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PREDICTING AND DETECTING TIPPING POINTS AND REGIME SHIFTS IN ANTARCTIC AND SOUTHERN OCEAN SYSTEMS

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Biotic and environmental responses to simulated permafrost degradation

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Permafrost degradation contributes to significant changes in soil hydrology, biogeochemical cycling, and soil communities by subsurface mobilization of water, biota and nutrients at the soil active layer. While climate warming can elicit such responses over years to decades, thawing events typically occur as discrete melt-water pulses. We simulated different frequencies of permafrost thawing events and characterized their associated impacts on soil communities and biogeochemical cycles in McMurdo Dry Valleys. We found that simulated permafrost thaw increases soil water content and heterogeneity in major ion content, as well as the structure of soil nematode communities. These effects are significant only at the patch scale, i.e., there are no significant plot level trends for either the pulse or press treatments, indicating that soil communities are resistant to massive water presses and pulses following permafrost thaw simulations over the time scale of five years. Treatments were statistically significant, but their ecological significance is subtle, perhaps only marginal compared with natural interannual variation. We discuss our findings in the context of ecological resistance and resilience, and the physical and biotic thresholds at which linear changes in structure and functioning emerge as non-linear, stabilized and reinforced regime shifts.

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Facing ecosystem collapse from Antarctica and the Subantarctic to the Tropics

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Ecosystem collapse, potentially irreversible change to ecosystem structure and function, imperils humans and global biodiversity. Systematic analyses of ecosystem collapse is urgently needed to successful risk mitigation strategies. Here, we examine the state and current trajectory of 19 collapsing ecosystems — spanning 58° of latitudinal range across 7.7 M km2, from terrestrial Antarctica, subantarctic islands to Australia's tropical coral reefs. We address the processes driving collapse and emerging patterns of change. Degradation is widespread, with all ecosystems showing evidence of local-scale collapse, but importantly none have collapsed across their full range. Climate change and regional human impacts have affected all ecosystems. We identified up to 17 pressures driving environmental deterioration, in response to increased temperatures and changes to precipitation combined with anthropogenic disturbances, occurring as chronic ('presses') and/or acute ('pulses') impacts. Pressures were often at unprecedented scale and severity. Habitat modification or destruction were the most common regional human impacts, but was least impactful in our Antarctica and subantarctic exemplars. We identified four collapse profiles (trajectories) — abrupt, smooth, stepped, and flickering. The breadth and range of collapsing ecosystems are a stark warning of the immediate need to address the ecosystem level challenge to conserve Nature upon which human wellbeing depends. Using insights gained from this analysis, we present a new three-step framework — awareness, anticipation and action —to mitigate against unprecedented and rapid environmental change and its accompanying risks to society and discuss the relevance of this framework to Antarctica, the Southern Ocean and associated ecosystems.

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Potential tipping points for life in the Southern Ocean: findings from an ACE-CRC report card

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There is now clear scientific evidence that climate change is causing rapid and unprecedented alteration of the Southern Ocean. These changes will have potentially serious impacts during the 21st century on the sustainability and management of many ecosystems. Anthropogenic alteration of pH, temperature, circulation and sea ice – along with potential for increased fishing pressure – are all likely to have far-reaching consequences for all species that currently inhabit the Southern Ocean. One of the fundamental questions is how climate change will alter the growth of key prey species including phytoplankton, zooplankton and krill. Phytoplankton are the base of the foodweb, and even small changes in sea-ice, ocean circulation, chemistry and temperature will affect which species live, thrive and die in the ocean. The biological outcomes from altered S. Ocean and Antarctic conditions will be determined by the environment, timing, rate and magnitude of change in each stressor, the order in which the changes occur, and the potential for consequences to be compounded when multi-stressors change concurrently. Hence, understanding climate change impacts on Southern Ocean biota requires us to consider which key species will be more sensitive to change, if change will have beneficial or detrimental effects, and how change will vary from regionally. These new insights will have important implications for management of fish stocks and high conservation-value species throughout the region. In this presentation we will provide an update on the latest developments in understanding the potential biological tipping points for the biota that comprise Southern Ocean ecosystems.

