Reflections on the IPCC and global change science: time for a more (physical) geographical tradition

SHORT TITLE: Physical geography and global change science

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Abstract

Over the last quarter of a century, physical geography has not been served well by the often homogenising influence of global change science, as exemplified by the structures and activities of the Intergovernmental Panel on Climate Change (IPCC). However, certain areas of physical geography may have been at fault in being too little, and too uncritically, engaged with international, interdisciplinary research programmes in global environmental change. Moving forward, physical geography should look towards an independently constituted framework that incorporates the complexities of landscape response to both external forcing and internal feedbacks and, above all, works with others to prevent the socio-spatial injustices associated with climate change from being realised.

Keywords: climate change, global environmental change, climate variability, landscape change, physical geography

- single factor climate change metrics, such as global mean temperature increase or global sea level rise, have little meaning for the explanation of landscape scale change

- global scale analyses struggle to incorporate landscape settings; the role of climatic variability alongside secular change; intrinsic systems feedbacks which modulate external forcing; and spatial and temporal cascades of energy and matter

- the ultimate goal of global change research should be the study of the implications of climate change for human lives and livelihoods and here the geographical tradition can make a significant contribution

Introduction

A particular feature of the environmental agenda of the late twentieth and early twenty first centuries has been the appearance of “second-order knowledge production”, assessments which synthesise the publication outputs of “first order knowledge production” generated by traditional scientific activity (Beck et al. 2014). The need for such synthesis no doubt reflects our growing awareness of the complexity of these problems, a complexity which science may help resolve. In this sense, at least part of this appearance is related to a second shift, which has emphasised “problem-oriented” or “Mode 2” science (Gibbons et al. 1994). Therein, greater emphasis is placed upon primary scientific research that responds to questions central to society which, in relation to the environment, has inevitably made climate change a central theme. On the one hand, the focus of Mode 2 science on interdisciplinarity appears to resonate with the multiple and complex causes and consequences of climate change. But it also sustains a particular model of scientific enquiry, one focused upon providing answers, and hence solutions, to very difficult questions over relatively short time scales.

In terms of climate change, a key milestone was the formation in 1988 of the Intergovernmental Panel on Climate Change (IPCC), by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The IPCC is a classic example of Mode 2 science. It has sought to form the bridge between fundamental science, much of it represented over the last three decades by a range of interdisciplinary, international global-change research programmes, and global climate policy. It is remarkable in Mode 2 science terms because of the ways in which an initial ‘top down’ governmental and global agency framework of control has been able to energise an extensive ‘bottom-up’ community of volunteer experts. The latter have provided, incrementally over five Assessment Reports (AR) between 1990 and 2014, the synthesis of an ever-growing body of knowledge on near-historical and contemporary climate change; and this has been done in such a way as to provide policy-relevant science to climate policy at the global scale. The First Assessment Report (FAR) played an important role in establishing the Intergovernmental Negotiating Committee for the United Nations Framework Convention on Climate Change (UNFCCC). As the recent signing of the Paris Agreement (December, 2015) shows, the UNFCCC continues to provide the overall policy framework for addressing the issue of climate change on the world stage - and continues to expect its decisions to be underpinned by a science base gathered by the IPCC (Hulme 2016).

