working closely together to address the role of digital technology in this important area.

3 Summit: organisation

3.1 Goals of the summit

The goals of the summit were as follows:

- To provide a timely forum for the necessary *dialogue* between those working at the cutting edge of technology and those working on grand challenges of the natural environment;
- To establish a *shared vision and roadmap* of what is required to allow the potential of digital technologies to be realised in this area;
- To build an international *community* working on the resultant open research questions.

3.2 Process and methodology

The summit was attended by 42 researchers (who are also co-authors of this paper), selected as leading experts operating at the interface between digital technology and the environmental sciences. The Ensemble research team¹⁸ hosted the summit in support of their vision of "working together for digitally inspired integrated environmental science".

The participants were selected to achieve a balanced representation across the different underlying disciplines of the environmental sciences, computer science and data science with representation from creative disciplines and social sciences. We also sought to ensure good and balanced coverage of i) the chain of innovation from data acquisition through to support for decision making, ii) the different challenges being faced by environmental sciences as they address global challenges related to environmental change, iii)

representatives of the emerging digital environment community, including research councils.

The methodology adopted in the workshop was one of creative facilitation to achieve the necessary cross-disciplinary discussion. This involved bespoke activities, stepping through a variety of phases and involving small/medium sized and whole group discussions, provocations, select presentations, pitches and panel discussions which were designed to move the participants through key thresholds by eliciting responses to the following questions:

- What motivated you to be here, and what do you want to get out of the event?
- What are research challenges and opportunities around the digital environment?
- How ambitious could and should this community be?
- What are the barriers and obstacles to achieving this and (later) how can they be overcome?
- What should the main research foci be of this community?
- What mechanisms would allow us to drive this forward?
- What must we not lose sight of as we leave this summit?

The groups were constantly changed to maximise interaction across the set of participants, and outputs from one discussion were often used as inputs to future discussions to encourage ideas to percolate through the collective group.

3.3 Facilitated discussion: from motivation to consensus

The process involved a number of phases inspired by the methodology and questions introduced in Section 3.2.

The first phase involved everyone capturing their motivation for attending the workshop followed by three rounds of dialogues (i.e. three way conversations) based on these motivating statements. This session was important in establishing the participatory approach and giving people time to get to know each other and set out what they wanted to achieve, especially given attendees came from very different disciplines. A sense of *ambition* emerged from these early discussions, and a strong feeling that we could do something quite profound if we worked together across disciplines. (Cross-disciplinary working is revisited in later sessions). There was also a keen desire to make an impact, which led to a strong emphasis throughout on the end-to-end data pathway from capture to its eventual *communication*, and how to *inform* society and policy makers.

The initial activity on motivations was followed by a series of five short five-minute provocations by select attendees, selected for their ability to introduce more *radical ideas* into the ongoing conversation. These provocations were on the topics of:

- Self-organising and self-adaptive systems in managing complexity (Ada Donescu)
- Technology futures and the cross-disciplinary challenge (Rachel Prudden)
- Virtual labs of the future (Chantal Huijbers)
- From environmental statistics to environmental data science (Phil Jonathan)
- Everything EverywhAir: Measuring everything everywhere for air quality (Stefan Reiss)

The provocations were followed by a presentation and discussion on opportunities around the theme of the digital environment, led by Sophie Laurie from the Natural Environment

Research Council in the UK. This presentation emphasised the *timeliness* of what we were discussing at the workshop and provided rich material to work with in subsequent sessions when we moved towards what we could achieve together.

Picking up on 'ambition', small groups were formed with the brief of working on *how ambitious we could be*. Important themes started to emerge at this stage including the need to really grapple with uncertainty from a new, cross-disciplinary perspective, the importance of trust right the way through the chain of scientific discovery and decision making, and the need for new tools that will allow for increased representation of the complexities found in the natural environment, including tools that draw on studies of complexity.

The discussion then moved on to *obstacles and barriers* in order to make them explicit in our discussion. This identified issues such as the lack of incentives for cross-disciplinary, risky and more long-term research; the lack of funding mechanisms and support structures to enable this; the challenges to a culture of open data and open science more generally; and the need to work within a system that emphasises other issues, such as business innovation and growth. There was also strong recognition that there was a lack of trained people in this cross-disciplinary space.

