The global turbidity current pump and its implications for organic carbon cycling

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ABSTRACT

Submarine turbidity currents form the largest sediment accumulations on Earth, raising the question of their role in global carbon cycles. It was previously inferred that terrestrial organic carbon was primarily incinerated on shelves, and most turbidity current systems were presently inactive. Turbidity currents were thus not considered in global carbon cycles, and global terrestrial organic carbon burial efficiency was low-to-moderate (~10-44%). However, recent work shows burial of terrestrial organic carbon by turbidity currents is highly (>60-100%) efficient in a range of settings, and flows occur more frequently than once thought, although they were far more active at sea-level low-stands. This leads to revised global estimates for mass-flux (~62-90 MtC/yr) and burial efficiency (~31-45%) of terrestrial organic carbon in marine sediments. Greatly increased burial fluxes during sea-level low-stands are also likely underestimated, thus organic carbon cycling by turbidity currents could play a role in long-term changes in atmospheric CO_2 and climate.

INTRODUCTION

Seafloor avalanches of sediment called turbidity currents form the largest sediment accumulations (termed submarine fans), deepest canyons and longest channel systems on our planet (Talling et al. 2015). Turbidity currents have a very wide range of runouts and speeds, but some flows can travel for hundreds or even thousands of kilometers (Piper et al. 1999; Talling et al. 2007), making them the longest sediment flows on Earth (Talling et al. 2022). Some flows sustain speeds of 5-8 m/s for over a thousand kilometers (Talling et al. 2022) or reach speeds of ~20 m/s (Piper et al. 1999; Gavey et al. 2017). Only rivers carry similar amounts of sediment over such large areas (Milliman & Farnsworth 2011; Syvitski et al. 2022) but sediment transport by turbidity currents is far more episodic, and a single event can transport more sediment than the combined annual flux from all rivers (Talling et al. 2007). For example, a turbidity current in the North-east Atlantic in 1929 carried ~25 times the modern global riverine annual sediment flux for ~800 km (Supplementary Figure 1; Piper et al. 1999; Syvitski et al. 2021). The mass of sediment carried by turbidity currents thus rivals any other global sediment transfer system (or 'pump'), including rivers, glaciers or vertical settling of sediment from the surface ocean (Fig. 1a).

As turbidity currents are one of the most important sediment transfer processes ('pumps') on Earth (Fig. 1a; Supplementary Figure 1), this raises the question of their importance for transfer and burial of organic carbon (OC) in that sediment. Indeed, turbidity currents can produce rapid sediment accumulation (e.g., 0.5-20 cm/year (Dennielou et al. 2017)), which favours efficient OC burial.

Efficient burial of OC within marine sediment may play a role in atmospheric CO_2 drawdown, impacting global climate over times scales of thousands of years or longer (Hilton & West, 2020). However, many previous influential analyses of global carbon burial in the oceans neglected the role of turbidity currents (Berner et al. 1982, 1989, Hedges et al. 1997, Burdige 2007, Blair & Aller 2012), assuming that terrestrial OC supplied by rivers was buried almost exclusively within deltas or other parts of continental shelves (Table 1). These past studies have also inferred that most terrestrial OC was remineralised on continental shelves, as occurs offshore from the Amazon River (Aller, 1998, Nittrouer et al. 2021), such that the present day global burial efficiency of terrestrial OC in marine sediments was relatively low (10-44%; Table 1). In addition, previous models (e.g. sequence stratigraphic; Posamentier & Kolla 2003) have concluded that present-day turbidity current systems are mainly inactive (Fig. 2c), as global sea-level rise during the Late Holocene flooded continental shelves. Sea-level rise detached the majority of submarine canyon-heads from river mouths; only ~180 of ~9,500 canyon heads currently extend to river mouths (Harris et al. 2014, Bernhardt & Swanghart 2021).

There is growing recognition that a wide range of turbidity current systems have remained active in modern times (Fig. 2d), which are not just the small number of systems globally where river-mouths still connect directly to canyon heads (Khripounoff et al. 2012, Liu et al. 2012, Bonneau et al. 2014, Azpiroz-Zabala et al. 2017, Talling et al., 2022), but include some systems fed by longshore drift (Covault & Graham 2010; Paull et al. 2018), or those where canyons are separated from river mouths by wider shelves (Rogers & Goodbred, 2010, Heijnen et al. 2022a). At these locations, burial of terrestrial OC can be highly efficient (Galy et al. 2007, Kao et al. 2007, Sampere et al. 2008, Bao et al. 2015, Baudin et al. 2020). For example, the Bengal Submarine Fan offshore from the Ganges and Brahmaputra Rivers is the largest sediment accumulation on Earth, and these two rivers alone account for 8-10% of the terrestrial OC transferred by rivers to oceans (Galy et al. 2007, Milliman & Farnsworth 2011). An analysis of seabed cores and comparisons to riverine sediment samples showed negligible loss of terrestrial OC in the deep-sea fan (i.e. 100% burial efficiency) (Galy et al. 2007). Other studies also concluded terrestrial OC burial by turbidity currents can be highly efficient in fjords (Smith et al. 2015, Bianchi et al. 2020, Hage et al. 2022), or in turbidity current systems fed by small mountainous rivers, such as offshore Taiwan (Kao et al. 2014, Bao et al. 2015). Efficient OC burial in these systems is linked to unusually rapid sediment accumulation within turbidity current deposits ('turbidites'), resulting in low O_2 penetration depth (a few centimeters) in seabed sediment (Galy et al. 2007, Rabouille et al. 2017, 2019).

It was once thought that turbidity currents were impractical to measure in action, due to their ability to damage sensors in their path, or flush them into the deep-sea (Kneller & Buckee 2002). However, over the last decade or so, turbidity currents have been measured in detail at a series of locations worldwide in a variety of settings (e.g. Khripounoff et al. 2012, Hughes Clarke 2016, Azpiroz-Zabala et al. 2017, Paull et al. 2018, Hill & Lintern 2022, Talling et al. 2022). Direct flow monitoring consistently found that turbidity currents were much more active than previously inferred by many (e.g. sequence stratigraphic) models (Posamentier & Kolla 2003). For example, multiple powerful (up to 6 m/s) turbidity currents occurred over ~1 year in Whittard Canyon, despite this canyon's head being located >300 from the coast (Heijnen et al. 2022a). Turbidity currents occurred even in canyons fed by rocky shorelines that lack obvious sediment sources (Normandeau et al. 2020). Powerful flows also occurred on open slopes outside submarine canyons (Hill & Lintern 2022), and over 100 flows occurred on a Canadian fjord-head delta in ~3 months (Clare et al. 2016), whilst flows occurred for 30% of the time in the river-connected Congo Submarine Canyon (Azpiroz-Zabala et al. 2017). This direct flow monitoring has been combined with sediment cores, and time-lapse seabed mapping that constrains sediment mass fluxes, to provide important new insights into how turbidity currents transfer and bury OC (Hage et al. 2020, 2022, Maier et al. 2019). For example, monitoring of turbidity currents that originated in the Congo Estuary showed how turbidity currents can efficiently transfer terrestrial OC to the deep-sea (Talling et al. 2022). Turbidity currents that travelled for > 1,100 km were associated with major river floods, but triggered weeks to months later at spring tides. They flushed a sediment mass equivalent to 19-35% of the global annual river sediment flux, down just one submarine canyon, in a single year (Talling et al. 2022). Monitoring also shows how sediment and OC transfer to the deep-sea occurs in multiple stages, effecting residence times and loss of OC (Heijnen et al. 2022b; Hage et al. 2022; Talling et al. 2022).

These new developments mean that it is timely to assess the role of turbidity currents in global cycling of OC at the present day. This includes whether previous estimates of modern global terrestrial OC burial in marine sediments of ~40-80 Mt/C/yr (Burdige 2005, 2007) need to be revisited (Table 1) and how turbidity current system types affect carbon cycling. Organic carbon burial efficiency by turbidity currents would have been far higher during glacial times (Cartapanis et al. 2016), when lower global sea-levels ensured that almost all rivers connected directly to submarine canyon heads (Harris et al. 2014). This review therefore also briefly assesses whether previous work (Cartapanis et al. 2016, 2018) may have underestimated glacial-interglacial variability in global terrestrial OC burial by turbidity currents (e.g., Cui et al. 2022).

The overarching aim of this paper is to assess the role of turbidity currents in OC cycling, especially that of terrestrial organic carbon. To do this, it addresses the following specific questions.

(1) What sources of OC do turbidity currents contain, and what controls their fate? (2) Do turbidity currents segregate different organic carbon types en-route: is there a leaky pipeline? (3) How does OC cycling by turbidity currents work in different types of setting, and what are the main controls on burial efficiency? (4) Do we need to revise global estimates for amount and efficiency of terrestrial OC burial in marine sediments? (5) How do glacial-interglacial sea-level cycles affect OC burial efficiency by turbidity currents within marine sediments, and have changes in global burial efficiency previously been underestimated?