However, within the over-arching mission of the IPCC, the detection and significance of human influences on the climate system, the balance of where the focus of assessment lies, as measured by page length counts, has shifted through time (Table 1). Whilst the initial outputs (1990 – 1992) were firmly focussed on the scientific basis of climate change (Working Group 1 (WGI)), as early as the Second Assessment Report (SAR, 1995) the dominant concern was with impacts (WGII) and that dominance has been maintained through AR4 (2007) to AR5 (2013-2014). Interestingly, the title of the WG II outputs have shown a subtle shift over time, from simply ‘Impacts’ (FAR, 1990), to ‘Impacts, Adaptation and Mitigation’ (SAR, 1995), to ‘Impacts, Adaptation and Vulnerability’ (TAR, 2001 onwards). This shift ought to have important implications for both Geography in general and physical geography in particular, as the growing emphasis upon impacts began to include the response of the earth surface system to human forcing of climate; and, if we accept the principle that geographers are well-placed to study the interface between environment and society, attempts to incorporate the consequences of climate change on people ought to have motivated geographical contributions more generally (Castree, 2015,2016). Physical geography should have been particularly well placed to contribute both material knowledge and expert personnel to this structuring of the global change debate from the early 1990s onwards. Furthermore, this focus has found echoes in the evolution of the component research programmes of the Earth Science System Partnership (ESSP; Leemans et al. 2009) and the intellectual pathway from UNEP's Global Biodiversity Assessment (1995), through the Millennium Ecosystem Assessment (2000 – 2005; but for its difficulties see Reid and Mooney 2016), to the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2013 onwards). Yet within these framings, physical geography appears to have achieved less meaningful influence. Rather, the global climate change discourse has in actuality 'massively diverted interest away from the geographer's traditional expertise in global environmental change' (Slaymaker 2005, 76); we give our reasons for this state of affairs below.

Table 1 near here

In this commentary, our interest is not in a critique of the IPCC. Rather, it is in a reflection upon physical geography's positioning within the IPCC, taking this experience as an exemplar of the subject's general engagement with the global environmental change debate. There are, we believe, important lessons to be learnt and acted upon now. It is clear that the new IPCC Chair, Hoesung Lee, intends to move the IPCC away from assessing more Earth system science and towards 'solutions', focusing on institutional and technological change, development pathways, poverty reduction and adaptation and mitigation financing (Lee 2015). And, as the ESSP morphs into the Future Earth programme, 'the focus should be redirected from the separate major global change issues towards the more integrative sustainability challenges' (Leemans 2016, 104). If, as we argue below, that physical geography largely missed the global environmental change boat the first time around, it really should not do so a second time, particularly if the shifts in approach and focus described above bring the debate even more firmly into the geographical domain. Castree (2016) has eloquently articulated how geographers might better engage with global change research; here we promote similar concerns but from a perspective more rooted in the traditions of physical geography.

Physical Geography and Global Change Science

Climate change is a key external driver of almost every environmental system of interest to physical geographers including glacial and periglacial systems, arid and semi-arid environments, rain forest, river basins, coastal and marine environments. In many cases, those systems themselves have the capacity to modulate climate (e.g. ice-atmosphere feedbacks; methane release following permafrost decay; fluvial erosion and transport of carbon) (Slaymaker et al. 2009). Yet, the direct engagement of physical geographers with the IPCC Working Groups (WG) has been relatively slight (9.6% of Coordinating Lead Authors and Lead Authors in IPCC AR4, WG II, (2007); 4.9% in AR5, WG II (2014)) suggesting an increasingly superficial influence despite the evolution of the IPCC's focus towards impacts and adaptation where physical geographers surely have a contribution to make. There have been noteworthy pockets of achievement, such as the critical evaluation of the widely propagated myth of the erosion, inundation and depopulation of islands on coral atoll rims by the physical geographer-led chapter on ‘Small islands’ in IPCC AR5 WG II (Nurse et al. 2014; and see also McLean and Kench 2015). But in general, Lane’s (2012, 106) observation of geomorphological involvement in AR4 is a fair summary of the wider state of physical geography’s involvement: “Reading the IPCC, one might wonder where all the geomorphology has gone”. However, this lack of *direct* quotation of physical geography research in relation to global environmental change in WG II contrasts markedly with the *indirect* influence of the physical science frameworks provided by IPCC WG I. Thus a great deal of predictive geomorphological science has been structured around landform change related to discrete timesteps of climate change and sea level change. Often, this focus is bracketed around starting points in the mid to late 20th century and with end points of AD2100. These limits are determined not by the phenomena under study (why should an interest in landscape change end at 2100?) but by the power that the IPCC now has in shaping academic enquiry. Indeed, the date AD2100 is more associated with the limitations of numerical modelling of climate than with any inherent landscape property.

