The Implications of the Recently Recognized Mid-Twentieth Century Shift in the Earth System

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Abstract:	Satellite observations offering detailed records of global environmental change are only available from 1979. Emerging studies combining high-quality instrumental and natural observations highlight that the Earth system experienced a substantial shift across the mid-twentieth century, one that appears to have taken place before the Great Acceleration of human activities from the 1950s. These new results have far-reaching implications for understanding ice-ocean-atmospheric interactions in the Anthropocene and the urgent need for drastic cuts in carbon emissions to limit the impact of future warming.

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Keywords: Antarctic; Anthropocene; Atlantic Meridional Overturning Circulation (AMOC); carbon emissions; climate change; Earth system thresholds; Paris Climate Agreement; Southern Ocean; tipping elements; tipping points.

There is an increasing realization that human activity has led to a profound, long-term shift in the operation of the Earth system that exceeds natural variability (Ripple et al., 2019). These changes appear to occur several decades after the start of the 'Great Acceleration' in global economic activity, consumption and human population after the Second World War (Steffen et al., 2015), an acceleration that was paralleled by increases in Earth System indicators such as atmospheric carbon dioxide (CO_2), methane and nitrous oxide, along with declining stratospheric ozone concentration (Steffen et al., 2020). The onset of global, geological-scale impacts arising from human activity since the mid-twentieth century are widely considered to mark the start of the Anthropocene epoch, although the precise onset is an area of ongoing research (Waters et al., 2018; Waters et al., 2016; Lewis and Maslin, 2015; Turney et al., 2018).

Whilst satellite observations offer highly-resolved measurements of recent, and often dramatic, environmental changes, continuous observations are only available from 1979 (Caesar et al., 2018; Jones et al., 2016), limiting our ability to understand global drivers(s), tipping elements and teleconnections across the Earth System (Chung et al., 2019; Thomas, 2016; Steffen et al., 2020; Steffen et al., 2018). Surface records through the Anthropocene offer to extend some of these time series but are geographically sparse before the 1950s (Mauelshagen, 2014). Here we focus on the relatively short duration of scientific (instrumental) observations of the Earth System **and describe the insights offered by alternative records of environmental change that offer considerable potential for reducing** projection uncertainties in an accelerating and more extreme, warmer Anthropocene world (Steffen et al., 2018; Caesar et al., 2018; Steffen et al., 2020).

There is a particular dearth of scientific observations in the mid to high latitudes (**notably the Antarctic**), where some of the greatest rates of change are currently seen (Jones et al., 2016; Trusel et al., 2018; Medley and Thomas, 2019; Miles et al., 2018; Kennicutt et al., 2019) and which have the potential to cause irreversible global impacts (IPCC, 2018). Ironically, these large rates of change appear to have taken place in many regions since continuous instrumental stations were first established (for instance, in the Antarctic during the International Geophysical Year 1956/57). This has led to increasing efforts to exploit the relatively untapped instrumental records archived around the world (for instance, using ship logs as highlighted by the Atmospheric Circulation Reconstructions over the Earth program; ACRE) to drive climate model reanalysis and reconstruct past weather back to the nineteenth century. This work is being supplemented by 'natural archives' of sub-annual to multi-decadal variability derived from climate-sensitive proxies preserved in high-resolution archives such as ice cores, tree-rings and peat sequences**, many from regions for which no instrumental observations exist.** These natural archives offer considerable potential to extend the instrumental record and gain new insights into the Anthropocene (Mann et al., 2008; PAGES 2k Consortium, 2013; Emile-Geay et al., 2017). **Whilst not offering the spatial coverage of satellite observations available since the late twentieth century, integration of natural archives with long instrumental observations provides an important baseline against which to detect long-term change and the emergence of a new 'anthropogenic' state as the Earth system shifts beyond what might be considered 'natural'.**

Whilst numerous studies have identified a long-term global temperature increase from the late nineteenth century (the 'pre-industrial period'), the relative roles of natural variability and anthropogenic warming remain uncertain globally and regionally (Abram et al., 2016; Turney et al., 2019). The potential offered by natural archives to help resolve this issue has recently been highlighted by a number of studies combining high-quality instrumental and

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natural archive observations that have identified a mid-twentieth century change across the Earth system that appears to exceed natural variability **and pre-date continuous satellite observations** (Steffen et al., 2018; Caesar et al., 2018; Trusel et al., 2018; Smith et al., 2017; Turney et al., 2017; Roxy et al., 2014; Marvel et al., 2019) (Fig. 1). This recognition of a global step-change in the Earth system has far-reaching implications for our understanding of ice-ocean-atmospheric interactions and the urgent need for substantial reductions in carbon emissions to limit the impacts of future warming.