BACKGROUND

How turbidity currents are part of wider global carbon cycles

The global carbon cycle involves the exchange of carbon between the major reservoirs at Earth's surface (atmosphere, terrestrial and marine biosphere, oceans) and storage in sedimentary rocks and the deeper lithosphere of the Earth (Sunquist & Visser 2004; Bianchi 2011, Hilton & West 2020) (Fig. 1b). Carbon dioxide (CO_2) is a focus of research because of its role as a greenhouse gas that helps set Earth's radiative energy balance and surface climate. Over short timescales ($<10^1$ to 10^3 years), the natural (non-anthropogenic) carbon cycle is dominated by exchanges between the atmosphere and living biosphere (e.g. via photosynthesis on land or in upper oceans), and CO_2 exchange between the ocean and atmosphere (Sundquist 1993). Over longer timescales (10^4 to $>10^6$ years) inputs of CO_2 from the solid Earth (Plank & Manning 2019), and additional sources of CO_2 from oxidative weathering of rock OC and sulfide minerals (Torres et al. 2014, Hilton & West, 2020), are removed from the surface reservoirs via silicate mineral weathering and carbonate mineral formation (Ebelmen 1845, Glavez & Gaillardet 2012), as well as through long-term OC burial in sediments (Berner 1982). Marine sediments represent the longest (10^4 to $>10^6$ years) store of organic carbon, which is roughly equally marine and terrestrial in origin based on modern-day estimates (Schlünz & Scheider 2000, Burdige 2005, 2007). Sediment transport processes play a central role in this geological carbon cycle, as they affect sedimentation rates that are a first order control of OC burial efficiency (Berner, 1982), and through the delivery of terrestrial OC to the ocean by rivers, as well as movement of OC across the shelf to the deep-sea (Galy et al. 2015, Hilton 2017).

In this review, we focus on the specific role of turbidity currents as a pathway for organic carbon transfer. Primarily, this transfers OC between the coast and the deep-sea, although depending on the timing and trigger of turbidity currents, this can directly couple terrestrial ecosystems to the deep-ocean in river flood waters (Hilton et al. 2008, Talling et al. 2022). In terms of net CO_2 transfers, sediment transfer by turbidity currents can aid the long-term preservation of terrestrial and marine OC in sedimentary deposits. In broader terms, any remineralisation of OC (i.e., the processes of organic matter decomposition by heterotrophic or chemotrophic mechanisms) within turbidity current deposits can release inorganic carbon into the deep-sea dissolved inorganic carbon reservoir, which already holds a very large mass of carbon (Dunne et al. 2007; Houghton 2007) (Fig. 1b). It may take thousands of years for relatively small fractional changes in this deep-sea inorganic carbon reservoir to exchange with the surface ocean and other reservoirs, and thus affect atmospheric CO_2 levels (Gruber et al. 2023). Transfer of more oxygen-rich waters by turbidity currents to the deeper ocean may also affect the rate at which OC is cycled through benthic ecosystems (Quadfasel et al. 1990, Bianchi et al. 2016). However, given the fluxes involved, it is unlikely that the turbidity current pump rivals the well-studied ocean carbon pumps that help control CO_2 concentrations in the atmosphere over short (10^3 to 10^4) years. Instead, based on our current understanding of the carbon fluxes involved in sediment-driven flows, changes in organic carbon burial and remineralisation associated with turbidites deposition are likely to affect atmospheric CO_2 and climate over millennial or longer ('geological') time scales (Galy et al. 2007).

Burial efficiency is a useful metric to describe the ratio of carbon buried to the supply of carbon to the burial site. Organic carbon burial efficiency within turbidity current deposits, and more generally on the seabed, is affected by a series of factors (Burdige 2005, 2007, Blair & Aller 2012, Arndt et al. 2013, Shang 2023). First, the source of OC is one important control on the rate of OC decomposition, which may decay quasi-exponentially over time (Blair & Aller 2012, Bianchi et al. 2018, Eglinton et al. 2021, Bradley et al. 2022). Marine OC is typically remineralised more quickly than terrestrial OC, which reflects its inherent reactivity and bioavailability for heterotrophs (Burdige 2007, Bianchi 2011, Blair & Aller 2012, Regnier et al. 2022). Source of OC is also critical as a food resource to the benthos, with unstable or "labile" OC promoting much greater benthic biomass than more stable "refractory" terrestrial OC (Amaro et al. 2016, Leduc et al. 2020).

A combination of sediment accumulation rate and the oxygen levels in that sediment affect a second important parameter that is the integrated oxygen-exposure time (Hartnett et al. 1998; Blair & Aller 2012; Bianchi et al. 2016). Faster sediment accumulation and lower oxygen levels promote more efficient carbon burial. Turbidity currents can produce unusually rapid sedimentation (Fig. 2e,f). For example, accumulation of sediment rich in terrestrial OC occurs at 0.5-20 cm/yr across the ~4,800 m deep lobe at the end of the Congo submarine system (Fig. 2e; Dennielou et al. 2017) or at 5-50 cm/yr in the canyon-head on the Bengal Fan (Fig. 2f; Rogers & Goodbred 2010). Remineralisation of this rapidly accumulating organic matter may lead to anoxic conditions within seabed sediments that also favours higher efficiency of OC burial (Fig. 3; Blair & Aller 2012; Arndt et al. 2013; Middelburg 2018; Rabouille et al. 2017, 2019).

Another important factor controlling carbon burial is organo-mineral associations, such as sorption to clays and complexation with Fe and/or Mn oxides (Lalonde et al. 2012, Keil & Mayer 2014, Shields et al. 2016, Blattmann et al. 2019, Hemingway et al. 2019). Consequently, hydrodynamic sorting during transport is key in controlling the OC composition and distance that organo-mineral materials, from riverine and/or resuspended shelf sediments, get transported to deeper waters (Prahl et al. 1994, Keil et al. 1997, Bianchi et al. 2002). In some cases, much of the terrestrially-derived particulate OC from rivers, which is largely in the organo-mineral form (Bauer et al. 2013, Regnier et al. 2022), can be replaced by marine OC that sorbs to clay particles as it moves across the shelf (Prahl et al. 1994, Keil et al. 1997).

Further background on turbidity current systems

Turbidity currents are mixtures of sediment and water that move down-slope due to the density contrast between this mixture and surrounding water (Kuenen & Migliorini 1950; Talling et al. 2012). These sediment flows are generated in many ways, such as by disintegration of landslides that mix with seawater, which produce the largest volume turbidity currents (Piper et al. 1999; Talling 2014; Talling et al. 2007, 2014). Submarine landslides are sometimes orders of magnitude larger than terrestrial landslides (Talling et al. 2014). The 1929 turbidity current in the NE Atlantic is larger than any terrestrial landslide in the last 350,000 years (Piper et al. 1999; Korup et al. 2007). Seabed failures of different sizes can be triggered in many ways including by earthquakes, storm-wave loading, and progradation of delta-lips or canyon-head lips (Talling et al. 2014), or sometimes even without a major external trigger (Bailey et al. 2021). Turbidity currents are also generated via river plumes. On rare occasions, and for just a few rivers, this river-plume can have sufficient suspended sediment to be denser than seawater and plunge to move along the seabed as a 'hyperpycnal flow' (Mulder et al. 2003; Kao et al. 2010; Liu et al. 2012, 2016). Much more often, turbidity currents are initiated by sediment settling from surface river plumes that are less dense than seawater, which occurs for rivers with a much wider range of sediment concentrations (Hage et al. 2019). Turbidity currents can be triggered by human activities such as seabed trawling, although these flows tend to be relatively small (Puig et al. 2012; Paradis et al. 2022).

Turbidity currents typically occur for < 0.1% of the time, and last for hours or minutes (Hughes Clarke 2016, Paull et al. 2018, Hage et al. 2019, Pope et al. 2022), although flows in the upper Congo Canyon occur for 20-30% of the time and can last for a week (Azpiroz-Zabala et al. 2017, Simmons et al. 2020). Transfer of OC by turbidity currents is much more episodic than for rivers that flow continuously, albeit with floods, or the steadier settling of OC from surface oceans. The magnitudes of turbidity currents are also extremely variable, ranging from very small flows travelling < 1 km

(Hughes Clarke 2016), to those carrying more sediment than the annual global riverine flux for ~1,000 km (Talling et al. 2007). Turbidity currents are separated into much larger events that erode and flush submarine canyons, which may occur every few decades to millennia, and smaller and more frequent flows that infill canyons (Allin et al. 2016, Talling et al. 2022). Thus, OC is often buried initially by canyon-filling flows, before being re-exhumed by infrequent canyon-flushing flows in second stage of transport during which OC may be partly remineralised and lost (Heijnen et al. 2020, 2022b, Hage et al. 2022, Talling et al. 2022).