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Light driven tipping points in polar ecosystems

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Seasonal snow and ice-cover periodically block sunlight reaching polar ecosystems, but the effect of this on annual light depends critically on the timing of cover within the annual solar cycle. At high latitudes, sunlight is strongly seasonal, and ice-free days around the summer solstice receive orders of magnitude more light than those in winter. Early melt that brings the date of ice-loss closer to midsummer will cause an exponential increase in the amount of sunlight reaching some ecosystems per year. This is likely to drive ecological tipping points in which primary producers (plants and algae) flourish and out-compete dark-adapted communities. We demonstrate this principle on Antarctic shallow seabed ecosystems, which our data suggest are sensitive to small changes in the timing of sea-ice loss. Algae respond to light thresholds that are easily exceeded\ by a slight reduction in sea-ice duration. Earlier sea-ice loss is likely to cause extensive regime shifts in which endemic shallow-water invertebrate communities are replaced by algae, reducing coastal biodiversity and fundamentally changing ecosystem functioning. Modelling shows that recent changes in ice and snow cover have already transformed annual light budgets in large areas of the Arctic and Antarctic, and both aquatic and terrestrial ecosystems are likely to experience further significant change in light. The interaction between ice-loss and solar irradiance renders polar ecosystems acutely vulnerable to abrupt ecosystem change, as light- driven tipping points are readily breached by relatively slight shifts in the timing of snow and ice-loss.

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Investigating basal thaw as a mechanism of ice flow changes in Antarctica

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Glacial thermal processes exert a fundamental control on ice flow by governing, among other processes, the ability of ice to slide on its base. Frozen-bed regions are characterized by high basal traction and no basal sliding leading to reduced ice flow compared to regions with thawed beds. In Antarctica, some frozen-bed regions separate fast-flowing glaciers and ice streams. Others separate inland catchments with thawed beds from the grounding zone of marine ice-sheet sectors. If these frozen regions experienced thawing, this transition could lead to ice-sheet acceleration, reconfiguration, and retreat. We use the Ice Sheet System Model (ISSM) to identify regions of Antarctica that are likely to be just below the pressure melting point at the ice bed interface and assess the impact of thawing these vulnerable regions on the broader Antarctic evolution over century time scales. This is the first assessment of the large-scale impacts that thawing at the ice-bed interface could have across Antarctica, allowing us to evaluate its potential significance for the future evolution, stability, and sea level contribution of the ice sheet.

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Criticality of Plio-Pleistocene glacial cycles

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Ice-age cycles have been studied for nearly 200 years (Agassiz, 1841; Croll, 1864), with links between cycle frequency and periodic variations in Earth's rotation or celestial orbit now well-established (Milankovitch, 1930; Imbrie et al., 1984; Berger et al., 2005). Over the last five million years (the 'Plio-Pleistocene') the amplitude of glacial–interglacial temperature variability progressively increased and cycles became increasingly asymmetric (Lisiecki & Raymo, 2005), with most recent terminations taking place nine times faster than their preceding growth phases (Hays et al., 1976). To date, no single theory exists that explains this progressive, epoch-scale, evolution of the global climate system (Raymo & Huybers, 2008). Here we show that the Plio-Pleistocene climate system can be plausibly viewed as one that has incrementally evolved to one of increased efficiency, ultimately giving rise to glacial cycles characterised by a criticality that is expressed through abrupt terminations. In this framework, glacial maxima are the phase-space attractors to which the climate system gravitates, and terminations are triggered at the point when the system as a whole becomes critically unstable. Our results also suggest that future elevated atmospheric CO2 may prevent the climate system reaching the critical glacial state and instead faciliate a return to environmental conditions last seen more than 1–2 Ma ago.