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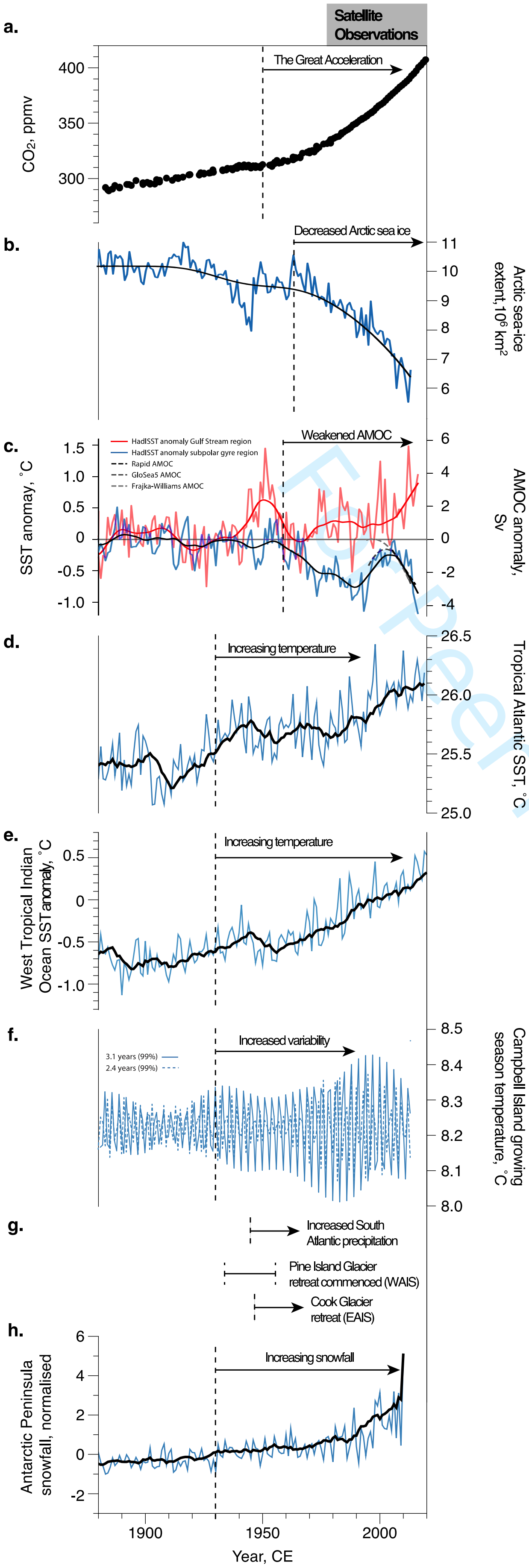

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Figure 1: Key climate and environmental datasets showing the mid-twentieth century shift in the Earth system. **Panel a: Tasmania's Cape Grim observations of atmospheric carbon dioxide (CO_2) back to the 1970s (https://www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/Latest-greenhouse-gas-data) and trapped air measurements reconstructed from the Antarctic Law Dome ice core (Etheridge et al., 1996), with onset of the Great Acceleration (Steffen et al., 2015) and the duration of continuous satellite observations (since 1979). Panel b: Observed changes in Arctic sea-ice extent (Trusel et al., 2018; Walsh et al., 2017). Panel c: Observed and reanalysis-derived measures of Atlantic Meridional Overturning Circulation (AMOC) (Caesar et al., 2018). Panel d: Mean annual tropical Atlantic (20˚S to 20˚N) sea-surface temperatures (SSTs) derived from HadISST and extracted using KNMI Climate Explorer (Rayner et al., 2003; Li et al., 2014b; Trouet and Van Oldenborgh, 2013). Panel e: Mean annual West Tropical Indian Ocean (WTIO; 10˚S to 10˚N, 50˚ to 70˚E) SSTs derived from HadISST and extracted using KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013; Rayner et al., 2003; Roxy et al., 2014). Panel f: Reconstructed subantarctic Campbell Island austral growing-season temperature (October-March) (Turney et al., 2017). Panel g: High southern latitude changes represented by increased south Atlantic (Stanley, Falkland Islands) austral spring/summer precipitation (Turney et al., 2016), reconstructed onset of retreat of Pine Island Glacier in West Antarctica (Smith et al., 2017) and Cook Glacier retreat in East Antarctic (Miles et al., 2018). Panel g: Reconstructed normalised snowfall on Antarctic Peninsula derived using a network of snow and ice cores (Thomas et al., 2017). Solid lines denote decadal running means. Vertical dashed lines denote inflection of individual datasets, consistent with a sustained mid-twentieth century change prior to the onset of continuous satellite observations.**