Submarine fans (Fig. 2a) are built by turbidity currents, and occur in locations worldwide (Normark et al. 1986; Covault 2011). Organic carbon may be hydrodynamically segregated within the flow, due to its different densities or sizes, as it moves across submarine fans, such that different components have variable accumulation rates and burial efficiencies (Stetten et al 2015, McArthur et al. 2017). Submarine fans are typically divided into a deeply eroded canyon, which continues as a less deeply incised channel (Fig. 2a; Normark et al. 1986, Covault, 2011). Sediment overspill from the channel creates adjacent upraised levees, whilst sediment deposition at the end of the channel produces a lobe (Hodgson et al. 2022). Exceptionally flat (< 0.05°) basin plains in the deep-sea also trap sediment beyond these lobes (Talling et al. 2007, 2012).

Highly mobile mud-layers on the shelf

Highly mobile layers of fluid mud play a key role in transfer of sediment and organic carbon across continental shelves from river-mouths to submarine canyons on the shelf-edge. These highly mobile muds are commonly found at the mouths of large river systems with high suspended loads, and they can be generated by resuspension of mud by wave-related or tidal currents (Kuehl et al. 1996, Aller 1998, Allison et al. 2007, Xu et al. 2015). For example, mobile muds off the Mississippi/Atchafalaya river systems, were transported offshore to the Mississippi Canyon after the passage of a hurricane, with much of the OC derived from marine organic matter from nearshore in the highly productive Mississippi River Plume (Bianchi et al. 2006, Sampere et al. 2008). These dynamic mud deposits can serve as incinerators of OC, due in part, to their high oxygen content and availability in redox sensitive elements (Fe, Mn and S) (Aller & Blair 2006, Aller et al. 2010, Zhao et al. 2023). These mobile mud-layers have also been hypothesised to trigger turbidity current events, for example, mud-layers may drain into the tributary canyon head of the Congo Canyon during spring tides (Talling et al. 2022).

DISCUSSION

What types of organic carbon do turbidity currents contain, and what controls those types?

The total mass of organic carbon (TOC) in turbidity current deposits can be relatively high (0.4 – 4%; e.g. Rabouille et al. 2017, 2019), exceeding global average values commonly assigned to deltas (0.75%) or continental shelf (1.5%) deposits (Berner 1982, 1989, Burdige 2005, 2007), or a global average TOC from rivers of 1.1-1.6% (Burdige 2005, 2007, Blair & Aller 2012) (Table 1). The fraction of terrestrial or marine OC in turbidity current systems broadly reflects how sediment is supplied. This includes from rivers mouths, littoral cells, or cross-shelf transport for terrestrial OC, or productivity of overlying surface waters for marine OC (Fig. 3).

The type and age of OC are also critically important for carbon cycling (Galy et al. 2007, Kao et al. 2014; Bao et al. 2015). Older forms of OC will tend to be less easily remineralised (i.e. be refractory), and marine OC is typically lost more rapidly (Blair & Aller 2012, Eglinton et al. 2021). Even more importantly, atmospheric CO_2 is drawn down via creation of fresh biospheric organic matter (OC_{bio}) via terrestrial or marine photosynthesis (Hilton & West 2020). Older and more refractory (petrogenic or OC_{petro}) OC that has been buried previously, and is now merely transported and reburied in another location, will not act to draw down atmospheric CO_2 (Galy et al. 2008; Fig. 1a). As marine OC is rapidly remineralised, this fossil OC (OC_{petro}) is often mainly terrestrial. It has been estimated that rivers globally supply ~157 Mt/yr of biospheric OC (OC_{bio}), and ~43 Mt/yr of fossil (OC_{petro}) organic carbon (Galy et al. 2015; Table 1). Previous work thus analysed the fraction of OC_{bio} or OC_{petro} in turbidites (Galy et al. 2007, Kao et al. 2014, Hage et al. 2020). For example, it was once assumed that OC exported by small mountainous rivers was mainly fossil OC (Blair & Aller 2012), but other studies show they can have a dominant OC_{bio} component (Kao et al. 2014), as is also the case in fjords (Hage et al. 2022).

Turbidity current systems are typically dominated by terrestrial OC, but in some locations organic matter is mainly marine, such as in the Kaikōura Canyon (Leduc et al. 2020, Gibbs et al. 2020). A large earthquake triggered canyon-flushing turbidity current transferred ~8 Mt of mainly marine OC to the deep sea in 2016 (Mountjoy et al. 2018), which compares to the 90-130 Mt/yr of marine OC buried globally, although canyon flushing events in Kaikōura Canyon may have recurrence intervals of ~140 years (Mountjoy et al. 2018).

Do turbidity currents segregate different organic carbon types: is there a leaky pipeline?

Organic carbon particles have lower densities than most sediment grains, as well as a wide range of sizes and shapes (Repasch et al. 2022, Schwab et al. 2022). Thus, different types of organic matter may be hydrodynamically sorted (Bianchi et al. 2002, Eglinton et al. 2021), ending up in different parts of submarine fans (e.g., McArthur et al. 2017), and thus being preferentially buried or remineralised within a 'leaky pipeline'.

Finer-grained organic matter tends to be deposited within turbidite mud layers (Bouma T_E interval; Talling et al. 2012, Blair & Aller 2012). Mud comprises >70 % of global sediment supplied by rivers to the oceans (Aplin et al. 1999), and many turbidity current systems are mud-dominated, especially larger submarine fans fed by major rivers (Normark et al. 1986). As discussed earlier, fine mud is often key in preserving terrestrial organic matter because clays can shield particulate OC from degradation (Blair & Aller 2012, Keil & Mayer 2014, Blattmann et al. 2019, Hemingway et al. 2019). But in some settings, large amounts of fresh $OC_{bio;}$ e.g., woody debris can be deposited within turbidite sands (Saller et al. 2006, Kao et al. 2014, Lee et al 2019, Hage et al. 2020). This woody material may be preferentially deposited within the finer upper-levels of a sand layer (Bouma T_D division; Talling et al. 2012), or with the largest woody fragments found towards the sand layer's base (Bouma T_A and T_B intervals), and also within muddy sands deposited via debris flow (hybrid beds) (Haughton et al. 2003, Talling et al. 2004, 2012, Hussein et al. 2021). Organic carbon deposited in turbidite sands may be protected from oxidisation by an overlying mud cap (Hage et al. 2020). Neglecting organic material in sand may then cause burial fluxes to be underestimated significantly, as has been shown in fjords (Hage et al. 2020). Standard methods to core the seabed tend not to penetrate sandy seabed deposits, which may lead to biases in global core data sets used for burial fluxes (e.g. Cartapanis et al. 2016, 2018, Li et al. 2023).

Rapid sediment accumulation in specific parts of submarine fans (e.g. lobes; Fig. 2a) favours more efficient OC burial at those sites, and lobes may be relatively sand-rich (Hodgson et al. 2022), albeit with exceptions (Dennielou et al. 2017), whilst levees are mud dominated (Normark et al. 1986; Covault 2011). Forensic tracking of different types of organic matter can show how it changes away from specific sources, such as particular rivers on the shelf (Gibbs et al. 2020). The shapes of an individual turbidite deposit may also affect OC burial efficiency. For example, very large volume turbidity currents may produce ponded mud deposits in basin plains that are tens of meters thick (Talling et al. 2007, 2012), with only the upper few tens of centimeters oxidised over thousands of years, such that majority of underlying mud is protected (Thomson et al. 1987). Conversely, flows that spread sediment thinly and evenly will cause a greater fraction of OC to be remineralised, other factors being equal.

Submarine fan sub-environments contain different sediment grain sizes and accumulation rates, which can affect OC burial. Rapid sediment accumulation in lobes (Fig. 2e) favours more efficient OC burial, and lobes may be relatively sand-rich (Hodgson et al. 2022), albeit with exceptions (Dennielou et al. 2017), whilst levees can also have high accumulation rates (Fig. 2e), but are mud dominated (Normark et al. 1986, Covault 2011, Baudin et al. 2020). Forensic tracking of different types of organic matter can show changes away from specific sources, such as particular rivers on the shelf (Gibbs et al. 2020). The shapes of an individual turbidite deposit may also affect OC burial efficiency. For example, very large volume turbidity currents may produce ponded mud deposits in basin plains that are tens of meters thick (Talling et al. 2007, 2012), with only the upper few tens of centimeters oxidised over thousands of years, such that majority of underlying mud is protected (Thomson et al. 1987). Conversely, flows that spread sediment thinly and evenly will cause a greater fraction of OC to be remineralised, other factors being equal.

