



Early Warning from Space for a Few Key Tipping Points in Physical, Biological, and Social-Ecological Systems

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Received: 5 December 2019 / Accepted: 18 July 2020
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Abstract

In this review paper, we explore latest results concerning a few key tipping elements of the Earth system in the ocean, cryosphere, and land realms, namely the Atlantic overturning circulation and the subpolar gyre system, the marine ecosystems, the permafrost, the Greenland and Antarctic ice sheets, and in terrestrial resource use systems. All these different tipping elements share common characteristics related to their nonlinear nature. They can also interact with each other leading to synergies that can lead to cascading tipping points. Even if the probability of each tipping event is low, they can happen relatively rapidly, involve multiple variables, and have large societal impacts. Therefore, adaptation measures and management in general should extend their focus beyond slow and continuous changes, into abrupt, nonlinear, possibly cascading, high impact phenomena. Remote sensing observations are found to be decisive in the understanding and determination of early warning signals of many tipping elements. Nevertheless, considerable research still remains to properly incorporate these data in the current generation of coupled Earth system models. This is a key prerequisite to correctly develop robust decadal prediction systems that may help to assess the risk of crossing thresholds potentially crucial for society. The prediction of tipping points remains difficult, notably due to stochastic resonance, i.e. the interaction between natural variability and anthropogenic forcing, asking for large ensembles of predictions to correctly assess the risks. Furthermore, evaluating the proximity to crucial thresholds using process-based understanding of each system remains a key aspect to be developed for an improved assessment of such risks. This paper finally proposes a few research avenues concerning the use of remote sensing data and the need for combining different sources of data, and having long and precise-enough time series of the key variables needed to monitor Earth system tipping elements.

Keywords Tipping point · Tipping element · Remote sensing · Earth observation · Atlantic · AMOC · SPG · Marine biology · Permafrost · Antarctic and Greenland ice sheets · Land use · Terrestrial resource use · Early warning · Bifurcation · Climate dynamics

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1 Introduction

The analysis of different systems in biology, physics, chemistry, and environmental sciences has highlighted for more than a century that sometimes a small perturbation of some of these systems can lead to large changes. This is a key property of nonlinear systems for which the response to a perturbation is not proportional to it. The system does not necessarily return to the initial state even if the perturbation leading to the change is removed or its direction reversed. Indeed, this type of bifurcation can lead to irreversible change (where irreversible means that the recovery time scale from this state is substantially longer than the time it takes for the system to reach this perturbed state, cf. Masson-Delmotte et al. 2018).

Milkoreit et al. (2018: p. 9) define tipping point as “the point or threshold at which small quantitative changes in the system trigger a nonlinear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible. This new state can be distinguished from the original by its fundamentally altered (positive and negative) state-stabilizing feedbacks”. The possible irreversible characteristic of this change of state is related to hysteresis behaviour, meaning that a return to the same value of the driving parameter does not necessarily lead to a return of the system to its former state. This involves the existence of multiple steady states for the same driving parameter values, which is at the origin of the potential irreversibility of the changes following a tipping point. This behaviour is related to positive feedback loops by which a perturbation is amplified until the system reaches another steady state, in which the system is kept by novel feedback mechanisms. The time required for the transition depends on the system considered and its inertia properties and can vary from about days to millennia. The abruptness of the transition thus depends on the system, but is classically defined by being faster than the forcing that leads to the transition.

Dynamical system theory from the mathematical field has analysed in detail the attributes of this type of systems and highlighted that the systems that are nonlinear are not necessarily complex and can be driven by relatively simple differential equations (e.g., Scheffer et al. 2009). A key aspect of these systems is constituted by the existence of thresholds in some driving parameters after which, when they are crossed, the systems can totally change in their state and nature. This threshold is also called bifurcation in the mathematical field, a word first introduced by Poincaré (1885) in a seminal paper showing such a behaviour in some mathematical objects.

The Earth system is constituted of several subcontinental-scale subsystems, crucial for climate mitigation, which are suspected of being tipping elements (Lenton et al. 2008), for example the Amazon rainforest, where crossing a tipping point would not only mean the Amazon rainforest turning locally into dry savanna, but modifying the global rain patterns, and possibly becoming a source of CO₂ as opposed to being a sink (Lovejoy and Nobre 2018).

Tipping elements are Earth subsystems at least subcontinental in scale, which can be switched into a qualitatively different state by relatively small perturbations (Lenton et al. 2008, 2019; Milkoreit et al. 2018), i.e. they contain a *tipping point*, or *critical threshold*, past which a bifurcation in the system leads to a large reorganization (Good et al. 2018).

This concept implies a radically different view on the potential effects of global change on such systems, and on associated costs and management options (Lemoine and Traeger 2014; Lontzek et al. 2015). Global warming is considered a key driver towards reaching tipping points in multiple ecological and physical systems as well as

in subcontinental-scale subsystems. Furthermore, there is growing evidence that these tipping elements are not isolated, and a tipping point in a subsystem can have cascading effects on the others, carrying huge impacts on human societies (Cai et al. 2016; Lenton et al. 2019). The risk of crossing thresholds in these subsystems was therefore a crucial argument to try to keep global warming in reasonable amplitude as initiated by the target of the Paris Agreement in 2016, and highlighted at about 1.5 °C in the recent special report from the Intergovernmental Panel on Climate Change (Hoegh-Guldberg et al. 2018).

A few examples of known key tipping elements will be depicted in the present paper and are represented in Fig. 1. They are covering the different realms of ocean, land, and cryosphere. These examples were chosen because of their potential high impact on societies and include ocean circulation structures like the Atlantic Meridional Overturning Circulation (AMOC) and the Subpolar Gyre (SPG) systems, the permafrost in the boreal regions, marine ecosystems, the Antarctic and Greenland ice sheets, and terrestrial resource use systems. We use the term terrestrial resource use systems to refer to the coupled human–nature interactions in the human use of land as a spatial resource, soil, water and plant, and animal biodiversity resources.

Ice cores analysis from Greenland has suggested the existence of abrupt climate changes in the past, happening in less than a decade (Dansgaard et al. 1993; Steffensen et al. 2008). The exact mechanisms causing these rapid events are still the subject of intense research, and a large number of potential processes have already been proposed (e.g., Clement and Peterson 2008). While ocean circulation changes certainly played a role, robust palaeoclimate data are still not sufficient to provide a definite view on the exact suite of events that leads to these rapid variations. Other subsystems of the climate system have also potentially changed state relatively rapidly in the past. An iconic example is the Green Sahara, showing that the south part of the Sahara was covered by vegetation 6000 years ago, but changing climate transformed it in just about 3 centuries

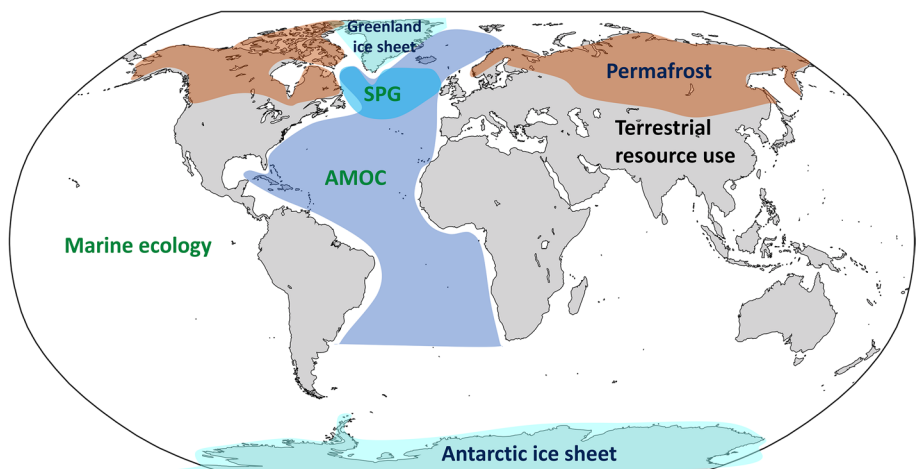


Fig. 1 Schematic of the tipping elements assessed in the paper. The systems found in the ocean realm are written in green, the ones from the cryosphere in dark blue and the one from the land in black. “Terrestrial resource use” includes land use systems and land cover

(Demenocal et al. 2000) into the desert that we know now, among the driest land on Earth (Claussen 1997; Hoelzmann et al. 1998).

While rapid transition and bifurcation behaviours have been found in a number of simplified models of tipping elements (Bathiany et al. 2016), more comprehensive models do not always exhibit such instabilities, highlighting that these models may be able to incorporate some stabilizing feedbacks. Drijfhout et al. (2015) led a systematic analysis of rapid transition of a number of variables in the comprehensive climate model database CMIP5 at a regional scale and found a number of rapid transitions (a few decades) in some key tipping elements. These include potential convection collapse in the North Atlantic and Southern Ocean, Amazon forest dieback, Arctic permafrost thawing, and Eastern Sahel greening. This study highlighted that some complex climate models can identify nonlinear behaviour in tipping elements, which may be key to forecasts in a changing climate.

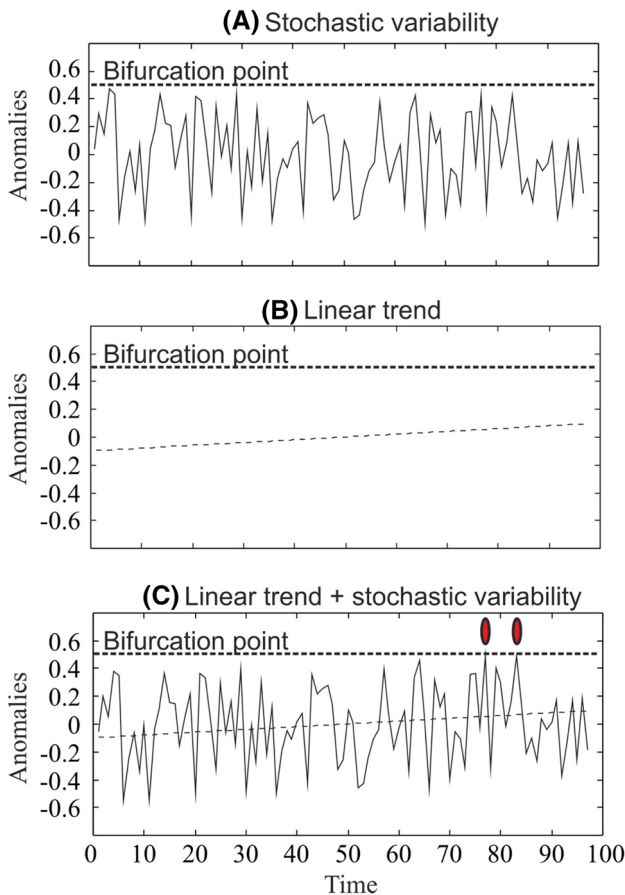


Fig. 2 Example of interaction between stochastic resonance and tipping points. **a** Stochastic variability, which can be compared to inherent climatic variability in this fictive example. Alone, this source of variability cannot reach a tipping point. **b** Long-term (low-frequency) linear trend in the same climatic parameter related to anthropogenic climate change (an example could be the warming trend). **c** Stochastic variability and trend. Red ovals indicate that the tipping (or bifurcation) point is reached. Stochasticity was modelled here by adding a Gaussian random variable of small intensity, following the method of Benzi (2010). From Beaugrand (2015)

Nevertheless, these simulations do not yet provide enough information on the time scale or the irreversibility of the forecasted events.

Stochastic resonance is an important mechanism by which anthropogenic climate change may interact with climatic variability to trigger acute species mortality at the species level or regime shift at the ecosystem level (Fig. 2). In the fictive example of Fig. 2, neither the stochastic (year-to-year) variability nor the long-term trend in climatic forcing can reach a tipping point on the given time window of 100 years (Fig. 2a, b). However, when both signals are combined, a critical threshold may sometimes be reached and trigger a major phase transition (Fig. 2c). It is extremely difficult to forecast the time at which a tipping point is crossed. The best we can, perhaps, do is to evaluate the probability to reach this point, as the bifurcation point itself is rarely known with accuracy. Once the tipping point has been crossed, the system can go in quite surprising directions and changes are often difficult to reverse. There are many ways to investigate stochastic resonance (Wellens et al. 2004). Here, we used in Fig. 2 a simple model by adding to the trend a Gaussian random variable (Benzi 2010).

In order to anticipate the occurrence of an abrupt change in a given system, detecting early warnings has become an intense field of research. Based on the findings that many systems modify their variability before shifting to another state (e.g., Scheffer et al. 2009; Beaulieu et al. 2012), this field analyses the statistical properties of key variables in various systems. It has been shown that rather different systems, at the proximity of a tipping point (e.g., lakes turning turbid, rise in an epidemic), exhibit common signals, for example increase in the variance and autocorrelation of some key variables (Bathiany et al. 2016; Dakos et al. 2015; Lenton 2011; Scheffer et al. 2009). These phenomena do not occur in all systems, and multidecadal time series are necessary to correctly assess the natural variability of the system and its changes near a tipping point. Despite these limitations, early warning is a very promising field, which can become a major element of disaster risk reduction (Melet et al. 2020) and deserves more research to become entirely applicable.