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Ecosystem Thresholds and Tipping Points in the Soils, Streams, and Lakes of the McMurdo Dry Valleys, Antarctica

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The McMurdo Dry Valleys are the largest ice-free region of Antarctica. The soils, streams, and lakes of this landscape host communities of invertebrates, algae, and microbes. Whereas glacial meltwater streams dry up for most of the year and soils freeze, the lakes provide a stable liquid water column underneath their permanent ice covers (3-5 m thick). Through several short (1 season) and long term (30 years) experiments and observations in this landscape we have evaluated ecosystem responses to environmental changes (high/low melt seasons, warm/cold seasons, etc.). In the soils, changes to nutrient, salt, and moisture availability are the most likely to drive habitat changes. If warming increases meltwater production and movement across the landscape, the salts that move with that water in seeps and water tracks would likely cause a significant impact to these communities. To date, however, trampling is the most significant deleterious impact we have observed. In the streams, microbial and invertebrate communities are dependent upon both streamflow conditions and hyporheic processes (trapping organic matter, transforming nutrients). As such, a tipping point for streams would come with larger flows than we have observed mobilizing bed materials and biological communities to the closed-basin lakes. Having adapted to the light cycle of Antarctica under stable ice covers, lake communities would face a significant challenge if ice covers were to disappear, promoting greater transmission of summer light and substantial mixing. As the climate of the dry valleys changes in the coming decades, the ecosystem will respond, perhaps in ways heretofore unobserved.

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Implications of CO2-induced Antarctic marine microbial communities for the Antarctic coastal food web and biological pump: insights from network modelling

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Antarctic waters are among the most vulnerable to ocean acidification and in coastal areas elevated CO_2 has been shown to alter the composition of microbial communities. A six level, dose-response ocean acidification experiment was conducted on a natural marine microbial community in Prydz Bay, East Antarctica. This showed a strong tipping point in the structure and function of the microbial community between 634 – 953 µatm CO_2. CO_2 values above this tipping point, caused the microbial community to become dominated by smaller phytoplankton cells and bacteria. This data collected during the experiment was used to model the implications of these CO_2-induced changes in the microbial community on the Antarctic food web and biogeochemical cycles. Qualitative network modelling was conducted over a range of CO_2 scenarios suggests that these CO_2-induced changes would significantly alter trophodynamic pathways by changing the quality and quantity of energy available to higher trophic levels. Changes in nutrient uptake due to the shift observed in the phytoplankton community and an increased bacterial abundance would impact the availability and remineralisation of macronutrients through the microbial loop. ln addition, the shift to a community dominated by smaller cells could favour respiration of carbon in the microbial loop and reduce the rate of carbon sequestration in nearshore Antarctic waters. Thus, CO_2-induced changes in the microbial community composition in coastal Antarctic waters could reduce the energy available to higher trophic levels and the efficiency of the biological pump, resulting in a positive feedback to atmospheric CO_2 levels and global climate change.

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Present feedback between melting Antarctic Ice Sheet and warming Southern Ocean

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Strong heat loss and brine release during sea ice formation in coastal polynyas act to cool and salinify waters on the Antarctic continental shelf. Polynya activity thus both limits the ocean heat flux to the Antarctic Ice Sheet and promotes formation of Dense Shelf Water (DSW), the precursor to Antarctic Bottom Water. However, despite the presence of strong polynyas, DSW is not formed on the Sabrina Coast in East Antarctica and in the Amundsen Sea in West Antarctica. Here we show that freshwater input from basal melt of ice shelves partially offsets the salt flux by sea ice formation in polynyas found in both regions, preventing full-depth convection and formation of DSW. Here warm waters can flood the shelf and cause rapid melting. Our results suggest that a further increase in the supply of glacial meltwater to other shelf areas may trigger a transition from a cold regime (characterized by full-depth convection, low rates of ice-shelf basal melt, and active bottom water formation) to a warm regime (warm water at depth, high rates of ice shelf basal melt, and reduced bottom water formation). A slowdown of DSW formation in response to increased glacial meltwater input would have consequences for the deep overturning circulation and abyssal ventilation. At the same time, meltwater-induced changes in stratification would facilitate the spreading of warm waters across the continental shelf to ice shelf cavities, driving increased ice shelf basal melt, reduced buttressing of the Antarctic Ice Sheet, and additional rise in sea level.