How does organic carbon cycling by turbidity currents work in different types of systems?

Here, we present a series of models that illustrate how OC transfer and burial works in different types of turbidity current system (Fig. 3).

Type 1: Submarine canyon-head connects directly to river-mouth (Fig. 3a)

Very few (~180 of ~9,500) modern submarine canyons connect directly to river mouths (Harris et al. 2014, Bernhardt & Schwanghart 2021), but they include rivers with large sediment fluxes, such as the Congo, Gaoping, and Var systems (Fig. 3a). These submarine fans are dominated by terrestrial OC (>70 to ~100%), but the fraction of fresh or fossil terrestrial OC depends on the river type, with < 2% fossil OC for Congo River on a passive margin (Baudin et al. 2020). Small mountainous rivers may have higher (e.g. 60-70 %) fractions of fossil OC, with OC supply also being highly episodic during floods (Kao et al. 2014; Bao et al. 2018). Turbidity currents are generated relatively frequently at river mouths in type 1 systems (Liu et al. 2012, Khripounoff et al. 2012, Azpiroz-Zabala et al. 2017, Talling et al. 2022). Organic matter may reside initially in canyon-floor deposits, maybe for years to decades, before being flushed into the deep-sea by far larger flows (Allin et al. 2016, Mountjoy et al. 2018, Talling et al. 2022). Organic carbon burial can be highly efficient (>70% to approaching 100%) in such systems (Galy et al. 2007, Kao et al. 2007, 2014). For example, a mass balance that includes canyon-flushing events suggests ~100% of Congo River sediment is transferred to the deep-sea over 20-50 year time-scales (Azpiroz-Zabala et al. 2017, Simmons et al. 2020, Talling et al. 2022), and deposited mainly beyond the channel-mouth or on flanking levees (Talling et al. 2022). It is estimated that ~15% of OC is remineralised and recycled on the seabed in the Congo system

(Rabouille et al. 2017, Baudin et al. 2020), with a burial efficiency of ~85% on the lobe (Rabouille et al. 2016), although lower if sediment is buried and re-exhumed multiple times. However, precise estimates of terrestrial OC burial efficiency are challenging, even in well studied systems, because they require constraints on riverine inputs and tracking of all sediment through the deep-sea system. Baudin et al. (2020) concluded that 33-69% of the terrestrial OC supplied by the Congo River was buried in the Congo submarine fan, mainly in lobes and levees. But about half of the OC supplied by the river was unaccounted for in their budget, and may have been flushed beyond the lobe by very large flows, as in 2020 (Talling et al. 2022). Thus, burial efficiency is likely to be somewhat higher than 33-69%.

Type 2: Submarine canyon connects to shore and fed by longshore drift (Fig. 3b)

Some of the ~180 modern canyons (Harris et al. 2014; Bernhardt & Schwanghart 2021) that extend close to the shoreline are fed mainly by littoral drift, with little or no direct connection to river mouths, yet show evidence of turbidity current events (Fig. 3b). Examples include Monterey Canyon (Paull et al. 2018; Maier et al. 2019), and Nazaré Canyon (Masson et al. 2010). Cores from Monterey Canyon are dominated by terrestrial OC, with similar annual sediment mass fluxes to the canyon (1-3 Mt/yr) and TOC values (~0.5%) as those for nearby rivers (Paull et al. 2006; Maier et al. 2019; Bailey et al. 2021). This suggests there is efficient (>80-100%) burial of terrestrial OC from rivers in the upper canyon, despite an intervening period of time being reworked on the shelf. Much higher TOC values (~1.2-2.9%) occur in sediment traps in Monterey Canyon, with a large proportion of this OC being absent from seabed cores (Maier et al. 2019). This suggests there is a large pool of easily resuspended and labile OC, likely primarily marine in origin, which is not buried. Nazaré Canyon has much higher (~2%) TOC values in seabed cores, with ~30% of OC in sediment trap samples estimated to be buried on the seabed (Masson et al. 2010). There may again be a pool of labile and easily resuspended by internal tides OC that is trapped in the upper canyon and remineralised before burial, albeit a smaller fraction than within Monterey Canyon. In both locations, canyon flushing flows occur every few hundred to thousand year (Allin et al. 2010), and some fraction of initially buried OC may be remineralised during this second transport stage (Thomson et al. 1987).

Type 3: Submarine canyon only partially indents shelf, but sediment still reaches it from rivers (fig. 3c)

About 30% of submarine canyons partly indent the shelf (Harris et al. 2014, Bernhardt & Schwanghart 2021), and at least in some cases, sediment is transferred effectively across the shelf to the canyon-head, triggering turbidity currents (Fig. 3c). This includes the Bengal Submarine Fan fed by the Ganges-Brahmaputra Rivers, which alone carry ~8-10% of global sediment and ~2% of the terrestrial OC flux from continents to oceans (Supplementary Table 1). Clinoforms on the shelf reach the canyon head, which is highly active with turbidity currents (Rogers & Goodbred 2010). Similar amounts of (mainly fresh) terrestrial OC characterise sediment from both river mouth and deep-sea fan, suggesting highly (80-100%) efficient burial of OC, despite a distance of ~140 km from river mouths to the canyon head (Galy et al. 2007). The sediment flux to this system is extreme (Milliman & Farnsworth 2011), but sediment can be transferred effectively across the shelf in other locations, albeit for somewhat shorter distances. For example, ~60% of sediment from Eel River is transferred across a ~12 km wide shelf, and is mostly trapped by a submarine canyon (Pratson et al. 2009). Cross-shelf sediment transport occurs via highly mobile muds-layers that are often partly supported by waves or tides (Kinecke et al. 1996, Kuehl et al. 1996; Wright & Friedrichs 2006), and thus may be favoured by locations with greater tide or wave amplitudes. Similar fractions (60%) of river sediment traverse the 30-40 km wide shelf offshore the Waipaoa River in Aotearoa New Zealand to reach the Poverty Canyon head (Kuehl et al. 2016). There is also evidence for recent sediment deposition in the Mississippi Canyon head (Bianchi et al. 2006), although the distal parts of that large submarine fan are dormant (Piper et al. 1997, Schlünz et al. 1999). The burial flux of terrestrial OC in such systems is variable, for example due to the fraction of sediment and sources of OC traversing the shelf, residence time on shelf, and the frequency of turbidity currents. But in some cases, e.g., the Bengal Fan, these systems may have terrestrial OC burial efficiencies of >50 to ~100% (Galy et al. 2007, Kuehl et al. 2016).

Type 4: Submarine canyon restricted to shelf edge, yet canyon is still active (Fig. 3d)

About 70% of all submarine canyons are restricted to the shelf-edge and continental slopes (Harris & Whiteway 2011, Harris et al. 2014) (Fig. 3d). For example, Whittard Canyon is located over 300 km from the nearest coastline, and does not indent the shelf (Amaro et al. 2016, Heijnen et al. 2022a). However, recent monitoring shows it had 4-6 powerful (up to 5-8 m/s) turbidity currents in one year, some of which ran out for over 50 km to water depths of >2 km (Heijnen et al. 2022a). It is thus as active as some canyons that connect directly to shorelines and littoral cells, such as Type 2 Monterey Canyon (Paull et al. 2018). It was previously thought that present-day turbidity currents played little role in transfer and burial of fresh (mainly marine) OC in Whittard Canyon (Amaro et al. 2016), with labile organic matter supplied to the canyon floor via vertical settling, but this was based mainly on moorings in deeper water (> 4 km; Amaro et al. 2016). Further work is needed to understand how sediment is supplied to such canyon heads, such as via sand-waves on the shelf (Heijnen et al. 2022a), and how far turbidity currents extend down these types of canyons. But there are thousands of other submarine canyons restricted to the continental slope (Harris et al. 2014), and work in Whittard Canyon (Heijnen et al. 2022a) raises the question of how many of those canyons are currently active. Even if that activity is restricted to their upper reaches, they could play a role in global carbon cycling, and delivery of OC to the deep ocean.