Remote sensing and Earth observations (EO) may strongly contribute to the knowledge about the different tipping elements of a system. Although the length of observations is currently limited, satellites are providing unprecedented knowledge about the dynamics and processes that govern the different tipping elements depicted in this review. These different pieces of knowledge, the utility they may have for early warning of any kind, and their caveats will be shown for the different case studies analysed in this paper and represented in Fig. 1.

In this paper, we address tipping points from an interdisciplinary perspective. We provide a review of a few key tipping points in physical and biological systems and in a societal terrestrial context, and assess the research avenues that need to be followed to improve our understanding of these elements and the way to set up early warning signals. We focus on the use of satellite observations for this purpose: how they can contribute to providing early warning signals, and how they can help to better understand the different systems analysed here.

2 Oceanic Tipping Elements

2.1 Ocean Circulation

2.1.1 AMOC Stability

The AMOC has become an iconic tipping element of the climate system. The first guess that this circulation can tip in response to changes in the atmospheric hydrological cycle was highlighted as early as 1961 by Henry Stommel in an influential paper (Stommel 1961). In this paper, Stommel showed—using a two-box model of the ocean circulation, one box for the equatorial area and the other for the northern polar region, connected by a current proportional to the density gradient between the two boxes—that the AMOC response to surface freshwater fluxes (FW) is highly nonlinear. A hysteresis diagram drives its steady-state variations with the possibility, for a range of FW forcing, of two AMOC stable states. He also found a bifurcation for a critical value of the FW forcing where the AMOC system jumps from one state to another. This result was then found in more sophisticated ocean models (e.g., Rahmstorf 1996) and is still true in three-dimensional coupled ocean–atmosphere climate model at the eddy-permitting resolution in the ocean (e.g., Mecking et al. 2016).

In parallel to these theoretical investigations, palaeoclimate data reveal that the North Atlantic climate was very unstable in the last glacial period (Dansgaard et al. 1993), as well as the Holocene (Renssen et al. 2001) and the last interglacial (Galaasen et al. 2014), i.e. for warm periods. This sub-millennial variability is difficult to reconcile with very slow changes in insolation and have been therefore associated with rapid changes in the ocean circulation and the instability of the AMOC (Rahmstorf 2002).

Worldwide climate impacts associated with AMOC variability are also deciphered from palaeodata (Collins et al. 2019). When the AMOC weakens, the associated decrease in northward heat transport strongly cools the North Atlantic regions by up to 10 °C (Jackson et al. 2015). The hydrological cycle is also perturbed with a southward migration of the intertropical convergence zone that strongly modifies the precipitation pattern throughout the world including the monsoons in southeast Asia (Monerie et al. 2019). Numerous other climatic impacts have been reported in response to a weakening of the AMOC, including a strengthening of the storm track position and intensity in the North Atlantic (Gastineau et al. 2016) or an increase in sea-level rise in the North Atlantic (Ezer 2015), among many others.

The main processes that explain the nonlinearity of the AMOC are related to the salt advection feedback. Indeed, when the AMOC weakens, it conveys less salty waters from the tropical area towards the North Atlantic, decreasing the sea surface salinity (SSS) there and further limiting oceanic convection that feeds the strength of the AMOC. This positive feedback is key for the AMOC's nonlinear behaviour and its stability (Weijer et al. 2019). It has been argued (Rahmstorf 1996) that the main driver of this stability is related to the salt transport by the overturning circulation inside the Atlantic Ocean at around 34°S. If the overturning transports freshwater, the feedback is negative and the AMOC is in a monostable state, if it transports saline water, then the feedback is positive and the AMOC is in a bi-stable state. Observations seem to indicate that present-day overturning transports salt at 34°S and thus the AMOC may be in a bi-stable state (Deshayes et al. 2013). Most of the CMIP5 models do not properly represent this transport (Weaver et al. 2012); hence, they may be too stable. Nevertheless, it should be highlighted here that the stability of the AMOC is a concept suited for steady-state analysis, which usually means hundreds of years of transient response for the ocean (Sgubin et al. 2015). Hence, if the AMOC is close to

a bifurcation point, it can shift from one state to another for a small perturbation, but the time scale of changes may still be relatively long, of the order of a century.

2.1.2 On the Possibility of Monitoring of Early Warning

The observations of the salinity transport both at 34°S and elsewhere in the Atlantic remain crucial to estimate ongoing changes in the AMOC. There exist a few in situ hydrographic arrays that allow such a monitoring: at 16°N (Send et al. 2011), 26°N (McCarthy et al. 2015), in the North Atlantic subpolar gyre (Lozier et al. 2019), between Portugal and the tip of Greenland (Mercier et al. 2015), and at 34.5°S (Meinen et al. 2018), among others. They allow regular evaluation of the strength of the AMOC as well as its characteristics and evolution.

While these observations are crucial to indicate some early warnings of strong weakening of the AMOC, which may precede changes in sea surface temperature (SST) by a few years (Knight et al. 2006), the analysis of time series variations may not allow per se to an estimate of whether the system is getting close to a bifurcation. Indeed, an analysis from Boulton et al. (2014) within a climate model showed that, to detect in advance the approach of a bifurcation in the AMOC, it will be necessary to decipher its statistical characteristic, hence to have hundreds of years of knowledge of AMOC variations. Since the AMOC has been directly measured continuously only since 2004, we are far from being able to use time series analysis to have any insights on the proximity of a bifurcation. Thus, the detection of early warning for an AMOC collapse is beyond our capability and knowledge at the moment, and we cannot state if we might have already crossed the threshold nowadays. Still, measurements of the AMOC are crucial to monitor its evolution and possible ongoing changes, which may allow us to slightly anticipate any rapid changes and also possibly help to detect early warning. The use of palaeodata would be helpful and necessary to reach this goal. Monitoring of the Atlantic remains crucial for knowing lower amplitude variations that are very useful to improve the initial conditions of decadal prediction system (e.g., Keenlyside et al. 2008; Swingedouw et al. 2013), which might help to anticipate abrupt transitions.

These hydrographic arrays also serve as references to evaluate the capacity of remote sensing to estimate oceanic variations through the use of key fingerprints of the AMOC variations. For instance, Frajka-Williams (2015) used the RAPID array at 26°N to evaluate the capacity of remote sensing altimetry using AVISO (Archiving, Validating and Interpretation of Satellite Oceanographic) data to capture changes in the overturning. They found a good correlation between AMOC variations measured at 26°N and changes in sea level at 30°N–70°W. They use this location to propose a reconstruction of the AMOC further back in time since the beginning of remote sensing altimetry in 1993. Mercier et al. (2015) also used altimetry (and in situ ocean velocity measurements) to propose a continuous reconstruction of the overturning along the OVIDE array that are measured in situ every two years in spring since 2002. Finally, Landerer et al. (2015) proposed a very innovative approach to evaluate the variations in ocean density over the whole water column and its link with circulation through geostrophy. They used the GRACE (Gravity Recovery And Climate Experiment) remote sensing products to infer the density variations in the deep ocean and then succeeded in reconstructing most of the observed variations from the RAPID array. These methods allow the estimation of the density variations with a wider spatial sampling than just arrays (although with coarse grid resolution of a few hundreds of

kilometres), which offers an unprecedented view of the adjustment of the deep ocean density to changes in the circulation. This new type of measurements of the deep ocean, which is currently poorly sampled by ARGOS floats, may offer some avenues to better understand the deep ocean variations that are still controversial (e.g., Lozier et al. 2019). It may indeed permit to understand the signal propagation between different arrays, and notably between the new OSNAP (Overturning in the Subpolar North Atlantic Program) array in the subpolar (Lozier et al. 2019) and the RAPID one at 26°N for instance.

Using SST as a proxy of the real AMOC, Caesar et al. (2018) suggested that the AMOC may have already weakened by around 15% over the last six decades, suggesting that this system may be already changing. Recent projections of the AMOC changes in the coming centuries including Greenland ice sheet melting show a weakening of the AMOC of 37% [15%, 65%; 90% probability] in 2100 in RCP8.5 scenario and of 18% [3%, 34%] in RCP4.5 as compared to year 2006 (Bakker et al. 2016). On the longer term (2300), there is a 44% likelihood of an AMOC collapse in RCP8.5 scenario, while it resumes in RCP4.5; RCP4.5 and RCP8.5 are two representative concentration pathways, i.e. two greenhouse gas concentration trajectories adopted by the Intergovernmental Panel for Climate Change (IPCC). This highlights the strong benefit of greenhouse gases mitigation concerning the possibility of crossing a threshold of the AMOC. Furthermore, present-day climate models are suspected to be far too stable for the AMOC (e.g., Liu et al. 2017), so that this estimate is believed to be too conservative.

2.1.3 The Subpolar Gyre as a Faster and Closer Tipping Element

A subsystem of the AMOC is constituted by the subpolar gyre (SPG) system. This circulation is found at latitudes just below the tip of Greenland. It is a cyclonic gyre that turns around two intermittent convection sites in the Labrador Sea and the Irminger Sea. It has been shown that this system may be a tipping element of the climate system, involving different processes than the large-scale AMOC. While the salt-advection feedback also plays a key role, it acts on more local spatial scale (Born et al. 2016) so that the SPG state change can occur on a faster time scale than the AMOC (about a decade compared to a century, e.g., Sgubin et al. 2017). In the “on” state, the convection in the Labrador and Irminger seas is active, leading to strong density in the middle of the gyre that intensifies the circulation and the arrival of warm and salty water from the subtropical gyre. When a critical threshold is reached for the stratification (due to increase in SST or decrease in SSS), the convection is not permitted anymore and the gradient of density between the centre and the periphery of the gyre decreases. This reduces the flow of the gyre and the import of warm and salty water from the subtropical gyre, which further decreases convection, i.e. a positive feedback. The climatic impact of such a collapse of convection mainly affects SST and air temperature in the subpolar gyre area. The transition occurs in less than 10 years and can induce a cooling of 2–3 °C of SST in the gyre vicinity, affecting the rate of warming in the neighbouring regions (Sgubin et al. 2017, 2019). It has also been proposed that such a cold blob in the SPG can modify the atmospheric circulation, leading to more heat waves in summer over Europe (Duchez et al. 2016).

Using some CMIP5 climate models that do show such an abrupt (< 10 years) shift (here, 4 models, with the abrupt collapse of the SPG occurring at different years within the 21st century), we can estimate the critical stratification in the subpolar gyre just preceding the collapse of convection that would shift the system in an “off” state. This critical stratification is presented in Fig. 3, together with the present-day stratification and the stratification

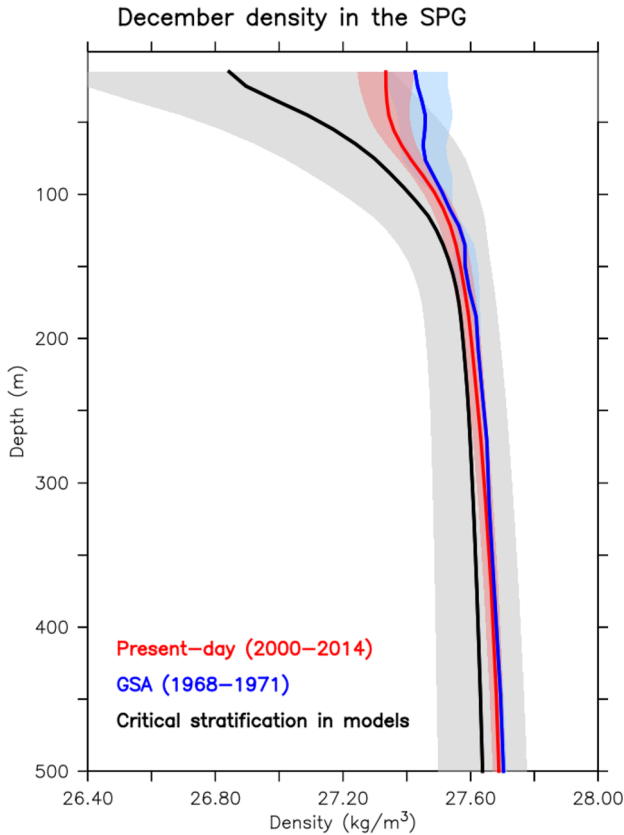


Fig. 3 Critical stratification in the subpolar gyre just preceding the collapse of convection. Density in the subpolar gyre ($62\text{--}27^\circ\text{W}$, $45\text{--}70^\circ\text{W}$) in 4 models from CMIP5 (in black) showing a collapse of the convection (CESM1-CAM5, GFDL-ESM2G, GISS-E2-R, MIROC5). The density profile is shown as an average for the three months of December just before the year of the convection collapse in the different models (which occur in different years, depending on the model). The overlap stands for the one standard deviation of the 4 models. The present-day density profile (in red) is shown from EN4 data, an objective analysis of most of the observational datasets available (Good et al. 2013), averaged over the December month between 2000 and 2014, with the envelope representing the associated standard deviation over this time period. Finally, the density profile of the Great Salinity Anomaly (GSA) occurring between about 1968 to 1971 in the subpolar gyre is shown in blue, once again as an average for the month of December and associated standard deviation as an envelope. A 20-m running mean has been applied to all profile to improve readability

during the Great Salinity Anomaly in the late 1960s (Belkin et al. 1998). From this figure, we can see that the present-day stratification in the Labrador Sea seems relatively far from the collapse threshold, which will require a further decrease in surface density of about 0.5 kg m^{-3} compared to the ensemble mean of the 4 models. Nevertheless, the error bar (defined here as one standard deviation) of models and of present-day observations overlaps, and even the average of observed density at the surface is very close to the models' uncertainty. From this, we can estimate that the SPG may be relatively close to the stratification threshold exhibited by some climate models, although the Labrador Sea is still showing vigorous convection in the recent years (Yashayaev and Loder 2017). Thus,

Earth observations (EO) of surface density, which can be achieved by measuring both SST (through microwave radiometer, e.g., GMI satellite, SLSTR, AVHRRs) and SSS (SMOS satellite), may allow us to monitor the proximity of the convection-collapse threshold. However, this proposition remains valid under the hypothesis that the threshold quantified by CMIP5 climate models is realistic, which may be disputable given the coarse resolution of these models and the poor representation of the impact of oceanic eddies on re-stratification processes within the Labrador Sea (Heuze 2017).