As Turnhout et al. (2016, 66) have noted “since the 1950s, the idea of ‘climate’ in western science evolved from being predominantly interpretative, and hence geographically differentiated, to becoming enumerated and hence readily globalized. … Climates — plural and situated in places — became global climate, singular and placeless” (and see also Miller 2004). As others have argued (e.g. Clifford and Richards 2005, Richards and Clifford, 2008), physical geography has not been served well by such “globalising instincts of knowledge construction about environmental change” (Hulme 2010, 599) during the 20th and the 21st Centuries. Not only has the debate been skewed by an over-emphasis on just one driver of environmental change, climate change (Slaymaker et al. 2009), but it has been further unbalanced by its expression through the deeply-embedded single metric of global average temperature change and the associated notion of critical thresholds to planetary wellbeing, variously set at 2°C (Liverman 2009; but see Tol 2007), 4°C (New et al. 2011) and even 6°C (Lynas 2007) of global warming above pre-industrial temperatures. As Beck et al. (2014, 81) perceptively recognise “the ‘global average temperature’ has long been the organizing device for the IPCC around which both scientific knowledge has been assessed and different policy options evaluated. Framing climate change in this way, as a universal risk that can only be reduced through collective action, creates the need for consensus-based knowledge production and decision support. It has been difficult, if not impossible, for the IPCC to break away from the early framing of climate change around global average temperature as the pre-eminent indicator of risk”. Whilst temperature change clearly directly drives weathering and other earth surface processes (e.g. Gislason et al. 2009), notably in environments close to certain critical temperature thresholds (e.g. those associated with alpine permafrost: Mercier 2010) such a single figure index has no explanatory power when it comes to the likely trajectory of future terrestrial landscape change. The impact of a global mean change only has meaning with reference to both the spatial distribution of extant temperature and the spatial distribution of the change itself. Even with such disaggregation, there are plenty of environments where temperature, as a component of climate, may be subservient to other parameters, such as precipitation (e.g. Eiriksdottir et al. 2011). The spatially-global and temporally-future scales of enquiry associated with the way that climate change has become framed are at odds with the scales that are characteristic of much physical geography and it is perhaps not surprising that this has made engagement of physical geographers in the IPCC difficult. It may also be reflected in the ways in which physical geographers seem often more comfortable with the kinds of Mode 1 fundamental science that proceeds through challenging what it is we think we know, through the progressive accumulation of knowledge, than the emphasis of Mode 2 science on problem-solving over relatively short timescales.

But the problems run much deeper. Right at the start of the IPCC process, a landmark paper by Turner et al. (1990) argued that environmental change can be seen as consisting of two components, systemic change and cumulative change. This is a critical distinction which deserves to have been more widely recognised and acted upon within global environmental change debates. Systemic change refers to occurrences of global scale, physically interconnected phenomena, whereas cumulative change refers to unconnected, local to intermediate scale processes which have a significant net effect on the global system. Hydroclimatic change and sea level change, prime foci of the IPCC Assessment Reports, are drivers of systemic change which is highly amenable to large-scale atmosphere and ocean systems modelling. Yet hydroclimatic modelling has failed to provide consistent model outputs in term of the changing patterns of precipitation (Goudie 2006). Indeed, the IPCC (2007[1]) itself revealed a basic problem based upon model intercomparison against known meteorological records: (global) climate model predictions of precipitation have only improved relatively slowly because such models struggle to get the detail of surface pressure right, the primary driver of extreme precipitation events, even if they do a good job for temperature. Similarly, considerations of climate change impacts upon coasts have often been reduced to the single factor of sea level rise, overlooking the often critical role of storms and storm surges (e.g. Castelle et al., 2015; Spencer et al., 2015), themselves strongly linked to pressure (Masselink et al., 2014). The fixation with sea level rise has led to an evaluation of coastal responses to systemic change only in the vertical and not in terms of the lateral movement of shorelines or the role of, for example, the often key control of changing sediment supply, itself only very weakly linked to climate. Thus, for example, in many UK east coast estuaries vertical saltmarsh surface elevation change over recent timescales (up to 40 years) has easily outpaced the rate of sea level rise over the same period. Yet, at the same time, there have been significant reductions in estuarine saltmarsh areal extent, exceeding 50% in some locations. The spatio-temporal dynamic of marsh erosion (and accretion), rather than being linked to sea level rise, appears to be determined by variations in estuarine process regimes, in turn shaped by the human interventions of dredging, reclamation and partial wetland abandonment (French and Burningham 2003).