Type 5: Submarine canyon at shelf edge, and assumed to be inactive (Fig. 3e)

It is often assumed that submarine canyons restricted to the continental slope are currently inactive, because limited sediment can reach the canyon head, especially where the shelf is wide (Fig. 3e). For example, influential studies of the Amazon system show how terrestrial OC is reworked repeatedly on the shelf within highly-mobile mud layers (Kinecke et al. 1997, Kuehl et al. 1996, Nittrouer et al. 2021), which cause this OC to be repeatedly exposed to oxygen and remineralised, reducing burial efficiency to 20-30% (Aller et al. 1998, Burdige 2005, 2007, Schlünz & Schneider 2000, Nittrouer et al. 2021). It has been inferred that negligible sediment reaches the Amazon Canyon's head at the shelf edge because the continental shelf is ~300 km wide (Nittrouer et al. 2021). Steep submerged delta fore-sets occur on the shelf about 100 km from the canyon-head, and monitoring shows episodic flows of fluid mud move down these fore-sets (Sternberg et al. 1996, Nittrouer et al. 2021). Fluid muds can be extremely mobile on low gradients, moorings for flow monitoring are yet to be placed in the upper Amazon Canyon, and cores are not available to determine whether recent sedimentation occurs. Monitoring is warranted to confirm inactivity, especially given the activity seen in Whittard Canyon, also 300 km from shore. However, the outer Amazon Shelf is dominated by sandy deposits and coral reefs, with little evidence of mud deposition from turbidity currents (Nittrouer et al. 2021, Vale et al. 2022), and reworked terrestrial OC that escapes from the shelf may have a high refractory component and thus play a limited role in drawdown of CO_2 from the atmosphere. Cores on levees from deeper (> 2 km) parts of the Amazon Fan clearly indicate that overspill of large turbidity currents ceased during the last sea-level rise (Piper et al. 1999), and much greater burial of both marine and terrestrial OC occurred in the deep-sea during low-stands in sea level (Schlünz et al. 1999).

Type 6: Fjords with turbidity current systems, where river-mouth feed directly into deep-water (Fig. 3f)

Efficient burial of both terrestrial and marine OC occurs within fjords, that are often characterised by high (average 2.6%) TOC, rapid sediment accumulation, and poorly oxygenated seabed conditions (Smith et al. 2015, Bianchi et al. 2018, 2020). Rapid transport of terrestrial OC from forests and soils, as well as episodic sediment supply from mountainous rivers, may also lead to a high percentage of fresh (biospheric) carbon (Smith et al. 2015, Bianchi et al. 2018, 2020, Cui et al. 2016, Smeaton & Austin 2022). Thus, despite their surface areas being ~40 times smaller than that of deltas and continental shelves, fjords have been shown to represent ~17% of the global terrestrial OC burial, and ~11% of the total OC burial in marine sediments (Smith et al. 2015). Well-developed turbidity current systems occur in many (Pope et al. 2019; Hage et al. 2020, 2022) but not all (Smeaton & Austin 2022) fjords, and they can play a key role in OC cycling (Fig. 3f). Significant amounts of terrestrial OC are buried in the sandy parts of turbidites (Hage et al. 2020), suggesting past global estimates of burial fluxes are underestimates as they primarily consider muddy fjord sediments (Smith et al. 2015). Efficient burial of terrestrial OC can occur within fjord turbidites (Supplementary Table 1; Smith et al., 2015; Hage et al. 2020; Supplementary Material) despite being remobilised in one or more stages by seabed flows (Heijnen et al. 2022a,b). For example, a detailed study of Bute Inlet suggests that 62% ± 10% of the OC supplied by the rivers is buried within surface marine sediment across this fjord (Hage et al. 2022).

Type 7: Mega-landslides and abyssal plains - infrequent but very large turbidity currents (Fig. 3g)

Some submarine landslides are exceptionally large (Korup et al. 2007, Talling et al. 2014; Table 1), and disintegrate to form turbidity currents which transport and deposit large amounts of OC in mega-turbidites in deep-water basin plains and trenches (Fig. 3g). Individual mega-landslides within submarine fan systems can be vast. For example, those on the Mississippi, Nile and Amazon Fans contain 400-800 km^3 of sediment (e.g. Maslin et al. 2005), whilst landslide deposits are 10-20% of the total mass of the Congo Fan (Picot et al. 2015). Very large landslides also occur on open continental slopes away from canyon-fed fans, such as the Storegga landslide off Norway which comprises > 3,000 km^3 (Haflidason et al. 2005, Talling et al. 2014).

If a landslide fails to disintegrate, then OC is trapped within landslide deposits that may be tens of meters thick, so negligible OC is remineralised. However, when mega-landslides mix with seawater to form a turbidity current, very large sediment volumes may be spread in a thin turbidite layer across a very wide area in deep-water basin plains or trenches, remineralising large amounts of OC (Talling et al. 2007, Piper et al. 1999, Thomson et al. 1987). These mega-turbidites in basin plains may originate from landslides on open continental slopes, or via canyon-flushing turbidity currents. Organic carbon in the upper part of distal mega-turbidites is then remineralised over long periods of hundreds to thousands of years between events (Thomson et al. 1987). The fraction of OC that is lost from these mega-turbidites also depends on whether thick layers pond in basin lows, which then protects most underlying OC from surface oxidisation (Thomson et al. 1987). Some submarine landslide events are triggered by earthquakes; the M_w 9.1 Tohoku earthquake in 2011 offshore Japan remobilised ~1 Mt of OC into a deep-sea trench (Table 1; Kioka et al. 2019).

Importantly, in contrast to smaller canyon-filling flows, the frequency of mega-turbidites that reach abyssal basin plains appears to be independent of sea level (Allin et al. 2016) and quasi-random in time (Clare et al. 2014). This may reflect that the mega-flows that reach basin plains have exceptional and more temporally random triggers, such as earthquakes. Flows that flushed Nazaré Canyon and reached the Iberian Abyssal Plain have an average frequency of ~2,000 years, and likely contained >~0.1 to >~1 km^3 of sediment (Allin et al. 2016), implying a flux of > ~0.1 to >~1 Mt/yr, which is a comparable to sediment supply via longshore drift to the modern canyon head (Duarte et al. 2019). Thus, the turbidity current pump may remain active during low-stands of sea-level through these exceptionally large but infrequent canyon-flushing turbidity currents, even in cases where canyon-filling flows are much reduced.

Do we need to revise global amount and efficiency of organic carbon burial in marine sediments?

Current estimates of global burial of both marine and terrestrial OC in marine sediments are ~160-170 MtC/y (Table 1; Hedges & Kiel 1995, Burdige, 2005, 2007; Smith et al. 2015, Hilton & West, 2020). This was derived by assuming that 66% of the annual sediment mass flux from rivers (i.e. ~18,000 Mt/yr; Milliman & Fahnesworth 2011) is deposited in deltaic areas, whilst 33% is deposited on continental shelves and upper slopes (Hedges & Kiel 1995, Burdige 2005). No OC was assumed to reach deep-sea submarine fans. Average TOC values of ~0.7% for deltas and 1.5% for shelves and slopes were used to compute OC burial fluxes, with a further ~22 MtC/yr assumed to be buried in marine sediment buried in other locations (e.g. beneath zones of high surface ocean productivity). It was then assumed that ~67% of the total OC in deltaic areas, and ~16% in shelves and slopes, is terrestrial OC. This led to an estimated burial flux of terrestrial OC in marine sediments of ~40-80 MtC/yr (Burdige 2005, 2007, Hilton & West 2020; Table 1). Rivers are estimated to supply ~200-300 MtC/yr of terrestrial OC to the oceans (Galy et al. 2015, Hilton & West 2020, Li et al. 2022; Table 1). This produces estimates of global burial efficiency for terrestrial OC in marine sediments of ~13-40% (Table 1; Supplementary Discussion).

However, from our discussions above, terrestrial OC burial can be much more efficient than 40% in a wide range of settings (Fig. 4; Supplementary Discussion and Tables), such type 1 systems that include the large Bengal Fan (Galy et al. 2007), or the Congo Fan (Baudin et al. 2020, Talling et al. 2022), Gaoping Canyon (Kao et al. 2014) and McKenzie systems (Hilton et al. 2015), or global fjords (type 6 systems; Smith et al. 2015, Bianchi et al. 2020, Hage et al. 2022). Some forms of terrestrial carbon thus appear able to survive repeated mobilisation and long-distance transfer (Blair & Aller 2012). It is therefore timely to reassess values for global burial of OC in marine sediments.

Three methods can be used to calculate global fluxes and burial efficiency of terrestrial OC. The first method uses the global OC flux from rivers and attributes it in different proportions to different settings such as deltas, shelves, submarine fans or fjords (Berner 1982, 1989, Burdige 2005, 2007, Blair & Aller 2012). This method neglects annual sediment supply to canyon heads via longshore drift which may be significant, include a component of coastal erosion, and not necessarily reflect the closest river (e.g., Gibbs et al., 2020). It is therefore not preferred here. The amount of sediment reaching the ocean from rivers globally has also declined due to human activities (e.g. dams) and it may now be ~50% (Syvitski et al. 2021) of the value of ~18,000 Mt/yr (Milliman & Farnsworth 2011) that was used to infer that 40-80 MtC/yr of terrestrial organic carbon is buried in marine sediments. This raises a question of whether terrestrial OC burial in the oceans has also declined by up to 50%, with a greater amount of OC buried in reservoirs and terrestrial settings. However, dams may preferentially trap sandy bedload with lower amounts of fresh OC (Bianchi et al. 2018, Syvitski et al. 2022), and rates of sediment deposition in coastal areas offshore North America do not seem to have declined since 1950 (Dethier et al. 2022).