Weakening in the AMOC or SPG has been reported to strongly impact the ocean biogeochemistry. For instance, SPG changes impact plankton (Hatun et al. 2016), fishes (Miesner and Payne 2018), seabirds (Descamps et al. 2013), and top predators such as tuna, billfish, and pilot whales (MacKenzie et al. 2014). AMOC weakening is also suspected to explain marine deoxygenation in the northwest coastal Atlantic (Claret et al. 2018). A recent study also suggested that net primary productivity has decreased by $10 \pm 7\%$ in the subarctic Atlantic over the past two centuries possibly related to recent changes in the AMOC (Osman et al. 2019). Other potential tipping elements in ocean biology and their linkage with remote sensing monitoring will be explored in the next subsection.

2.2 Marine Ecosystems

In marine ecology, the complex equilibrium of the interconnected species composing the ecosystem is continually subject to natural and anthropogenic stressors. The ecosystem's capacity of maintaining the characteristics within its original regime as conditions change is called *resilience* (Holling 1973). As continuing or additional stressors erode the ecosystem resilience, the ecosystem may reach a tipping point, past which even a smooth additional stress triggers a drastically different system behaviour, a phenomenon called regime shift.

Regime shifts (also known as *critical transitions*, *phase shifts* in benthic ecology, *abrupt shifts* when feedback mechanisms are not identified), are large, abrupt (less than a few years in many ecosystems), persistent changes in the structure and function of a system, corresponding to a profound restructuring of the trophic web into a novel, often alternative state (Biggs et al. 2012; Scheffer et al. 2009, 2001; Scheffer and Carpenter 2003). While in some cases (*abrupt shifts*) the system can switch back to the original state, in other cases (*discontinuous shifts*) feedback mechanisms maintain the novel state. In mathematical language, the system response to stressors forms a fold bifurcation with hysteresis and the possibility of reversal to the previous state is extremely difficult as the forcing needed to switch back to the original state must be higher than the original one. Examples of discontinuous phase shifts in the ocean are the worldwide collapses of productive and scenic kelp bed habitats to persistent sea-urchin-dominated barren grounds (Ling et al. 2015), and the worldwide shifts from coral state to the alternate state of fleshy algae (Bellwood et al. 2004).

Multiple studies in the marine environment indicate that tipping points are common (Beaugrand et al. 2019; Hunsicker et al. 2016; Möllmann et al. 2015)—in fact regime shifts have been found in all marine ecosystems where long time series are available, often in concurrent periods. In the pelagic environment, abrupt (about a year) shifts were found in the North Pacific in 1976–1977, 1988–1989 and 1998–1999, in the South Pacific (Humboldt Current) in 1968–1970 and 1984–1986, in the north-west Atlantic in 1989–1990 (see review in Beaugrand 2015). Regime shifts were observed in the late 1980s also around all European seas: the North Sea, the Baltic Sea, the north-west European shelf, the eastern

(Adriatic) Mediterranean Sea, and the Black Sea (see review in Conversi et al. 2010). In the benthic environment, widely publicized shifts examples include the worldwide, dramatic phase shifts from coral reef to algal barren (Bellwood et al. 2004, 2019; Hughes 1994; Hughes et al. 2017, 2010) and from kelp reefs to sea urchin barrens (Ling et al. 2015).

2.2.1 Drivers of Marine Ecological Shifts

Marine ecological shift drivers pertain to both the exogenous/physical and the endogenous/biological (trophic predator–prey interactions) environments (Boada et al. 2017; Conversi et al. 2015; de Young et al. 2008). Major, large-scale stressors eroding the ecosystem resilience include climate change and overfishing. Overfishing of top predators affects all species linked to it (e.g., their preys, the predators and preys of those, and so on), in a phenomenon called trophic cascading that can trigger regime shifts over entire marine basins (Beaugrand et al. 2015; Casini et al. 2009; Daskalov et al. 2007; Jackson et al. 2001; Llope et al. 2011). Global change, on the other hand, affects both the physical environment (e.g., circulation changes, marine oxygen decline, ocean acidification, etc.), and the species physiology and resilience through temperature increase, simultaneously affecting multiple trophic levels in the marine food chain (Kirby and Beaugrand 2009; Conversi et al. 2015). Global change impacts on marine communities include poleward shifts, spatial homogenization, phenology changes, bleaching phenomena, etc. (Beaugrand et al. 2009; Burrows et al. 2011; Magurran et al. 2015; Hughes et al. 2017). In addition to these, local drivers (chemical pollution, eutrophication, alien species introduction) can be important for triggering shifts from local to regional scale, such as bays, coastlines, basins. There is the possibility that multiple drivers add synergistically to bring an ecosystem beyond a tipping point. In fact, there are many examples indicating regime shifts triggered by more than one driver (Bruno et al. 2019; Mackinson et al. 2009; Möllmann and Diekmann 2012; Papworth et al. 2016); and that shifts in a Earth climate subsystem can have cascading effects on the others (Lenton et al. 2019). On the other hand, there are several studies indicating that a single driver, temperature, can be used to predict ecological shifts (Beaugrand 2015; Beaugrand et al. 2019), which makes this variable extremely valuable for predictions. In many cases, regime shifts can have large impacts on ecosystem services and on the societies utilizing them (Bellwood et al. 2019; Sguotti and Cormon 2018). For example, the phase shifts from coral to algal dominance affect also all ecosystem services provided by the coral reefs (biodiversity, tourism, fishing, and coastal zone protection). Shifts involving major fishery collapses can have disastrous economic consequences on the fishing industry (Blenckner et al. 2015).

2.2.2 Ecological Shifts Predictions

Understanding and foreseeing the proximity of tipping points is of major importance not only from an ecological point of view, but also from a socio-economic point of view (de Young et al. 2008; Hewitt and Thrush 2019). The early detection of incoming shifts is a field of study on its own, which has evolved a lot in recent years. Studies focus on temporal, spatial, or mixed spatial–temporal indicators. In fact, temporal (local) variance and autocorrelation often rise when approaching an unstable equilibrium prior to a critical transition; spatial variance may increase and spatial correlation

may change before a catastrophic shift (Carpenter and Brock 2006; Lindegren et al. 2012). An analysis of false/true indications in temporal variance and autocorrelation shows, on the other hand, a majority of false indications. Thus, a multivariate approach on a suite of potential indicators is best (Burthe et al. 2016).

Scientists and resource managers often use methods and tools that assume ecosystem components respond linearly to environmental drivers and human stressors. This mental model is probably inadequate, and tipping points should be considered an ordinary, rather than an exceptional, possibility. In fact, the pervasivity of nonlinear relationships is shown by Hunsicker et al. (2016): these authors conducted a wide literature review on the degree of nonlinearity in single-driver-response relationships in pelagic marine systems, and found that nonlinearities comprised at least 52% of all driver-response relationships—which they actually consider an underestimate.

2.2.3 How Can Remote Sensing Help Understanding Processes Behind Ecological Shifts, and Provide Early Warning Signals?

Even if most animal marine communities are hidden from EO tools, the latter can provide crucial information for understanding, and possibly predicting, tipping points. The first crucial factor is the temporal/spatial scale. Because of budget and logistic constraints, monitoring programs usually sample near the coast (there are very few open-ocean time series), with low sampling frequencies (rarely daily or weekly, often monthly, sometimes seasonally or yearly)—in other words, they collect data that are not very representative of the world ocean. However, since some monitoring collections have been running for several decades, they do provide inestimable baseline information. In particular, decadal collection is necessary for the retrospective analysis of ecosystem shifts, as regimes, by definition, last many years. On the other hand, EOs provide precious high temporal frequency (hours, days), high spatial frequency (small-meso-large scale), global coverage, in some cases (e.g., SST, ocean colour radiometry) over several decades. Thus, EO data are vital for extrapolating information beyond the range of in situ monitoring and for large-scale modelling.

The second crucial factor is the multivariate information that EO provide: for example, pressure, wind intensity and direction, wave and current data, all help to define the large-scale physical environment that constrain marine animals and plants, both pelagic and benthonic. Temperature data provide the baseline metric for global change, as well as defining the life conditions of the individual species. However, we have to keep in mind that abundance of data does not translate necessarily in needed data, and that we need to continue to find novel ways to use EO data without falling prey to “reification fallacy”, which in this case would be treating convenient but incomplete indicators as inclusive (Bush et al. 2017).

2.2.4 Chlorophyll

In the case of phytoplankton, EO can provide rather good information. Phytoplankton is at the basis of the food web; in fact, it produces directly or indirectly the food for all marine animals. Although it accounts for <1% of the photosynthetic biomass on Earth, it contributes to almost half of the world’s total primary production, and has a major role in regulating carbon dioxide sequestration (Falkowski 2012).

Climate change can modify the seasonal cycle of the oceanic primary productivity by changing SST and the quantity of nutrients and light available to phytoplankton growth. This could lead to shifts in the phenology of the phytoplankton, and, vice versa, changes in phytoplankton abundance can modify the climate (e.g., changes in the depth of light penetration, Mignot et al. 2013). Thus, it is important to monitor phytoplankton in order to understand the impact of natural and anthropogenic factors on its variability.

Chlorophyll-a is a common pigment of phytoplankton, and since this pigment enables phytoplankton to absorb blue to green light, it can be measured by satellite colour sensors. This is an extremely developed field, and algorithms linking colour to phytoplankton are continually developed, for example, to separate chlorophyll into different phytoplankton components (e.g., nanoeukaryotes, *Prochlorococcus* spp., diatoms, Synechococcus-like cyanobacteria, and phaeocystis-like), using specific radiance spectra measured by ocean-colour sensors (Alvain et al. 2005; Mouw et al. 2017).

Several studies have been undertaken in the past decades to study the potential changes of phytoplankton in the global ocean due to anthropogenic factors. The first study was from Polovina et al. (2008) using a 9-year time series of SeaWiFS data. They focused on the most oligotrophic areas (with values of chlorophyll-a concentration lower than 0.07 mg m^{-3}) and showed that those areas have expanded at averaged annual rates of 0.8 to 4.3% per year. Their findings were in accordance with global warming scenarios (increase in the SST leading to warmer subtropical gyres) showing an increase in the heat content and vertical stratification. Furthermore, they suggested that these areas will keep increasing with the continuation of global warming.

Other studies have focused on the variations in phytoplankton phenology (timing, amplitude, duration of the blooms), since these can impact the entire trophic chain. These changes are controlled by the physical environment (SST, wind regime, water column stratification, solar radiation), which are routinely measured by satellites (Friedland et al. 2018; Henson et al. 2013; Holt et al. 2016). For instance, Zhang et al. (2017) studied the change in time and amplitude of phytoplankton blooms in the North Pacific (NP) and North Atlantic (NA) over 2002–2015. They showed that in the NA the spring blooms occurred earlier and their magnitude decreased, while it was the contrary for the autumn blooms. In NP, delays and increased magnitude were observed for the spring and autumn blooms. These changes in the timing and magnitude of the biannual blooms in these two regions can have a huge impact on the marine food web and fisheries.

The case of phytoplankton is particular, since it is not simply affected by climate (e.g., via changes in SST, ocean circulation, nutrient availability, ocean acidification), but it has in turn the potential to affect climate. In fact, its huge blooms can change the Earth albedo and radiative processes, via dimethyl sulphide production (e.g., phaeocystis) which contributes to cloud condensation nuclei, or via direct sunlight reflection (e.g., coccolithophores) (Charlson et al. 1987; Hays et al. 2005; Kim et al. 2018). Phytoplankton variations in the CO_2 oceanic pump can affect global warming. This field is extremely interesting, especially if associated with tipping points that could destabilize the negative feedbacks that keep Earth's balance. Abrupt shifts in marine phytoplankton abundance or species composition can obviously have vast consequences both on the marine trophic chain and on Earth's climate. At the moment, our knowledge is not advanced enough to know whether we are near these kinds of tipping points; hence, monitoring phytoplankton, its drivers and its effects (e.g., albedo, dimethyl sulphide) on a global scale is extremely important (Kokhanovsky et al. 2020), and EO can be extremely useful.

