

## Invited Abstracts

### Plenary speakers

Tuesday 11<sup>th</sup> May

#### **The time scales of climate models** **Andrew Jarvis**

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Both time scale and gain of climate change in response to anthropogenic forcing are important considerations in climate change decision making. Because of their significant inertia, the oceans play a central role in determining these system attributes. Using a familiar, simple representation of the oceans based on the advection dispersion equation, we show that, in the absence of any large-scale circulation, gain is inversely distributed with time scale leading to power law behaviour. However, we also show that the introduction of large-scale circulations such as MOC leads to the emergence of a limited number (three) discrete gain-time scale distributions in the surface response of these models to forcing. We find the same behaviour is observed for more complex EMIC and A-OGCM models. This feature allows for the partitioning of overall system gain (e.g. equilibrium climate sensitivity) between a limited number of discrete, identifiable time scales; a feature which could greatly simplify the consideration of both time scale and gain in the climate decision making process.

#### **Terrestrial biogeochemical feedbacks in the climate system: from past to future**

**Almut Arneth**<sup>1</sup>; Harrison S. P<sup>2,3</sup>..; Zaehle, S<sup>4</sup>; Tsigaridis, K<sup>5</sup>.; Menon, S<sup>6</sup>; Bartlein, P<sup>7</sup>; Feichter, J<sup>8</sup>; Korhola, A<sup>9</sup>; Kulmala, M<sup>10</sup>; O'Donnell, D<sup>8</sup>; Schurgers, G<sup>1</sup>; Sorvari, S<sup>10</sup>; Vesala, T<sup>10</sup>.

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Numerous exchange processes take place between the terrestrial biota and the atmosphere that contribute to the regulation of atmospheric composition and weather/climate on timescales from hours to millennia.

Recent studies have highlighted the importance of the exchange at the land surface for simulation of the pre-industrial and present atmosphere, and potential for large vegetation climate-chemistry feedbacks in the coming century. We will provide an overview over the key processes involved, and an assessment on their relevance for

radiative forcing calculations based on an emerging number of studies that attempt to isolate and quantify terrestrial biota's contribution.

### **Can we infer climate-carbon cycle feedback from past records?**

**Pierre Friedlingstein<sup>1</sup>** and I.C. Prentice<sup>1,2</sup>

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Several lines of evidences point towards a strong reciprocal link between climate and atmospheric CO<sub>2</sub> concentration. From interannual to glacial-interglacial time scales, observations show that climate excursions are generally associated with changes in CO<sub>2</sub>. The question of which variable is lagging and which is leading depends on the time scale. On short time scales, as for example during El Nino events, positive anomalies of CO<sub>2</sub> concentration are a response to the climate anomaly. On multi-millennial time scales, as for example during a glacial inception, a CO<sub>2</sub> decrease (induced by the global cooling) feeds back and amplifies the initial cooling. Therefore, on short time scales the observations provide information on the carbon cycle sensitivity to climate, whereas on longer time scales, the observations can constrain the climate-carbon cycle feedback.

Earth System Models that couple the physical climate system to the land and ocean carbon cycles have shown that in the coming century, there is a substantial risk that climate change will reduce the efficiency of both the land and ocean sinks for CO<sub>2</sub>, leaving a larger fraction of anthropogenic CO<sub>2</sub> emissions in the atmosphere and thereby producing a positive climate-carbon cycle feedback. Models generally simulate this feedback as positive, but the uncertainty in its magnitude is larger than the signal: prompting us to seek independent observational constraints.

Several studies have already attempted to use atmospheric CO<sub>2</sub> and temperature data at different time scales to infer a quantity that could help to constrain this climate-carbon cycle feedback. We have reviewed these studies and we have shown that all published to date are either conceptually wrong, or right but ineffective in the context of reducing model uncertainty. We combine a mathematical framework for feedback analysis with the known dynamics of the carbon cycle to reinterpret the available observations and to provide best estimates for the carbon cycle sensitivity to climate and of the amplitude of the climate-carbon cycle feedback.

### **Connectivity and Inequality: Tipping Points in the Human-Earth System**

**John Finnigan<sup>1</sup>**, Brede, M<sup>1</sup>; Newth, D<sup>1</sup>; Gunasekara, D<sup>1</sup>; Harman, I<sup>1</sup>

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The multifaceted problems of a world undergoing global change often dictate partial solutions. These solutions can be sub optimal or downright pernicious because they have unexpected consequences for the full system. In this talk we present a conceptual model of the human-earth system, discuss its key features and illustrate the connected nature of its dynamics by considering tipping points of the human-earth system. We may encounter these earlier than the climate tipping points, which climate change mitigation seeks to forestall.

We consider a world system driven by four variables, each of which has substantial inertia on decadal timescales. These are population, aspiration (the human desire for material improvement), global connectivity and biogeochemical change. Taking these in turn we look at population as a balance between fertility and mortality and consider how family-level and state-level wealth affect both sides of this balance. We next look at aspiration and the way this drives economic activity and growth of wealth, taking both a historical and a forward-looking perspective. The third driver, connectivity, is less often discussed but can be shown to be a key feature of the globalised modern world.

The global network of trade and material flows became connected (in a formal, mathematical sense) before the First World War, became disconnected as a result of that conflict and did not reconnect between the two world wars. Since the 1950's, however, the world has been strongly connected and it can be argued that exponential growth of material and information flows between all parts of the planet has taken the human-earth system to a state that humanity has never before experienced. Finally, the impacts of economic activity on the biogeochemical cycles that sustain the natural processes of the planet have been profound with these impacts also accelerating since the 1950's. This conceptual model provides a framework for modelling global dynamics in the Anthropocene. The fundamental importance of social and economic processes in determining these dynamics is apparent when we consider how the world trade system can intersect with material inequality to subvert development goals.

The present (and projected) world population depends on global trade in food and energy. This world trade system, comprising both material flows and flows of financial information, is fundamentally unstable in both the global and local senses so that small disturbances in supply and demand are often amplified into large changes in food price and availability. Global wealth is inequitably distributed both between and within countries. The poorest countries tend to have the most inequitable distributions of wealth. Changes in food prices, which have relatively small impacts in rich nations, can be disastrous for poor ones. This in turn has implications for global security as well as global welfare and poverty. Considering the world as a whole, such processes have serious implications for limiting world population without catastrophe. They emphasize also the importance of better quantification of economic and social dynamics in world scenario modelling.

**Spatial and temporal scales and levels in human systems: Some examples in the context of food security**  
**John Ingram<sup>1</sup>**

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Food security is a fundamental human goal. The pursuit of food security has been one of the main drivers of human systems for millennia and has given rise to a highly complex ensemble of cultural, institutional and technological developments over the ages. Agriculture has been intimately interwoven with the evolution of many societal structures including laws and regulations, customs and ceremonies, and trade and commerce. Food security is arguably of most interest for individuals in the near future. However, as population increases and globalisation proceeds, society is

increasingly concerned with food security over decades ahead, and we need to be able to look across spatial and temporal scales and levels as never before. This is particularly important in relation to identifying adaptation options for food systems in response to global environmental change (GEC).

Human-ecosystem interactions operate at many levels along complex spatial and temporal scales<sup>a</sup>. While new research approaches are emerging to help the interactions across human systems, the majority of food security/GEC studies are still conducted at either global or local levels. Work to link these via research at the intermediate, or “regional” level (i.e. sub-continental/supra-national), and how it relates to phenomena at both lower and higher levels, is particularly important as it helps to integrate issues along the spatial scale with the host of jurisdictional issues that emerge over a range of spatial and temporal levels. The “food systems” concept developed as part of the international research project “Global Environmental Change and Food Systems” (GECAFS) helps by integrating food security issues across space and time. Specifically, it provides a structure within which to discuss interactions within the human systems related to food security and how they interact with environmental and other societal goals.

This paper aims to:

- i) discuss the significance of scales and levels in human systems;
- ii) show how regional research helps to integrate between global and local levels;
- iii) show how a “food systems” framework helps identify key aspects of human systems in the context of food security; and
- iv) give some examples of how the human dimension of food systems can enhance or hinder alleviation of food insecurity.

<sup>a</sup> “Scale” is the spatial, temporal, quantitative or analytical dimension used to measure and study any phenomenon, and “level” is the unit of analysis that is located at different positions on a scale (Gibson et al, 2000; Cash et al, 2006).

Wednesday 12<sup>th</sup> May

**Fluxes of bio-available iron to the ocean**

**Akinori Ito<sup>1</sup> and Yan Feng<sup>2</sup>**

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Iron (Fe) is an essential nutrient for marine phytoplankton. The iron-containing soil dust mobilized from arid regions supplies the majority of the iron from the atmosphere to the oceans. However, the key flux is the amount of the soluble or bio-available iron as for the biogeochemical response to the atmospheric deposition. It has been proposed that atmospheric processing of mineral dust aerosols by anthropogenic pollutants (mainly sulphuric acids formed from their precursors) may substantially transform insoluble iron minerals into soluble forms. On the other hand, mineral dust aerosols also have a potential of neutralizing the acidic species due to the alkaline buffer ability of the associated carbonate minerals. However, only dust particles internally mixed with carbonate minerals can be buffered in this manner on an individual particle basis. Iron emitted from combustion sources is another important source for the bio-available iron, because it could be more soluble, and found more frequently in smaller sizes. In the present study, we investigate the impact of dust alkalinity on the bio-available iron deposition to the N. Pacific Ocean. In our model, faster removal of larger particles leads to larger fractions of fine particles in total aerosols over the remote ocean (i.e., more soluble iron from combustion sources). Additionally, the buffering capacity of mineral aerosol in the fine mode is consumed more efficiently due to the preferential condensation of acids on smaller particles. Notably, our results suggest that smaller dust particles may yield increased amounts of soluble iron relative to larger particles due to possible variations in mixing state of alkaline dust as a non-linear function of iron-containing aerosol particle size. Taking into account of this non-linearity, we have improved our ability to estimate the iron fractional solubility in different particle sizes; but quantitative, episodic, and predictive capabilities of the soluble iron remain a challenge. Using this scenario, we showed that the deposition of soluble iron from smaller dust particles could be a dominant source of bio-available iron over the eastern North Pacific Ocean. As a result, the timing and location of the atmospheric iron input to the ocean may be very different from those assumed in previous studies, where dust is often assumed with a constant solubility. As global warming has been predicted to intensify stratification and reduce vertical mixing, past and future changes in aerosol supply of bio-available iron might have a large impact on the marine phytoplankton production in the upper ocean. It may further influence the feedback of climate change through the ocean uptake of carbon dioxide as well as via aerosol-cloud interaction. While much of the research on understanding the role of mineral-dust iron in ocean productivity has focused on larger dust particles, further work would be required to study the atmospheric processing of mineral aerosols for different size modes in conjunction with size-fractionated mineralogy.

## How robust are responses of carbon-nitrogen cycle models to increasing atmospheric CO<sub>2</sub> and climatic changes?

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A number of recent studies have demonstrated the importance of considering nitrogen dynamics for projecting the responses to the terrestrial carbon cycle to increasing atmospheric CO<sub>2</sub> and climatic changes [1-4]. However, there are considerable differences in the global and regional responses of individual models concerning the strength and even the sign of the effect of N dynamics on the dynamics of the terrestrial carbon cycle. Here, the implications of alternative hypotheses on key nitrogen cycle characteristics that determine vegetation responses are tested to assess the reliability of the modelled responses. For this purpose, the terrestrial biosphere model O-CN model, derived from the land-surface scheme ORCHIDEE of the IPSL Earth system model, is used in different configurations, namely the elasticity of the plants' C:N stoichiometry, and the capacity of vegetation to increase biological nitrogen fixation as a function of N demand and C excess.