A second method uses the abundance of terrestrial OC, and sediment accumulation rates measured in seabed sediment cores, together with representative areas, to calculate burial fluxes (Smith et al. 2015, Cartapanis et al. 2016, 2018, Rabouille et al. 2019, Baudin et al. 2020, Li et al. 2022). Although this method is currently not feasible due to spatially limited OC measurements in cores from turbidite systems, it holds promise for future estimates of terrestrial OC burial in submarine fans, by extending published core data for submarine fan accumulation rates (e.g. Covault & Graham 2010) to include TOC and terrestrial OC fractions. It should also be noted that cores from submarine fans may be under-represented in global core data bases previously used for total (TOC) burial estimates in marine sediments (Cartapanis et al. 2016, 2018, Li et al. 2022). Furthermore, sandy seabed areas are often impractical to core via traditional piston or gravity corers, potentially leading to other biases.

A third method is to estimates burial efficiencies in a small number of well-studied locations or system types with larger OC burial fluxes, which are (i) the Ganges-Brahmaputra Rivers and Bengal Fan, (ii) Congo River and Fan, (iii) Amazon and Fly Rivers and their offshore areas, as well as (iv) Oceania systems (derived from Taiwan; see Supplementary Material), and (v) fjords, and (vi) all other systems not included in categories (i) to (v) (Supplementary Table 1; and see Supplementary Discussion). The percentage of global OC supplied by rivers to each of these categories is calculated, for both TOC and OC_{bio} (fresh biospheric organic carbon). A range of burial efficiencies of terrestrial OC in marine sediments are then defined for each system (Supplementary Table 1). For example, burial efficiency of 80-90% is assumed for the Bengal Fan (Galy et al. 2007), 60-90% for the Congo Fan (Baudin et al. 2020, Azpiroz-Zabala et al. 2017, Talling et al. 2022), 60-80% for fjords (Smith et al. 2015, Bianchi et al. 2020), 60-90% for systems in Oceania fed by small mountainous rivers (Kao et al. 2017, Bao et al. 2015), or 30% for the Amazon and Fly Shelves (Blair & Aller 2012; their fig. 9). Burial efficiencies of 20% and 30% are then modelled for the 'all other rivers' categories' (Supplementary Table 1 and Supplementary Discussion). The fraction of global TOC and OC_{bio} supply buried within seabed sediment is then calculated for each of these categories, which are then summed to derive an overall global burial efficiency for TOC and OC_{bio} (See Supplementary Material for details, and justification of the values chosen in Supplementary Table 1).

This method derives a global burial efficiency for terrestrial OC in marine sediments of 31-45% and 28-51% for biospheric OC (see Supplementary Table 1 and Supplementary Discussion for details). This range is significantly higher than burial efficiencies of 10-30% proposed by Hedges et al. (1997), Schlünz & Scheider (2000), and Burdige (2005, 2007), and somewhat greater than the 20-44% estimate of Blair & Aller (2012; Table 1). Using the revised terrestrial OC burial efficiency of 31-45%, and a flux of 200 MtC/yr of terrestrial OC from rivers (Galy et al. 2015), a burial flux of terrestrial OC in marine sediments of 62-90 MtC/yr is derived, which is higher than values of 40-80 MtC/yr previously cited (Hilton & West 2020; Tables 1 & 2).

How do glacial sea-level cycles affect global OC burial efficiency in marine sediments?

Far more rivers would connect directly to the heads of submarine canyons during glacial periods due to lower global sea level (Fig. 3h; Harris et al. 2014, Bernhardt & Schwanghart 2021), and this will profoundly affect transfer and burial of OC in the deep sea. Numerous submarine fans would therefore likely have burial efficiencies for terrestrial OC of >60% to almost 100%, as occurs in modern type 1 systems where river mouths connect to canyon heads (Figs. 3a & 4), such as the Congo Fan and Bengal Fan, or small mountainous rivers in Oceania exemplified by the Gaoping River-Canyon system (Supplementary Table 1; Supplementary Materials). Global burial efficiency of terrestrial OC in marine sediments would thus potentially reach values 60-80% during glacial periods, rising significantly from value of 31-45% derived in the previous section, or past estimates of 10-44% (Table 1). If it is also assumed that the flux of OC (200 Mt/yr; Table 1) from land did not change, which is supported by an overall erosional control on OC export in river sediments (Galy et al. 2015, Hilton 2017), burial of terrestrial OC in marine sediment during glacial periods would increase from 40-80 Mt/yr to 130-255 Mt/yr (Table 1; Supplementary Discussion). Assuming burial of marine OC from surface oceans (90-130 Mt/yr) remained unchanged, the total OC burial flux in marine sediments would rise to 152-220 Mt/yr. However, we also note that sediment and organic carbon export from rivers to the ocean may vary systematically and significantly between glacial and interglacial periods (e.g. Mariotti et al. 2021).

Our analysis suggests that the total amount of OC buried in marine sediments may have nearly doubled during glacial periods, reflecting an increase in terrestrial OC burial efficiency from 31-45%

to 60-80% (Table 1). A similar doubling of total OC burial within deep-sea (> 1 km) cores was noted by Cartapanis et al. (2016) (Fig. 5a). However, they only considered sites at water depths > 1 km, and also omitted submarine fans built by turbidity currents, so that OC burial fluxes they calculate are thus ~10% of those calculated here (Table 1; Fig. 5a). Cartapanis et al. (2016) attributed the increased OC burial in marine sediments to enhanced nutrient supply, better preservation of organic matter due to reduced oxygen exposure, as well as more efficient transfer of terrestrial organic matter to the deep-sea by turbidity currents.

This raises a question of how highly variable burial flux of OC in marine sediment affects global carbon cycling and atmospheric pCO_2 levels, and thus climate (Cartapanis et al. 2016, 2018, Li et al. 2022). Burial of OC in marine sediment affects atmospheric CO_2 levels only over long (> 1,000 year) time scales (Galy et al. 2007, Blair & Aller 2012, Hilton & West 2020). Over shorter time periods (days or months to millennia), atmospheric pCO_2 is determined by exchange of CO_2 between atmosphere, ocean-water reservoirs, or terrestrial biomass (Sundquist 1993). Interaction between these shorter term ('active') reservoirs, and longer term ('geological') carbon reservoirs such as marine sediments can be complex, not least because many factors other than the turbidity current pump likely varied between glacial to inter-glacial periods (Sigman & Boyle 2000, Cartapanis et al. 2016). For example, increased surface ocean productivity is commonly inferred to have reduced atmospheric pCO_2 levels during glacial periods, thus amplifying reductions in atmospheric pCO_2 (Sigman & Boyle 2000). More efficient burial of OC by the turbidity current pump would also be a positive feedback (Galy et al. 2007, Cartapanis et al. 2016, 2018), further reducing pCO_2 levels during glacial periods, but over much longer (> 1,000 year) time scales. However, the magnitude of change in OC burial flux via turbidity currents between glacial and inter-glacial periods (~30-95 Mt/yr; Table 1) may rival or exceed changes in global OC burial previously proposed to drive other longer-term climate fluctuations (Fig. 5). For example, Li et al. (2023) inferred moderate changes in global OC burial flux (e.g., ~90 Mt/yr) were an important positive feedback for global warming during the Neogene (~23 to 3 Ma) (Fig. 5b).

Role of turbidity currents in terrestrial organic carbon cycling by ice sheets

Large fluctuations in OC storage and release can also occur due to growth and decay of ice sheets (Zeng 2003, 2006, Wadham et al. 2019; Cui et al. 2022), and turbidity currents may play some role in such OC storage and release. For example, terrestrial OC may be buried beneath ice sheets during glacial periods, but efficiently remineralised as ice sheets melt (Zeng 2003, 2006). Fjords at the margins of ice sheets may then bury the OC that is released from within or below glaciers, as sea level rises during deglaciation (Smith et al. 2015, Cui et al. 2022). Turbidity current systems will play a role in how OC is buried within many such fjords (Smith et al. 2015, Hage et al. 2020).