While chlorophyll can be detected from space relatively well offshore and provide good estimates for phytoplankton, EO detection of zooplankton, or of any non-superficial organism remains constrained by EO limits (Behrenfeld et al. 2019). However, indirect, interlinked measures are continually investigated. For example, the size of productivity fronts estimated from the horizontal gradient of chlorophyll-a content appears to be directly linked to mesozooplankton biomass (Druon et al. 2019).

More specifically, the EO potential for detecting regime shifts or for providing early warnings is still undeveloped, but continually growing. A recent example is given in Beaugrand et al. (2019). Using METAL (MacroEcological Theory on the Arrangement of Life) predictions based on a single stressor—temperature—these authors have shown that abrupt shifts occurred in multiple pelagic ocean communities over the last decades, and have increased in magnitude and extent in the last few years. Their work suggests that as global temperature continues to increase, we should expect intensification of the phenomena we are already experiencing: ecosystem regime shifts, as well as biogeographic shifts, poleward migrations, local extinctions. In general, EO global SST information can be associated with ecological models for forecasts related to ecosystems shifts.

Public services with applications to tipping points are being developed. For example, EO SST data are incorporated into algorithms that provide near-real-time global maps of coral bleaching thermal stress risk (<http://coralreefwatch.noaa.gov>) (see also Melet et al. 2020). These are just a few examples. As these applications increase, and the observation time span reaches a few decades, EO data will provide more invaluable information for management, models, and forecasts.

3 Cryospheric Tipping Elements

3.1 Permafrost

3.1.1 Monitoring Permafrost

Permafrost is defined as ground, which stays frozen for at least two consecutive years. Monitoring of permafrost itself is a major challenge. The identification of its existence below ground relies on in situ measurements and boreholes. A global network exists but is still scarce (Biskaborn et al. 2015). Only a fraction of sites provides records long enough for identification of trends related to climate change. A continuous increase can be, however, reported from those which are available (Biskaborn et al. 2019). Satellite data cannot be used to directly monitor permafrost. Surface changes are used as proxy, and related observable parameters such as land surface temperature and snow are used as input for models (Trofaier et al. 2017). Only the latter can provide global information. So far, the extent of terrestrial permafrost on the northern hemisphere has been estimated from traditional sources to be 24–25% of the total land area. A new estimate, which utilized satellite records (land surface temperature and land cover), comes to 22% (Obu et al. 2019). The state of submarine permafrost is even less known as very little observations are existing. Overduin et al. (2019) estimate that about 2.5×10^6 km² of the Arctic shelves is underlain by permafrost of which 97% are currently thinning.

3.1.2 Status of Tipping Element Discussion and Drivers

Permafrost as a tipping element is quantified by its volume according to Lenton et al. (2008) and is controlled by soil temperature. Critical values of thresholds are rarely defined. Key impacts are release of methane (CH₄) and carbon dioxide (CO₂), which lead to further warming at the global scale and therefore potentially further permafrost thawing (i.e. a positive feedback related to carbon cycle). Soil temperatures increase, and the seasonal thaw layer on top of permafrost (active layer) increases. Lenton et al. (2008) suggested that projections of permafrost thaw are expected to be quasi-linear and do not exhibit threshold behaviour. This was attributed to the fact that the effect of permafrost thawing on the global carbon positive feedback is rather weak. No study convincingly demonstrated that permafrost is a tipping element according to Lenton et al. (2008). Schuur et al. (2015) also suggested gradual release of greenhouse gas emissions with permafrost thaw. However, an additional positive feedback has been recently described in the literature at a more local scale. This feedback is related to the local heat production, while the permafrost is thawing, which is caused by microbial decomposition of the soil and may further enhance permafrost thaw (Bathiany et al. 2016). Its effect is expected to become of relevance after a certain rate of local warming is exceeded (Luke and Cox 2011). This would suggest a rate-induced tipping point (Bathiany et al. 2016) which cannot be represented with a bifurcation diagram. A further issue is subsea permafrost and methane hydrates at the sea floor, for which little observations exist in general (e.g., Shakhova et al. 2017). It has been so far rarely discussed in the context of tipping elements. It is expected that methane from the permafrost affected sea floor will be gradually released rather than through an abrupt release event (Duarte et al. 2012; Lenton 2012, Schuur et al. 2015). Recent laboratory experiments, however, indicate that when the permafrost exceeds a critical temperature, rapid dissociation of gas hydrates can produce active methane emission, which means that minor warming of subsea permafrost may lead to hazardous dissociation in the Arctic shelf (Chuvilin et al. 2019).

3.1.3 Predictions

Loss of permafrost carbon is one of the expected changes which are irreversible on time scales that matter to contemporary societies (Steffen et al. 2018). This assumption is based on the strength of the permafrost carbon positive feedback by 2100 in the order of 0.09 (0.04–0.16) °C for a RCP4.5 scenario. Values do, however, increase to 0.29 ± 0.21 °C for RCP8.5 (Schaefer et al. 2014). Bathiany et al. (2016) argued that the permafrost carbon-associated feedback is not strong enough to lead to self-acceleration of permafrost thaw. Steffen et al. (2018), however, found large-scale permafrost loss a self-perpetuating response after crossing a tipping point. Loss of permafrost is expected to occur when 5 °C of warming is exceeded (Steffen et al. 2018). Model simulations from Yumashev et al. (2019) indicate that the permafrost carbon feedback is increasingly positive in warmer climates and nonlinear.

3.1.4 Potential Added Value of Satellite Data

A major issue is the limited knowledge on carbon stocks, which are vulnerable to thaw, especially regarding subsea permafrost (Bathiany et al. 2016). Accounts for storage of organic matter on land exist but are also lacking detail and consistency across the Arctic.

Interpolated maps from in situ records are currently the main source, but land cover and land surface properties, as identified from space, can be partially used to fill the gaps (Hugelius et al. 2013, Bartsch et al. 2016a). The latter specifically helps to identify near surface carbon but cannot account for larger depths as of high importance in case of peatlands.

A challenge is the heterogeneity of tundra landscapes. The mosaic of anoxic and oxic conditions adds to the complexity of processes relevant for reactions to permafrost thaw. Thaw under anoxic conditions leads to the establishment of methane producing microbial communities (Knoblauch et al. 2018). After their stabilization, the production of methane and CO₂ from these sites is equal. This leads eventually to a twice as high production of CO₂ at anoxic sites than for oxic sites. Soil wetness is determined largely by terrain, which is changing with permafrost thaw. Novel approaches are needed to represent such heterogeneity in climate models. Knowledge on current day conditions is required in a first step. Satellite data have been so far of limited applicability for this purpose due to lack of spatial resolution at pan-arctic scale to accurately represent wetland patterns (e.g., Bartsch et al. 2016b). The use of satellite data for terrestrial ecosystem modelling has been limited to coarse resolution inundation datasets in this context (Oh et al. 2020; Watts et al. 2014). Airborne observations of methane concentrations demonstrate the importance of heterogeneity in Arctic landscapes specifically related to water bodies (Elder et al. 2020). Upscaling of methane emissions based on satellite data has been so far only demonstrated at the local scale. A further aspect in this context is that thaw of soils gives also access to additional nutrients, which can increase aquatic macrophyte biomass and total CH₄ emission by 54% and 64%, respectively, in tundra wetlands (Lara et al. 2018).

Knowledge on soil type and snow cover is crucial for modelling of sub-ground temperatures as they determine heat conductivity. Changes in snow conditions affect ground thaw. This is amplified by vegetation. Shrubs advance the timing of snowmelt when they protrude through the snow surface, thereby exposing the active layer to thawing earlier in spring (Wilcox et al. 2019). Their height and thus potential snow trapping capabilities can be regionally estimated with remote sensing. Snow water equivalent can also be derived from satellite data, even producing time series over several decades, but the spatial resolution and data quality are too low to be applicable in heterogeneous permafrost landscapes (Trofaier et al. 2017).

Land cover derived from satellite data is commonly used to make assumptions about soil types, but this usually is only applicable locally (Bartsch et al. 2016b). Terrain height is changing over large areas due to the high ice content in the ground. The ice melts with increasing temperature, leading to irreversible lowering of the terrain. This can be monitored with methods such as InSAR (Interferometry using Synthetic Aperture Radar). Variations in seasonal behaviour of heave and subsidence can in addition reveal the sensitivity of certain soil types to increasing temperatures. Areas which are characterized by an organic layer on top show little change in warm years (Bartsch et al. 2019). The seasonally unfrozen layer thickness remains stable.

Earth observation has been shown to provide insight into related land surface change but cannot be directly used to identify changes of the tipping element permafrost. Consistent land surface observations and products (by satellites) of the vast land area underlain by permafrost are also still lacking to date. Satellite observations of methane concentration over the Arctic may contribute to observations of methane transport from sub-seabed sediments to the atmosphere (Angelopoulos et al. 2020; Yurganov et al. 2019) as well as the terrestrial environment but are to date not exploited.

3.2 Ice Sheets and Shelves System

3.2.1 Ice Sheets Mass Balance

Ice sheets form when snow accumulation over a continent remains from one winter to the other. Buried successive snow layers compact and turn into ice, which progressively flows towards the periphery of the continent. Surface melt might occur (mainly at the ice sheet margin) if surface temperatures allow it and, ultimately, the ice reaches the ocean, possibly comes afloat to form ice shelves and finally calves. (The limit between the grounded ice sheet and the floating ice shelves is called the grounding line.) Ice sheets retain a huge amount of water out of the ocean and have been the pacemaker of the large-scale sea-level changes during the Quaternary. For instance, during the Last Glacial Maximum, as a consequence of two massive ice sheets resting over North America (Laurentide) and Scandinavia (Fennoscandia), the global sea level was approximately 130 m below the observed current level (Dutton et al. 2015). Rapid loss of these ice sheets during the deglaciation occurred, and raised sea-level to present level in less than 10,000 years, with contribution to global mean sea-level rise (SLR) up to 4 m/century during the melt water pulse 1A (Dutton et al. 2015). Such rapid and massive contribution might have been due to large dynamical changes in the ice sheets. Nowadays, there remains approximately 58 m of equivalent SLR over Antarctica (Fretwell et al. 2013) and 7 m over Greenland (Morlighem et al. 2017). Sea level has been relatively stable during the last centuries, and ice sheets are believed to have been roughly in balance during that period, precipitation balancing mass loss by surface melt at the surface, or below ice shelves and iceberg discharges (Church et al. 2013). Since the early 1990s, Greenland and Antarctica are losing mass at an increasing rate (300 Gt year⁻¹, van den Broeke et al. 2017; and 71 Gt year⁻¹, The IMBIE team 2018, respectively), contributing together to currently raise the global mean sea level by approximately 1 mm year⁻¹ (Shepherd et al. 2012).

Remote sensing has been crucial in determining the first sign of imbalance and constraining mass loss. For instance, the retreat of the grounding line of the Pine Island Glacier in West Antarctica by about a kilometre per year has been detected using InSAR interferometry (Rignot 1998), the collapse of the Larsen B ice shelves in the Antarctic Peninsula has been recorded in March 2002 (Scambos et al. 2004), massive retreats of the front of Greenland outlet glaciers, associated with an increase in their surface velocities, have been recorded (e.g., the ice tongue of the Jakobshavn Glacier almost completely collapsed in 2003 and ice surface velocity increased from 5.7 km year⁻¹ in 1992 to 12.6 km year⁻¹ in 2003, cf. Joughin et al. 2004). In general, mass balance of ice sheets has been progressively monitored through (i) surface altimetry (e.g., Pritchard et al. 2009), (ii) InSAR measurements of surface velocities to estimate ice outflow (e.g., Rignot and Kanagaratnam 2006) or (iii) mass gravimetry (e.g., Velicogna and Wahr 2006). All these three methods progressively converged (Cazenave 2006), all highlighting similar regions of ice sheet primary concerned by mass loss, before converging on the quantity of ice flushed into the ocean (Shepherd et al. 2012). Nowadays, evolution of ice sheets, Antarctica in particular, is the main uncertainty in SLR projection for the coming centuries (Church et al. 2013). In particular, in the context of a warming environment, there is a risk that both ice sheets cross tipping points (Pattyn et al. 2018), which may lead to self-sustained massive release of ice into the ocean up to a 1-m contribution from Antarctica alone in 2100 (DeConto and Pollard 2016). Ice sheet and climate models have been decisive in understanding the underlying mechanisms behind these instabilities (e.g., Charbit et al. 2008; Favier et al.

2014; Robinson et al. 2012; Schoof 2007; Weertman 1974) which are further described for Greenland and Antarctica in the next paragraphs.