The alternative hypotheses result in substantially different projected land C storage by the year 2100. However, they do not prevent i) that there is a significant reduction of the net land C storage resulting from CO<sub>2</sub> fertilisation compared to the model version not accounting for terrestrial N dynamics; and ii) that on the global scale the limiting effect of N dynamics on the CO<sub>2</sub> fertilisation response is stronger than the stimulating effect of increased N release from soil organic matter decomposition in a future warmer climate.

1. Sokolov, A.P., et al., Consequences of considering carbon-nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. *Journal of Climate*, 2008. 21(15): p. 3776-3796.
2. Jain, A., et al., Nitrogen attenuation of terrestrial carbon cycle response to global environmental factors. *Global Biogeochemical Cycles*, 2009. 23: p. GB4028, doi:10.1029/2009GB003519.
3. Thornton, P.E., et al., Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model. *Biogeosciences*, 2009. 6: p. 2099-2120.
4. Zaehle, S., P. Friedlingstein, and A. Friend, Terrestrial nitrogen feedbacks may accelerate future climate change. *Geophysical Research Letters*, 2010. 37: p. L01401, doi:10.1029/2009GL041345.

## Probing the ice-core record of atmospheric methane: to what extent have changes in methane sinks influenced its concentration and carbon-isotopic composition?

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As the climate warmed between the last glacial maximum, about 21,000 years ago, and the pre-industrial era, roughly 200 years ago, the concentration of atmospheric methane rose from 360 ppbv to 700 ppbv, and  $\delta^{13}\text{CH}_4$  decreased by about 4‰. The question is, what led to these changes? How much was the result of changes in methane sources, and how much can be attributed to changes in methane sinks? In contrast to recent studies, we present results to a number of model calculations that suggest: the oxidising capacity of the troposphere changed little during this period, and the change in methane concentration was almost entirely due to an increase in methane sources; whilst a change in the strength of a relatively minor methane sink, namely oxidation by atomic chlorine in the marine boundary layer, which would have had little effect on the concentration of methane, could have made a significant contribution to the change in  $\delta^{13}\text{CH}_4$ .

### **Effective international policy to reduce emissions from deforestation**

Arthur van Benthem<sup>1</sup> and **Suzi Kerr**<sup>1,2</sup>

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Applying the offset approach of the Clean Development Mechanism to the problem of deforestation would be ineffective and potentially environmentally damaging. We explain why, providing empirical results to back up our theoretical argument. To effectively address emissions from deforestation we need both an international policy to address the global nature of the climate problem - and domestic policies to effectively respond to the international policies as well as to take unilateral action. We focus on the former. The key challenges in REDD policy are monitoring, permanence, and additionality leakage and adverse selection - as well as the risks involved if REDD is linked explicitly to international carbon markets. We propose an international system based on national baselines, temporary rewards for protection and externally replicable monitoring and illustrate the potential outcomes in terms of additional carbon storage, the cost of emissions reductions, and transfers of resources between countries. We then briefly discuss how national governments might respond to an international policy of this type.

### **Does climate uncertainty mean we will need large-scale air capture?**

**Niel Bowerman**<sup>1</sup>

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The uncertainty in the climate response to carbon emissions implies a strong likelihood that a temperature target such as limiting global warming to 2°C or even 4°C may be exceeded almost irrespective of emission policies adopted today. Due to the thermal inertia in the climate system, however, a period of negative emissions might stabilise temperatures if the response turns out to be higher than expected. We explore the likelihood of such a scenario and the magnitude of negative emissions in light of the current understanding of the climate response to cumulative carbon emissions. We also investigate the impact of these negative emissions on the hydrological cycle.

We consider an adaptive learning scenario in which society's understanding of the climate system improves over time. In this scenario, society responds to improvements in understanding by adapting its emissions pathways in order to reach a static temperature target. The magnitude by which temperatures rise faster or slower than previously considered is used to determine how much society perturbs its emission scenarios in the positive or negative direction. We consider initial unperturbed emission scenarios that will result in a best-guess carbon-dioxide-induced global warming of 2°C, noting that this also allows a high-likelihood of greater, or lesser, warming due to the uncertainty in the temperature response. Two strategies are explored: in one case society perturbs emissions if it finds itself living in a world that might not have 2°C of warming, and in another society perturbs emissions only if it finds itself living in a world where temperatures might rise above 4°C. We assess the relative likelihood of different levels of negative emissions during the 21st Century for each of these cases. We find significant likelihood that emissions must become negative in order to avoid more than 2°C of warming.

These findings suggest that, in the absence of albedo modification, we cannot rule out the need to use large-scale air capture to avoid 2°C of warming in the future. If such large-scale carbon capture turns out to be technologically and economically unfeasible, then we cannot rule out temperatures rising by more than 2°C in the future, even on an initial emissions pathway with a best-guess warming of only 2°C. We also find that if air capture is adopted rapidly and on a large scale, there are significant changes to global mean precipitation.

**Parallel session speakers  
Tuesday 11<sup>th</sup> May**

**Models and Observations**

**Regional trends in the land carbon cycle: validating a DGVM**

**Stephen Sitch**<sup>1</sup>, P. Friedlingstein<sup>2</sup>, P. Canadell<sup>3</sup>, P. Ciais<sup>4</sup>, P.M. Cox<sup>2</sup>, P. Foster<sup>5</sup>, E. Gloor<sup>1</sup>, C. Huntingford<sup>6</sup>, C. D. Jones<sup>7</sup>, S. Piao<sup>4</sup>, I.C. Prentice<sup>8</sup>, C. Le Quere<sup>9</sup>, P. Levy<sup>10</sup>, M. R. Lomas<sup>11</sup>, L. Mercado<sup>6</sup>, S. I. Seneviratne<sup>12</sup>, N. Viovy<sup>4</sup>, F. I. Woodward<sup>11</sup>

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In this study we identify regional trends in the land carbon cycle and investigate their underlying mechanisms for the period 1980-2008. A set of Dynamic Global Vegetation Models are run over the historical period 1901-2008. We output an extended list of variables in order to evaluate the model results against a wide range of evidence covering both hydrological and carbon related variables.

We explain simulated regional carbon sink/source trends in terms of the land response to regional changes in temperature, precipitation and radiation over this period, and their differential response on plant productivity and heterotrophic respiration. Results show that in some key regions the DGVM response is due to recent trends in reduced precipitation. Separate EO derived soil moisture data are in line with these findings in showing reductions in soil moisture over these key regions.

**From physiological observations to global ecosystem structure using plankton functional type modelling.**

**Erik Buitenhuis**<sup>1</sup> and Le Quéré, C<sup>1</sup>

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Until recently, ocean global biogeochemical models were formulated and tuned using global datasets of nutrient distribution. This left no data to evaluate these models, and thus risked ending up with models that reproduce the current state but get responses to climate change wrong. The approach we've used over the last few years to get around this is to synthesize large databases of PFT physiology to formulate and parameterise a 5 PFT model, and at the same time to synthesize databases of PFT distribution to combine with existing nutrient databases to evaluate this model. Initially, results showed improved representation of the targeted PFT without model tuning. As we progress through the ecosystem, we are also starting to see improvements in the untargeted PFTs and global rates (e.g. primary production, export and atmospheric CO<sub>2</sub> sink).

## **Effects of climate-induced changes in isoprene emissions after the eruption of Mount Pinatubo.**

**Paul Telford**<sup>1</sup>, Lathiere, J.<sup>2</sup>; Abraham, N.L.<sup>1</sup>; Braesicke, P.<sup>1</sup>; Johnson, C.<sup>3</sup>; Morgenstern, O.<sup>4</sup>; O' Connor, F.<sup>3</sup>; Pike, R.<sup>5</sup>; Wild, O.<sup>6</sup>; Young, P.<sup>7</sup>; Beerling, D.<sup>8</sup>; Hewitt, C.N.<sup>6</sup>; Pyle, J.<sup>1</sup>;

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In the 1990s the rates of increase of greenhouse gas concentrations, most notably of methane, were observed to change, for reasons that have yet to be fully determined. This period included the eruption of Mt. Pinatubo and an El Nino warm event, both of which affect biogeochemical processes, by changes in temperature, precipitation and radiation. We examine the impact of these changes in climate on global isoprene emissions and the effect these climate dependent emissions have on the hydroxy radical, OH, the dominant sink for methane. We model a reduction of isoprene emissions in the early 1990s, with a maximum decrease of 40 Tg(C) per year in late 1992 and early 1993, a change of 9%. This reduction is caused by the cooler, drier conditions following the eruption of Mt. Pinatubo. Isoprene emissions are reduced both directly, by changes in temperature and a soil moisture dependent suppression factor, and indirectly through reductions in the total biomass. The reduction in isoprene emissions causes increases of tropospheric OH which lead to an increased sink for methane of up to 5 Tg=year, comparable to estimated source changes over the time period studied.

## **QESM: The QUEST Earth System Model**

**Manoj Joshi**<sup>1</sup>; Gregory, J.<sup>1</sup>; Osprey, A.<sup>1</sup>; Spessa, A.<sup>1</sup>; Le Quere, C.<sup>2</sup>; Buitenhuis, E.<sup>2</sup>; Pyle, J.<sup>3</sup>; Abraham, L.<sup>3</sup>; Carslaw, K.<sup>4</sup>; Mann, G.<sup>4</sup>; Blyth, E.<sup>5</sup>; Clark, D.<sup>5</sup>; Fisher, R.<sup>6</sup>; Hooker, J.<sup>1</sup>; Fisher, J.<sup>7</sup>; Harris, C.<sup>8</sup>

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Climate modelling has historically been split into two approaches: global circulation modelling or GCM modelling involves integrating state-of-the-art components representing the atmosphere, land surface, and the ocean. Earth system models, or ESMs, consist of a more diverse set of components which can simulate more elements of the complexity of the environment, such as the terrestrial and oceanic carbon cycles. The latter approach enables simulation and understanding of more feedbacks than can be obtained by integration of GCMs alone. In addition ESMs can be integrated on much longer timescales than GCMs. The flip side of this complexity is that the components of ESMs tend to be much simpler than their counterparts in GCMs.

The QUEST Earth System Model or QESM, managed by NCAS Climate, is one of two ESMs whose development was funded by the QUEST programme. QESM is an attempt to understand the Earth system feedbacks that are important to climate on decadal to centennial timescales by combining elements of the two approaches above. The QESM is comprised of model components that represent important Earth system feedbacks. However, unlike ESMs, each model component approaches the state-of-the-art in its own right. QESMs computational load is kept down by degrading the resolution of some components compared to their climate GCM equivalents. Here we describe the main scientific differences between GCMs and ESMs, we describe the QESM and its components, and review its progress.

### **Observation networks: Community Initiative for Emissions Research and Applications (CIERA)**

**Claire Granier**<sup>1,2</sup>, Frost, G<sup>1</sup>; Falke, S<sup>3</sup>; Keating, T.<sup>4</sup>; Lamarque, J.-F<sup>5</sup>; Melamed, M.<sup>6</sup>; Middleton, P.<sup>7</sup>; Mieville;<sup>2</sup> Pétron, G.<sup>8</sup>; Smith, S.<sup>9</sup>

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While emission inventories at a variety of spatial and temporal scales are critical inputs to the understanding and prediction of air quality and climate, inconsistencies in the methodology and structure of these inventories have hindered research progress. Systematic inventory evaluations and quantification of emission uncertainties and their impacts are crucial to establish confidence in these datasets.

We will present the Community Initiative for Emissions Research and Applications (CIERA), which is under development in the USA. The goals of the work planned within this multi-agency project are to harmonize global and regional emission inventory development and to improve the exchange of emission inventory data. CIERA will facilitate the evaluation of inventories produced using a variety of methods, the investigation of the impacts of emission uncertainties and changes, and the use of these findings by the community.

We will discuss the motivation for organizing this collaborative initiative and the first steps taken. We will present plans for developing the CIERA web-based distributed data system. We will also encourage the international community to join the CIERA effort and describe how CIERA is already working with the Global Emissions Inventory Activity (GEIA).