Alignment of natural archive climate reconstructions with long observational records from key parts of the Earth system have detected a mid-twentieth century shift across both hemispheres**, in some regions prior to the onset of the Great Acceleration in 1950** (Figure 1). For instance, temperature-sensitive tree-ring records from the Southern Ocean reveal a sustained increase in climate variability from the 1930s, and appear to be associated with increasing projection of tropical Pacific warming on the mid-latitude westerly wind belt

(Turney et al., 2017). Similar trends and associations have been observed in the Indian Ocean since the mid-twentieth century (Rodrigues et al., 2019; McIntosh and Hendon, 2018; Roxy et al., 2014). These teleconnections have extended to higher latitudes via an atmospheric Rossby wave train (a so-called 'atmospheric bridge'), driving temperature and precipitation trends over the subantarctic Atlantic and Antarctic Peninsula (Medley and Thomas, 2019; Thomas et al., 2018) that are unprecedented over recent millennia and have led to a greening of ice-free areas (Kennicutt et al., 2019; Turney et al., 2016). Recent work has highlighted that feedbacks associated with southern high-latitude warming can extend back to the tropical Pacific, with global implications (England et al., 2020). The changing teleconnections between ice-ocean-atmospheric systems does highlight the risk of interpreting modes of variability informed by calibration data that represent a shifting climate state in a non-natural system, implying some reconstructions may be conservative. Of particular concern, however, is these changes appear to have resulted in increasing sub-surface ocean temperatures near the grounding lines of numerous Antarctic glaciers, including the western Thwaites Glacier (Smith et al., 2017) and eastern Cook Glacier (Miles et al., 2018), the latter a part of the Wilkes Subglacial Basin that holds an estimated 3 to 4 metres of equivalent global sea level rise **(Mengel and Levermann, 2014)**.

Mirroring the above, another step change that pre-dates satellite observations is seen in seasonal atmospheric circulation changes in the Northern Hemisphere (Figure 1). Here, the high northern latitudes experienced similarly large changes that pre-date satellite observations, substantially greater than the global mean ('polar amplification') (Bekryaev et al., 2010; Kim et al., 2019). For instance, a sustained change in seasonal atmospheric circulation has been recognized as a major cause of Arctic warming since the 1940s, resulting in dramatic sea ice and Greenland ice mass loss, exceptional in the context of at least the last 350 years (Trusel et al., 2018; Kinnard et al., 2011) (Figure 1). Observations made by ocean traffic across the North Atlantic since the nineteenth century, in combination with climate model simulations, suggest a parallel 15% weakening of the Atlantic Meridional Overturning Circulation (Caesar et al., 2018), resulting in pronounced surface cooling from the reduced northward transportation of warm waters (Figure 1). Such changes in ocean circulation have potentially global impacts: here, the warming equatorial waters have been linked to increased penetration of Rossby wave trains into the higher latitudes (Kennicutt et al., 2019; Li et al., 2014a), similar to that observed in the Pacific, possibly accounting for the spatial contrasting trends in Antarctic sea ice since 1979 (Kennicutt et al., 2019). Improvements in the parameterization of Earth system models capture this newly observed sensitivity to greenhouse gas forcing (Caesar et al., 2018; Marvel et al., 2019).