The remainder of the workshop was then devoted to synthesising the material and ideas into tangible outputs in terms of our desired vision and roadmap, and steps to building an international community. We were particularly seeking insights and outputs that could transcend the obstacles and barriers identified in the paragraph above. A panel of five people selected to be representative of the diversity in the summit were asked to distil the discussions into important elements of a roadmap. These were then discussed in depth by all attendees. This important process led to the emergence of the Windermere Accord as presented in Section 4.

A parallel exercise, facilitated by artists-in-residence, was used to capture the personal stories and concerns of participants. This proved to be a core exercise, which brought the motivations/fears/aspirations of the participants right into the heart of the discussion. The exercise revolved around the following key questions: i) what are your earliest formative experiences of nature, ii) what do you fear the next generation may not witness or experience in the natural world, and iii) what can I/we do to address our disconnect with nature and better understand and manage the richness of environmental ecosystems. This culminated in a gallery around the room involving Polaroid images of all the participants and their statements in answer to these three questions. The collective responses have been distilled into a reflection¹⁹, and also a poem reproduced in Appendix A below.

Space was left during the workshop for group walks in nature and a boat trip, and these proved to be important in terms of enhancing dialogue and developing the conversations further in a more relaxed environment.

Images representing the different phases of the workshop can be found in figure 1.



Figure 1: Images from the summit: (a) the initial triologue session; (b) small group working; (c) synthesising the outcomes; (d) working with our artists-in-residence; (e) relaxing and feeling inspired.

4 The Windermere Accord

The summit produced a clear consensus over future directions around digital technology and the environment, resulting in what we refer to as the Windermere Accord, offering a framework and roadmap to take this area forward. This *accord framework* is depicted in figure 2, community as the base and four pillars all feeding into decision-making (the archway).

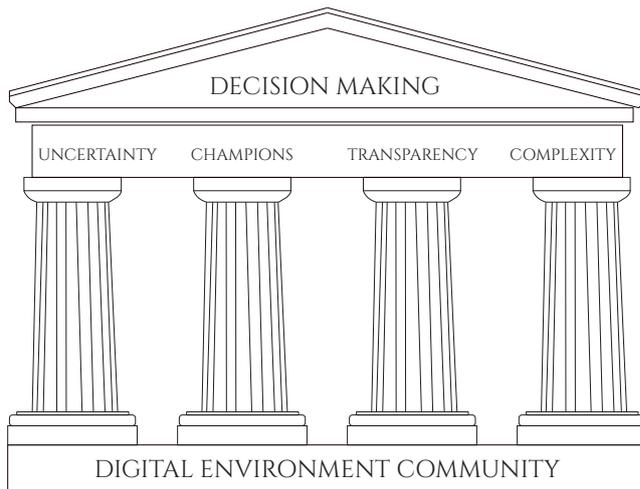


Figure 2: Pillars of the Windermere Accord

The key elements of this framework are discussed in more detail below. The participants were also asked to state what they felt was most important to them for each element of the accord, and these were captured and replicated in full in Appendix B, with key elements pulled out in the discussions below.

Foundations: Building a Digital Environment Community. There was a strong consensus of the importance of building on the summit and developing a much larger international community working on the theme of a digital environment. There was a sense that the existing community is too small and fragmented and hence there is a need to make some noise about the importance of this area and also have a strong narrative around grand challenges in this area to draw others in (drawing on the work of champions as discussed in pillar 2). There is also a strong need to have mechanisms in place to support ongoing conversation on this topic, and to nurture and grow the community. In terms of concrete actions and next steps, the participants proposed creating integrating and fundamentally cross-disciplinary international conferences and journals in this area and, key to this is drawing together existing smaller communities such as Climate Informatics, ICT4S, etc (see list in section 2.3). It is encouraging to see new journals emerging in this space. We also boldly propose a research institute around the digital environment (discussed further in next steps).