### **Reconciling carbon fluxes in the Arctic**

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Arctic ecosystems are responding rapidly to observed climate change. Quantifying the magnitude of these changes, and their implications for the climate system, requires observations of their current structure and function, as well as extrapolation and modelling (i.e. “upscaling”) across time and space. A major challenge is to connect detailed surface flux information from intensive observation networks to remote sensing platforms that enable us to extrapolate this information at greater spatial scales. Here, we attempt to reconcile surface observations from MODIS, carbon flux information from the global FLUXNET database, and remote sensing & carbon flux data from the International Polar Year ABACUS project.

We begin with a synthesis of eddy covariance and meteorological observations from FLUXNET. We demonstrate that a simple model parameterized using pan-arctic chamber measurements explains over 80% of the variance of half-hourly CO<sub>2</sub> fluxes measured using eddy covariance during the growing season across most tundra, boreal grassland and boreal wetland ecosystems given accurate measurements of leaf area index (LAI). The MODIS LAI product is compared against tower data and more often than not disagrees with direct observations and model estimates, complicating our ability to scale C flux to pan-Arctic regions and suggesting that the MODIS LAI algorithm should be improved for process-based studies in arctic regions.

We then provide a detailed analysis of chamber to flux tower to aircraft upscaling from the ABACUS project and demonstrate that these fluxes are scalable using the same simple model. Flux and remote sensing data from the University of Edinburgh G-GEOS aircraft broadly agree with tower observations, further suggesting that arctic CO<sub>2</sub> flux observations are scalable across space. The importance of the spatial and probability distributions of LAI is emphasized. We demonstrate an application to estimate these surface patterns using MODIS data by treating subgrid scaling as an ill-posed problem in mathematics and providing theoretically-consistent solutions to this problem via Tikhonov Regularization.

## Earth System feedbacks and interactions

### Rate-dependent Tipping Points in the Earth System

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It is now widely understood that the climate system could undergo abrupt changes even in response to a smoothly varying forcing from humankind (Lenton et al., 2008). There is growing interest in estimating how the risk of such “climate tipping points” varies with the extent of global warming, as this is seen as having great relevance to the selection of stabilization targets designed to minimize the risk of “dangerous” climate change in the context of international climate negotiations. However, the impacts of climate change on natural and human systems depend on the ability of these systems to adapt to a changing climate, and this itself depends more on the rate of climate change than the equilibrium climate change at stabilization. Furthermore, it is now becoming clear that there are a whole class of tipping points that are triggered beyond some critical rate of increase of the external forcing, rather than by a given absolute increase in forcing. This talk will give two examples of such rate-dependent tipping points from our recent research.

The first relates to the stability of peatland soil carbon under global warming. Under warming decomposition is expected to accelerate leading to concerns that soil carbon could be released to the atmosphere, accelerating the rate of carbon dioxide and methane increase and providing a positive feedback on global warming. Although many global climate-carbon cycle models predict loss of soil carbon under global warming, few properly deal with organic soils such as peats, and all ignore the effects of biochemical heat release associated with microbial decomposition (Khvorostyanov et al., 2008). We will present theoretical work on the “compost bomb instability” which suggests that biochemical heat release could destabilize peatland carbon above some critical rate of global (Luke and Cox, 2010).

The second rate-dependent tipping point relates to the coupling between climate and the economy. It is widely accepted that climate change will have major impacts on water, food, human health and ultimately economic growth. Global CO<sub>2</sub> emissions, which are the largest contributor to anthropogenic climate change, have, to date, been highly correlated with economic output. As a result there is a negative feedback between climate change and economic growth that is mediated by CO<sub>2</sub> emissions: an increase in human wealth causes an increase in emissions and global warming, but the warming damages human wealth, slowing its rise or even making it fall. In principle this climate-economy feedback could lead to a “soft-landing” of the coupled human-environment system in which the background rate of CO<sub>2</sub> emissions growth (i.e. that would occur in the absence of climate change) is balanced by the suppression of economic growth (and therefore CO<sub>2</sub> emissions) due to climate damages. Instead our analysis suggests that historical rates of economic growth and decarbonisation, which together have led to the historical rates of growth of CO<sub>2</sub> emissions, put the climate-economy system in a dangerous oscillatory regime.

## **Uncertainty in future ecosystem changes from terrestrial ecosystem modelling**

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Terrestrial ecosystems are sensitive to climate and are also able to influence it through both biophysical and biogeochemical feedbacks, with many studies having shown positive feedbacks in which ecosystems can amplify climate change (e.g. Friedlingstein et al., 2006) and influence global emissions pathways to stabilisation. Changes in climate may also lead to significant changes in the ecosystems themselves, especially tropical (Phillips et al., 2009) and boreal forests (Sitch et al., 2008). Natural carbon uptake will play a key role in the future evolution of CO<sub>2</sub> and climate, but due to long response timescales the ecosystems themselves may be committed to long-term changes.

Jones et al. (2009) demonstrate that the global terrestrial biosphere can continue to change for decades after climate stabilization and that ecosystems may be committed to long-term change long before any response is observable: for example, they find that the risk of significant loss of forest cover in Amazonia rises rapidly for a global mean temperature rise above 2°C. This defines the new concept of committed ecosystem changes due to climate change but the quantitative details will inevitably be model dependent. Plattner (2009) describes this first study as providing a proof-of-principle for the concept of ecosystem commitment to climate change but now we need a more comprehensive understanding of the potential magnitude of ecosystem commitments across a range of models and scenarios, and for a number of different ecosystem types.

Uncertainty in such results can come from both climate model uncertainty and ecosystem model uncertainty. Here we present results from a study to quantify and understand the latter: the uncertainty in future committed ecosystem changes due to terrestrial ecosystem modelling. We use the IMOGEN model framework to drive 5 dynamic global vegetation models (DGVMs) to equilibrium using climate change patterns from the HadCM3LC GCM for climates from 1 degree to 5 degrees above pre-industrial. The DGVMs are HyLand, LPJ, Orchidee, SDGVM and TRIFFID as used in the recent intercomparison of Sitch et al. (2008). We present results of this study in terms of both future committed changes in ecosystem composition and carbon storage including a discussion of which aspects are robust across DGVMs and where major uncertainty exists. Future work will then address uncertainty due to different future climate change patterns from multiple climate models.

Friedlingstein et al., 2006, J. Clim.  
Jones et al., 2009, Nature Geosci.  
Phillips et al., 2009, Science  
Plattner, 2009, Nature Geosci.  
Sitch et al., 2008, Glob. Change Biol.

## **Atmospheric responses to methane pulse emissions**

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Natural emissions of methane may increase in a warmer climate due to potential feedbacks in the Earth System related to wetlands, permafrost, and marine hydrates. As a result, atmospheric methane concentrations could continue to rise over the next century despite efforts to reduce anthropogenic emissions.

In this study, the atmospheric response to methane pulse emissions is investigated and the sensitivity of the response to the size, location, and season of release is also explored. A particular focus of the atmospheric response is on methane itself, methane lifetime, tropospheric ozone, stratospheric water vapour, radiative forcing, and the 100-year global warming potential. The impact of methane emissions on the direct and indirect effects of sulphate and nitrate aerosol is also examined.

On the basis of these experiments, the forcing resulting from a methane release from wetlands and/or permafrost is estimated for a range of climate change scenarios.

## **Response of the carbon cycle to a collapse of the Atlantic Meridional Overturning Circulation**

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The biogeochemical changes in the land, ocean and atmosphere are investigated using a comprehensive, fully coupled carbon cycle and climate model (NCAR, CSM1.4-carbon), which is forced with five different freshwater perturbations applied at the North Atlantic and Southern Ocean deep water formation sites under preindustrial climate conditions. Ensembles of five simulations are generated for two of the perturbations to test the sensitivity to initial conditions. The perturbations are constant in time and last 100 years; model simulations are carried onwards for another 200 years in each experiment. The AMOC reduces in each experiment with varying degrees. The physical climate fields show changes that are well documented in the literature but there is a clear distinction between northern and southern perturbations.

Changes in the physical variables, in return, affect the land and ocean biogeochemical cycles and cause a reduction or an increase in the atmospheric CO<sub>2</sub> of up to 20ppmv, depending on the location of the perturbation. Land biosphere reacts with a strong reduction in carbon stocks in some tropical locations as well as in high northern latitudes, to a North Atlantic perturbation and with a somewhat opposite response to a southern perturbation. The ocean is generally a sink of carbon, although re-organizational changes occur throughout various basins. This study shows that southern and northern origin reductions in the AMOC can cause global and distinguishable changes in the biogeochemical cycles. Furthermore, it also indicates that a significant reduction in the AMOC in the future due to increased

freshwater discharge to the North Atlantic operate as a positive feedback to further increase atmospheric CO<sub>2</sub> concentration.

### **Biomass burning in the Americas post 1492**

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The degree to which indigenous population collapse, caused by post-1492 European Contact, led to a decline in biomass burning across the Americas, is a topic of considerable debate. Here, we investigate this issue by synthesizing charcoal records from the Americas, as a proxy for biomass burning over the past 3000 years. We find a clear, widespread signal that the Americas experienced a post-1492 decrease in biomass burning, with a nadir centered ca. AD 1600-1800, although inter-regional comparisons show that the amplitude of this downturn varied considerably. Comparison with paleoclimate records and pre-Columbian population estimates suggests that Little Ice Age cooling played a greater role than indigenous population collapse in driving this decline.

### **Careful choice of data-sources greatly improves the accuracy of past carbon cycle reconstructions**

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Records of the past show a link between climate and atmospheric CO<sub>2</sub>. Over the past 800,000 years, high atmospheric CO<sub>2</sub> levels have coincided with warmer climates and reduced global ice-sheet volume. However, agreement over the precise combination of mechanisms responsible for altering atmospheric CO<sub>2</sub> remains elusive, even for the relatively small atmospheric CO<sub>2</sub> change during the Holocene. The mechanisms that controlled past atmospheric CO<sub>2</sub> levels are not directly measurable, and thus many proxy data sources are combined when reconstructing past carbon cycling. When reconstructing the carbon cycle, modelled proxy values are compared for consistency with their real-world measured counterparts. Here, it is shown that the particular combination of proxies used greatly affects the accuracy of the carbon cycle reconstruction: numerical models can be consistent with multiple proxies even if their carbon cycle reconstructions are not accurate. A new framework is provided to evaluate how uncertainty in the proxy-observables propagates into uncertainty in the carbon cycle reconstruction. When previous modelling studies, seeking to evaluate the causes of the CO<sub>2</sub> increase in the late Holocene, have sought consistency with ocean temperature reconstructions, ocean carbonate ion reconstructions, and the isotopic ratio of atmospheric CO<sub>2</sub> as observables, uncertainties in the data sources are amplified by over two orders of magnitude when reconstructing the mechanisms responsible for CO<sub>2</sub> increase. Incorporating the isotopic ratio of dissolved carbon in the ocean since 8000 years ago, as a data source, significantly reduces the amplification of uncertainties, making this observable a priority for future research. If the causes of past atmospheric CO<sub>2</sub>

change are ever to be identified, a combination of proxy data sources must be found that provides a well-conditioned reconstruction of the responsible mechanisms for each time period, with reasonable uncertainty propagation.