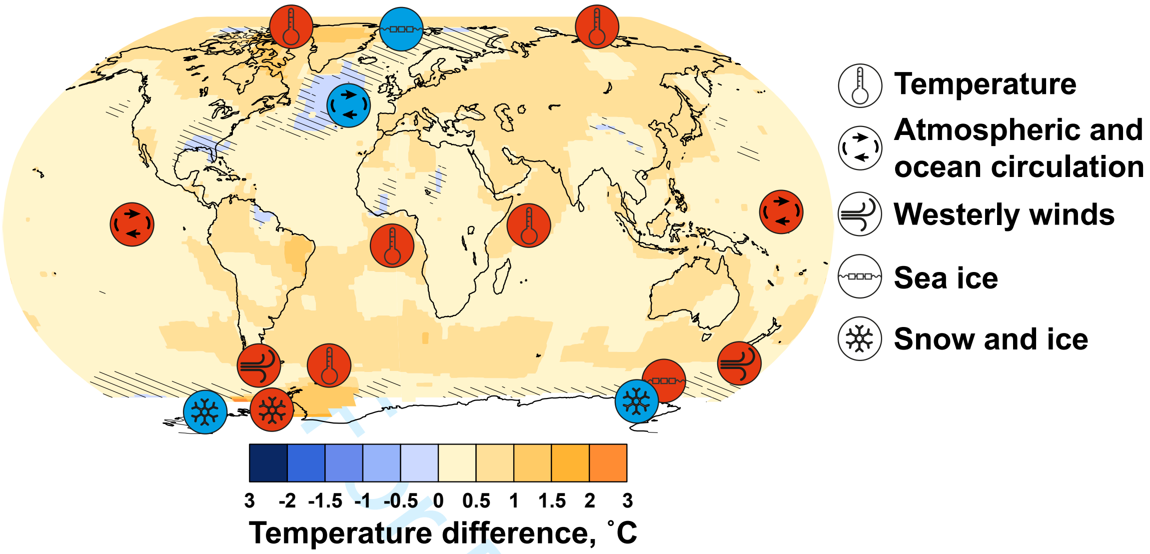

Figure 2: Global distribution of mid-twentieth changes in the Earth system. **The globe shows mean surface temperature differences between the two periods 1901-1950 and 1951-2018, derived from Goddard Institute for Space Studies (GISTEMP v3). Hatching represents areas where the signal is larger than one standard deviation of natural variability, determined using KNMI *Climate Change Atlas* (https://climexp.knmi.nl).** Red-colored symbols denote long-term increases in one or more components of the Earth system described in the text; blue symbols denote decreases in the component of the Earth system.

Despite this recent work, there remain remarkably large knowledge gaps in some regions of the planet that based on our current understanding of the Earth system, are considered to be globally significant. There is an urgent need to prioritise the development of datasets that capture a more 'natural' state of variability during the first half of the twentieth century, most notably in Antarctica and the Southern Ocean (Jones et al., 2016). Furthermore, these observed changes in ice-ocean-atmospheric teleconnections highlight the risk of producing multi-centennial reconstructions of climate modes of variability 'calibrated' by contemporary observations that represent a shifting climate state (Liu et al., 2017). As increasing modelling efforts are made to forecast future changes under different emission scenarios, it is imperative a global interdisciplinary approach is undertaken to integrate these with instrumental and natural archive records to truly capture natural variability, teleconnections and trends. A focus on developing datasets in the first half of the twentieth century – before the full emergence of an anthropogenically-changed climate state – will likely improve with the calibration of proxy records for palaeoclimate reconstructions. Such coordinated international efforts will greatly help determine the trajectories and identify thresholds across all parts of the Earth system, supporting societal decision making into the future (Ripple et al., 2019).

It therefore seems that until recently, our understanding of the human impact on the Earth system was substantially skewed by continuous satellite observations which only began in 1979. If the relatively sparse instrumental records which extend back through the twentieth century and beyond are combined with the growing number of 'long' records reconstructed from natural archives, a new perspective emerges: that the Earth system experienced a substantial shift across the mid-twentieth century (Figure 2), one that appears to have been underway before the Great Acceleration of human activities from the 1950s. These studies underline the importance of baseline observations that extend back in time to capture 'natural' conditions before the emergence of an anthropogenic influence (Caesar et al., 2018; Marvel et al., 2019).