3.2.2 Instability of Ice Sheets: Driving Mechanisms

Greenland ice sheet experiences intense seasonal surface melting at its margin. In a rapidly warming environment enhanced by the Arctic amplification ($\sim +2$ °C in summer since the mid-1990s, cf. Hanna et al. 2012), melting at the surface of the Greenland ice sheet has substantially increased (Trusel et al. 2018). Large imbalance of the Greenland ice sheet is observed since the early 1990s, rising up to a 300 Gt year⁻¹ mass loss in average between 2011 and 2015, 61% of this loss being ascribed to the decrease in surface mass balance, the remaining being attributed to increase in ice discharge (van den Broeke et al. 2017). This extensive surface melting induces two intertwined positive feedbacks: (i) melting reduces the surface albedo and therefore enhances further melting, (ii) mass loss of the ice sheet leads to a progressive decrease in surface elevation, a subsequent increase in local temperature and an associated increase in melting. This might progressively lead to an obvious threshold for ice sheet sustainability: if surface mass balance becomes negative in average (i.e. no perennial accumulation of snow), the ice sheet would irremediably shrink and ultimately disappear. An ensemble of numerical simulations of the Greenland ice sheet evolution indicates that such a threshold could occur with an increase in global mean temperature above preindustrial between +1.9 and +5.1 °C (95% confidence interval) with a best estimate of +3.1 °C (Robinson et al. 2012).

Owing to much colder surface temperatures, melting of the Antarctic surface is far more limited, and outlet glaciers feed large floating ice shelves. Ice shelves exert a buttressing over upstream glaciers, limiting their outflow. A change in the geometry of the ice shelf, induced by an increase in sub-marine melt or calving, might reduce the buttressing and therefore enhance the outflow (Pattyn et al. 2018). The loss of the Larsen B ice shelf has been a prominent natural example with an up to eightfold increase in upfront glacier velocity as observed after its collapse in 2002 (Scambos et al. 2004). Following an enhanced sub-ice shelf melt (Pritchard et al. 2012), a large acceleration of the Amundsen Sea outlet glaciers has been recorded (Mouginot et al. 2014). This region is currently driving the Antarctic mass loss (The IMBIE team 2018), and it will most probably remain so in the coming century (Ritz et al. 2015). A key aspect of this region explains this fact: most of the outlet glaciers flowing into the Amundsen Sea embayment rest over a bedrock below sea level and present a retrograde bed slope (Fretwell et al. 2013). In the theoretical and simplified flow-line hypothesis, it has been demonstrated that at the grounding line, the flux of ice is a power function of the ice thickness (Schoof 2007). As a consequence, when resting on a retrograde bed slope, initial grounding line retreat leads to an increase in the ice thickness which translates into an enhanced outflow, leading to further retreat in turn: this is the Marine Ice Sheet instability (MISI, see Fig. 4, Schoof 2007; Weertman 1974). However, on an actual three-dimensional geometry, the mechanical impact of the ice shelf is crucial as buttressing can stabilize the grounding line retreat (Gudmundsson et al. 2012) and geometrical consideration on the bedrock is not sufficient enough to undoubtedly consider the glacier as unstable. Accurate ice sheet modelling is required to make progress on this complex issue. Modelling experiments of the Pine Island Glacier (Favier et al. 2014) and Thwaites Glacier (Joughin et al. 2014), the two main glaciers of the Amundsen Sea region, indicate that these two glaciers might have already initiate a MISI. Furthermore, if important increase in temperature of the atmosphere and surface melt occurs in the future, enhanced

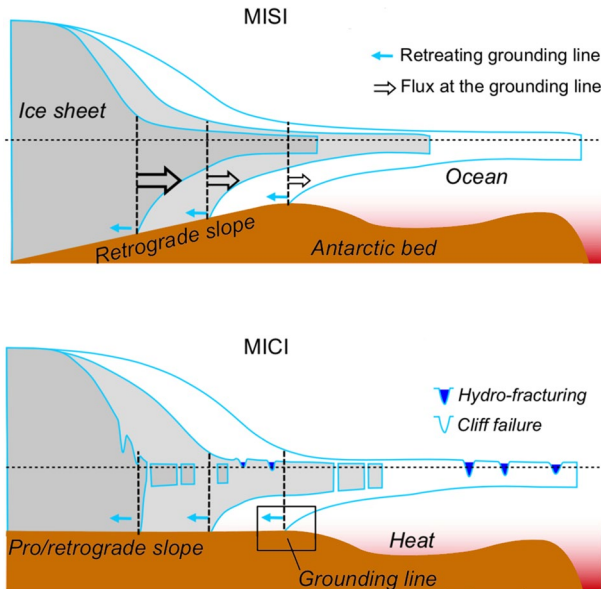


Fig. 4 Depiction of MISI (top) and MICI (bottom), adapted from Pattyn et al. (2017). Ice discharge generally increases with increasing ice thickness at the grounding line. For a bed sloping down towards the interior (retrograde bed slope) this may lead to unstable grounding-line retreat (MISI), as increased flux (for example, due to reduced buttressing) leads to thinning and eventually flotation, which moves the grounding line into deeper water where the ice is thicker. Thicker ice results in increased ice flux, which further thins (and eventually floats) the ice, which results in further retreat into deeper water (and thicker ice), and so on. MICI is the result of collapse of exposed ice cliffs (after the ice shelf collapses due to hydrofracturing) under their own weight. MISI applies for a retrograde slope bed, while MICI can also apply for prograde slopes. Both MISI and MICI are thus superimposed for retrograde slopes. The red colour beneath the ice shelf suggests that the deeper the ice the higher it is subjected to melt and grounding-line retreat (after DeConto and Pollard 2016)

fracture propagation by water (hydrofracturing) might initiate and strongly weaken the mechanical integrity of the ice shelves, therefore limiting the buttressing they exert on the upstream grounded glaciers. Ultimately, if hydrofracturing leads to ice shelf break up and formation of ice cliffs higher than approximately 100 m, they would mechanically not support their own weight and collapse, leading to the formation of even higher cliffs upstream which in turn could not sustain themselves (Fig. 4). This process named Marine Ice Cliff Instability (MICI) could strongly increase the rate of retreat, possibly leading to a 1-m contribution to SLR from Antarctica in 2100 under a RCP8.5 scenario (DeConto and Pollard 2016).

3.2.3 Intertwining Remote Sensing and Modelling: A Corner Stone to Better Apprehend Ice Sheet Tipping Points

In recent decades, remote sensing observations have highlighted the vulnerability of ice sheets, their ability to respond faster to environmental changes than previously thought and now provide a continuous monitoring of their evolution. In the meantime, owing to the

improved understanding of the previously described feedbacks that could lead to self-sustained large-scale retreat or collapse, ice sheets have been suspected to have tipping points. This has been progressively confirmed by improved understanding of processes through step changes in ice sheet numerical modelling, particularly in the ability of adequately tracking the grounding line movement and initializing the ice sheet models through assimilation of EO (Pattyn et al. 2017). Because the dynamics of the outlet glaciers has changed and might enter into a so far unobserved regime, direct extrapolation of current trends in their contribution to SLR might be misleading. Furthermore, if changes in both ice sheets mass balance will considerably affect the sea-level height, they also have the potential to strongly affect the oceanic currents. Indeed, the increase in freshwater released in the ocean might substantially reduce the salinity of the surface ocean around this region, which may increase the stratification of the surface that can crucially modify the oceanic conditions. In the North Atlantic, this may lead to a weakening of the AMOC and SPG as mentioned in Sect. 2.1, which may cool the temperature over Greenland and can be seen as a negative feedback for the ice loss (Pritchard et al. 2012). In the Southern Ocean, the input of freshwater might also mitigate the global warming effect through the enhancement of sea ice production by the oceanic stratification (Swingedouw et al. 2008). Nevertheless, this stratification also increases the subsurface warming of the ocean, which might further enhance the melting of the ice shelf at depth. It is not clear up to now, which of the processes might dominate and therefore if the ocean might act as a positive or negative feedback for the Antarctic ice sheet.

A better anticipation of ice sheet contribution to future SLR and impact on the climate system requires an improved intertwining of remote sensing and modelling. Indeed, the huge increase in the amount of data available from remote sensing since 2013 now allows high spatial and temporal survey of all the outlet glaciers of both ice sheets. Assimilation of these new data into ice sheet models will progressively allow reanalysing past ice sheet mass loss, therefore improving our understanding of the underlying processes, the part of annual and decadal variability into the observed trends, and initiate attribution studies. This will greatly improve the ability of ice sheet models to reproduce past changes and therefore give more confidence in the reliability of their projections. Integrating dynamical ice sheet models into Earth system models is a mandatory effort to further investigate the feedbacks between ice sheets, ocean, and atmosphere. This will be an unavoidable prerequisite to quantify the various tipping points, the climate conditions required to cross the identified thresholds, and determine early warning variables that could be directly observed.

4 Tipping Elements in Land and Resource Use Systems

Land and resource use systems are social-ecological systems characterized by interactions of land resources (e.g., land as space, soil, water, and vegetation), the natural environment, and human activities, such as agriculture. Tipping elements in land systems differ from the other realms because of nature-human interactions and the associated multiple drivers and complex feedbacks. Hence, there are many tipping points in land systems, which differ, depending on the land use and land management goals or focus species, and cannot be generalized (Johnson 2013). Land system change is a major factor implicated in biophysical processes affecting the functioning and resilience of the Earth system (Steffen et al. 2015). For these reasons, we deviate in this section from framing tipping elements according to

realms to framing them according to social-ecological interactions using a land use systems lens.

Many land use systems are local and have not been identified as tipping elements as such, but together with the increasingly globalized land systems (Popp et al. 2017), their combined impacts have global implications (Rockstrom et al. 2009). Land system change is a major process contributing to carbon emissions. According to the Intergovernmental Panel on Climate Change (IPCC), only 420 Gt of CO₂ can still be added to the atmosphere until around 2050 to stay below the 1.5 °C temperature threshold (Rogelj et al. 2018: 96). Steffen et al. (2015) estimate global average boundaries of phosphorous flows from fertilizers to erodible soils at 6.2 Tg per year, which have been surpassed by current values of about 14 Tg per year. Regarding nitrogen (N), Steffen et al. (2015) highlight the need to limit global average of introduced reactive N to 62 Tg N per year, although this limit is already surpassed by the current estimated value of about 150 Tg N per year. For land system change, the authors propose increasing globally the “area of forested land as a percentage of original forest cover” or for biomes “area of forested land as percentage of potential forest” (Steffen et al. 2015). Globally, they estimate retaining 75% of forested area as being “safe”, although, currently only 62% remain forested. While these thresholds are challenging to apply at local and regional scales (Hossain and Speranza 2020), countries have begun introducing and incentivising measures to reduce the adverse impacts of land system change on biodiversity and human wellbeing (United Nations 2015; Ellison and Ifejika Speranza 2020).

To illustrate tipping elements in land and resource use systems and to fit the scope of this article, we present the case of (1) forests and (2) agricultural land use. We chose these two examples as they capture many challenges facing human use of land and natural resources and their impacts for Earth system processes.

4.1 Forests

Forest systems are social-ecological systems that provide various ecosystem services—they serve as habitat for biodiversity, influence local–regional rainfall patterns, serve as carbon sinks, and regulate hydrological flows, among others (Lenton et al. 2008; Nobre et al. 2016; Ellison and Ifejika Speranza 2020). Their status depends on the land use system, which itself can irreversibly change ecosystems such as through severe land degradation including deforestation, habitat loss and biodiversity loss or extinction. Besides climate change, land use change is a key driver, and both drivers can interact to fasten ecosystem degradation. The dieback of the Amazon forest, the greening of the Sahel and linked collapse of the West African Monsoon, and the dieback of boreal forests are among the tipping elements of the Earth’s climate system identified by Lenton et al. (2008).

Boreal forests depend on a complex interplay of permafrost, tree physiology, and fire (Lenton et al. 2008). The Boreal forest dieback is associated with decreasing winter temperature, increasing summer temperature, linked to rising CO₂ emissions. These changes expose the forests to fires, insect pests, biodiversity loss (Lenton and Ciscar 2013) and their boreal transition to continental steppe grasslands (Lenton et al. 2008).

For the Amazon rainforest, land use and land cover change (LULCC) driven largely by agricultural development, causes deforestation and biodiversity loss. Nepstad et al. (2008) showed that global demand for biofuels, cash crops (soya, sugar, corn), and beef could lead to a tipping point resulting in Amazon forest degradation and forest dieback. They identified global warming, logging, drought, and forest fire to cause tree mortality and

subsequently lead to a grass and herb invasion and Amazon forest dieback (Nepstad et al. 2008). The Amazon rainforest dieback is also associated with large-scale transformation of forests to pasture, which have increased atmospheric temperature and decreased evapotranspiration rates and regional rainfall (Lovejoy and Nobre 2018; Nobre et al. 1991). This in turn can result in further droughts, fires, and biodiversity loss (Lenton and Ciscar 2013). Thus, deforested areas can influence regional climate (e.g., Lenton et al. 2019).