## Human – environmental conceptualisations and impacts

### Atmospheric Services

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The terms Weather Services, Meteorological Services and Climate Services have existed for some time as part of the commercial and public services offered by national and private meteorological providers. These services supply information about the state of the atmosphere (e.g. weather forecasts, climate prediction, weather and climate data sets, weather derivatives, weather insurance etc.). Atmospheric Services on the other hand, as explored in this paper, refers to the intrinsic set of natural goods and services that the atmosphere itself brings to life on Earth: from the air that we breathe to the protection provided by the ozone layer, to the transmission of sound, to the support of air transport and to the provision of natural global warming. Twelve basic Atmospheric Services have been identified with a Total Economic Value of between 100 and 1000 times the Gross World Product (GWP). (Ecosystem Services have been valued at approximately twice GWP). This analysis shows that the atmosphere is the most precious and valuable of all natural resources in the Earth System. This paper attempts to justify the valuation of these atmospheric resources and also infers that the atmosphere should be treated as a global commons and responsibility for its sustainable management should be shared equally amongst all of society. The atmosphere is fragile and at a time of enhanced climate change it requires very careful management and protection, indeed a “Law of the Atmosphere” may be required, especially at a time when there is rising interest in the possible future need for geo-engineering the climate on a global scale.

### A probabilistic approach to exploring global dynamics

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We demonstrate an approach to modelling world system dynamic interactions in a way that explicitly characterises the variability in the data informing model assumptions and the uncertainty in functional relationships. There are strong arguments based on global datasets for the existence of two attractors in global human dynamics: the 'poverty trap' characterised by high birth rates and very low GDP per capita and a 'good life attractor' characterised by a stabilised population and high GDP per capita. To what extent can constraints from natural resources, impacts of global environmental change (including climate change), and behaviour of the economic system tip the global system across the boundary separating these attractors, triggering positive feedbacks characteristic of the poverty trap attractor? This is a key question in the Anthropocene. The purpose of our model is to seek such insights into interactions between human population, cumulative CO<sub>2</sub> emissions and GDP.

Our model choice was informed by the following considerations. Firstly, even a low-dimensional characterisation of the system requires a model to illuminate the consequences of chains of cause and effect and feedback loops, and such interactions warrant analysis as they offer insights into influences on aggregate global dynamics. Secondly, rates are constrained to be consistent with world datasets where feasible so embedding a data driven philosophy into the dynamic model. Thirdly, a probabilistic approach offers an effective way to deal with poor specification of functional relationships and variability inherent in data informing such relationships, so empirical relationships inferred from data are probability densities instead of single value functions, and model analysis is based around the analysis of ensembles of runs rather than single trajectories.

In our model, population and CO<sub>2</sub> emissions each change over time according to birth rate, death rate and energy use per capita, each of which are estimated from empirical relationships inferred from United Nations and World Bank datasets. These empirical functions are probability densities constructed using cluster-weighted modelling. The probability densities characterise the variability inherent in the data and by running ensembles of model realisations it is possible to characterise the effect of that variability propagated through the model. The representation of key feedbacks such as climate damages on population and economy is a highly contentious and immature field of endeavour. There are neither the data to inform such relationships nor robust theoretical insights from which reliable functional forms might be inferred. Our approach is to choose a generic functional form which again is amenable to ensembles of runs exploring the effect of different assumptions.

We use the model to highlight key features that result from the relative rates of change in the system and the nature of the feedback loops, and demonstrate the main influences on whether model trajectories are characteristic of 'poverty trap' or 'good life' attractors. Such an aggregated analysis offers a useful lens through which to study and interpret more detailed and realistic integrated models of human-biosphere dynamics.

### **Global maps of climate change impacts on the favourability for human habitation and economic activity** **Hans-Martin Füssel<sup>1</sup>**

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This paper analyzes the relationship between climatic factors and the global distribution of population and economic activity. Building on this analysis, a new method is developed for assessing geographically explicit impacts of climate change on the suitability of regions for human habitation and economic activity. This method combines information about differences in the conditional distributions of population density and economic activity across climate categories with climate change projections from an ensemble of general circulation models. In contrast to other cross-sectional analyses of the economic impacts of climate change, the non-parametric method applied here does not require specific assumptions about the functional form of the relationship between climatic and non-climatic factors on the one hand, and population density and economic activity on the other. The results indicate that future climate change will improve the habitability of some scarcely populated regions, in particular in Canada, Scandinavia, Russia, Mongolia, northern China, Tibet, and parts of Central Asia, but impair the habitability of many densely

populated regions in the eastern USA, southern Europe, northern and southern Africa, eastern China, and parts of Australia. Most parts of India, South-East Asia and Oceania, Central America and northern South America, the Sahara and the Sahel are projected to experience climatic conditions during this century that have no geographical analogue in the present climate. Hence, a large majority of the world's population is living in regions whose habitability is either projected to decrease or that are projected to experience globally unprecedented climate conditions within this century under a business-as-usual emissions scenario.

**Counting the costs of the 2005 Amazon drought: a preliminary assessment**  
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The Amazonian forest-climate system represents one of the key “tipping elements” in the Earth System. Future scenarios include the possibility that deforestation and climate change could push the system towards a drier climatic state during the course of this century. In this paper we explore the impacts of a significant regional drought and discuss its implications for management of the system through the provision of payments for ecosystem services

The 2005 Amazon drought provides an indication of the potential future impacts of climate change in Amazonia. During 2005 the south-western and western portions of Amazonia experienced one of their driest periods in 60 years, compounded by extensive forest fires. Although previous recent droughts in the region have been associated with El Niño Southern Oscillation, the cause of the 2005 drought was warmer global temperatures, leading to raised sea surface temperatures in the northern tropical Atlantic Ocean, and ultimately lower rainfall in Amazonia (Marengo, 2008; Cox et al. 2008). The diminished rainfall resulted in exceptionally low water levels in the Amazon River, draining many floodplain lakes and streams and isolating hundreds of riverine villages and communities. The government called a state of emergency and mobilized the army to provide water and medical supplies to these communities and to contend with the intense forest fires in Brazil's western state of Acre (Brown et al., 2006). Many fires were clustered close to forest edges, indicating that human activities made the forest more fire prone (Aragão et al., 2007). The drought led to substantial long-term carbon losses from the forest to the atmosphere, mainly through increased tree mortality: in 2005 the above ground biomass of the forest is estimated to have decreased by more than 3 billion tonnes (Phillips et al., 2009).

Our preliminary analyses based on the economic costs of the 2005 drought on regional weather and socio-economic datasets indicate that the impacts were felt across multiple sectors supported by rainforest ecosystem services, including: river fisheries, human health, agricultural production and river transport. The emerging picture is that within the Amazon region the impacts were severe at both regional and local levels. We illustrate this here with analysis of the impacts on health, fire incidence, and fisheries. Compilation of data from Brazil's health service ([www.datasus.gov.br](http://www.datasus.gov.br)) on the costs of treating waterborne diseases in Acre State, Brazil, where the drought was felt particularly strongly, indicate a large (up to 2-fold)

increase in the cost of treating water-borne diseases at the time of the drought. Similarly the incidence of peak fire incidence in the region was strongly correlated with drought intensity in Acre, although high fire incidence was also visible across the region along lines of existing development. These data demonstrate a high vulnerability within Amazonian communities to the impacts of drought, and a high associated cost with their management. Increasing the ability to resist and mitigate the impacts of such change (Nepstad et al. 2001) is likely to be a priority for regional governments and local communities alike. A PES system that contributed to reducing vulnerability to such ES loss might thus be very attractive, if it was considered acceptable and workable.

The GCP is a global alliance of governmental and non-governmental organisations linking major studies of forest canopies worldwide into a collaborative programme of research, education, and conservation addressing biodiversity, climate change and poverty alleviation.

### **How should we estimate climate change impacts on hunger and malnutrition** **Simon Lloyd<sup>1</sup>, Kovats, RS<sup>1</sup>, Chalabi, Z<sup>1</sup>.**

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Hunger and malnutrition are pervasive, thought to be worsening in absolute terms, and are major contributors to global ill health. Efforts to reduce malnutrition are expected to be curtailed by climate change, with changes in average conditions and extreme events likely to reduce crop productivity in many regions, which may in turn impact on health. The causes of malnutrition, however, are complex, and, in addition to lack of food availability, include a diverse range of socioeconomic factors such as water and sanitation provision, education and underlying health status.

Models for projecting future crop productivity and food access are available. However, projecting future malnutrition is constrained by a lack of socioeconomic data describing future worlds; scenario data is essentially limited to gross domestic product (GDP) and population. This paper provides an overview of the consequences of these constraints, and suggests new approaches to quantifying the future burden of malnutrition.

We will provide an overview of: the burden, causes and consequences of malnutrition, the indicators used to assess hunger and malnutrition, and previous modelling efforts and gaps. It will also identify steps towards developing new modelling strategies, including an outline of our work in progress.

### **How does fire intensity and frequency affect miombo woodland tree populations and biomass?**

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Miombo woodlands are the largest savanna in the world and dominate southern Africa. They are strongly influenced by anthropogenic fires and support the

livelihoods of over 100 million people. Managing the fire regime of these flammable systems is difficult, but crucial for sustaining biodiversity, ecosystem services and carbon stocks. Fire intensity is more easily manipulated than fire frequency, as suppression is expensive and ineffective. However, there are important issues relating fire intensity to impacts on woody vegetation that need to be understood to inform management approaches. Such impacts include the links between fire intensity, tree top-kill, resprouting and regrowth rates. Here we present results from a fire experiment in Mozambican miombo; the results of a 50-year fire experiment in Zimbabwean miombo; and observations of forest structure at a dry forest site in Mozambique. We synthesise these data with a process-based gap model of stem growth, regeneration and mortality, which explicitly considers the effect of different frequencies and intensities of fire. We use the model, tested against the field data, to explore the sensitivity of woodland tree populations and biomass to fire intensity and frequency.

Wednesday 11<sup>th</sup> May

## Earth system dynamics and future projections

### Biophysical versus carbon cycle effects of anthropogenic land cover change

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The last decade has seen substantial advancement in the integration of land use and land cover change in Earth system models. Both scientists and policy makers have recognized the importance of an accurate representation of land cover change in climate modeling frameworks to understand and quantify its effects on the climate system. This knowledge is critically important on two scales: first, the climate response to global land cover change, to understand past and project future global change. Second, the climate response to local land cover change, because future land use decisions likely will be based, in part, on their potential to help mitigate global climate change.

The challenge of assessing the effects of land cover change lies in the complexity of biosphere-atmosphere interactions. On the one hand, deforestation for land use causes CO<sub>2</sub> emissions, thus contributing to the greenhouse effect. On the other hand, it alters the physical properties of the land surface, often associated with cooling caused by increased albedo. Due to these counteracting effects, anthropogenic land cover change is one of the few climate forcings for which it is still uncertain whether the global effect is a cooling or a warming.

Here, we quantify the climate response to global land cover change by performing transient climate simulations over the last millennium, which separate carbon cycle and biophysical effects. We include unprecedented detail by (i) using a coupled atmosphere/ocean general circulation model (ECHAM5/JSBACH/MPIMOM/HAMOCC), and (ii) applying a highly detailed reconstruction of historical land cover change. We find that biophysical effects have a slight cooling influence on global mean temperature (-0.03 K in the 20th century), while the carbon cycle effects lead to strong warming (0.16-0.18 K). The simulated overall global climate response to land cover change is therefore dominated by the greenhouse warming, and becomes significantly larger than natural variability in the 19th to 20th century.

Since the amount of CO<sub>2</sub> emissions and the change in biophysical properties depend on the region and type of land cover change, it is not clear how each single location has contributed to the global climate signal. We quantify this contribution by comparing radiative forcing from CO<sub>2</sub> to that from surface albedo changes. We find that the CO<sub>2</sub> forcing dominates in many regions, including the high to midlatitudes, while the albedo forcing dominates in marginal regions. The CO<sub>2</sub> dominance in high latitudes contrasts previous studies that investigated hypothetical deforestation across latitudinal bands, but can be explained by the preferential allocation of historical agriculture on productive, and relatively snow-free, areas that tend to cause higher carbon losses and smaller albedo changes. Our analysis provides a basis to predict the climate consequences of continuing deforestation. Because regions of

past deforestation can potentially be reverted to their natural state, it also provides a reference point for estimating the potential of reforestation as a mitigation tool.

