effectively couples the westerly winds at higher altitudes to the near-surface winds, producing brief but fast westerlies at the surface whenever a storm occurs.

Charnay *et al.* next examine how these brief westerly storm gusts affect net sand transport over a Titan year. They use a combined wind model that takes the annual cycle of predominantly easterly winds from a global atmospheric model, and adds fast storm westerlies at both equinoxes. For a sufficiently high saltation threshold, they find that the westerly sand transport dominates, explaining the west to east motion of Titan's equatorial dunes (Fig. 1).

That winds strong enough to produce sand movement occur rarely suggests that Titan's equatorial dunes are old. Ewing *et al.*[6] used measurements of dune reorientation in Cassini Radar images to estimate that Titan's dunes form on timescales longer than 88 kyr. This is much longer than diurnal or seasonal timescales, and roughly twice as long as the precession period of Saturn's perihelion, which controls the season when Titan is closest to the Sun. But, as noted by Ewing and colleagues, this timescale is a lower limit because they assume a saltation threshold of zero[5] and thus a large sand transport rate. A more realistic threshold would produce a smaller sand transport rate, yielding a longer timescale. Using the high saltation threshold required to produce west to east dune motion, Charnay *et al.* estimate an average sand transport rate two orders of magnitude smaller than that used by Ewing *et al.*, yielding a dune formation time

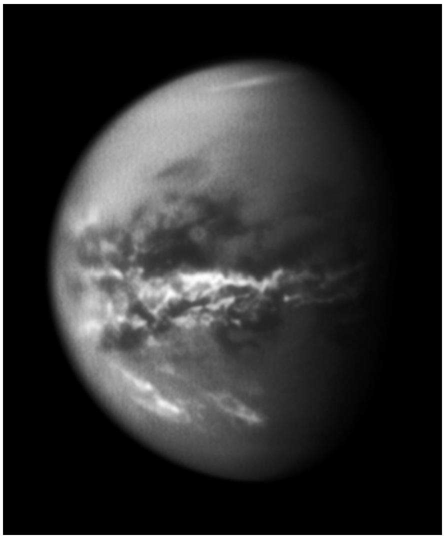

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Figure 2 | Storm clouds near the equator of Titan as imaged by the Cassini spacecraft in late 2010, shortly after northern spring equinox.

of about 15 Myr — a timescale much longer than orbital cycles.

The combined wind model of Charnay *et al.* also explains some other features of Titan's dunes. For limited sand availability, linear dune crest orientations will align with the net sand transport direction[7]. Averaging results over simulations with perihelion at the current and opposite time of year to reflect the long timescales of dune formation, the predicted and observed dune orientations match well in several regions, particularly polewards of about 15°. However, numerous mismatches exist at lower latitudes. This may be due to a lack of topography in the global model. Also, some dunes may have formed in unlimited sand, in which case dunes orient such that sand transport perpendicular to the crest is maximized[8].

Charnay *et al.*[4] suggest that the west-to-east motion of Titan's equatorial dunes is due to fast westerlies generated during infrequent methane storms. Fully understanding Titan's dunes requires consideration of a wide range of timescales, from the hours or days involved in a single methane storm to the tens of thousands of years over which Saturn's orbit precesses. Sand availability, topography, gravitational tides due to Titan's eccentric orbit of Saturn, and details of the saltation process are also likely to be important to the formation and evolution of dunes. ❐

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HOLOCENE CARBON CYCLE

Climate or humans?

Analyses of ice-core carbon isotopes show that variations in atmospheric CO_2 levels during the past millennium are controlled by changes in land reservoirs. But whether climate variations or human activity were mainly responsible is uncertain.

Jed O. Kaplan

The thousand years of human history that led up to the Industrial Revolution established the political, technological and cultural foundations of the modern world. Over this interval, roughly AD 800 to 1800, climate variations may have affected societies[1], but there is also the possibility that human action influenced the global environment[2]. Ice cores are unparalleled archives of past environmental changes: the record of CO_2, represents the competing effects of carbon sources and sinks. The isotopic composition of CO_2 provides additional clues to the relative importance of the different sources and sinks. Writing in *Nature Geoscience*, Bauska and co-authors[3] identify fluctuations in atmospheric CO_2 concentrations during the past millennium that occur against a background of major societal change.

Bauska *et al.*[3] measured atmospheric CO_2 concentrations and the carbon isotope composition of that CO_2 in bubbles from the West Antarctic Ice Sheet Divide ice core, for the period from 760 to 1850. Their record shows two main features over that period: a general decline in atmospheric CO_2 concentrations from the beginning of the twelfth to the beginning of the nineteenth centuries, and superimposed on this long-term trend, increases and decreases lasting on the order of several decades. Combining the CO_2 and carbon isotope records in a mathematical technique called double deconvolution — this is essentially a two-equations-two-unknowns problem —

Bauska *et al.* conclude that the main sources and sinks of atmospheric CO_2 over the period of record were in the terrestrial biosphere as opposed to the oceans.

However, understanding which sources and sinks of carbon on land were most important over the period of the study is more difficult; the different carbon pools and biosphere processes do not have unique carbon isotope signatures. The millennial-scale decline in atmospheric CO_2 concentrations reflects a persistent carbon sink by the terrestrial biosphere.