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The Poles, Tipping Points and Earth System trajectories

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The polar regions play an exceptionally important role in the functioning of the Earth System. This talk will explore the role of the polar regions in this contemporary period of rapid change as the Earth System accelerates away from the relatively stable conditions of the Holocene and more deeply into the Anthropocene. The focus is on tipping elements in the Earth System and their role in potential tipping cascades that could strongly influence the trajectory of the Earth System as a whole. We will use control theory to assess the risk of initiating a tipping cascade over the next decade or two, where a global tipping point might lie, and what the outcome of a tipping cascade might be. Finally, we'll discuss the actions humanity needs to take - and their timing - the minimise the risk that we'll trigger a global tipping cascade and irreversibly put the Earth System on a trajectory to a fundamentally different state.

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Potential Tipping Points of Antarctic Ice Sheet Basins

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Antarctica is loosing mass in an accelerating way and these losses are considered as the major source of sea-level rise in the coming centuries. Ice-sheet mass loss is mainly triggered by the decreased buttressing from ice shelves mainly due to iceocean interaction. This loss could be self-sustained in potentially unstable regions where the grounded ice lies on a bedrock below sea level sloping down towards the interior of the ice sheet, leading to the so-called marine ice sheet instability (MISI). Recent observations on accelerated grounding-line retreat and insights in modelling the West Antarctica ice sheet give evidence that MISI is already on its way. Moreover, similar topographic configurations are also observed in East Antarctica, particularly in Wilkes Land. We present an ensemble of simulations of the Antarctic ice sheet using the f.ETISh ice-sheet model to evaluate tipping points that trigger MISI by forcing the model with sub-shelf melt pulses of varying amplitude and duration. As uncertainties
in ice-sheet models limit the ability to provide precise sea-level rise projections, we implement probabilistic methods to investigate the influence of several sources of uncertainty, such as basal conditions. From the uncertainty analysis, we identify confidence regions for grounded ice interpreted as regions of the Antarctic ice sheet that remain ice-covered for a given level of probability. Finally, we discuss for each Antarctic basin the total melt energy needed to reach tipping points leading to sustained MISI.

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Identifying Antarctic tipping points under past warming

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Ir-re-versible shifts of large-scale com-po-nents of the Earth sys-tem (so-called 'tip-ping el-e-ments') on pol-icy-rel-e-vant timescales are a ma-jor source of un-cer-tainty for pro-ject-ing the im-pacts of fu-ture cli-mate change. A wealth of geological, chemical, and biological records indicate large-scale and often irreversible shifts in the Antarctic took place in the past (centennial to millennial in duration). The forcing behind these changes appear to have been relatively small, implying specific thresholds, or tipping points were triggered (reached by self-reinforcing feedbacks), driving extreme, nonlinear changes across the Antarctic. Identifying past tipping points in ice-sheet stability is critical to projecting the response of Antarctica to future change and assessing potential for triggering tipping cascades across the Earth system. Generic rules can be used to identify early warning signals across the Antarctic and Southern Ocean that may be identified on the approach to a tipping point, generated from characteristic fluctuations in a time series as a system loses stability.

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Prediction, detection and characterisation of regime shifts in Southern Ocean ecosystems

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The potential for regime shifts - fundamental changes in ecosystem structure and function – is of great concern for Southern Ocean ecosystems. Growing awareness of the importance of regime shifts has triggered growth in research and development of analytical tools and approaches for predicting regime shifts (and to a lesser extent for detecting regime shifts once they have occurred). However, so far there is no unifying approach for ecologists and ecosystem managers wanting to evaluate an ecosystem for evidence of past regime shifts or the risk of future regime shifts.

We developed a framework for assessing the likelihood of regime shifts in ecological systems based on a review of theoretical and ecosystem case study literature. We identified a set of ecosystem qualities that increase risk of regime shifts, assessed existing capabilities for predicting and detecting regime shifts, and identified potential new approaches for doing so.

In this presentation, we present the application of this framework to Southern Ocean ecosystems. We highlight the data and methods currently available and suitable for assessing Southern Ocean ecosystems for regime shifts, and also gaps that could be targeted to maximise capability for predicting, detecting, characterising and managing such shifts in the future.

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