Cumulative change refers to unconnected, local to intermediate scale processes which have a significant net effect on the global system and where the human footprint, so invisible or unimportant in the IPCC's WGI representation of the world (Fogel 2004), is strong, and often dominant. Topographic relief, and land cover and land use changes, are drivers of cumulative change but their spatial and (in the case of surface characteristics) temporal variability, and hence the difficulties of both definition and spatial resolution, make the incorporation of their effects into Global Circulation Models (GCMs) a continuing challenge (Slaymaker et al. 2009). Whilst there are regional assessments in the IPCC volumes, they are still predicated on the outputs of GCMs and the causality of argument is always one way, from the global to the regional (Nielsen and Sejersen 2012). This no doubt goes a long way towards explaining the 'extraordinary relative silence that prevails on the question of land use change' (Slaymaker 2005, 71) in climate change discourse. Whether global to regional or regional to global, smaller scales of interest tend to be represented as spatially aggregated statistical parameters that may not well describe the experience of an individual or a community whose concerns relate more to their position within this distribution. The question then arises as to whether the ultimate goal of global change research is the prediction of global change. It is surely the implications of climate change for human lives and livelihoods (which are themselves, of course, highly spatially differentiated) that should be driving, or at least reframing, the research agenda (RESCUE, 2011). Whilst hydrometeorological and sea

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[1] See https://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-8-11.html

surface datasets can be described by smooth time series distributions, their landscape impacts are decidedly non-linear, with clear thresholds to landscape change in the disturbance regime. Any approach, therefore, that sees the land surface as a passive stage upon which climate change occurs, and adaptive strategies as a response to at best continental-scale changes in climatic extremes, can only provide a very simplified view of the reality facing those who have to live with current climate, even before it has changed. It is precisely the direct engagement with this reality, at the kinds of scales recognised under the label of 'cumulative change', where physical geographers have most to offer.

Opportunities for a physical geographical contribution to global environmental change science

Rather than discussing how physical geography might interface with such a flawed intellectual framework[2], how might physical geography start to build its own response to the challenges of global environmental change science? What concepts should be taken into account when building such an independently constituted framework? In a brief commentary, we cannot provide an exhaustive listing but in the spirit of Castree's (2015, 2016) analyses of the potential for human geographers' engagement in the global change research, we identify four key areas where physical geographers might also make a contribution.

Firstly, physical geography recognises the importance of landscape setting. Setting can be formalised by the development and usage of landscape typologies. Thus, for example, mangrove forest ecosystems can be classified according to functional type (Figure 1a) which can be related to process controls (Figure 1b) and, in turn, to human-induced degradational pressures (Figure 1c).