Pillar 1: Using Technology to Tame Uncertainty. The first pillar focuses on uncertainty particularly in how uncertainty can be estimated and managed in relationship to environmental modelling²⁰. This is arguably the core challenge in supporting decision making in environmental science. Uncertainty may arise from a number of areas including from the framing of the problem and consideration of external forces, data itself and how it is measured, from the assumptions and structures within a given environmental model or models, from the parameter selection for that model, from how a model is implemented, and how results are analysed, presented and interpreted. This becomes a huge challenge when modelling complex systems involving model chains where results of one model feed into another model or models and where feedbacks need to be considered. Often uncertainty is considered from a statistical perspective. There was a consensus in the summit from our discussions that we need fresh perspectives on uncertainty. In particular, we need a cross-disciplinary approach to the subject taking input from statistics, data science, computer science, environmental sciences, social science and arts-based subjects. It is also important that uncertainty is addressed in an end-to-end fashion from data acquisition through to visualising and presenting uncertainty in support of decision-making. Finally, place-based approaches are important supported by rich data about that place (cf. the models of everywhere approach that advocates collecting rich and varied environmental data about specific geographical locations to enhance knowledge about that particular place in all its dimensions^{21,22,23}).

Pillar 2: Advocates and Champions to Enable, Empower and Influence. The second pillar focuses on people and, in particular identifying and developing a generation of leaders to take forward the rich agenda on the digital environment. We identified the importance of having people who understand both the capabilities of digital technologies and also the challenges of the environmental sciences, seeing such 'glue people' as crucial in the development of this area. We also recognise that such people are in scarce supply so additional training is urgently needed. Furthermore, there is a need to raise the profile of environmental challenges to draw people towards this field, especially given the financial rewards of taking their digital skills elsewhere. This includes communicating scientific questions and challenges and their significance. A number of the attendees also asserted that we can all be champions, taking leadership in this area now and helping it to thrive.

Pillar 3: Digital Technology Leading the Way in Openness and Transparency. There was strong recognition that contemporary digital technologies enable a new kind of science that is open, transparent and also completely reproducible, and this is also essential in terms of enhancing trust. Participants also highlighted the importance of honesty and full disclosure of scientific limitations in enhancing this trust. We see *cloud computing* as crucial in providing the core building block to support this openness and transparency especially when coupled with the scalability inherent in cloud technologies. This is greatly enhanced by *virtual labs* offering integrated data, modeling and analyses around a particular (collaborative) scientific quest²⁴. It is also important that audit trails can be provided and again recent technological advances can support this, e.g. blockchain technology²⁵. While this is now technically feasible, there was recognition that there has to be a strong cultural shift towards openness across the community⁷.

Pillar 4: Integration and Feedbacks in Complex Systems. Environmental systems are highly complex systems and scientists need new tools to understand this complexity^{26,27}. There was a high level of agreement in the summit that digital technology can provide a new set of

tools to enhance our understanding of this complexity in terms of supporting a more holistic approach to science inspired by systems thinking. This includes the development of software frameworks to support integrated environmental modeling around ecosystem services, included more sophisticated support for model coupling and also enhanced techniques to understand feedbacks in such integrated systems. We note existing studies that argue for the benefits of advanced software engineering principles and techniques in support of sustainability research, particularly in managing complexity²⁸. There was also recognition of the potential role of autonomic computing^{31,30} in managing this complexity and also supporting reasoning across scales, complementing existing approaches based on data assimilation^{25,32}. Can knowledge gained from data analyses be used to more precisely dynamically define model parameterisation to ensure that models represent current observations? Going further, is it possible for example for environmental models to self-organise or adapt their fine-grained behavior to match observations over time? Can measures of uncertainty in models be used to determine adaptive sampling strategies to generate the necessary additional data to reduce such uncertainties? As with uncertainty, the key message is that it is timely to re-examine complexity from a fresh, cross-disciplinary perspective.

Archway: Decision-Making. The final part of the accord was recognition that the various pillars and the underpinning community are all mechanisms to support more informed decision-making and indeed this is core to everything we do around a digital environment. There is a tremendous opportunity to develop decision-support systems based on rich environmental data and this requires innovations at each step of the chain from data acquisition through to the presentation of the analyses. These various steps need to be brought together in one logical place, hence our emphasis on virtual labs in pillar 3, which we now say should offer explicit support for decision-making. We see a strong role for creative data visualization and presentation and this again needs a cross-disciplinary approach requiring input from arts disciplines. There was also recognition that this support is required across all scales from individual decisions, through local decision making to regional, national and global decisions around environmental change. This relates strongly to the goal of translating data to information to knowledge and eventually to wisdom, a stated motivation behind artificial intelligence (AI).