A major question that this recent work immediately raises from a policy point of view is whether the scientific and political communities have been blindsided over recent observations? Whilst satellite observations provide exquisite details into how the Earth system has operated since 1979, natural and instrumental archives are providing a richer story with considerable implications:

1. First and foremost, the new studies suggest the global climate system is highly sensitive to greenhouse gases, more so than hitherto thought. With atmospheric CO_2 concentration now exceeding 410 ppm – higher than at any time since the Pliocene (2.6 to 5.3 million years ago) – and emissions continuing to rise, there is an urgent need to 'bend the curve' and drastically cut global carbon emissions (Ripple et al., 2019; IPCC, 2018).
2. Secondly, and deeply worryingly, the multi-decadal warming trend in the Arctic appears to have exceeded the 'natural' background state before many other regions, implying the high northern latitudes are particularly sensitive to forcing, and may have already tipped the Earth system into an cascade of changes that has since been

observed during the 40-year satellite era (Trusel et al., 2018). In the Antarctic, recent dramatic loss of ice appears to have been primed by conditions during the 1940s (Smith et al., 2017; Miles et al., 2018; Kennicutt et al., 2019), highlighting the significance of past changes for amplifying the impacts of current and future forcing.

Whether natural feedback systems will accelerate us into an irreversible 'Hothouse Earth' remains to be seen (Ripple et al., 2019; Steffen et al., 2018) but given the above changes occurred with global warming of <1˚C, it seems likely that the 2˚C target identified in the Paris Climate Agreement is an optimistic threshold for many, if not all, parts of the Earth system (Schellnhuber et al., 2016), raising serious concerns over society's ability to successfully plan robust adaptation or mitigation strategies. With the United Nations Climate Change Conference in Glasgow (COP26) now delayed until 2021, there is an urgent need to use the available time to build a global consensus for considerably more ambitious targets to cut carbon emissions. Given the magnitude of changes observed across the twentieth century, **humanity** cannot delay any longer.