Figure 1 near here

Furthermore, the dynamics of such settings can be studied in the conceptualisation of the relationships between system state and environmental forcing. Figure 2 shows two examples: one for lake eutrophication (based upon Lau and Lane 2001)); and one for controls of river channel pattern (modified from Graf 1979). In both cases, the x-axis is some measure of the forcing of the system and the y-axis the average state of the system. The forcing continually evolves in the system (e.g. phosphorous loading, 2a; stream power, 2b), but as long as the system can absorb that forcing through negative feedbacks (it is resilient) the emergent property that is being described (e.g. chlorophyll-a concentration, 2a; stream sinuosity, 2b) only changes subtly. In both cases in Figure 2, vegetation plays a critical role in this resilience through a well-described set of negative feedbacks. The system has thresholds: a discrete forcing event may be big enough to substantially change the system state, its emergent property (e.g. from oligotrophic to eutrophic, from single thread to braiding), but the size of the event needed is a function of the system state (where the system is on the *x* axis when the event occurs) as well as the event itself. The thresholds are intrinsic. Similar kinds of examples can be found in a range of other kinds of environments (e.g. channel networks – Phillips 2014; weathering – Phillips 2005). They share properties long described in geomorphic systems (e.g. Brunsden and Thornes 1978; Graf 1979; Phillips 1992): that

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[2] And the same arguments could be made for any number of similarly globalising approaches such as Earth Systems Science (Pitman 2005), Planetary Boundaries (Rockström et al. 2009) Tipping Points (Barnosky et al. 2012), and even the Anthropocene (as Brown et al. (2013) argue).

environmental systems are capable of absorbing external forces (they are resilient) but in doing so, elements of the system may subtly change, so impacting their sensitivity to future forcing. Little things may indeed make a big difference if the system has evolved to a particularly sensitive state. This kind of conceptualisation suggests that major events need not always cause a major impact (and note what this means for looking for extreme events in the depositional record; e.g. Sambrook-Smith et al. 2010). They may also be good (e.g. a flood that provides resources such as seed propagules or organic matter to encourage floodplain development, Bätz et al. 2015) or bad (e.g. a flood that destroys large amounts of floodplain vegetation). The conceptualisation also explains why attempts to restore seriously degraded environmental systems can be so difficult (Lau and Lane 2001), emphasising the importance of more precautionary approaches to environmental management.

Figure 2 near here

Such approaches highlight the importance of intrinsic system thresholds and their interaction with external controls. This is not trivial in the context of global environmental change. Kirwan et al. (2016), for example, argue that predicted near-future global wetland loss rates have been over-estimated as a result of the neglect of the 'ecogeomorphic interactions' that characterise the dynamics of intertidal saltmarshes. In addition, different settings have different degrees of connectivity to other landscape systems and it is here that geomorphology has provided the organising principle of sediment cascades (e.g. Caine 1974; Spencer and Reed 2010). The notion of cascades emphasises that any kind of climate signal is likely to propagate through the landscape as a function of time. In geomorphology, it has now been well-established that this propagation is a function of connectivity (Fryirs 2013) and the spatial organisation of this connectivity at the landscape scale that controls how temperature signals propagate through such cascades (e.g. Micheletti et al. 2015; Lane et al. 2016). The importance of cascades questions the wider hypothesis that depositional systems (e.g. lacustrine deposits) provide an archive of recent environmental change, and work is needed to understand precisely the kind of environmental records provided by depositional settings (e.g. Sambrook-Smith et al. 2010). These observations emphasise that there is a wealth of conceptual material on how "*To interpret the Earth*" (Schumm 1991) encompassing research that pre-dates by some time the concerns of the IPCC with climate change impacts.