### **Accounting for physical and biogeochemical feedbacks in the climate system: contributions of uncertainty to future projections**

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Information of the uncertainty in the Earth System response to future greenhouse gas emissions is needed to inform on future climate risks and hence policy. Much of the current research is focused on quantifying the contributions arising from the atmospheric physics uncertainties, mainly cloud feedbacks. This is just one component of the earth system. Here we present work which aims to quantify uncertainties in four components of the Earth System within a common AOGCM: Atmospheric Physics, Aerosol Physics, Ocean Physics and the Terrestrial Carbon Cycle components.

We show how uncertainties (due to terrestrial carbon cycle formulation) in future atmospheric CO<sub>2</sub> concentrations for a single emission scenario are larger than the traditionally quoted SRES concentration range (when carbon cycle uncertainties are neglected). We also show that uncertainties in future global mean temperature response arising from carbon cycle uncertainties are as significant as uncertainties arising from atmospheric physics. This work provides both an opportunity to reassess how uncertainties within individual components interact within an Earth System framework and a future challenge on how we can identify observational constraints on the range of responses.

### **Bioclimatic envelope modelling of the current and future distribution of blanket peatlands at the global and regional scales**

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Blanket peatlands are ombrotrophic mires that cover the landscape almost independently of topography (Moore & Bellamy, 1973, Moore, 2002). Since they occur in regions of extremely oceanic climate, they constitute a rare ecosystem type at the global scale found only in the maritime fringes of the continental masses. The regional distribution of different types of peatlands has been mapped in Canada (Gignac et al., 2000) and Fennoscandia (Parviainen & Luoto, 2007) using different bioclimatic envelope statistical techniques; no attempt has previously been made to model the distribution of mires at the global scale using bioclimatic envelope techniques. We applied a process-based bioclimatic envelope model, PeatStash, to predict the current global distribution of blanket bogs. The model is remarkably

transparent and parsimonious, depending on just three bioclimatic limits (moisture index (MI), mean annual temperature and mean temperature of the warmest month), acting independently, to accurately describe the current distribution of blanket mires according to available global maps (Lindsay et al., 1988). Simulation runs using seven climate model outputs for a prescribed scenario of +2°C warming by 2050 (Mitchell & Osborn, 2005), resulted in generally similar patterns of declining areal extent of the bioclimatic space of blanket bogs in almost all current areas covered in blanket mires, although differing in degree. Additionally, the model was applied at a finer scale to Great Britain, where more detailed maps exist of the extent of blanket mires. The model captures the present areal extent ( $Kappa=0.77$ ) and is highly sensitive to both temperature and precipitation changes. When the model is run using the UKCIP02 climate projections for the time periods 2011-2040, 2041-2070 and 2071-2100, the geographical distribution of blanket bogs gradually retreats towards the north and the west of the British Isles. Increasing summer temperature is the main driver of the projected changes in areal extent. The eventual fate of blanket bogs left outside their bioclimatic space is uncertain both in terms of the resilience to carbon loss (including interaction with land management) and the rate of carbon loss.

#### References:

- Gignac LD, Halsey LA, Vitt DH (2000) A bioclimatic model for the distribution of Sphagnum-dominated peatlands in North America under present climatic conditions. *J. Biogeogr.* 27:1139-1151
- Lindsay RA, Charman DJ, Everingham F, O'Reilly RM, Palmer MA, Rowell TA, Stroud DA (1988) *The Flow Country: The Peatlands of Caithness and Sutherland*, Vol. Nature Conservancy Council, Peterborough
- Mitchell TD, Osborn TJ (2005) *ClimGen: a flexible tool for generating monthly climate data sets and scenarios*. Tyndall Centre for Climate Change Research Working Paper (in preparation), Norwich, UK
- Moore PD (2002) The future of cool temperate bogs. *Environmental Conservation* 29:3-20
- Moore PD, Bellamy DJ (1973) *Peatlands*, Vol. Unwin Brothers Ltd., Surrey, UK
- Parviainen M, Luoto M (2007) Climate envelopes of mire complex types in Fennoscandia. *Geogr. Ann. Ser. A-Phys. Geogr.* 89A:137-151

### **Patterns of decadal climate variability and their impact on global rainfall and the biosphere** **Peter Baines<sup>1</sup>**

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In recent years it has become increasingly clear that the global climate on time scales longer than those of ENSO (the El Niño-Southern Oscillation, say 4-5 years) is dominated by at least four patterns of behaviour with differing dynamics. These may be seen by an analysis of sea surface temperature (SST) from a variety of data sets: HadISST1 from the Hadley Centre, erSSTv3 from NASA/NOAA and the Kaplan SST from Lamont-Doherty. The four main patterns are, respectively, global warming, the Pacific Decadal Oscillation (PDO), the Atlantic Meridional Oscillation (AMO) and the Pacific Gyre Oscillation (PGO). These patterns may be projected onto other relevant variables such as surface winds and mid-tropospheric velocities to infer the dynamical structure that accompanies them. Here the focus is on observed rainfall over land over the past 110 years, and the contributions of these patterns to long-

term variability in this variable are assessed. In particular, their influence on recent long-term droughts is to be estimated, and results are presented for prominent regions in the US, Australia, Europe and Africa.

### **Regional climate change under high-end global warming**

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The climate projections from the IPCC Fourth Assessment Report suggest that global temperatures will increase between 1.6 and 6.9 °C by 2100, relative to the pre-industrial period. Here, we examine changes in temperature and precipitation for summer and winter from several ensembles of climate models where global mean temperatures increase by 4°C or more; such projections are termed 'high-end'. We have examined projections from the AR4 models, and the Hadley Centre's perturbed physics ensembles (Qump). We find that high-end projections generally have similar patterns of change in temperature and precipitation to non high-end projections. This result indicates that high-end models do not behave very differently to non high-end models. Enhanced warming, of up to 15°C, is projected over the Arctic in the high-end projections. Other areas which are projected to experience a large degree of warming are Canada and northern Asia, west and southern Africa, central Asia, and parts of Australia. The projected warming in northern hemisphere winter is much greater than that seen in the summer period.

All projections from an ensemble of models which included carbon cycle feedbacks on climate were classed as high end. For the business-as-usual SRES emissions scenarios, the magnitude of carbon cycle feedbacks is expected to play a major role in whether high-end climate changes are realised by 2100. Currently, the most likely data is the 2080s.

## Understanding and responding to climate change

### Adaptation strategies to reduce vulnerability to future environmental change

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Many adaptation strategies focus on improving immediate or medium-term capacities to cope with environmental change but ignore the possibility that they can increase vulnerability to future, possibly unforeseen, change. To help develop more effective long-term strategies, a new framework that includes a conceptual model highlighting the dual importance of bio-physical and human behavioural drivers and that views adaptation within dynamic and changing contextual landscapes is presented. To ensure that existing problems are not exacerbated by adaptation, strategies need to: (1) remove the human-induced and bio-physical drivers of undesired ecological change; (2) maintain a diversity of future response options; and (3) nurture human capacities to enable the up-take of those response options. These requirements are often not met when adaptations overly rely on technological fixes because they tend to concentrate on coping with the bio-physical symptoms of problems rather than addressing the human behavioural causes. Further, to develop more effective longer-term adaptation strategies, much greater emphasis is needed on strategies that enhance rather than erode the human values, adaptive capacities, skills, and behaviour conducive to environmental sustainability.

### Scenarios of global climate change mitigation through competing biomass management options

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Many countries have set up bioenergy policies to support and regulate the production and use of fuels from biomass feedstocks (e.g. US, EU, Brazil, China, and India). Substituting biofuels for fossil fuels can decrease greenhouse gas emissions because the carbon that is emitted during their combustion was recently extracted from the atmosphere by growing plants. But biofuels are hotly debated today because their overall impacts are uncertain and difficult to assess, being highly dependant on both the bioenergy fuel chain (choice of crop and technology), and on the existing land use. Direct biofuel benefits are linked to indirect land use impacts and may lead to adverse externalities regarding GHG emission balances, ecosystem services, and security of food and water. In particular, the implementation of biofuel targets might conflict with other mitigation options like avoided deforestation or enhancing forest carbon stocks.

A thorough assessment of biofuel impacts and biomass carbon management has to integrate many different scales. On the one hand, a global representation of agricultural and forest commodity markets is needed because these commodities are traded internationally and trade is the fundamental driver of indirect land use

changes. On the other hand, such assessments need a relatively high spatial and technical disaggregation to adequately account for heterogeneous land qualities, technological differences and possible adaptations.

Within the QUATERMASS Project, we employ complex biophysical process models to simulate, inter alia, possible agricultural management adaptations and their impacts on yields, GHG emissions, and water requirements under different land qualities. Explicit technological data for agricultural and forest management alternatives as well as first and second generation biofuel processes are simultaneously integrated in a bottom-up, partial equilibrium model of the global agricultural and forest sectors, GLOBIOM. This model is used here to assess different global scenarios of bioenergy use regarding their market feedbacks and their direct and indirect land use impacts on alternative options for biomass carbon sequestration and emission reduction such as forest management and avoided deforestation.

**QUATERMASS: Modelling greenhouse gas baseline projections and mitigation potentials in the forestry sector and their relevance for policy**  
**Robert Matthews**

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The QUATERMASS project uses scientific analyses of carbon uptake and release by forestry, biofuels and other land-use changes to investigate climate change mitigation options. It is using new approaches to land-use evaluation, and integrated forestry and agro-economic modelling (of agricultural, forestry and bioenergy production with global trade) to create a scientific framework for policy. It then analyses the environmental and socio-economic impacts of mitigation options and trade-offs of ecosystem services by country and region. It is funded by the UK's Natural Environmental Research Council under the Quantifying and Understanding Earth Systems programme (QUEST).

**Exploring mechanisms for treaty formation in an energy-climate-economy model**

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In this talk we discuss the effects of including a dynamic mechanism for the negotiation of climate agreements in an optimal control model that explores the dependence of world GDP growth on Climate Change and investment paths in the energy and goods producing sectors. The energy-economy-climate model describes the interrelated dynamics of the energy sector, consisting of carbon and non-carbon based energy supplies, a goods producing sector and the climate. In this context, three inter temporal investment decisions about the economic output have to be made over a planning time horizon. Current economic output can either: (i) be reinvested into the goods-producing sector thus accelerating economic growth, (ii) be invested into carbon-based energy supply, (iii) be invested into non-carbon based energy supply that comes at a higher cost than carbon based energy sources, but

profits from learning by doing or (iv) be consumed. Economic regions are thus faced with a trade off between using more non-carbon energy, leading to early mitigation and decelerated growth but reduced climate damages and using more carbon-based energy yielding initially fast economic growth, late mitigation, and the heavy price of substantial future climate damages.

Each economic region will desire a global emissions cap that allows it to adopt optimal strategies for growth according to its own circumstances. Those most impacted by climate will want a stringent global cap and vice versa. We can reasonably expect that the eventual global emissions cap will reflect the weight of each actor at the negotiation table. Two limiting scenarios for the weight of actors suggest themselves (I) economic weights proportional to economic output and (II) demographic weights proportional to population size. The most plausible scenario, however, will be found somewhere between the extremes of (I) and (II) by weights that correspond to a combination of population size and economic power. Given the weights of the actors, any global emissions agreement can be represented as a weighted sum of the desirable outcomes for the individual actors. As economic regions interactively determine their investment paths, agreements will thus be an integral part of the multi-actor energy-economy-climate model.

To reduce the computational costs in a first series of experiments, we studied a four-actor world. One group of actors represents developed countries with high climate damage costs. A second group, developed countries with low climate damage costs and the third and fourth groups, developing countries with low and high climate damage costs, respectively. We present initial results that investigate the spectrum of possible world outcomes and analyse development paths for the four different economic regions.

Climate agreements will almost certainly alter development patterns in the world. Changes in the economic and population structure of the world will, in turn, impact on mitigation aspirations of economic actors and the balance of power between them. As a result the real path of mitigation will be adaptive and our results illustrate the interplay in the dynamics of negotiated climate agreements and world development.