Changes in temperature and rainfall also influence forest conditions. Nobre et al. (2016) showed that the temperature in the Amazon region increased by 1 °C in 60 years (from 2016 backwards) and with deforestation of about 20%. Modelling studies have identified two tipping points for a transition of part of the Amazon forest to a savannah landscape—a 4 °C increase in global temperature (Lenton et al. 2008; Lovejoy and Nobre 2018; Nobre et al. 2016; Salazar and Nobre 2010) or deforestation of over 40% (Sampaio et al. 2007; Nobre et al. 2016). Lenton et al. (2008), drawing on Zeng et al. (1996), reported that part of Amazonian rainfall is recycled; hence, its deforestation causes about –30% precipitation reduction in some areas, the prolongation of the dry season and raised summer temperatures that make it difficult for the forest to recuperate (Kleidon and Heimann 2000). Among others, the El Niño–Southern Oscillation-driven fluctuations in SST have been associated with droughts affecting large forest areas (e.g., Amazon; Nobre et al. 2016). With global warming, the incidence of severe droughts and longer dry seasons may increase, thereby adversely affecting forests due to water loss and increase in forest fires (Abatzoglou and Williams 2016; Duffy et al. 2015). On the other hand, CO₂-enriched atmosphere can contribute to faster growth of trees due to CO₂ fertilization. Other factors and processes may also play a role in the fate of this complex system and are now better and better observed thanks to remote sensing (Sellers et al. 2018). An example of a threshold for the land realm is desertification, a persistent decrease in the productivity of dry lands. Indeed, an increasing literature now shows land systems can be subject to climatic hazards such as droughts and flooding, and climate change through global warming (Biggs et al. 2018). Aridification triggered by climate change may also drive desertification (Bachelet et al. 2016; Prince et al. 2018), but overgrazing can also cause desertification (e.g., semi-arid northern Eurasian agricultural frontier; Horion et al. 2016). The roles played by agricultural land use in regime shifts thus need closer attention.

4.2 Agricultural Land Use Systems

Being a social-ecological system, agriculture is dependent on biophysical conditions of soil, water, and various natural cycles, which interact with human agricultural practices aimed at producing food and fibre, among others. Agricultural production has affected land resources such as forests, wetlands, water, and soil causing biodiversity loss, water scarcity and pollution and interfering with biogeochemical cycles (e.g., carbon, nitrogen, phosphorous). In turn, as land systems are coupled social-ecological systems, agricultural practices, socio-economic, and political factors can directly and indirectly affect land use systems (e.g., through choice of production systems; agricultural subsidies) but also through land system outcomes (e.g., crop yields and incomes).

High crop yields, high chemical and fertilizer inputs, and low labour inputs are common features of intensive agricultural systems. Large-scale soy production such as in South America has established at the expense of forests. Yet, they are also exposed to various drivers, many being socioeconomic and political such as the high demand for soy as animal feed or favourable international prices for such agricultural products (Ramankutty and

Coomes 2016). These external drivers can keep the production system in a basin of attraction over decades even increasing the land areas under production (at the detriment of other land uses). Yet global price collapse or policies change (e.g., EU policy response to Bovine spongiforme Enzephalopathie by banning the use of animal protein to feed livestock) incentivised expansion of soy cropping, thus displacing other land uses (Ramankutty and Coomes 2016). Since the goal of such production systems is to maximize productivity, practices (e.g., fertilizer and herbicide application), to achieve this goal can adversely affect the underlying ecological and biophysical systems through interfering with nutrient recycling or causing soil degradation for instance. In the following, we elaborate the different ways tipping elements might evolve in agricultural land use systems.

4.2.1 Fragmented Agriculture-Forest Landscapes

Through human use of land for agriculture, landscapes in many world regions have become fragmented agriculture-forest mosaics. Features of a landscape system include habitat quality and size, connectivity, and heterogeneity, among others (Donaldson et al. 2016). Human population and activities continue to reduce animal habitats, transforming about 40% of terrestrial ecosystems to agricultural landscapes from which run-off pollute surface and underground water, thereby contributing to altering atmospheric and ocean chemistry (Barnosky et al. 2012). These have been linked to global-scale forcings such as global warming that can cause shifts in other ecosystems. Hence, local- and planetary-scale drivers interplay to drive critical transitions at planetary scales (Barnosky et al. 2012).

Although it is difficult to identify a tipping point a priori, changes in a landscape such as large-scale deforestation and fire in the Amazon can affect its hydrological cycle and trigger a shift from forest to non-forest ecosystems (Brando et al. 2014; Nobre et al. 2016). Landscape tipping points such as land cover and habitat fragmentation also result in adaptation failures whereby habitat size is no longer adequate to support certain species, hence leading to biodiversity loss (Fernández-Giménez et al. 2017; Khishigbayar et al. 2015).

4.2.2 Salt-Affected Agricultural Soils

Agricultural practices can significantly affect soil fertility in ways that critically reduce yields—a tipping point in an agri-food system. Associated land degradation processes relate to practices such as leaving soils uncovered and prone to erosion, changing the nutrient content of the soil, such as not adding nutrients to the soil (mining soils) or adding the wrong or too many nutrients to soils.

Salt-affected agricultural soils occur in many world regions, in particular in arid, semi-arid and sub-humid conditions, under rainfed and irrigated agriculture. Salinity in agricultural land has been a major factor for the collapse of past civilizations (e.g., Mesopotamia, Shahid et al. 2018). Areas affected by salt-induced land degradation include, for example, the Aral Sea Basin in Central Asia, the Indo-Gangetic Basin in India, the Indus Basin in Pakistan, the Yellow River Basin in China, the Euphrates Basin in Syria and Iraq, the Murray-Darling Basin in Australia, and the San Joaquin Valley in the USA (Zdruli et al. 2017).

Saline soils, that is, soils with electrical conductivity equal or exceeding 4 deci Siemens per metre (dS m^{-1}) at 25 °C (Shahid et al. 2018) affect crops through crop water stress, thereby influencing crop growth (for less salt-tolerant crops) and raising crop canopy temperature (Ivushkin et al. 2018). Soil salinization, that is, “salt accumulation in the root zone”, can reduce yields by up to 30% (Cherlet et al. 2018; Shahid et al. 2018). Shahid

et al. (2018) estimate that globally about 2000 ha is lost to salinization daily. Salinization can be through primary (natural processes, e.g., weathering of rock parent material) and secondary sources (human-induced—e.g., inappropriate irrigation, overuse of fertilizers, restricted drainage and replacing deep-rooted trees with shallow-rooted annual crops) (Cherlet et al. 2018). In extreme cases, salinization can lead to desertification (Daliakopoulos et al. 2016). Soil salinization can disrupt biological, biochemical, and hydrological cycles (Daliakopoulos et al. 2016), thereby affecting among others agricultural production and by extension human well-being. These changes in agricultural productivity thus have consequences for food availability but also feedback to the livelihoods and incomes of dependent social actors, which in turn can affect the choice of agricultural practices in the following season.

4.2.3 Groundwater-Based Agricultural Systems

To raise and maximize yields per unit land, agriculture has been intensified by adding external inputs such as inorganic fertilizers and extracting river and ground water for irrigation. The Central Valley in California, a semi-arid but one of the most productive agricultural regions globally, depends largely on irrigation using surface and groundwater water abstraction. In some cases, water withdrawals exceed groundwater recharge. This mode of production led to groundwater drawdowns and subsidence of about 54 cm from 2008 to 2010 (Faunt et al. 2016). Realizing the possibility of ground-water drawdown, the State of California promulgated the 2014 Sustainable Groundwater Management Act to protect its aquifers and promote sustainable groundwater use (Faunt et al. 2016). Although not framed in the language of tipping elements, the drawdown of aquifers will likely necessitate a reduction in irrigated croplands.

4.2.4 Agricultural Fertilizer Management

Fertilizer application can increase crop yields, but it can also adversely influence nutrient cycles. Agriculture contributes about 60% to global anthropogenic emissions of nitrous oxide (N_2O), a major greenhouse gas (Syakila and Kroeze 2011). Changes in the global nitrogen (N) cycles are associated with the persistent increase in use of N fertilizer, slurry, and low nitrogen use efficiency (NUE). N and phosphorus fertilizer application have been linked to eutrophication of lakes in agricultural landscapes (Le Moal et al. 2019; Schindler et al. 2016). Reactive nitrogen is also implicated in soil degradation and loss of biodiversity and diminished quality of drinking water (Le Moal et al. 2019). While low food production in many world regions, in particular Africa, has been attributed to low fertilizer use and negative nitrogen (N) balances, high use of inorganic fertilizer adds N to soils and can lead to nonlinear increases of N_2O emissions (Hickman et al. 2015). Lu et al. (2019) identified thresholds in N fertilizer use rate for corn and winter wheat, over which NUE starts declining, in other words, when crop yields slow down. Dari et al. (2018) propose using the soil P storage capacity (SPSC) and soil P saturation ratio (PSR) to determine the amount of P to add to a soil and in that way reduce P runoff to the wider environment. Improving NUE (in fertilizer application and livestock production), including integrated fertilizer management, is thus critical (Fageria and Baligar 2005).

4.2.5 Multiple Feedback in Land and Natural Resource Use Systems

Because natural and human systems are coupled, a change in an environmental tipping point can lead to a change in ecosystem services such as food and changes in socio-economic variables such as food prices and human well-being. In response to climate change, biomass-based climate mitigation technologies are increasingly promoted. Biomass Energy with Carbon Capture and Storage (BECCS) may affect food production such as planting trees that compete for land and water resources with food production. In places where climate change causes water scarcity, it may limit the extent to which BECCS can be deployed to maintain carbon emission budgets (Séférian et al. 2018). In turn, the water demand from BECCS is likely to cause declines in available water, thereby raising water scarcity and further constraining the deployment of BECCS-based mitigation (Séférian et al. 2018).

Changes in land use systems can disrupt ecosystem processes such as primary production, nutrient and water cycling, or soil formation, among others (Biggs et al. 2018). Through land use practices, biodiversity and ecosystem services (e.g., food crops and fibre, water regulation, soil erosion regulation) may change in ways that adversely affect human well-being (food and nutrition, livelihoods, and land use). This in turn, may feedback to intensify adverse land use practices (e.g., deforestation, leaving soil bare, overgrazing) that positively feedback in further disruption or collapse of certain ecological processes. Such tipping land system elements can be at a local scale (e.g., a degraded watershed) or at a regional scale (e.g., tropical forests such as the Amazon), but they are also known to connect across scales (e.g., many local level deforestation and land degradation contributing to global greenhouse gas emissions) (Rockstrom et al. 2009). Timescales of regime shifts thus depend on the social-ecological system and can range from weeks to centuries (Biggs et al. 2018).

4.2.6 Reversibility in Agricultural Land Use Systems

Some regime shifts are irreversible while some show hysteresis. The degradation and loss of land resources can be (ir)reversible depending on the resource and the time scale. For instance, draining peatlands for crop farming has often led to an irreversible change in the amount of soil organic matter, soil biodiversity, and caused soil subsidence (Könönen et al. 2018). Studies on irrecoverable carbon show that peatlands and mangroves are most at risk as the average time it takes to recover carbon in these ecosystems is at least 100 years (Goldstein et al. 2020). Recovery can be slow, thereby requiring long-term monitoring. McCrackin et al. (2017) in a meta-analysis of 89 studies found recovery periods in lakes and coastal marine ecosystems affected by eutrophication to range from 10 to 34 years for phosphorous- and nitrogen-cycles variables after a complete reduction in nutrients application.

4.3 Using Remote Sensing Data for Monitoring and Identifying Tipping Elements in Land and Resource Use Systems

Very few studies approach land and resource use systems directly from a tipping element lens, although one can argue that monitoring can provide early warning about tipping elements. Generally, combining data from optical sensors and radar instruments helps use the synergies between these different sources. Multi-sensor (combining optical and radar information) and multi-methods approach that combine statistical, object-oriented or machine

learning methods are increasingly applied (cf. Ali et al. 2016; Chlingaryan et al. 2018). As land and resource use systems are heterogeneous, we provide illustrative examples of how remote sensing products or Earth observation data are used for monitoring and early warning for identifying tipping points.

Depending on availability of long-term time series, four statistical measures can be used as early warning of an approaching tipping point—increase in autocorrelation, skewness, variance and exceeding a threshold (Krishnamurthy and Krishnamurthy 2016). However, a long-term time series against which a tipping point can be identified relative to baseline is often missing for some variables.

Most approaches applying remote sensing data for monitoring or to identify tipping points use historical time series data; hence, remotely sensed data often serve as a basis for subsequent statistical analysis and simulation modelling of conditions/drivers that are likely to trigger regime shifts. Change detection, that is comparing remote sensing images of different dates or time series to identify changes or differences in land cover and land use, is often a first step to identifying tipping points in social-ecological systems. Change detection such as through time series data analysis is often followed by spatial statistics, numerical modelling or scenario planning to identify potential tipping points in the system. While remote sensing studies have often examined the spatial and temporal variations in a particular phenomenon, e.g., increases and decreases in vegetation greenness (Eckert et al. 2015), few of them have explicitly applied the concept of “tipping points” to identify thresholds (e.g., a shift from grasslands to forests or vice versa) in a land use system.