Secondly, physical geography recognises the importance of climate variability and its interaction with longer-term trends, with the role of the magnitude, frequency and spacing of extreme natural events and with the value of extending timescales of analysis back into the near (centennial) and far (millennial) historical past. Such analyses have often shown that responses to contemporary flood events that characterise them as 'unprecedented', and thus a potential signal of climate change, in fact turn out to have precursors in the historical record and sit within the geological timescale envelope of possible system response (e.g. Foulds and Macklin 2016). The instrumented water level record is generally too short for the derivation of accurate extreme value statistics or extreme flood probabilities derived solely from numerical simulations, even if the notion of 'unprecedented events' somehow absolves those responsible for managing them. For example, the extreme Superstorm Sandy that impacted New York City in October 2012, has been assigned a return period of between 900 and 1570 years, based on a simulated hurricane climatology and generalized extreme value return curves from existing tide gauge data respectively. However, archival records and sedimentary deposits have revealed significant flood events in this region attributed to hurricane strikes in 1693, 1788, 1821 and 1893, and it is therefore likely that "the true return interval for such extreme events to New York City is probably significantly shorter than current estimates" (Brandon et al. 2014, 7). Of course, what is important here is to educate decision-makers and the public about the need to disentangle the hazard from the change in vulnerability, engendered by the spread of rising populations into increasingly unsuitable physical locations and the often inappropriate engineering responses to the protection of such populations (Pielke 2014). In an earlier paper, Pielke et al. (2008) estimated the damage that historical storms affecting the USA would have caused if they had made landfall under contemporary socio-economic conditions, adjusting historical damages by changes in national inflation, growth in wealth and changes in population in the US counties affected by each storm. In this approach there is no long term trend in losses; indeed, the damage in the period 1926 –1935 was nearly 15% higher than in 1996 – 2005.

Thirdly, the concept of a morphodynamic cascade can be used to link these spatial and temporal scales together (see Figure 3 for an illustration from coral reef systems). This highlights the complexity, and intellectual challenges, of a better understanding of the scales that lie between the micro and macro scales at the ends of this morphodynamic staircase. The notion that temperature signals cascade through landscapes implies that short-term and small-scale events may take some time to emerge at larger spatial scales, being transformed as they are transferred. Traditional analyses based upon magnitude and frequency don't help in landscape systems because they assume that the cause and effect are temporally and spatially coincident, even though it is well-established that the relationship between magnitude and frequency is conditioned by the state that the landscape is in, that is its geography and history (Lane and Richards 1997; Richards 1999). For example, integration of a discharge rating curve and a suspended sediment rating curve may show which discharge is dominant but that has no necessary causal meaning if the form of the rating curve is a function of the history of sediment delivery to the system under a suite of different processes.

Figure 3 near here

Fourthly, we draw attention to the analytical techniques and 'big data' now becoming available to physical geography and the possibilities that 'data driven' approaches now offer to environmental problem solving (e.g. Murray et al. 2009). Whilst the ease with which data can now be generated in physical geography may be faster than we can generate questions to which these data can be applied (e.g. from current and historical imagery using almost fully automated Structure from Motion photogrammetry; Fonstad et al. 2013), the kind of spatial and historical contingency implicit in Figure 3 is becoming increasingly measurable at least to the decadal and km scales. These data are allowing direct reconstruction of how landscapes have responded to climate forcing (e.g. Micheletti et al. 2015) rather than requiring it to be inferred from erosional (e.g. cosmogenic isotopes) or depositional records that may destroy partially or fully the spatial structure of the processes that produce them and where the methodology being used defines the temporal resolution and spatial extent of the questions that can be asked and so which questions become defined as important. At the kinds of scales that have interested the IPCC (decades to centuries), we contend that the km-scale spatial signal is not just noise, but a critical element of system response. 'Big data' collection programmes that can capture signals with fine resolution over decadal to centennial time-scales may provide very different models of how climate forces landscape change.