In addition, when ice streams reach the shelf-edge they can form extremely large-volume sediment accumulations (called trough-mouth fans), whose scale rivals the largest river-fed submarine fans (Nygard et al. 2007). For example, the sediment mass flux to the North Sea Trough-Mouth Fan at the peak of the last glacial was ~1,100 Mt/yr, which occurred for just ~1,000 years (Nygard et al. 2007). This sediment flux is similar to the modern Amazon or Ganges-Brahmaputra Rivers (Milliman & Farnsworth 2011). Terrestrial OC burial is highly efficient within these episodically active trough mouth fans, which are built by thick submarine debris flow deposits and turbidites (Nygard et al 2007, Bellwald et al. 2020). Therefore, trough mouth fans need to be included in estimates of global terrestrial OC burial in marine sediments during glacial periods (Fig. 3i), although it is likely that they contain a high fraction of fossil OC, and relatively low TOC (King et al. 1998). For example, if trough mouth fans globally supplied 2,000 to 3,000 Mt/yr of sediment with TOC values of ~0.5% (King et al. 1998), this would be an additional burial flux of 10-15 Mt/yr of terrestrial OC in marine sediments, raising the global burial flux to 130 - 255 Mt/yr (Table 1).

CONCLUSIONS

Turbidity currents are one of the most important sediment transport processes ('pumps') on Earth (Talling et al. 2015), yet they were previously not included in analyses of global OC cycles (Berner 1982, 1989, Burdige 2005, 2007, Blair & Aller 2012). It was once assumed that terrestrial OC was primarily incinerated on continental shelves, such that global burial efficiency was low (~10-44%; Table 1), and the vast majority of turbidity current systems were inactive in the modern sea-level high-stand (Berner 1982, 1989, Posamentier & Kolla 2003). However, it is now emerging that deep-sea burial of terrestrial OC by turbidity currents can be highly (~60-100%) efficient, and in a relatively wide range of settings (Supplementary Table 1; Galy et al. 2007, Kao et al. 2007, Baudin et al. 2020, Smith et al. 2015). Direct monitoring and dated cores are also showing that turbidity currents are presently much more active than once thought (e.g. Clare et al. 2016, Normandeau et al. 2020, Talling et al. 2022, Heijnen et al. 2022a), and they would be even more active in glacial sea-level low-stands (Schlünz et al. 1999, Harris et al. 2014, Cartapanis et al. 2016).

The role of turbidity currents in global carbon cycling is therefore reassessed, leading to revised global estimates for mass-flux (~56-135 Mt/yr) and efficiency (31-45%) of terrestrial OC burial in marine sediments (Table 1 & Supplementary Material). Burial of terrestrial OC during glacial periods of sea-level low-stand was far more efficient than at present, as most submarine canyons connected to river mouths (Harris et al. 2011). We estimate that terrestrial OC burial doubled during glacial periods, and this is consistent with previous analysis of deep-sea (> 1 km) cores (Fig. 5a). Assuming a global average burial efficiency of 60-80% by turbidity currents, the total OC burial flux in marine sediments could rise to 220-345 Mt/yr (Table 1). Similar changes in seabed burial flux of OC from surface ocean carbon pumps are thought to be an important positive feedback mechanism for global warming (Li et al. 2023; Fig. 5b). The fluctuating strength of the turbidity current pump may therefore also affect atmospheric pCO_2 levels and climate over longer (>> 1,000 year) geological time scales (Galy et al. 2007, Kao et al. 2007, Cartapanis et al. 2016).

FUTURE RESEARCH DIRECTIONS

(1) This review is a rallying call for additional flow monitoring, allied to time-lapse bathymetric mapping and sediment sampling, to understand the frequency and nature of turbidity currents in a much wider range of settings. This direct monitoring work can then underpin better constrained estimate of mass transfer and burial fluxes of OC within marine sediments. Ideally new methods are needed to measure sediment concentrations and mass fluxes directly in turbidity currents (e.g., Simmons et al. 2020), which are currently estimated via time-lapse mapping (Hage et al. 2022, Heijnen et al. 2022b, Talling et al. 2022) or dating of widely spaced sediment cores (Covault & Graham 2010).

(2) There is a need to understand where and how sediment and OC is transferred efficiently across wide (>> 10 km) continental shelves (Figs. 2d & 4), as this may produce a far greater number of active submarine canyons (Harris et al. 2011, Bernhardt & Schwanghart 2021). Whittard Canyon is over 300 km from the nearest coast, yet it is currently active (Heijnen et al. 2022a). Future work should aim to determine the ultimate fate of extremely mobile (fluid) mud layers on the continental shelf (Wright & Friedrichs 2006, Kinecke et al. 2007, Kuehl et al. 2007), and whether they occasionally escape the shelf, as these fluid muds occur on some of the largest systems that have a disproportionate effect on global fluxes. For example, it is often assumed that Amazon (Nittrouer et al. 2021) and Mississippi Canyons are inactive, but moored-sensors have not yet been placed in these canyons, whilst dated cores from the upper Mississippi Canyon suggest recent flows (Bianchi et al. 2002).

(3) Improved estimates of global OC burial fluxes are based on seabed core databases, both for the Quaternary (Cartapanis et al. 2016) or older geological periods (Li et al. 2023). However, these core data bases are strongly biased, as they have few or no cores from submarine fans (Cartapanis et al. 2016, Li et al. 2023), where sediment and OC accumulation rates are unusually high (Fig 2; Baudin et al. 2020). Future studies thus need to include representative cores from submarine fans. Traditional coring methods tend not to recover sandy sediments, and there should also be efforts to account for

OC buried within sandy sediment, including with studies of modern carbon stock on continental shelves (Atwood et al. 2020).

SEPARATE SIDEBAR BOX

Wider implications of the turbidity current pump

A more active turbidity current carbon pump has significant implications for seabed life. These flows supply OC that underpin food webs, although seafloor biomass is more dependent on labile marine carbon than refractory terrestrial carbon dominating some flows (Leduc et al. 2020, Gibbs et al. 2020). Powerful turbidity currents both scour the seabed, sometimes to depths of tens of meters, and deposit thick sediment layers that smother ecosystems (Mountjoy et al. 2018). Rapid accumulation of organic-rich sediment sometimes favoured chemotrophic ecosystems resembling those around black smokers (Karine et al. 2017), whilst turbidity currents provide a template of sediment or bedrock types for different ecosystems.

There is increasing focus on how carbon stocks on continental shelves are remobilised by human activities such as trawling (Atwood et al. 2020). Where trawling occurs close to canyons, turbidity currents play a key role in exporting and remineralising carbon (Puig et al. 2012, Payo Payo et al. 2017, Paradis et al. 2022). Turbidity currents may also transfer microplastics in the deep-sea, potentially explaining why ~99% of plastic entering the ocean is currently unaccounted for (Kane & Clare 2019). There is also a question of whether onshore water reservoirs, which may now trap ~50% of global river sediment (Syvitski et al. 2021), affect offshore turbidity currents, and their carbon cycling.

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Glossary

Terrestrial organic carbon: Organic carbon (OC) produced by organisms living in the terrestrial biosphere (e.g. plants and terrestrial bacteria).

Marine organic carbon: Organic carbon (OC) produced by organisms living in the marine biosphere (e.g. plankton, algae, and marine bacteria).

Burial efficiency: the fraction (or percentage) of organic carbon buried in sediments over geological time scales relative to that initially supplied or produced: terrestrial organic carbon burial efficiency is most commonly viewed relative to river inputs to the ocean.

Remineralisation: Process by which organic carbon is turned into CO_2.

Total organic carbon (TOC in %): Concentration of all types of organic carbon (OC) within a sample.

Biospheric OC (OC_{bio} in %): Concentration of organic carbon (OC) in a sample either produced by living organisms in terrestrial or marine settings ('fresh' or 'modern' biospheric organic carbon), or occurring as degraded ('old biospheric' or 'pre-aged') terrestrial organic carbon within soils.

Petrogenic OC (OC_{petro} in %): Concentration in a sample of older (i.e., fossil, depleted in ^{14}C) organic carbon (OC) derived from the erosion of rocks.

Refractory: Organic carbon (OC) that is less prone to remineralisation.

Labile: Organic carbon (OC) that is more prone to remineralisation.

Heterotroph: An organism that cannot produce its own food, instead taking nutrition from other sources of organic carbon.

Turbidity current: A submerged mixture of sediment and water that is denser than surrounding water, and thus flows down-slope along an ocean or lake floor.

Turbidite: A layer of sediment deposited from a turbidity current.

Hyperpycnal flow: If a river plume contains sufficient sediment, it is denser than surrounding sea or lake water and plunge to flow along the ocean or lake floor, as a hyperpycnal flow.

Submarine fan: An accumulation of sediment that is formed by turbidity currents on the seabed, which typically comprises a submarine canyon and/or submarine channel, and a lobe (see Fig. 2).

Submarine canyon: A valley that is deeply incised into the seabed through which turbidity currents flow.