The use of indices to monitor the spectra of various land cover remains widespread. Often, similar indices are applied for vegetation monitoring, whether for forests, crops or for grasslands. Such indices include the normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), soil-adjusted vegetation index (SAVI), and the normalized difference salinity index (NDSI). Break points in NDVI time series have been used to monitor vegetation changes (Browning et al. 2017; Burrell et al. 2017). At global scale, root-zone soil moisture observations have been derived from the Soil Moisture and Ocean Salinity (SMOS) mission (Dumedah et al. 2015).

4.3.1 Tipping Points in Vegetation (Forests, Grasslands, Croplands) Conditions

Image analysis in land use and resource systems usually involve identifying a time series of several years (often more than 10 years) and calculating NDVI as a proxy for vegetation biomass production. Decreases in NDVI or “negative slopes in NDVI residuals” are then interpreted as vegetation degradation, while “positive slopes in the NDVI residuals” indicate improved vegetation (Fernández-Giménez et al. 2017). Tipping points in vegetation conditions can be inferred from monitoring trends in baseline vegetation (Barnosky et al. 2012), identifying sharp declines in vegetation greenness indices (e.g., NDVI) and Land Surface Water Index (LSWI) (Zhou et al. 2017), from solar-induced chlorophyll fluorescence (SIF) values (Sun et al. 2017) and from evapotranspiration (ET) levels (Fisher et al. 2017).

Fernández-Giménez et al. (2017) used remote sensing data to monitor forage use and increased grazing pressure on rangelands, cropping density, shifts in plant species/vegetation and other changes in biomass conditions. Fernández-Giménez et al. (2017) conducted a trend and tipping point analyses of time series Advanced Very-High-Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data of Mongolian rangelands and identified significant increases in the AVHRR NDVI over

1982–2012. Using residual trend analysis, no trends in the residuals of human-induced change were detected after filtering out the effects of climate from human activities except in Western Mongolia, or when considering the combined effect of temperature and precipitation. A residual trend analysis of MODIS NDVI (2000–2013) also showed no significant trends. Using the coefficient of variation (CV), and 5-year moving windows for standard deviation and autocorrelation, they identified increasing trend in variability of forage production, which they interpreted as a potential tipping point in rangeland conditions (Fernández-Giménez et al. 2017).

Often, other non-remote sensing data (e.g., in situ data) are required for a comprehensive analysis of social-ecological tipping points. For example, Fernández-Giménez et al. (2017) also integrated data on livestock population dynamics and percentage forage use over time to strengthen their identification of potentially approaching tipping points for the Mongolian rangelands.

Using MODIS NDVI and RADAR Vegetation Optical Depth (VOD) monthly data time series of evergreen tropical forests across Africa, Southeast Asia and South America, Verbesselt et al. (2016) showed that declining rates of recovery captured by temporal autocorrelation can be used to identify thresholds for collapse of tropical forests facing drought and high temperatures. Using additive regression models, they analysed the dynamics of tropical forests as a function of mean annual precipitation (MAP) using TRMM data and showed that temporal autocorrelation steeply increases as MAP decreases to levels identified as being critical (e.g., 1500 mm) for tropical forests. They suggest that “critical slowing down” identified in satellite time series data can also be applied as an indicator in other tipping elements such as boreal ecosystems, lakes and drylands.

Similarly, Xu et al. (2016) used vegetation structure (e.g., tree cover and canopy height) as a composite indicator of a tipping point. Xu et al. (2016) distinguished three vegetation states at global scale, namely tropical forest, savannah, and treeless landscapes according to mean annual precipitation tipping points of 600, 1500 and 2000 mm. Using LiDAR estimates of canopy heights and MODIS-derived tree cover data and MAP data, Xu et al. (2016) identified three canopy heights (~40, ~12, and ~2 m) to correspond to “forest, savannah and treeless landscapes”. They show that tropical forests respond to rainfall in a discontinuous manner as forests rapidly decline at 1500 mm MAP, while at 600 mm, trees no longer characterize the landscape (Xu et al. 2016). According to the authors, the identified modes align with the hypothesis of a “forest-savannah bistability” in areas with an average yearly rainfall ranging from ~1500 to ~2000 mm.

4.3.2 Land Use Driven Forest Loss and Fragmentation

Land use-driven forest loss and fragmentation increase the vulnerability of species to environmental influences and act as forerunners of a tipping point characterized by the extinction of species (Drechsler and Surun 2018; Taubert et al. 2018). Factors driving forest and land use systems towards tipping points are largely socio-economic and political although a natural hazard such as a hurricane or a flood can fasten the process (Drechsler and Surun 2018; Nepstad et al. 2008). Here remote sensing can provide insights by identifying and monitoring such threatening processes. Applying percolation theory to a global forest cover map made from high-resolution remote sensing imagery and simulation modelling of forest fragmentation, Taubert et al. (2018) identified patterns that indicate fragmentation of tropical and sub-tropical forests is near a critical point of percolation. Their analysis of forest fragmentation dynamics showed the number of forest remnants initially increased

slowly but their numbers abruptly increased (in a few decades) after passing a critical point with many more forest remnants of decreased sizes (Taubert et al. 2018). Observations from remote sensing confirmed the authors' simulation of forest fragmentation.

4.3.3 Monitoring Non-vegetation Variables in Agriculture

Remote sensing data have also been used in monitoring other variables in land and resource use systems, to assess soil salinity (Ivushkin et al. 2018), aquifer volume and groundwater drought (Thomas et al. 2017; Vasco et al. 2019), and temperature warming over landscapes and oceans (FEWS NET 2018a, b). It has been used to identify hotspot areas of high N inputs and to model biogeochemical processes of N flows in agricultural systems (Liu et al. 2020). Threshold values have been applied for phosphorous monitoring to reduce eutrophication in lakes (Schindler et al. 2016).

Thomas et al. (2017) used NASA's GRACE satellite mission data to quantify groundwater storage deficits in California's central Valley, enabling them to capture groundwater drought. Using InSAR, Vasco et al. (2019) could better match the identified change in aquifer volume in the valley with point observations, an improvement compared to using only the GRACE data.

4.3.4 Monitoring Food Insecurity and Famine

Remote sensing-data analysis also informs exposure to natural hazards of different intensities (Helderop and Grubestic 2019), hazard planning and preparedness. Slow-onset natural hazards such as droughts can cause the drying up of vegetation, crop loss, food insecurity, and famines. Remote sensing data are thus a critical data source for famine early warning systems. The Famine Early Warning Systems Network combines the Climate Hazards Infrared Precipitation with Stations (CHIRPS), Rainfall Estimates Version 2.0 (RFE2), and Africa Rainfall Climatology Version 2 (ARC2) data and mean annual eMODIS NDVI data in a tool to assess agro-climatology, rainfall, and vegetation conditions as a season progresses (FEWS Network 2018a, b). It uses the coefficient of variation as compared to normal standard deviation to monitor food security (FEWS Network 2018b). Interpretation of these and other data such as the water requirements and phenology of crops, and regional seasonal forecasts provide early warning on impending food crises, hence contributing to forestalling tipping points in food systems. It then uses the Integrated Food Security Phase Classification (IPC) scale to identify food insecurity conditions (FEWS Network 2018a, b).

Choularton and Krishnamurthy (2019) found the Famine Early Warning Systems Network food security projections to be generally of high accuracy in Ethiopia. However, they identified decreased accuracy of FEWS Network food security early warning during extreme events such as the 2015/16 El Niño and in data-scarce areas in Ethiopia. From a tipping point perspective, they also found mixed forecasting accuracy in the transition phase from "food security to food crises" (Choularton and Krishnamurthy 2019). Other remote sensing-based crop monitoring systems include among others, China's global crop-monitoring system (CropWatch; Wu et al. 2014), the European Commission AGRI4CAST program (European Union 2019) or the FAO Global Information and Early Warning System (GIEWS) (FAO 2019).

A fused image multispectral SPOT imagery 10 m and panchromatic SPOT of 2.5 m have been used to derive population vulnerability to natural hazards (Zeng et al. 2012). Ahmed et al. (2017) used multi-temporal MODIS NDVI time series and Landsat-8 OLI derived data to assess the impact of a 2017 flash flood on rice production in Bangladesh. By delineating the areas affected by the flash flooding, estimates were made about the acreage of crop damage and impact on food security, which if extreme, may indicate a tipping point in inability of dependent land users to meet their food security. Such information can be further processed with other spatial data to identify the proportion of population affected, thereby providing insights on likely social tipping points.

Most of the literature focussing on use of remote sensing data for identifying tipping points in land and resource systems infer tipping points or regime shifts from monitoring time series—an approach that rather looks back instead of looking forward. Hence, most remote sensing-based analysis for tipping points in land and resource use systems either use remote sensing data as baseline or draw on them to confirm results from simulation modelling. Steps usually include identifying a potential driver, a change-point in time such as detecting a significant change in the mean, using the coefficient of variation, nonparametric statistical tests of difference between periods, trend analysis, applying principal component analysis and chronological clustering (Andersen et al. 2009; Fernández-Giménez et al. 2017). Other analyses apply spatial modelling in Geographic Information Systems, statistics or scenario analysis to identify potential tipping points in land and resource systems (cf. Ali et al. 2016; Thellmann et al. 2018).

Using remote sensing as an early warning for tipping points in land systems thus often draws on additional data such as census and livelihoods data to determine, for example, food security status and potential population at risk. The assumption is that if such adverse environmental (land cover) and resources (e.g., water availability) conditions continue, biophysical drivers (e.g., rainfall, drought, hurricanes) might lead to a socio-economic collapse of dependent livelihoods and economies. Remote sensing data thus provide critical data for tipping point analysis in land and resource use systems.

5 Synergies for Cascading Tipping Points

The different tipping elements of the climate system may interact with each other, potentially leading to a cascade of tipping points. For instance, a large weakening in the AMOC in the future may induce a southward shift of the Inter Tropical Convergence Zone (ITCZ) which may strongly affect the precipitation in the Sahelian region, potentially triggering social tipping points in these regions. The study by Defrance et al. (2017) evaluated that the decrease in precipitation associated with a ~70% weakening in the AMOC can reduce the available cultivable area for sorghum down to a million of square kilometres, thereby affecting tens of millions of inhabitants of this region. To reach such estimates, this study coupled off-line—integrating one model after the other, not a two-way coupling—a climate model with a crop model and then a demographical estimate for the near future. This example illustrates the potential interactions between tipping points explored in Sect. 2.1 and 4 of this paper. We argue here that further research will be certainly useful to improve these first rough estimates and start thinking of some adaptation scenario to such an event.

Such a catastrophic scenario drawing attention to the potential interaction between different tipping elements has also been highlighted in Cai et al. (2016). They suggested that a rapid melting of the Greenland ice sheet can trigger a collapse of the AMOC, itself

modifying the ITCZ in the tropical area which may amplify the Amazon dieback in its northern part, warm the Southern Ocean, push the West Antarctic ice shelf beyond a critical threshold, and induce large sea-level rise in the coming centuries. The impact of an AMOC collapse on marine biology would be also large, changing primary production (e.g., Mariotti et al. 2012), while it may provide a negative feedback for the permafrost loss. Nevertheless, the lack of precise estimates of the different thresholds and interactions between tipping elements prevent to have a clear idea on the likelihood of such a suit of events.

Research on such cascading events remains very limited at the moment. Nevertheless, even low probability events remain key for adaptation measures especially if they carry potentially huge consequences. As suggested by Sutton (2018), the scientific community needs to further improve its risk assessment by also evaluating the exact impact of these low probability yet rapid events to start preparing appropriate adaptation and mitigation measures.

Additional examples of huge impacts on human society when crossing key thresholds include the potential implication of sea-level rise from shrinking ice sheets, even on a long time scale. The impacts on populations and urban areas could be enormous as most megacities are located along the coasts (IPCC 2019). Also, the melt of glaciers in the mountains means a critical change in livelihood activities in certain areas (Collins et al. 2019). These few examples clearly highlight that crossing some tipping points might have crucial implication on human livelihood and ecosystems survival. As Lenton et al. (2019) state, these events are “too risky to bet against” and a wait and see approach is not appropriate at all.

6 Conclusions

In this paper, we have reviewed a few pieces of knowledge concerning different tipping elements of the Earth system with a specific focus on how remote sensing data can help to make progress in their understanding and how they can provide some early warning signals of an approaching tipping point. The main findings and assessments are summarized in Table 1.