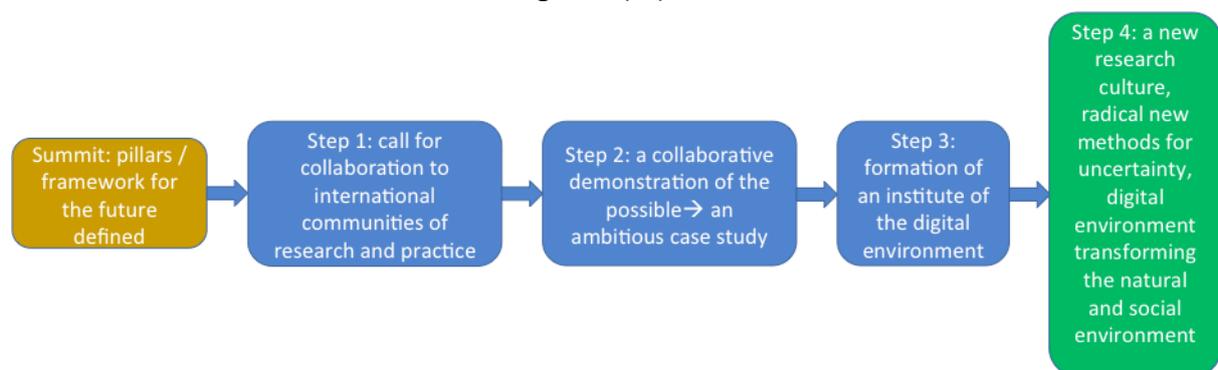


Figure 3: The associated roadmap

The summit concluded with a proposed *roadmap* in the form of a series of next steps leading to a new cross-disciplinary research culture informed by further work on the different pillars (see figure 3). Note that these steps are also not necessarily sequential and would be more agile and overlapping in practice. The summit is a small step towards such a vision and the authors, as the participants in this summit, pledge to embrace this new

culture and now reach out to others to join together in this quest for a new data-enriched, collaborative approach to some of the biggest grand challenges of our time.

Since the summit, quite a lot has changed, including increasing motivation and promising initial steps towards our vision. If anything, climate change is even more in focus having witnessed the Australian bushfires and extensive floods and droughts worldwide, and increasing voices for change often inspired by Greta Thunberg. The current COVID-19 pandemic has also been linked to interference in nature. We are also seeing growing interest in the role of digital technology in the environment. In the UK context, there have been considerable developments within the CDE programme introduced in section 2.3, with a series of pilot projects now up and running and larger demonstrator projects about to be awarded. This level of research and innovation activity is also reflected in other countries. For example, in Australia we see significant investment in digital platforms for climate research, e.g. the Ecommons programme³³. We also see international initiatives particularly around technological platforms, including the European Open Science Cloud³⁴, D4Science³⁵ and Pangeo³⁶.

Returning to CDE, it is interesting to note that the programme very quickly took three complementary actions: i) they appointed champions for the programme, ii) they set up a Digital Environment Expert Network that also includes early career researchers (again representing a concrete step to broaden the number and range of champions), and iii) they recognised the importance of cross-disciplinary thinking through the multi-disciplinary and interdisciplinary research & innovation (MIDRI) initiative that sits at the heart of the programme. There is also an emphasis on demonstrators in this programme (cf. case studies as identified in step 3 of our pathway). These are important steps that are very much in line with the accord. Although in a UK context, this is also a model that could be replicated elsewhere. The publication of this perspective also represents an important call for collaboration (step 1 of figure 3). Internationally, there are other interesting developments but the position is still rather fragmented so it is timely to repeat our call to draw together internationally to create a strong cross-disciplinary community to work on this urgent and important topic. Would it not be fantastic to see a truly global Institute of the Digital Environment emerge in the post-COVID-19 world, pushing of from progress on steps 1 and 2 towards the latter stages of our roadmap.

5 Concluding remarks

This short paper has presented the outcomes of a summit on the “Role of Digital Technology in responding to the Grand Challenges of Environmental Change”, a unique cross-disciplinary gathering bringing together environmental scientists, data scientists, computer scientists, social scientists and the representatives of the creative arts. The key output of this workshop was an agreement of a vision and framework/roadmap for this important area, captured in the Windermere Accord. This accord envisions a new kind of environmental science underpinned by unprecedented amounts of data, with technological advances leading to breakthroughs in taming uncertainty and complexity, and also supporting openness, transparency and reproducibility in science. These are precisely the tools that are required by decision makers at all levels to make more well-informed decisions in the face of profound environmental change. Crucially though to support this it is essential to build a cross-disciplinary community working on these themes and also to identify and grow champions for this area.