## Food systems, uncertainty and future risks

### Crop failure and climate change: assessing impacts and adaptation options Andy Challinor

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Ensemble simulations of climate and crops are increasingly used to assess future crop productivity. This presentation uses these simulations to examine the likelihood of increased crop failure, and the potential for adaptation, using spring wheat in northeast China as a case study. Other studies are used to examine the robustness of statements regarding the impact of climate on mean groundnut yields in India. Conclusions are presented both for the specific case study and, more broadly, regarding the nature of future research that is needed in this field. Two projects that are beginning to address these needs are briefly outlined.

A number of ensemble simulations are used together with the GLAM crop model to produce crop yield ensembles that vary the response of crop and/or climate to increases in CO<sub>2</sub>. The sensitivity of other crop models to climate change was also tested, and compared to that of GLAM. The transient 17-member SRES A1B QUMP ensemble was used as crop model input for China. For India, both the 53-member equilibrium doubled-CO<sub>2</sub> QUMP ensemble and the SRES A2 scenario with the PRECIS regional climate model were used to drive the crop models. Results are presented and analysed in terms of local and global mean temperature increase. Using a combination of field data and simulations, potential adaptation measures are also assessed. These include: i. switching to another existing cultivar, ii. irrigation, and iii. crop varieties developed to tolerate the impact of heat stress during anthesis.

The relationship between local mean temperature increase and mean crop yield for groundnut in India vary across crop models and differs to that of the IPCC AR4. Incidence of crop failure in China tends to increase monotonically with both local and global mean temperature change. Subsampling crop simulations within single QUMP ensemble members revealed different threshold responses of crop yield to mean temperature increase. Adaptation significantly reduces crop failure for all magnitudes of climate change; although it tends to become less effective at higher temperatures.

#### Conclusions

The study demonstrates how a systematic analysis of uncertainty can be used to make statements regarding impacts and adaptation for crop production systems. The analysis suggests that statements regarding mean crop yield as a function of temperature may be difficult to make. Statements regarding the impact of extremes may be more robust, with incidences of crop failure tend to increase monotonically with global mean temperature. The study also demonstrates that in spite of the inherent uncertainties, adaptation strategies, such as irrigation and the development of heat-tolerant crop varieties, can be identified and prioritised based on model simulations. Progress in this area relies upon: 1) improved methodologies for designing, evaluating and using climate mode ensembles with impacts ensembles and 2) use of ensemble crop and climate modelling as part of broader efforts to inform adaptation, including analyses of existing crop germplasm, local agricultural practices and crop breeding. These issues are being addressed by the NERC EQUIP consortium and the CGIAR CCAFS programme.

## **Modelling social-ecological systems in Earth Systems Science: Food security under global climate change.**

**Terence Dawson<sup>1</sup>, Perryman, A.H.<sup>1</sup>**

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The first of the United Nations Millennium Development Goals is to “Eradicate extreme poverty and hunger” with a target to halve the proportion of people who suffer from hunger. However, rapidly growing populations in developing countries coupled with global climate change and variability is expected to have significant negative impacts on food security. Food security, defined as: “the availability at all times of adequate world supplies of basic food-stuffs”, is a complex set of factors including: (1) Availability of staple foods (access to productive land, agricultural production and other market sources); (2) Stability of supplies (based upon future global market trends taking into account the climate, socio-economic and political situation); (3) Access to adequate supplies (derived from price of staple foods and physical access); and (4) biological utilisation of food (using nutritional indicators).

In recent years, the dietary energy provision-based methodology, adopted by the Food and Agriculture Organisation (FAO) has become the de-facto standard for rapid assessment of undernourishment as an indicator of food (in)security. This methodology is derived from the principle that food deprivation is based on a comparison of usual food consumption expressed in terms of dietary energy (calories) with minimum energy requirement norms. The proportion of the population with food consumption below the minimum energy requirement is considered at risk of undernourishment. A new modelling framework has recently been developed under the QUEST-GSI programme, which we have termed FEEDME (Food Estimation and Export for Diet and Malnutrition Evaluation). The model uses country-level FAO Food Balance Sheets (FBS) to determine mean calories on a per-capita basis, and a coefficient of variation to account for the degree of inequality in access to food across the population. Calorific values of individual food items in the FBS of selected countries were modified by revision of the crop production values and population changes under the SRES A1b climate change and social-economic scenarios respectively for 2050. Important plant-and vegetable based foods were allocated to one of the provided reference crop types (Wheat, Maize and Soybean) according to their physiological behaviour (C3 or C4 photosynthetic pathways) and crop model availability.

Results show a large geographical variation in the ability of individual countries achieving an adequate level of food security with countries such as China and India failing to meet their nutritional needs on a massive scale. Both countries are predicted to have a significant increase in population (28%) with overall crop yields declining under the HADCM3 A1b 2050 scenario. Undernourishment results for sub-Saharan Africa countries were highly dependent on projected population changes. However, the model does not account for future trends in technology, improved crop varieties, prescribed agricultural trade or land cover, although it is clear that all of these adaptation strategies will need to be embraced on a global scale if society is to ensure adequate food supplies for a projected global population of greater than 9 billion people.

### **Acknowledgements**

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**QUESTFish: Potential climate change impacts on the coastal/shelf seas.  
Business as usual?**

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The aim of QUESTFish is to examine how climate change would affect the potential future production for global fisheries resources in the absence of exploitation. In this study we investigate the relative impacts of global climate change, under the IPCC “Business as Usual” scenario, on twelve coastal/shelf sea regions around the globe. These regions cover twenty of the Large Marine Ecosystems, which account for over 60% of the global fish catch. Using a high-resolution coastal/shelf seas model coupled to an ecosystem model (POLCOMS-ERSEM) we focus on changes on the physical properties (stratification, mixed layer depth, off-shelf on-shelf coupling etc.) of the coastal/shelf seas and their impact on primary production. These results form the basis for the socio-economic and impact assessments on ecosystems and fisheries under climate change conditions within other QUESTFish modules.

**Modeling plant disease risk areas based on Brazilian climate change scenarios**

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In order to help reduce the steep technical and economic losses that threaten the profitability of producers and the economy of Brazil, geoscience and statistics were applied to develop predictive models to study the areas of risk to soybean rust (*Phakopsora pachyrhizi* Sydow) in soybean (*Glycine max* L.), coffee leaf rust (*Hemileia vastatrix* Berk & Br) in coffee and Black Sigatoka (*Mycosphaerella fijiensis* var. *difformis*) in banana, according to Brazilian climatic characterization and distribution of soybean, coffee and banana crops in the current period of 1950 to 2000 and A2 climate change scenarios of 2020, 2050 and 2080. Modeling techniques based on nonlinear regression were used to characterize the monocyclic process of Asian soybean rust, coffee rust and banana black sigatoka through data obtained under controlled conditions. Average values of production, harvested area and cultivated area of soybean, coffee and banana were obtained from data series of IBGE (Brazilian Institute of Geography and Statistics) from 1990 to 2008. Temperature and precipitation data were used to estimate the moisture index for Brazil, according to a linear regression model developed in previous work. The moisture index was used to generate the leaf wetness, based on the ratio between the average monthly duration of relative humidity greater than or equal to 90% and the moisture index of each season, based on a series of 30 years of climatic elements related to 39 major meteorological stations of the National Institute of Meteorology - INMET, located at Minas Gerais state, Brazil. The projections of climate change considered in the present study were derived from a hierarchy of models based on climate, environment, land use, socioeconomic and technological

aspects, coupled to state standards for global and regional climate change. It should be noted that these scenarios vary according to the degree of anthropogenic interference in the environment, where: A2 scenario describes a future world where very heterogeneous regionalization is dominant. The technique of principal components allowed to generate 1 variable based on 57 variables in order to determine an index that explained 87%, 88% and 90% of the variability of the data of soybean, coffee and banana crops in Brazilian municipal districts. The climate model of each disease was used to generate coffee rust, soybean rust and black sigatoka zoning based on temperature and leaf wetness data. Subsequently, the areas of favorability of the diseases were plotted inside to the main coffee, soybean and banana growing regions. Thus, it was possible to estimate the potentially favorable areas to coffee, soybean and banana diseases in Brazil, according to the spatial and temporal variability of climatic variables and the geographical distribution of hosts. It was possible to visualize the variation of the epidemics favorable areas according to the studied scenarios of climate change.

**The effects of Land Use and Land Cover Change and its implications as an indirect driver of climate change: A spatio-temporal case study from the Alaknanda Valley, Garhwal Himalayas, India, on the human-environment interplay**

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That man-environment interactions constitute a singularly determinant factor as driver of climate change, whether on a global, regional or local-scale, today, form the universal basis for understanding key underlying behavioural patterns influencing the land-surface-atmosphere reciprocity governing climate change. Societal mannerisms have guided and affected land cover and land-use changes (LULC), an unavoidable but a most important consequence of human intervention, over a certain period of space and time. The feedback mechanism operating between humans and nature has always manifested itself through a transformation in the environment, irrespective of scale, time and space, a direct consequence of the different, changing land-use practices and an indirect consequence of the subsequent but inevitable manipulation of the hydrological resources at hand. The delicate balance existing between humans and nature is dependent on this feedback loop and the various internal and external factors driving the feedback loop. The behaviour of people towards utilising the natural resources and the extent of use and exploitation of these resources is responsible towards tilting the inherent stability balance in the environment. While the positive impacts of the human-environment interplay is demonstrated through crop production and effective sustainable land management and land development, it is the de-stabilising negative externalities of accelerated land-erosion, deforestation, pollution, unplanned management and unhindered exploitation of water resources, which compromises the sustainability of the human-environment feedback loop.

The Himalayas not only constitute the youngest and highest chain of mountains in the world, but through their geographic location, topography and elevation, they are also one of the major influences in the weather patterns over the Eurasian region. Some of the world's largest glacial and river systems on which millions are dependent for fresh water and livelihood, originate in the higher reaches of the Himalayas. They are also one of the most sensitive zones tectonically in the world. Again, the ever-complicated politics of the region, the tremendous diversity in

ethnicity, cultures and the resultant pronounced socio-economic variances, underscores the Himalayas as one of the most sensitive and ideal regions for the study and understanding of the myriad factors at play with respect to the natural environment, its stability and exploitation of the hydrological resources. As emphasized time and again (IPCC FAR 1990; 1992; 1995, 1996; IPCC TAR 2001; 2007; IPCC statement on the melting of Himalayan glaciers, 2010), the climate change scenarios and the human-land-surface-atmosphere interactions in these mountainous areas are still “highly uncertain [...] and poorly resolved even in the higher resolution Global Climate Models (GCMs)”. This is largely due to the deficiency arising from the extraordinary heterogenous and individualistic nature of human-environment interaction from one end to the other of the Himalayas.

This paper endeavours to explore the patterns of land cover and land use change (LULC) spatio-temporally over four decades in a sub-catchment of the Alaknanda river basin in the Garhwal Himalayas, India, which epitomizes all the characteristics, both natural and man-made, as stated above, in their role towards climate change in the study area. Satellite images, and SRTM-generated DEM, along with relevant ground-data form the basis of this study. At the same time, this paper also probes into the debate of the classic “Himalayan Dilemma” (Ives and Messerli, 1989) and its significance in the wider context of climate change.

## Breakout Sessions

Tuesday 11<sup>th</sup> May

### The AVOID Project

#### An Overview of the AVOID project

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#### AVOID Work Stream One

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AVOID Work Stream One has produced emission scenarios that simulate potential future global emission pathways for greenhouse gases during the 21st century. The study explored the influence of three key features of such pathways: (1) the year in which emissions peak globally, (2) the rate of emission reduction, and (3) the minimum level to which emissions are eventually reduced. We examined the resultant climate change, climate change impacts and economic implications using computer simulations. Avoided impacts, carbon taxes and GDP change increase throughout the 21st century in the models.