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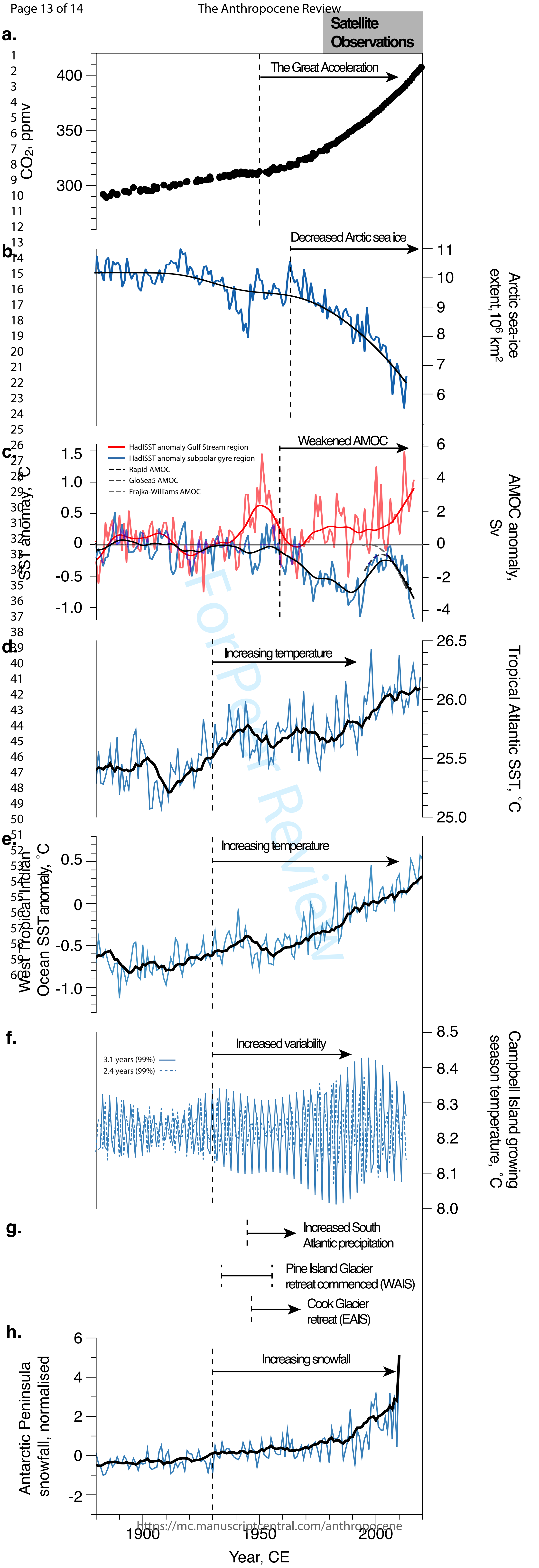
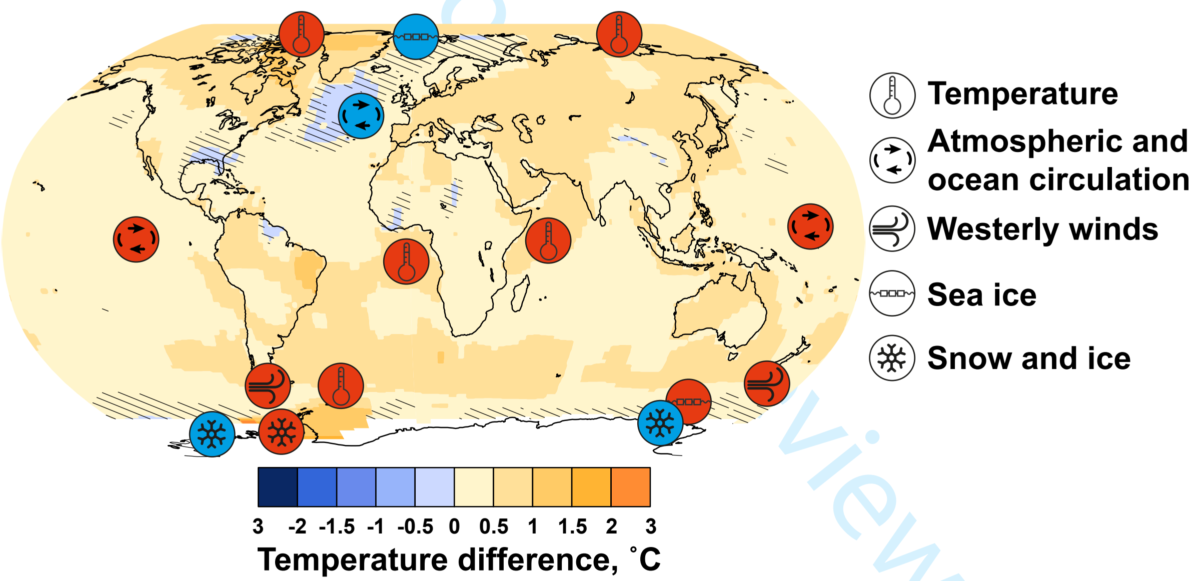

Satellite Observations
a.
The Great Acceleration
CO_2, ppmv
400
350
300
b.
Decreased Arctic sea ice
Arctic sea-ice extent, 10^6 km^2
11
10
9
8
7
6
c.
Weakened AMOC
HadISST anomaly Gulf Stream region
HadISST anomaly subpolar gyre region
Rapid AMOC
GloSea5 AMOC
Frajka-Williams AMOC
SST anomaly, °C
AMOC anomaly, Sv
d.
Increasing temperature
Tropical Atlantic SST, °C
26.5
26.0
25.5
25.0
e.
Increasing temperature
West Tropical Indian Ocean SST anomaly, °C
f.
Increased variability
3.1 years (99%)
2.4 years (99%)
Campbell Island growing season temperature, °C
8.5
8.4
8.3
8.2
8.1
8.0
g.
Increased South Atlantic precipitation
Pine Island Glacier retreat commenced (WAIS)
Cook Glacier retreat (EAIS)
h.
Increasing snowfall
Antarctic Peninsula snowfall, normalised
1900
1950
2000
Year, CE


Temperature
Atmospheric and ocean circulation
Westerly winds
Sea ice
Snow and ice
3 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 3
Temperature difference, ˚C