Finally, a more thoughtful physical geography of environmental change would harness the opportunities provided by a geographical tradition. Rather than contrasting the indirect (i.e. greenhouse gas driven) and direct impacts of human activity, they would focus upon the ways in which natural and social systems continuously couple and feed back into one another, so co-evolving, to make particular environments (e.g. see Ashmore 2015). Ironically, one of the great areas of success in the IPCC world has been the framing of risk, hazard and vulnerability and engagement with adaptation. But this has not been carried forward in any meaningful mapping onto the biophysical elements of the IPCC exercise and all too often the questions asked of adaptation have been overtly framed by a (natural) scientific framing of climate change (RESCUE 2011). Physical geography has a strong sense of both landscape sensitivity (Knight and Harrison 2012) and resilience (the ability of an environmental system to absorb forcing). It now needs to explore: (i) the extent to which landscapes can recover from extreme weather events and how locally-specific management strategies can improve the detailed trajectory of system recovery; and (ii) establish societally acceptable levels of landscape change and variability. But a more human focus on environmental change needs to go much further and question the global, homogenising and people-free influence of global change science, one in which scientists predict such that society can respond (see RESCUE 2011 for a review of what this might entail). It is about a move away from what Castree (2015, 11) calls the narrower and shallower forms of socio-environmental enquiry that "presume scientific knowledge can bracket value questions and piece together data about physical and human dimensions, such that normative issues arise 'downstream'." Rather, and following Lave et al. (2014) and Lövbrand et al. (2015), it is about giving a broader and a deeper attention to the myriad ways in which the relations of social power constrain, enable and evolve with the environment and how these may be harnessed in the service of social and environmental transformation. The goal becomes bringing the normative to the fore, with less emphasis being placed upon predicting climate change in the Anthropocene (arguably the limits of the IPCC's contribution) and the associated focus upon Mode 2 ways of problem solving, and more emphasis upon how it is possible to "alter the differentiated landscape of matter, meaning, and affect that is life in the Anthropocene" (Castree 2015, 12), that is to challenge the very nature of the questions being asked and solutions being advocated. This takes us back to David Harvey's seminal observation of 1972 that a perceived preoccupation of making mathematical models of urban inequality more correct needed to be replaced by an interest in understanding those conditions that needed to be addressed to prevent the inequalities emerging in the first place. Perhaps this is what a post-IPCC academic world will look like, one where geographers of multiple persuasions work together to address the socio-spatial injustices associated with climate change from being realised. Regardless, it may be the case that the time has come for the global emphasis of global change science to be replaced with a research agenda that is much more local in its academic endeavour (c.f. Richards and Clifford 2008), centred on the spatial and temporal scales associated with the day-to-day rolling on of life in the Anthropocene.

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Table 1: Changing emphases in the IPCC Assessment Reports, 1990 – 2015, as indicated by the page lengths of the three Working Group volumes in each Assessment.

	FAR 1990 and Supplement 1992	SAR 1995	TAR 2001	AR4 2007	AR5 2013-2014
Working Group I	628 (**49%**)	572 (**30%**)	881 (**33%**)	996 (**35%**)	1535 (**32%**)
Working Group II	322 (**25%**)	861 (**46%**)	1052 (**39%**)	976 (**35%**)	1820 (**38%**)
Working Group III	330 (**26%**)	448 (**24%**)	753 (**28%**)	851 (**30%**)	1435 (**30%**)
Total no: of pages	1280	1881	2686	2823	4790

% difference in total length post 1992	+47%	+110%	+121%	+274%

List of Figures

Figure 1
(a) Relationships among three functional types of mangrove forests (river-dominated, tide-dominated and interior sites), dominant physical processes (in italics), and six types of neotropical forest types (after Woodroffe 1992); (b) three functional types and process gradients (after Ewel et al. 1998); (c) sources of major environmental degradation related to functional classes of mangrove as defined by Woodroffe (1992) and Ewel et al. (1998) (after Dodd and Ong 2008).

Figure 2
Conceptualisation of the relationship between driving forces and system state for the case of lake eutrophication (2a, based upon Lau and Lane 2002) and river channel pattern (2b, based upon Graf 1979).

Figure 3
(a) Hierarchy of processes operating within reef environments at different temporal (instantaneous (up to days/weeks), ecological (up to 100 years), geomorphic (100 s– 1,000 s years) and geological (up to 10,000 s years)) and spatial scales. Grey circle shows the time/space scales over which reef community “phase shift” processes illustrated in (b) are important (after Perry et al. 2008).