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Declaration of interests

The authors declare no competing interests.

Word length: ~4,062 words

References

- [1] Dictionary.com, Definition of digital technology, <https://www.dictionary.com/browse/digital-technology>
- [2] Blair, G.S., Henrys, P., Leeson, A., Watkins, J., Eastoe, E., Jarvis, S., Young, P.J., 2019, Data science of the natural environment: a research roadmap, *Frontiers in Environmental Science*, 7(121), <https://doi.org/10.3389/fenvs.2019.00121>
- [3] Zhang, Q., Cheng, L. Boutaba, R., 2010, Cloud computing: state-of-the-art and research challenges. *J. Internet Services and Applications (JISA)*, 1, 7–18, <https://doi.org/10.1007/s13174-010-0007-6>
- [4] Rolnick, D., Donti, P., Kaack, L., Kochanski, K. Lacoste, A., Sankaran, K., Ross, A., Milojevic-Dupont, N. Jaques, N. Waldman-Brown, A. Luccioni, A. Maharaj, T., Sherwin, E., Mukkavilli, S.K., Kording, K., Gomes, C., Ng, A., Hassabis, D. Platt, J., Bengio, Y., 2019, Tackling Climate Change with Machine Learning, Pre-print available from: <https://arxiv.org/abs/1906.05433>
- [5] Hey, T., Tansley, S., Troll, K. (eds.), 2009, *The Fourth Paradigm: Data-Intensive Scientific Discovery*, Microsoft Research.
- [6] Blair, G.S., 2020, A tale of two cities: reflections on digital technology and the natural environment, *Patterns*, 1(5), Cell Press.
- [7] Royal Society, 2012, Science as an open enterprise, Available from: https://royalsociety.org/~media/Royal_Society_Content/policy/projects/sape/2012-06-20-SAOE.pdf
- [8] Coalition for publishing data in the earth and space sciences (COPDESS), <https://copdess.org/>
- [9] Stall, S. et al., 2018, Advancing FAIR data in earth, space and environmental data, *Eos*, 99, <https://doi.org/10.1029/2018EO109301>
- [10] UKRI, Constructing a Digital Environment Programme, <https://nerc.ukri.org/innovation/activities/environmentaldata/digitalenv/news/ao/>
- [11] Microsoft, AI for Earth, <https://www.microsoft.com/en-us/ai/ai-for-earth>
- [12] Google, Sustainability Mission, <https://sustainability.google/>
- [13] Climate Informatics Community, <http://climateinformatics.org/>