Peatlands are one potential sink[4], but human activities could also have resulted in carbon sequestration. Soil erosion in Eurasian agricultural landscapes accelerated during the last millennium[5]. This sediment would have eventually found its way into rivers, lakes, reservoirs and the oceans, burying organic carbon[6,7]. This sedimentary sink would have been augmented by the storage of carbon in the expanding area of continuously cultivated rice paddies[6].

The decadal to centennial variations in atmospheric CO_2 concentrations seen in the record are even more fascinating. Easily mobilized carbon is abundant in natural ecosystems from tropical forests to boreal soils; short-term variations in emissions from uptake in these pools could be caused by climate variability. Bauska *et al.* suggest that a combination of Arctic and tropical temperature variability, or possibly Northern Hemisphere temperature more generally, can explain the observed changes in atmospheric CO_2 concentrations.

Bauska and colleagues do, however, not explore in detail how important events in human history could also have influenced carbon stocks. For example, the small drop in atmospheric CO_2 concentrations around 900 corresponds with the sharp decline and displacement of Mesoamerican populations at the end of the Classic Maya period[8]. The rise in CO_2 from 975–1080 corresponds not only with a period of accelerating urbanization[9] and deforestation (*Les grandes défrichements*)[10] in Western Europe but also with the Chinese Song Dynasty, which is known for a sixfold increase in iron production[11] and the widespread expansion of agriculture south of the Yangtze[12] (Fig. 1). In contrast, the second half of the fourteenth century saw widespread land abandonment and reforestation related to social turmoil caused by a series of severe droughts in Asia[13] and the Black Death in Europe[10]. These historical events correspond with a sharp drop in atmospheric CO_2 concentrations. The establishment of a massive frontier of deforestation and agricultural development across the landscapes of eastern and northern Europe as a result of Dutch commercial innovations[14] may be responsible for the rapid rebound in CO_2 concentrations shortly thereafter. These developments were, however, dwarfed by the impact of the collapse of the indigenous populations of the Western Hemisphere following European contact. A regrowth of forests and reduction in burning in the Americas can explain much of the drop in CO_2 levels observed between 1530 and 1620[15].

By 1700, atmospheric CO_2 concentrations had started their relentless, exponential rise towards the modern era. Global gross domestic product in 1700 was $371 billion (1990 international dollars), by 1820 it had nearly doubled[16]. Coal production in Britain increased sixfold from 1700 to 1815; the total carbon emissions of British coal consumption in the eighteenth century could have approached 0.5 Gt (ref. 17), equivalent to about a year of modern UK emissions. Colonization in the Americas, Australia, and along the Eurasian steppe frontier led to the rapid expansion of agricultural land with concomitant losses in forest and soil carbon stocks.

The close correspondence between CO_2 concentrations and major events in human history points to the fact that the world's socioeconomic system left its mark on atmospheric CO_2 concentrations centuries before the industrial revolution[18]. Climate variations such as the Little Ice Age probably played a role in influencing ecosystems at ecological limits such as alpine and polar timberlines, as Bauska *et al.* suggest, but in my opinion, human action provides a more parsimonious explanation for both the long-term trend and decadal variability in CO_2 observed in ice cores.

The ice-core data reported by Bauska *et al.*[3] provide robust insights into the timing and magnitude of carbon cycle changes during the past millennium, and show that these changes were mainly controlled by terrestrial sources and sinks. To what extent the fluctuations were caused by climatic variations or human activities continues to elude us. ❐

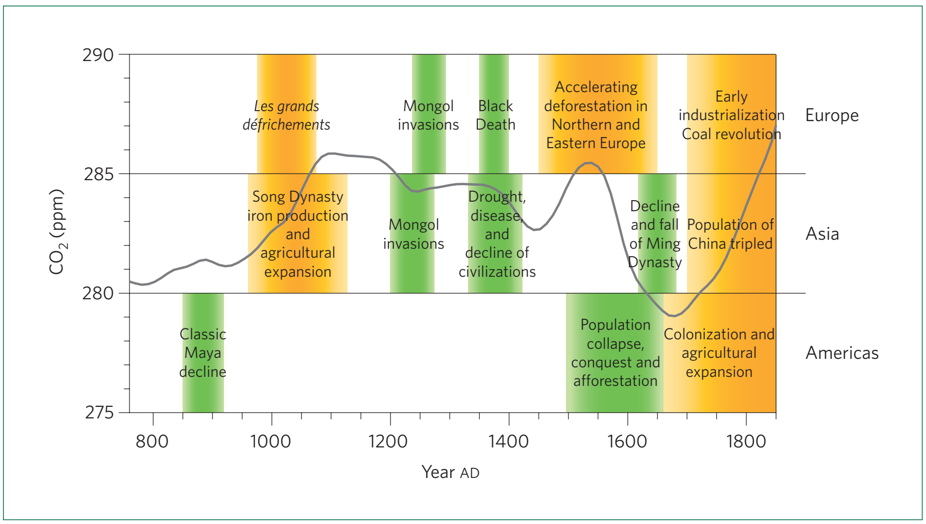

Figure 1 | Humans and carbon dioxide. Bauska *et al.*[3] have shown that in the 1,000 years leading up to the Industrial Revolution, atmospheric CO_2 concentrations fluctuated as carbon moved between terrestrial sources and sinks. Although they favour a climate-related explanation, the timing of changes in atmospheric CO_2 concentrations also coincide with changes in the world system that could have released (orange) or sequestered (green) carbon. Gradients indicate that some events in human history both built up and declined in intensity over time, and that the impact on atmospheric CO_2 would also be subject to a time lag.

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