In the absence of climate policy it is very likely that global mean temperatures would exceed 3 degrees and there are even chances that the temperature would rise by 4 degrees relative to pre-industrial times. Scenarios that peak emissions in 2016 were more effective at constraining temperatures to below 3 degrees than those that peaked in 2030: one "2016" scenario achieved a probability of 45% of avoiding breaching of a 2 degree threshold. Scenarios peaking in 2030 were inconsistent with constraining temperatures to below 2 degrees.

Correspondingly, scenarios that peak in 2030 are more effective at avoiding climate impacts than scenarios that peak in 2016, for all sectors that we studied. Hence the date at which emissions peak is more important than the rate of subsequent emissions reduction in determining the avoided impacts. Avoided impacts increase with time, being negligible in the 2030s, significant by the 2050s and large by the 2080s. Finally, the choice of GCM influences the magnitude of the avoided impacts

strongly, so that the uncertainties in our estimates of avoided impacts for each scenario are larger than the difference between the scenarios.

Our economic analysis is based on models which differ greatly in the assumptions that they make, but generally show that the date at which emissions peak is a stronger driver of induced GDP changes, and, with some exceptions, carbon taxes, than the rate at which emissions are subsequently reduced. In models which assume perfect rationality and foresight and/or assume the economy to be in equilibrium with full employment, then mitigation could cause GDP to decrease. In models which do not make these assumptions, mitigation could cause GDP to increase. In either case the effects are small (a few % of GDP lost or gained in 2100) and insignificant when compared with the 600-1200% increase in global GDP forecast between 2000 and 2100 in the SRES A1B reference scenario used in this study. Estimates of carbon taxes required differ widely between models.

### **Climate change impacts for emission paths that peak and decline.**

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The AVOID programme has produced emission scenarios that represented possible future global emission pathways for greenhouse gases during the 21st century. Differences between the scenarios are detailed in a simple fashion by varying three parameters: the year in which emissions peak globally, the rate of emission reduction, and the minimum level to which emissions are eventually reduced. The scenarios show emissions gradually deviating after the peak year from a baseline, the A1B SRES scenario.

In this paper, the PAGE2002 integrated assessment model is used to find the climate change impacts of a range of these scenarios, and then comparing these with the impacts for the baseline A1B scenario, in order to deduce the avoided impacts. PAGE2002 is the model that was used to perform the impact calculations in the Stern review. It uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single "best guess" could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing over 50 key inputs to the calculations by probability distributions, making the characterization of uncertainty the central focus.

We find that the date at which global emissions peak is a stronger driver of avoided impacts than is the rate at which emissions are subsequently reduced. By 2100 policy scenarios in which emissions peak in 2016 avoid about two thirds of the impacts globally compared to the A1B reference scenario. Policy scenarios in which emissions peak in 2030 only avoid about one half of the impacts.

## **Sea level response and impacts on people at risk across different scenarios during the 21st century**

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Using the Dynamic Interactive Vulnerability Assessment (DIVA) model (DINAS-COAST Consortium, 2006), the potential impacts of a range of sea-level rise were explored, including scenarios of climate mitigation. While six climate scenarios are considered, in terms of sea-level rise, there are three distinct scenarios: (1) unmitigated emissions, (2) emission scenarios that peak at 2016 (termed the 2016R policy scenario), and (3) emission scenarios that peak at 2030 (termed the 2030R policy scenario). The socio-economic scenarios are all based on the A1B scenario. Impacts with and without adaptation are also considered.

Five main conclusions are apparent from the results:

1. Emission reductions will slightly reduce the global losses of saltmarsh and mangrove after the 2050s. Impacts are almost identical to the 2050s and diverge thereafter. Under the 2016R policy scenario, global losses of saltmarsh and mangrove are lower by roughly 5% by the 2080s, compared to unmitigated emissions.
2. The size of the coastal flood plain population is insensitive to sea-level rise. The number of people in the coastal flood plain is about 200 million people in 2000 and the future size is mainly determined by socio-economic change. Hence, mitigation has little influence on these numbers.
3. However, emission reductions will reduce the global number of people experiencing flooding by 2050, and the benefits are substantial by 2100, assuming no adaptation. The number of people who experience flooding grows rapidly with sea-level rise (and also to a lesser degree the growing coastal population under the A1B socio-economic scenario). About 3 million people per year are estimated to experience coastal flooding in 2000. By 2050 this number grows 6.5 to 10 times without mitigation. The 2016R policy scenarios can reduce the number of people being flooded by 2 to 5 million per year. By 2100, the effect of mitigation is much larger, and the reduction of people could be 36 to 69 million people per year under the 2016R policy scenario. However, even with this policy scenario, the incidence of flooding will have increased 10 to 20 times on levels in 2000, and significant adaptation would also be necessary.
4. These reductions in flood impacts represent delayed rather than avoided damages. Earlier research by Nicholls and Lowe (2004) demonstrated that climate mitigation will only delay rather than avoid flood impacts due to the inertia in sea-level rise which will increase for centuries even if climate is stabilised. In other words, the impacts avoided during the 21st Century are still expected to occur in the 22nd Century. This reinforces the importance of adaptation for coastal areas.
5. Assuming quazi-optimum adaptation greatly reduces the benefits of mitigation identified above. Assuming adaptation, it is difficult to distinguish the impacts between mitigated and unmitigated scenarios. In this analysis the main benefit of reduced sea-level rise is to reduce the required investment in protection. Hence this work supports the message that the most appropriate policy response to sea-level

rise is a combination of adaptation to deal with the inevitable rise, and mitigation to limit the long-term rise to a manageable level as discussed in the IPCC AR4 assessment.

## **Economic impacts to avoid dangerous climate change using the AIM/CGE model**

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In order to avoid dangerous climate change, less than 2-degrees temperature increase from the pre-industrial level is required and drastic GHG emissions abatement is necessary to achieve it. This study purposes to analyze the economic aspects of defined climate policies using the AIM/CGE[Global] model. This study is for Work Stream 1 of the AVOID programme. The results of this study are compared with those of the other participating models. The reference case is based on the SRES A1B scenario and five policy scenarios (2016.R2.H, 2016.R4.L, 2016.R5.L, 2030.R2.H, and 2030.R5.L) are prepared. The policies are expressed as emissions pathways of several gases and the differences among them are the emissions abatement and their peak.

The AIM/CGE[Global] model is a recursive dynamic CGE model on the global scale. Some important characteristics of this model can be summarized as follows: power generation by some non-renewables and renewables is considered; CCS is modeled; traditional and purpose-grown bio-energy is included; international markets are modeled for trade of fossil fuels; relationships between the costs and resource reserves of fossil fuels are modeled. The model is run with 10-year time steps until 2100.

For the reference setting, GHG emissions are not controlled by any additional policies and the model is run based on the drivers (expected GDP and population for A1B) and exogenous technological change. Due to the differences of some assumptions, the emissions pathways from the model are not identical with the prescribed emissions for AVOID A1B. For the scenarios, the model is run under emissions constraints. In particular, for each scenario, the constraint on each gas in each year is derived. The percentage emissions abatement that occurs between the AVOID A1B case and the particular scenario for each gas is first calculated, and then these percentages are applied to the AIM reference case to derive the constraints over the 21st century.

The main results provided were carbon prices and GDP. About the former, the higher the emissions abatement and the earlier the peak, the higher the carbon prices will be, and the prices tend to be higher over time (\$536/tCO<sub>2</sub> in 2100 for 2016.R5.L). These trends are largely different from those of the E3MG model which assumes constant carbon tax for each scenario (\$232/tCO<sub>2</sub> for 2016.R5.L). In addition, the higher carbon prices are necessary in the AIM/CGE model, especially in the latter half of the century.

About the GDP trends, negative GDP changes occur for all scenarios, and higher GDP damage is observed as the abatement becomes larger and the peak comes earlier (-7.04% in 2100 for 2016.R5.L). These trends are extremely different from those of the E3MG model which shows positive GDP effects (+4.89% in 2100 for

2016.R5.L). The differences among the two are caused by (1) technological change assumptions, (2) revenue recycling methodology, (3) timing of emissions cuts, and (4) modeling approaches.

### **Future fossil fuel use and carbon capture technologies**

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This work reviews what is being done to deal with CO<sub>2</sub> emissions in the power and industrial sectors, and considers: “what needs to be done?” Specifically, we focus on the suite of carbon dioxide (CO<sub>2</sub>) capture technologies under development, including closest-to-market technologies targeted for the first large-scale carbon capture and storage (CCS) demonstrations, and more advanced technologies that are expected to be brought to the market post-2020. The main impetus for technology development is the potential to minimise the cost of CO<sub>2</sub> capture and reduce the parasitic energy penalty imposed on the power generation process. A reduction in the energy penalty translates into a reduction in fossil fuel consumption, CO<sub>2</sub> production, waste generation, and minimises the potential environmental impacts. Thus, specific consideration is given to how the energy efficiency penalties may change with the transition to more advanced technologies, as well as the prospects for synergies between CO<sub>2</sub> capture systems and heavy emitting industry, such as cement manufacturing.

The maturity levels of the main CO<sub>2</sub> capture technologies have been evaluated based on a review of current RD&D programmes, demonstration projects, and peer-reviewed journal publications, and this analysis ranks post-combustion capture technology ahead in terms of development. Cost-efficiency estimates of the different systems are not dissimilar given the margins of uncertainty and suggest that the costs of electricity generation with CCS will increase by between 30% and 80%. Preliminary analyses of more advanced technologies suggest that there is considerable scope for cost reduction, although caution must be applied when comparing cost-efficiency estimates because significant uncertainty is introduced when comparing technologies at different stages of development and deployment. Demonstration of the mature technologies at full-scale can be categorised as most urgent; however significant research effort, and funding, is also needed to ensure progress towards more advanced technologies, which will minimise the cost of CO<sub>2</sub> capture and the associated adverse environmental impacts.

## Budget and recent trends in the global carbon cycle

### **The benchmark for carbon models: net ecosystem productivity of us forests estimated from forest-inventory data**

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International negotiations for a new global treaty to limit greenhouse gases are based in part on understanding the current and potential role of forest offsets. In the U.S., many studies and methods have been used to gain knowledge of carbon sequestration capacity of forests: remote sensing, eddy flux tower data synthesis, and ecosystem modeling. However, each of these approaches has limitations for covering the full extent of forested lands and diversity of forest ecosystems, and none has been well validated with ground data. In this study, we developed spatially-explicit estimates of net ecosystem productivity (NEP) at 250m resolution for the US forests (excluding Alaska and Hawaii) based on forest inventory and analysis data (FIA), empirical equations, forest type classifications, and a forest age map. Our results indicate that the forests of the continental US are robust carbon sinks. Total NEP of the US continental forests is about 485 Tg C/yr, which is significantly larger than net carbon sequestration because losses of C from harvesting amount to about 2/3 of annual forest productivity. Regionally, forests and NEP are affected by different dominant factors. High NEP occurs in forests of the eastern US: young and highly productive forests in the southeast US because of intensive industrial forestry practices; and in forests of the northeast US and lake states, recovery from agricultural land abandonment and forest harvests in the early 20th century has produced a large area of middle-aged and productive forests. All together, the forests in the eastern US account for about 77% of total annual NEP of US forested lands. In contrast, forest coverage in the western US is less and often on sites with lower NEP such as in the Rocky Mountains. However, industrial forests and high NEP in a relatively small region of the Pacific Coast account for 14% of total annual NEP of US forested lands. Because our estimates are based on periodic remeasurement of sample plots, our results represent the average NEP over the landscape of different regions, which is related to forest type and current status of forests. Our study produced an important ground-based NEP data layer that can be used as the benchmark for validating estimation by large-scale carbon models and remote sensing, and for interpolating the eddy flux-tower measurements to landscape scales from the tower footprints.