- [14] ICT for Sustainability (ICT4S) community and conference series, <http://www.ict4s.org/>
- [15] Sustainability Informatics Group, University of Toronto, <https://web.cs.toronto.edu/research/sustainability-informatics>
- [16] Intelligent Systems and Geosciences Community and Coordination Network, <https://is-geo.org/>
- [17] Dagstuhl Seminar: Modeling for Sustainability, <https://www.dagstuhl.de/de/programm/kalender/semhp/?semnr=18351>
- [18] Ensemble Projects, <https://www.ensembleprojects.org/>
- [19] Fraser, H., Fraser, R., 2018, The role of digital technology in addressing the grand challenge of climate change: a reflection, available at <https://www.ensembleprojects.org/wp-content/uploads/2018/11/Ensemble-summit-on-Environmental-Change-Harriet-and-Rob-Fraser-response.pdf>
- [20] Beven, K., 2009, Environmental modeling: an uncertain future, Routledge, Abingdon, UK.
- [21] Beven, K J, 2007, Working towards integrated environmental models of everywhere: uncertainty, data, and modelling as a learning process. *Hydrology and Earth System Science*, 11(1), 460-467.
- [22] Beven, K. J. and Alcock, R., 2012, Modelling everything everywhere: a new approach to decision making for water management under uncertainty, *Freshwater Biology*, 56, 124-132, doi:10.1111/j.1365-2427.2011.02592.x[30]
- [23] Blair, G.S., et al., 2019, Models of Everywhere Revisited: A Technological Perspective. *Environmental Modelling & Software*, 122.
- [24] Hollaway M.J., Dean G., Blair G.S., Brown, M., Henrys P.A., Watkins, J., 2020, Tackling the challenges of 21st century open science and beyond: a data science lab approach, *Patterns*, 1(7), Cell Press.
- [25] Zheng, Z., Xie, S., Dai, H-N., Chen, X. and Wang, H., 2018, Blockchain challenges and opportunities: a survey, *Int. J. Web and Grid Services*, 14(4), 352–375.
- [26] Kastens, K.A. et al., 2009, How Geoscientists Think and Learn. *Eos, Transactions*. 90(31), 265-266.
- [27] Easterbrook, S., 2014, From computational thinking to systems thinking: a conceptual toolkit for sustainability computing, *Proc. International Conference on ICT for Sustainability (ICT4S)*, <https://doi.org/10.2991/ict4s-14.2014.28>
- [28] Kienzle, J., Mussbacher, G., Combemale, B., Bastin, L., Bencomo, N., Bruel, J-M., Becker, C., Betz, S., Chitchyan, R., Cheng, B.H.C., Klingert, S., Paige, R.F., Penzenstadler, B., Seyff, N., Syriani, E., Venters, C.C., 2020. Toward model-driven sustainability evaluation. *Commun. ACM* 63(3), 80-91. DOI:<https://doi.org/10.1145/3371906>
- [29] Kephart, J.O. and Chess, D.M., 2003, The vision of autonomic computing. *Computer*. 36(1), 41-50. DOI: <http://dx.doi.org/10.1109/MC.2003.1160055>
- [30] Kounev, S., Kephart, J.O., Milenkoski, A., Zhu, X. (eds.), 2017, *Self-aware computing systems*, Springer International, ISBN 978-3-319-47474-8.
- [31] Niu, S., Luo, Y, Dietze, M.C., Keenan, T.F., Shi, Z., Li, J., Chapin, F.S., 2014, The role of data assimilation in predictive ecology. *Ecosphere* 5(5), 65. <http://dx.doi.org/10.1890/ES13-00273.1>
- [32] Park, S.K. and Xu, L. (eds.), 2017, *Data assimilation for atmospheric, oceanic and hydrologic applications*. Vol. 3. Springer Science & Business Media.
- [33] Ecocommons Australia, <https://ardc.edu.au/project/ecocommons-australia/>
- [34] The European Open Science Cloud, <https://www.eosc-portal.eu/>

[35] D4Science Infrastructure, <https://www.d4science.org/>

[36] Pangeo: A community platform for big data geoscience, <https://pangeo.io/>

Appendix A: What comes next?

Inspired by the Windermere Accord Summit, October 2018

Harriet Fraser

Estimated anthropogenic global warming is currently increasing at 0.2°C (likely between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (high confidence).

Where do you want to walk?
Shall we stroll together through the Valley of Despair,
kick our feet through leaves of fear,
brush against obstacles in industry, academia, politics?
Shall we wander in this fog endlessly?
Shall we retreat?

Avoiding overshoot and reliance on future largescale deployment of carbon dioxide removal (CDR) can only be achieved if global CO₂ emissions start to decline well before 2030 (high confidence).

Or shall we stride up to the heights
to feel the light and take a wider view?
Shall we be ambitious, and push modesty away,
negotiate obstacles, face uncertainty,
keep our feet on the ground, earthed,
and as a community propose a new road map?

With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming.

We have seen coral reefs dying
We have imagined their passing
We have modelled their death

We have imagined summer fields without butterflies
We have watched decline
We have modelled depletion
We have imagined a world without wild

The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (high confidence).

What else might we imagine
from the sunlit heights?
Can we imagine a rapid end
to the toxic emission of carbon dioxide,
to the warming?
Can we imagine forests, growing
or the ocean, clean?
Can we make that happen?

Education, information, and community approaches, including those that are

informed by Indigenous knowledge and local knowledge, can accelerate the wide scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C.

There's pressure
to look for what you expect to see
where you expect to see it
but that's not where the interesting stuff lies

There are always questions
Where do we predict that we are going?
What do we need to know?
If we use models as tools to think with
are we choosing the right models?

Limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (medium confidence).