We have highlighted that two systems of ocean circulation in the Atlantic are considered to be at risk of crossing a tipping point. These are the large-scale Atlantic Meridional Overturning Circulation (AMOC) and the more local North Atlantic subpolar gyre (SPG). The risk of an AMOC collapse is considered to be low at the end of the twenty-first century whatever the emission scenario (Collins et al. 2019), while there is a chance of about one in two that of an AMOC collapse in 2300 if we follow a strong emission pathway (RCP8.5, Bakker et al. 2016). The impacts of an AMOC collapse are potentially huge so that, even though the risk is low at the end of the twenty-first century, it is a scenario to be considered and preparation to adaptation may be useful, notably in the Sahelian region. Concerning the SPG, the risk of a collapse in the coming century is larger than for the AMOC, since the proximity to a convection threshold is potentially close to present-day conditions as shown in Sect. 2.1. The time scale of the response is faster (one decade) relatively to AMOC. However, the climatic and societal impacts are far lower and may mainly moderate the warming of the North Atlantic region. A few studies have used remote sensing to improve estimates of AMOC variations in the past through the use of oceanic fingerprints, but a lot still remains to be done and some original ideas are emerging by coupling data from different types of satellites. In any case, the use of in situ measurements

Table 1 Synthesis of the knowledge concerning the different tipping elements, in terms of time scale of abrupt change, irreversibility potential of the change, regions impacted, and a rough assessment of the likelihood of bifurcation (i.e. system switching to an alternative state), depending on the emission scenario

Realm	System	Time scale of abrupt change	Irreversible	Regions impacted	Likelihood of bifurcation in the 21 st century	Use of EO
Ocean circulation	AMOC	Centuries	Yes	Global, including monsoon systems and phytoplankton production	< 10% whatever the scenario, but larger for high emission scenario	In its infancy but promising
	SPG	Decade	Yes	Atlantic bordering region	~50% whatever the scenario	In its infancy but promising
Marine ecosystems	Coral reefs	Decade	Probably	Reefs worldwide	Not clarified	Advanced
	Pelagic ecosystems	Decade	Unlikely	Worldwide	Not clarified	Advanced for phytoplankton. Indirect for zooplankton but promising
	Fish communities	Decade	Possibly	Worldwide	Not clarified	None
	Species extinctions	Decades to century	Yes	Worldwide	Not clarified	None
Permafrost	Terrestrial (carbon cycle)	Gradual, but under discussion	Yes, regarding permafrost carbon	Arctic and Global through carbon cycle	Not clarified (rather gradual/ rate induced change)	In its infancy but promising
	Submarine (carbon cycle)	Gradual, but under discussion	Yes, regarding permafrost carbon	Arctic shelves	Not clarified	In its infancy but promising
Ice sheets	GrIS and AIS	Centuries to millennia	Yes	Global through SLR	high for global mean temperature increase 1.5-2°C above pre-industrial average.	Advanced
Terrestrial resource use	Various – forests (Amazon, boreal)	Varying	Varying	Forest biomes, global	Possible but varies	Advanced
	Agricultural land use systems	Varying	Varying	Various local-regional scales	Possible but varies	Progressing

The last column indicates the use of EO for monitoring the systems: *Low* means that EO of these systems are not yet developed; however, indirect measurements can be developed; *Medium* means that indirect measurements are being developed for monitoring these systems; *High* means that direct or indirect measurements are already key in the monitoring protocols

appear to be still necessary at the moment to correctly assess variations of these complex three-dimensional oceanic circulations, notably beyond 2000 metres depths, which is the present-day limit of ARGOS floats.

The ocean circulation is still poorly observed from space. The coupling between in situ observations and different remote sensing data like altimetry and gravimetry can be very useful to assess the three-dimensional changes in circulation and density properties. Also, the recent acquisition of SSS is very promising, but still need to be evaluated, notably in the high latitude where the resolution and precision might be very poor (Estella-Perez et al. 2020). Coupling this different source of information, using data assimilation techniques may be promising and may help to reduce the large uncertainty that is found for the moment in large-scale ocean circulation from oceanic reanalysis (Karspeck et al. 2017).

The inclusion of remote sensing data within climate models through assimilation is a key avenue to make progress on early warnings based on models. It has to be noted that decadal prediction systems are still in their infancy and are confronting the difficult challenges avoiding the effect of model bias on their predictions. These decadal prediction systems use initialized forecast in the ocean and explore the diversity of potential responses due to chaos and noise through relatively large ensemble of simulations. Once refined, they will be of great help evaluating the risk and proximity of crossing a threshold in ocean circulation systems.

With regard to marine communities, regime shifts have occurred at some point in every habitat where long-term data exist. These shifts have so far been identified by historical time series observations because marine animals (be that transparent zooplankton, or deep-sea fishes) are mostly invisible to satellites, and also because the Earth observations (EOs) time series did not go back in time enough. Detecting tipping points in marine animals can be potentially done via proxy, and since temperature has been found to be a primary driver (or a co-driver) in most ecological shifts, global scale, long-term SST satellite measures continue to be essential.

The trends of change of phytoplankton concentration (as indicated by EO of ocean colour) over the past twenty-plus years are still uncertain. Current trends indicate an increase in the size of most oligotrophic areas although more observations are needed to confirm these results. Combining ocean colour radiometry observations with data assimilation will help to merge different sensors and to distinguish trends. For the detection of trends in ocean colour (phytoplankton mainly) and tipping points, it is necessary to continue the development of new sensors and to plan them in advance (such as the Sentinel-3 program from the European Space Agency) for avoiding holes in the measurements (as it happened in Europe between MERIS (2002–2012) and OLCI (2016–)). A huge gap could be filled in by merging standard passive ocean colour radiometry measurements with active observations such as Lidar. Lidar can provide information on the water column (up to 50 metres) and coupled with standard ocean colour sensors and bio-Argo floats could lead to a three-dimensional view of the ocean (Hostetler et al. 2018; Jamet et al. 2019).

With regard to the topic of tipping points in marine ecosystems, the future belongs to studies linking these variables to ecological communities and to applications for management, such as the coral reef heat risk alert maps (see Melet et al. 2020) and to improved algorithms related to early warning for tipping points, for example, changes in variance and autocorrelation in multiple variables (Carpenter and Brock 2006; Lindegren et al. 2012). New types of biological global-scale models based on EO are being implemented to anticipate as early as possible regime shifts in the pelagic ocean. They are operational, and their implementation may help in the real-time detection of regional regimes shifts (Henson et al. 2010). Nevertheless, at least thirty years of continuous EO are needed to observe the impact of climate change and to observe tipping points. Particular attention must be paid to the Arctic Ocean, an area strongly impacted by global climate change, where severe biological shifts are currently expected.

In recent decades, there have been huge investments at European and international scale aiming to develop and implement effective ocean observing capacity, some including in situ observatories and EO (among which EOOS (<http://www.eoos-ocean.eu>), Jerico, Jerico next (<http://www.jerico-ri.eu>; mostly in situ data but also radar), and of course the ESA Sentinels), which are providing an enormous amount of new knowledge. What is needed now, with regard to tipping points, is to incorporate tipping point knowledge in their algorithms and products, so in addition to global patterns and trends, they can start providing early signals for tipping points and relative alerts (taking into consideration that this is a field under development).

Permafrost monitoring relies largely on in situ data which are scarce, specifically long time series. There are different views on whether permafrost is a tipping element, whether it exhibits threshold behaviour. Recently, described processes such as heat production by microbial decomposition lead to a different view: a rate-induced tipping point. The strength of the permafrost carbon feedback effect is debated. It is argued that it is rather weak, but the loss of carbon is irreversible on time scales that matter to contemporary societies. Different views also exist on self-perpetuating response after crossing a tipping point. Remote sensing data can be used as proxies for permafrost-related processes to address some of these issues but has not been extensively used yet in this context. Knowledge on soils and landscape heterogeneity is crucial. The fusion of land cover information and terrain change is expected to be the key to utilization of satellite data.

Inconsistent acquisition strategies for high-to-medium resolution satellite data are one of the main issues for land applications. This applies specifically to permafrost-related monitoring, a phenomenon which occurs over 22% of the Northern Hemisphere terrestrial environment. Also, here, merging active and passive observation methods may provide the required information, especially to address the issue of the permafrost carbon feedback.

EO of the Greenland and the Antarctic ice sheets revealed during the last two decades an increasing trend in their mass loss. This resurrects a long-standing hypothesis on possible instabilities of ice sheets resting on a bedrock below sea level, the so-called Marine Ice Sheet Instability (MISI). Recent progress in ice sheet modelling tends to confirm that the Pine Island and Thwaites Glacier flowing into the Amundsen Sea might be engaged in a self-sustained retreat which might possibly initiate a massive collapse of the West Antarctic Ice Sheet on centennial to millennial time scales. However, this remains to be confirmed by further modelling efforts to better constrain the threshold before the retreat and subsequent rate of mass loss. Undoubtedly, increasing the duration of remote sensing observations is mandatory to better constrain the models and validate the simulations.

Land use can drive tipping elements in terrestrial resource use systems such as the Amazon forest dieback, the greening of the Sahel and the dieback of boreal forests, and influence climate-land feedbacks. As land and resource use systems result from interactions between social and ecological systems, tipping points in land use systems differ depending on land management goals and type of terrestrial systems, making their monitoring difficult. EO has mainly been used for change detection analysis in these tipping elements. Identifying tipping points in land and resource use systems is still largely based on analysis of historical observations (time series) with identification of likely future tipping points mainly dependent on additional statistical analysis, modelling and increasingly machine learning approaches.

Remote sensing can aid early warning for identifying tipping points in landscape systems, land cover and land use fragmentation, as well as the linkages between fast and slow

onset natural hazards with land and resource systems. However, this is mainly through a retrospective “historical approach” and in some cases with only a short lead time between an ecological condition (e.g., drought) and its consequences (food scarcity). The advent of data from new sensors such as the greenhouse gas sensors (cf. Sellers et al. 2018) can complement data derived from optical sensors to infer how climate affects the carbon cycle especially during El Niño event, and by extension, potential dynamics in land and resource use systems. However, complex statistical and numerical modelling is likely additionally needed for assessing tipping points in the complex climate-land coupled system.

As some features are not directly observable from Earth observations, the interacting links between components (e.g., SST and precipitation or vegetation-rainfall connections such as for the Amazon) indicate that a variable may serve as a proxy indicator. Hence, observing such factors (e.g., SST) can provide complementary information on the potential dynamics of land cover and vegetation condition. One way of looking forward in addition to using historical time series EO data is therefore to monitor other related variables associated with land conditions such as is done in drought monitoring. Hence, instead of monitoring land conditions using normalized difference vegetation index (NDVI), monitoring SST and ocean circulation, which predate drought occurrences on land even by a few weeks, can provide early warning of impending drought or floods. Also, Sellers et al. (2018) report that satellite data on greenhouse gases can be related to terrestrial photosynthesis through solar-induced fluorescence (SIF), thus providing information on the net ecosystem exchange (NEE) of CO₂, photosynthesis of gross primary production (GPP), and the burning of fossil and biomass.

Furthermore, vegetation–climate feedbacks as well as the influence of global warming and links to large-scale circulations (e.g., the AMOC) mean that land-based mitigation and adaptation measures may be limited in their effectiveness in the face of collapse of such large-scale circulations—this raises the question of combining spatial and temporal scales of EO. Land-based actions (e.g., reforestation) can be effective in the short term and at a regional scale to ameliorate the impacts of climate change and climate variability on ecosystems and dependent livelihoods. Yet, the prospect of the collapse of the AMOC indicates a further need for other responses that adequately consider the global ramifications and highlight the uncertain outcomes of the interactions between multiple drivers (e.g., vegetation–climate interactions, global warming, SST and changes in regional or large-scale circulations) and cascading effects on other tipping elements. Hence, more studies are needed that explore the links between the different factors or multiple stressors and how well they serve as early warning of tipping points.

Generally speaking, remote sensing observations are still covering a short time frame. This is a crucial issue to correctly identify anthropogenic forced variations from natural variability. Also, classical early warning methods that necessitate long time frames can hardly be applied to the different tipping elements analysed here, based only on remote sensing EO. Nevertheless, the knowledge gained from EO concerning the different systems analysed is clear and may help to improve the modelling of these systems. Indeed, given the limit of the statistical methods to provide early warnings, modelling is an alternative to estimate from large ensembles the risk of crossing a threshold for a given tipping element. Currently, the uncertainty concerning the value of key variables and the thresholds of tipping elements is usually very large, necessitating improvements in the modelling of these elements. The interactions between the different systems have been highlighted here as another key aspect of development. Coupling effectively numerical and process-based models of the different realms will help to better evaluate the risk of cascades of tipping points, which are very poorly evaluated at the moment. Such an approach will necessitate further multi-disciplinary approach, which we encourage, to go from the physical and biogeochemical information concerning nonlinearities

to the potential societal nonlinear responses. Even though some of such scenarios are believed to be low-probability from present-day models (which usually exhibit strong limitations), their impacts are potentially so large that we cannot risk not accounting for them in the adaptation policies that are developed worldwide.

Acknowledgements We thank Teodolina Lopez and Anny Cazenave from ISSI who organized the Workshop leading to this review paper. We acknowledge very constructive and inspiring comments from one anonymous reviewer that clearly helped to improve the manuscript clarity. DS is supported by Blue-Action (European Union's Horizon 2020 research and innovation program, Grant Number: 727852) and EUCP (European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 776613) projects. CIS' inputs contribute to the Programme on Ecosystem Change and Society (www.pecs-science.org) and the Global Land Programme (www.glp.earth). AB benefited from Nunataryuk project (H2020 Research and Innovation Programme under Grant Agreement No. 773421) as well as ESA Climate Change Initiative project on Permafrost (4000123681/18/L-NB). GD was supported by the TIPACCs project (European Union's Horizon 2020 research and innovation programme, Grant Number: 820575).

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