### **Towards detection and attribution of the climate-carbon cycle feedback**

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The recent debate about a possible increase or decrease in the airborne fraction has highlighted the need for better data and better analysis methods for the detection of subtle but consequential changes in the global carbon cycle. Such changes are expected as soon as carbon uptake via oceans or CO<sub>2</sub> fertilisation starts to saturate, or as climate change itself leads to a decrease in carbon sinks. A possible way of

detecting them is through trends in the airborne fraction of anthropogenic CO<sub>2</sub> emissions. There is currently no consensus whether such a trend exists. Here, we use simulated atmospheric CO<sub>2</sub> concentrations from the C4MIP project until 2100 for specified SRES emissions scenarios to calculate at what point in time we would expect to be able to detect a trend in the airborne fraction, given current levels of uncertainties in emissions and concentrations. We assess this for different models participating in C4MIP, and for a case with or without climate-carbon cycle feedback. Finally, we discuss how much of the hypothetical trend is attributable to changes in carbon sinks, and how much to changes in emissions. The method is suggested as a guidance for the design of Earth system observation programmes that are able to detect positive climate feedbacks.

### **What do decadal-scale variations and trends in CO<sub>2</sub> airborne fraction tell us about carbon sink efficiency?**

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The ratio of CO<sub>2</sub> accumulating in the atmosphere to the CO<sub>2</sub> flux into the atmosphere due to human activity, the airborne fraction (AF), is central to predict changes in earth's surface temperature due to greenhouse gas induced warming. This fraction has remained remarkably constant in the past five decades, but recent studies have reported an apparent increasing trend and interpreted it as an indication for a decrease in the efficiency of the combined sinks by the ocean and terrestrial biosphere. We investigate here whether this interpretation is correct by analyzing the processes that control long-term trends and decadal-scale variations in AF. To this end, we use a simplified linear model for describing the time evolution of an atmospheric CO<sub>2</sub> perturbation. We find firstly that the spin-up time of the system for the AF to converge to a constant value is on the order of 200-300 years and differs depending on whether exponentially increasing fossil fuel emissions only or the sum of fossil fuel and land use emissions are used. We find secondly that the primary control on the decadal time-scale variations of the AF are variations in the relative growth rate of the total anthropogenic CO<sub>2</sub> emissions. Changes in sink efficiencies tend to leave a much smaller imprint. Before interpreting trends in the AF as indication of weakening carbon sink efficiency it is therefore necessary to account for these variations. Using atmospheric CO<sub>2</sub> data and emission estimates for the period 1959 through 2006 we find based on our simple model that these causes of variations and omissions in land use emissions can explain the observed trend, so that claims for a recent decrease in the carbon sink efficiency are unsupported by atmospheric CO<sub>2</sub> data and anthropogenic emissions estimates.

### **Land use change, uncertainty and mitigation**

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Changes in land use (primarily deforestation) have been responsible for about 20% of all anthropogenic emissions of CO<sub>2</sub> to the atmosphere over the past two and a half decades, but this term is the most uncertain in the carbon budget.

The estimated emissions from land use change for the 1990s in the IPCC Fourth Assessment Report were 1.6 GtC/yr with a range of 0.5 to 2.7 GtC/yr. This wide range of 2.2 GtC/yr across different estimates is primarily due to differences in quantification of the area and nature of land use change, and the fate of the carbon. A more up to date estimate of land use change emissions, by the Global Carbon Project, is  $1.5 \pm 0.7$  GtC/yr from 1990 to 2005. The estimate is based on the Houghton methodology (Houghton 1999, 2003) previously included in the IPCC assessments, but with updated deforestation rates. This talk compares Houghton's results to other recent estimates of historical emissions.

A reduction in the range of uncertainty over the IPCC estimate is justified by recent updated data and by accounting for methodological differences between estimates. However, uncertainty is still high and has implications for climate policy. Policy targets to reduce the impacts of climate change focus on reducing net anthropogenic emissions of CO<sub>2</sub> in reference to a baseline emission. If actual emissions are higher than the baseline being used, this implies deeper cuts will need to be made later on. Combining the current fossil fuel emissions with the Global Carbon Project estimated land use emissions means total anthropogenic emission already exceed the SRES projections in year 2000.

The pathways of reduction in emissions to meet specified targets for CO<sub>2</sub> concentration or temperature are sensitive to uncertainties in emissions, and uncertainties in the response of land and ocean sinks including climate-carbon cycle feedbacks. If land use change emissions are at the high end of the estimates, it will be more difficult than expected to meet targets for emissions reduction, and deeper cuts in emissions may be required. In the near term (2020), the uncertainty in land use change emissions of  $\pm 0.7$  GtC/yr is greater than the uncertainty in climate feedbacks on the carbon cycle which we estimate to be  $\pm 0.4$  GtC/yr by 2020 (around a median modelled feedback of 0.7 GtC/yr). The implications of being at the high end of this uncertainty should be considered in assessing risks of failing to meet near term targets. On the other hand, if land use change emissions are at the low end of the estimated, the potential for emissions reduction from avoided deforestation will be less than expected.

Wednesday 12<sup>th</sup> May

## The AVOID Project

### **Future changes in climate extremes under an aggressive mitigation scenario**

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Future changes in the frequency and severity of climate extremes is of intense interest since the economic, social and ecological consequences of extremes can be very large.

Whilst reducing greenhouse gas emissions is likely to reduce global mean temperature, the effect on extremes, particularly precipitation extremes, is less well understood. A key question is whether changes in extremes scale with changes in global mean temperature?

We present an assessment of changes in temperature and precipitation based climate extremes indices using the HadGEM2 coupled ocean-atmosphere GCM. We assess changing extremes at the end of the 21st Century under a business as usual scenario, and also using results from a new aggressive mitigation scenario which sees carbon dioxide equivalent emissions peak in 2045 before stabilising at around 450ppm by the 22nd Century. We see that most indices of temperature extremes scale linearly with the increasing global mean temperature, but precipitation extremes show more regional variability.

### **The impacts on crop production of a range of climate policies**

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This study assessed the potential impacts on crop production avoided by a set of defined climate policies as part of the AVOID project. The General Large Area Model for annual crops (GLAM) was used to simulate the growth and development and, ultimately, yield of wheat, maize and soybean across the globe. GLAM was driven with climate scenarios representing the effects of a range of different climate policies, as well as a “business-as-usual” climate. The study assessed not only the amount of impacts that are potentially avoided, but also the sensitivity of estimated avoided impacts to the spatial pattern of change in temperature, rainfall and other variables associated with a given change in global average temperature, as simulated by different climate models.

Global production of each crop is reduced from baseline conditions under all future climate scenarios, although the magnitude, and even sign, of changes in productivity vary spatially. The implication of mitigation varies by timescale (represented by 2050, 2080 and 2100 time-slices), by policy (i.e. early or late peak in emissions), by crop and, for some regions, by climate model. Because crop growth is stimulated by

increased levels of CO<sub>2</sub> in the atmosphere, the results reveal an interesting pay-off between limiting emissions to limit climate change, and limiting impacts on crop productivity.

### **Future water scarcity with climate change**

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An important modifier of estimates of future water scarcity with climate change, which up until now has not been explored, is the likely benefits of various policy scenarios. These mitigation scenarios reduce future global greenhouse gas emissions and lead to lower global average temperature increases. Here we look at the benefit of mitigation in terms of reduced regional and global populations at increased risk of water scarcity due to climate change, and the uncertainty in this quantity resulting from using a range of different climate models. The consideration and treatment of this “climate modelling uncertainty” has been limited in previous studies.

Climate change has the potential to increase water resources stresses for many millions of people. The climate policies evaluated here reduce the effects of climate change, with the earlier the peak in emissions the greater the reduction. There is, however, considerable uncertainty in the numbers of people adversely affected by climate change and “saved” by climate policy, largely due to differences in projected changes in rainfall between different climate models. For example, by 2100 policies which peak emissions in 2016 avoid between 20 and 55% of the adverse effects of climate change, with the range largely due to differences in projected change in rainfall (and hence water resources) in southern Asia. The effect of uncertainty due to differences between climate models is larger than uncertainty due to either uncertainty in change in temperature for a given emissions scenario, or uncertainty in future socio-economic characteristics.

### **Damage function estimates of climate change impacts for the AR5 RCPs**

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Many impacts of climate change are dependent only upon the current socio-economic and climatic conditions and/or their rates of change, rather than historical changes. For such sectors, impacts models can provide estimates for particular conditions which can be aggregated into regional or global “damage functions” for impacts sectors.

A study combines pattern scaling of climate change from AR4 GCMs and impacts modelling to calculate damages functions for a variety of climate change impact sectors. These are used with projections from a climate model of reduced complexity to make probabilistic projections of impacts for the IPCC fifth assessment report RCPs to demonstrate the utility of such an approach.

## **CO<sub>2</sub> removal from the atmosphere**

**Hannah Chalmers**<sup>1,2</sup>, Flower, M.<sup>1</sup>; Gibbins, J.<sup>2</sup>; Hirst, N.<sup>1</sup>; McGlashan, N.<sup>1</sup>; Shah, N.<sup>1</sup>; Workman, M.<sup>1</sup>

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Recent work (e.g. Allen et al, 2009 - Nature 458, 1163-1166) examining likely changes in global temperatures as a result of carbon dioxide (CO<sub>2</sub>) emissions has suggested that cumulative CO<sub>2</sub> emissions could be more significant than the differences between particular emissions pathways in determining how the global climate might change in response to CO<sub>2</sub> emissions. This suggests that effective measures to mitigate the risk of dangerous climate change will need to limit cumulative emissions of CO<sub>2</sub>. Further, if cumulative CO<sub>2</sub> emissions overshoot acceptable limits, it will become necessary to remove CO<sub>2</sub> from the air in so-called “negative emissions”. Technologies that effect “negative emissions” could also be used to offset additional anthropogenic emissions from sectors where greenhouse gas emissions are difficult or impossible to reduce beyond certain, still relatively high, limits.

This paper presents results from research conducted to provide performance estimates of various options for capturing CO<sub>2</sub> from the air on a full-cycle basis. The scope focuses on a range of emerging technologies that capture and store CO<sub>2</sub> originating from the air, including the capture of CO<sub>2</sub> emissions from biomass/biofuel use (including co-utilisation of biomass with fossil fuels) and the direct capture of CO<sub>2</sub> from the air. In addition to technological assessment, a number of non-technical issues are considered. The related issue of how long it might take to deploy different options in an “emergency” is also assessed.

Key concerns for limits on capture rate for both biomass + carbon capture and storage (CCS) and air capture are a particular focus of this work. For biomass, new work on supply chains relevant for CCS applications is presented. The importance of identifying appropriate methods for producing and transporting biomass so that the overall lifecycle atmospheric greenhouse gas emissions are negative is discussed. Public domain literature on air capture options is typically less developed, so the work presented in this paper focuses on exploring energy limits and possible location requirements for the most promising systems.

An important consideration for both biomass + CCS and air capture is the implications they have for CO<sub>2</sub> transport and storage network design. The location constraints for typical CCS projects using fossil fuels include the location of fuel reserves or relevant import facilities. Especially for direct capture from the air, but also if different fuels are used, the location of CO<sub>2</sub> sources to be included within potential CO<sub>2</sub> transport and storage networks, may change significantly. This may mean there is the potential to reduce or remove the need for long pipelines. The storage capacity available to store CO<sub>2</sub> removed from the air, as well as CO<sub>2</sub> captured from fossil fuel use, must also be considered. A finite amount of CO<sub>2</sub> can be produced by fossil fuel reserves, but the total storage capacity required if “negative emissions” technologies are used widely could be significantly increased. Implications for storage capacities needed and potential approaches to increase available storage volumes if “traditional” geological formations for CO<sub>2</sub> storage are not sufficient are, therefore, reviewed.