Who's in the community?
What's in our tool box?
Sensors, computers, hope,
Knowledge, stories, reason
Empathy, connection, drive

We are part of the system:
systems within systems,
creating, adapting, imagining, learning
in the human-digital age,
integrated, inter-connected,
as natural systems are,

and we know: *Collective efforts at all levels,
in ways that reflect different circumstances and capabilities,
in the pursuit of limiting global warming to 1.5°C,
taking into account equity as well as effectiveness,
can facilitate strengthening the global response to climate change,
achieving sustainable development
and eradicating poverty
(high confidence).*

Quotes taken from the IPCC (Intergovernmental Panel on Climate Change) report summary for Policy Makers, October 2018

Appendix B: Annotations around the elements of the Accord

1. USING DIGITAL TECHNOLOGY TO TAME UNCERTAINTY IN A CROSS-DISCIPLINARY WAY.

Use what we already know about uncertainty in env. science. DT/Env. Ch. communities learn from each other's approaches.

Including understanding the role of uncertainty in decision making - also starting with this understanding when defining research

Bringing together experts in uncertainty & environmental science

WHICH UNCERTAINTY FAMILY MATTERS

VALUE STUFF WE KNOW MORE THAN

QA of Data and Models

technology to detect unexpected events & react to minimise undesirable effects

It's a long game - slow for uncertainty - value -> improve -> feedback on policy intervention (on policy reform)

No longer being scared of uncertainty

Critical thinking about existing results. Improve what we "used to do"

STATISTICAL THINKING ↔ PERSONAL UNDERSTANDING

SELF-ADAPTIVE MODELLING & SYSTEMS FOR TAMING UNCERTAINTY

DEFINING THE STRUCTURE OF WHAT WE KNOW FOR SURE, ITS OUTLINES AND BORDERS

USING SEMANTICS TO UNDERSTAND THE MEANING OF DATA AND UNCERTAINTY, IN PARTICULAR

translate uncertainty to local decision

- Communicating it, policymakers don't like uncertainty
- Technology can also add uncertainty
- Think about certainties
- Accept ambiguity.

POLYGENOUS NOT LINEAR LOOK AT THE SHAPES AND HOW MANY FEET BUT UNCERTAINTY

Feedback loop between model uncertainty & data uncertainty

UQ

Extract meaning from uncertainty in decision contexts

don't lock to fully close uncertainty gap just improve it.

SPECIFIC CHALLENGES & COMMON LANGUAGE

Need to 'anchor' these abstract notions in concrete environmental context. Can one have an equivalent of "1000 genome project" for example? How about "The Windermere project" capturing environmental change data over 50-100 yrs?

Capture uncertainty which is coming from digital technology itself.



Communicating uncertainty not just in stats but in visual ways, "show & tell" evidence

a virtual catchment -> where everything complex parts and all are integrated (feedback + complexity) -> model is modelled & explored

Can we embrace uncertainty instead of taming? Then understand where we need more knowledge/process/complexity in order to effect/influence decisions? (Complex into concrete?) help messaging

4. INTEGRATION AND FEEDBACK

(WE KNOW WHAT WE MEAN) multi-scale self-adaptive integration
Integrative solution oriented tools & methods

Knowledge map - gap analysis - big env. Qs
- what can be done already?
- what needs improving?
- which methods (data sci / physical process) are better when?

Brand as "AI for Environmental Science"
for political relevance

DYNAMIC ADAPTIVE MODELS & SYSTEMS

we shouldn't ponder to one term: 'of the day'

we should hold ourselves in higher esteem

PROVIDE AN INTEGRATED VIEW (NOT THE SAME AS HOMOGENEOUS)

linking platforms to enable cross-disciplinary and whole of life cycle research approach

Environmental Equilibria is totality

Social narratives + social sciences to add richness + stories to data & tech

Being able to understand how you are fit into the bigger picture

Semantics + uncertainty with semantic modelling
FOCUS ON WHAT MAKES A DIFFERENCE AND MAKE COMPLEX PROBLEMS TRACTABLE (80/20 IT!)

avoiding trade-offs not being avoided (i.e. sub-optimal policies leading to worse off students)

Technology for Adaptive Integration

Facilitating the communication between different scientific disciplines

20% PROACTIVITY / NEED TO BE AGILE + ADAPTIVE
Just do it? and don't worry about it failing?

MULTIMODAL DATA

"NOT JUST PASSIVE DATA" - no 'skinny answers'

INTEGRATED PLURALITY OF VIEWPOINTS

ENABLE SYSTEMS TO SELF LEARN TO IMPROVE CREATIVITY / USEFULNESS

Developing a common language to facilitate the integration

Using digitalization of the environment & data science techniques to better understand climate feedback mechanisms

never stop learning and allowing for change.

NEW WAYS OF TACKLING COMPLEX PROBLEMS WITH DISTRIBUTED TEAMS AND SHARING KNOWLEDGE RAPIDLY ACROSS GLOBALLY TEAMS

Self Adaptive models with a feedback loop
Some supporting framework

IMPACTS OF MULTIPLE DRIVERS ON MULTIPLE ENDPOINTS

Need to plan feedbacks into project lifecycles otherwise information may be lost after 3/5 years when projects finish

4

A good example helps...
Can we try to do it for somewhere?

Collaborative working practice to bring approaches together

Tolerance and understanding of different perspectives

5. BUILDING A DIGITAL ENVIRONMENT COMMUNITY FOR 'TODAY AND TOMORROW'] FOR THE FUTURES

Diverse voices and perspectives

COORDINATION OF DIFFERENT ENVIRONMENTAL DATA SCIENCE TO MAXIMISE VALUE TO UK + WORLD

E.G. ENSEMBLE, DEFRA DIGITAL TRANSMISSIONS, DAFNI, JASMIN

not just focusing on virtual! lessons such as Planets + in water - it is short-lived + and makes other issues LOW-TEMP COMMUNICATION AND COLLABORATION

INTRINSIC MOTIVATION WE NEED FASCINATING PROBLEMS!

How do you give a home to digital champions of tomorrow do you?

Enable more opportunities to internet

Make it fun + funky

Hold annual "All Hands Conference" (worked for eScience...)

Using the dig. tech. to open science to transparency to the wider community

TAKE THAT COMMUNITY OUT OF DIGITAL ADDRESS THE PRACTICAL QUESTIONS GRANTED IN ASIA

Long-term, sustainable, virtual & physical community

nature early career researchers

Attract great people (esp. Comp Sc.) to meet community.

Inspire "wider" Digital Community to take initiatives + be part of this effort.

promoting cross-disciplinary seminars to bring people together

Find way of talking + maintaining community + growing community.

What can we learn from other facing similar cross-disciplinary community issues (esp. when we are not co-located physically)

WORKED EXAMPLES FOR UNDERSTANDING SCIENCE AND CITIZENRY AND OF

MAKE NOISE

Resource - need people to do grass-roots research.

- Institute
- Conference
- Journal

at the DT / Env change integrate. Increase social support community in the

Commitment, motivation, appropriate space. own interventions to the wider community. Integration of digital technology in undergraduate curriculum and graduate curriculum. "KNOWLEDGE FABRIC"

Attract more people through doing

DECISION-MAKING (THE ARCH)

NOT THINKING ABOUT SOMETHING IS STILL A DECISION

COMMUNICATE 'KILLER FACTS' TO SET POLICY MAKERS DIRECTION OF TRAVEL

Both the process and the decision recognising that decisions require a partnership to implement + evaluate

HOW DOES IT REALLY HAPPEN? NEEDS UNDERSTANDING TO INFLUENCE

Who makes the decisions?

minimize the gap between knowledge (about the environment) and decisions (impacting the environment)

Making people aware that we can/make decisions

Make informed decisions easy

Clear agendas

POWER = ACCOUNTABILITY

CAN LIE WITH THE MANY NOT PRINCIPLED DECISIONS JUST THE FEW WHERE UNCERTAINTY ABUNDANTS

FRAMING QUESTIONS SINCE ANSWERS THE FOLLOW

Communicate impacts of decisions influencing 'up' and 'down' in financing 'down' in financing 'up'

Train scientists in skills for DECISION MAKING AT DIFFERENT SCALES

Talking to people involved in making decisions and finding out what they do and how they approach

e's placements with natural hazard incident responses, govt (local, national), business.

Understand the un-understandable! Why decisions are made? Where does evidence go?

DECISION-SUPPORT ISN'T PROBLEM. WE NEED TO CHANGE BEHAVIOURS

Salient, robust and how good decisions with societal buy-in

CROSS-DISCIPLINARY EFFORTS FOR BETTER INFORMED DECISIONS

Making (everyone) decision maker

spread allow them to spread/prepare mind the gap