Submarine channel: A valley that is less deeply incised into the seabed, whose margins (termed levees) may be higher than the surrounding seafloor, through which turbidity currents flow.

Lobe: Area of sediment accumulation at the end of submarine canyons or channels, where turbidity currents expand laterally and thus decelerate, often leading to rapid sediment deposition or scours.

Levees: Area on the flanks of a submarine channel, which may also be higher than the surrounding seafloor.

Hydrodynamic sorting: Process by which grains of different sizes, densities or shapes (and thus settling velocities) are segregated into different parts of a flow.

FIGURES AND TABLES

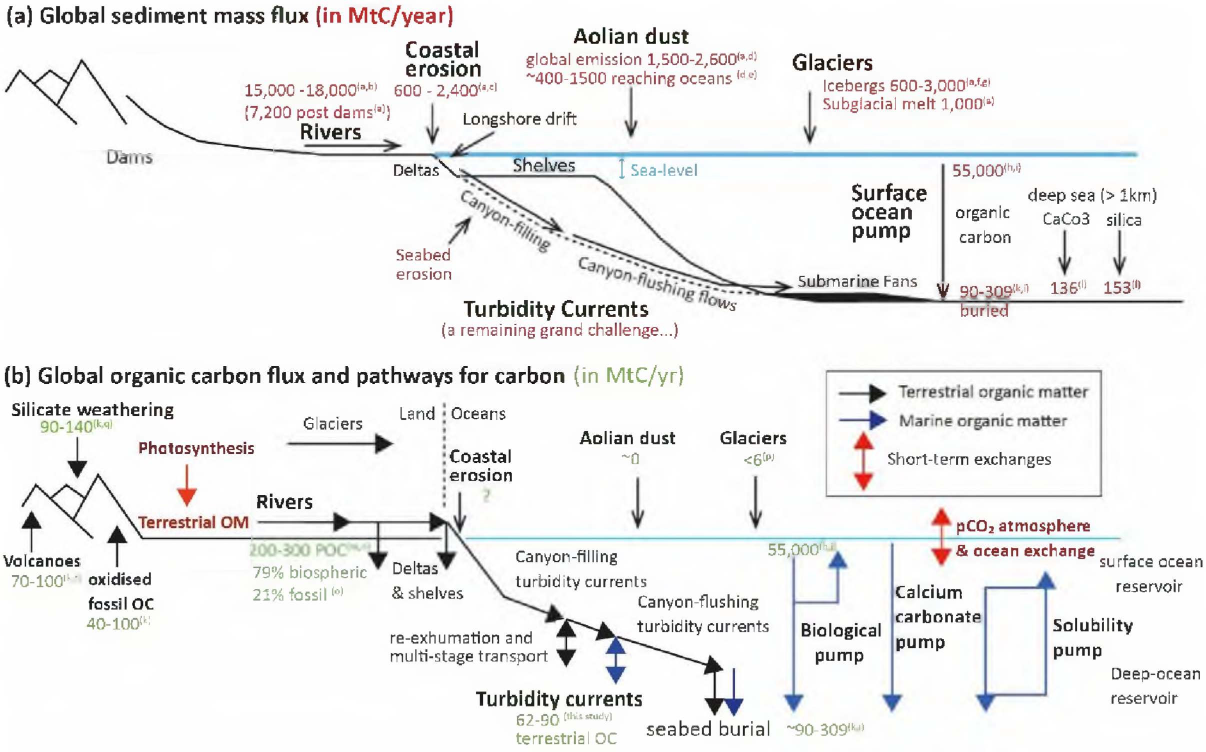


Figure 1. Summary of different global sediment and organic carbon pumps, including the turbidity current pump. (a) Global sediment mass fluxes in Mt/yr (in red), with values from Syvitski et al. (2022)[(a)], Milliman & Farnsworth (2011)[(b)], Regard et al. (2022)[c], Jickells et al. (2005)[d], Maher et al. (2010)[e], Raiswell et al. (2008)[f], Hasholt et al. (2022)[g], Burdige (2005, 2007)[h,i], Cartapanis et al. (2018)[j], Hilton & West (2020)[k], and Hayes et al. (2021)[l]. Values of Hayes et al. are for water depths > 1 km. Quantifying the global sediment flux carried by turbidity currents is a remaining grand challenge. **(b)** Global organic carbon (OC) mass fluxes in Mt/yr (in green). Values from Hilton & West (2020)[(k)], Li et al. (2022)[n], Galy et al. (2015)[o], Wadham et al. (2019)[(p)], Burdige 2005[(h)], Gaillardet et al. (1999)[q], and Plank & Manning (2019)[r]. Diagram summarises global pathways of terrestrial (black) and marine (blue) organic carbon.

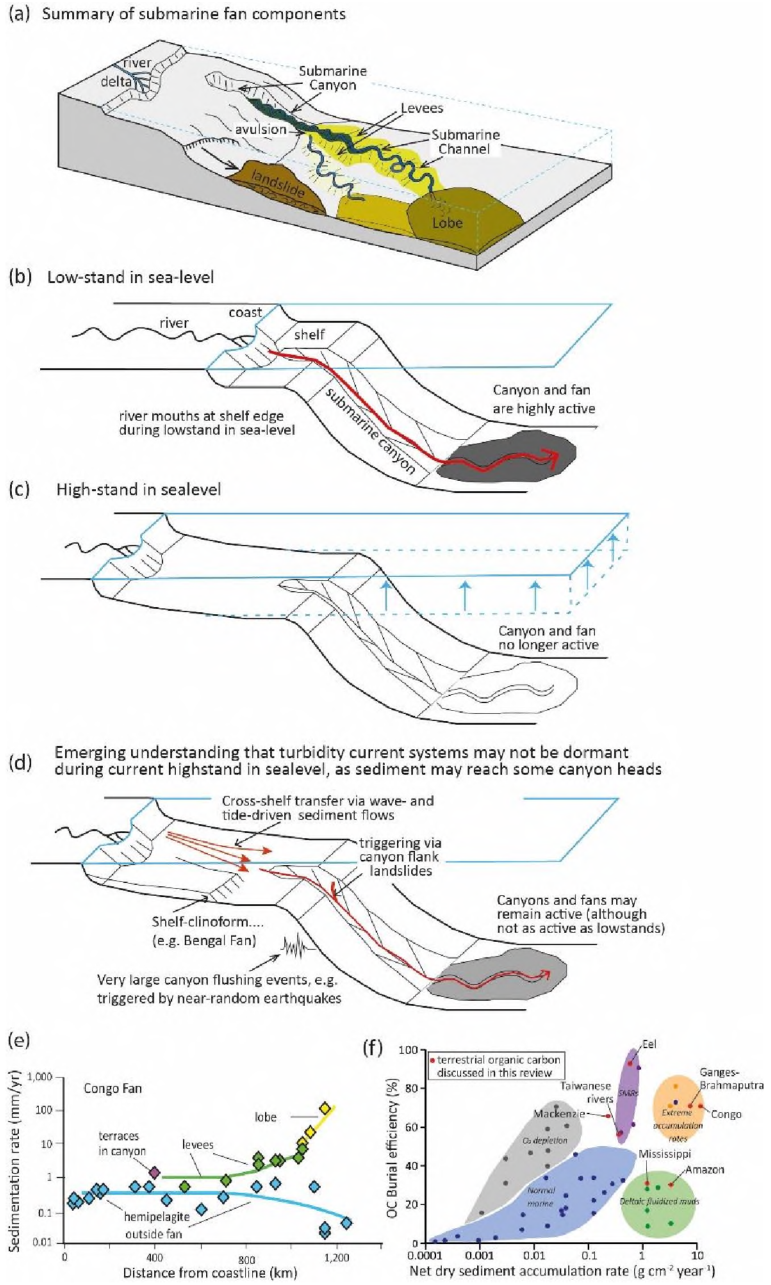


Figure 2. Controls on efficiency of sediment and organic carbon transfer or burial efficiency within submarine fans. (a) Basic components of a submarine fan. **(b)** During sea-level low-stand there is highly efficient transfer of sediment and OC, as almost all river mouths connect to canyon heads. **(c)** Past sequence stratigraphic models assumed most submarine fans are dormant during high-stands in sea-level, as most river mouths are separated from canyon heads (e.g. Posamentier & Kolla, 1993). **(d)** Emerging understanding that turbidity current systems in many locations may not be dormant during high-stands in sea-level. **(e)** Sediment accumulation rates in different components of the Congo Submarine Fan (after Baudin et al. 2020). **(f)** Relationship between sediment accumulation rates and OC burial efficiencies in different settings (after Blair and Aller, 2012), including for burial of terrestrial OC in submarine fans at sites discussed in this paper (red dots).

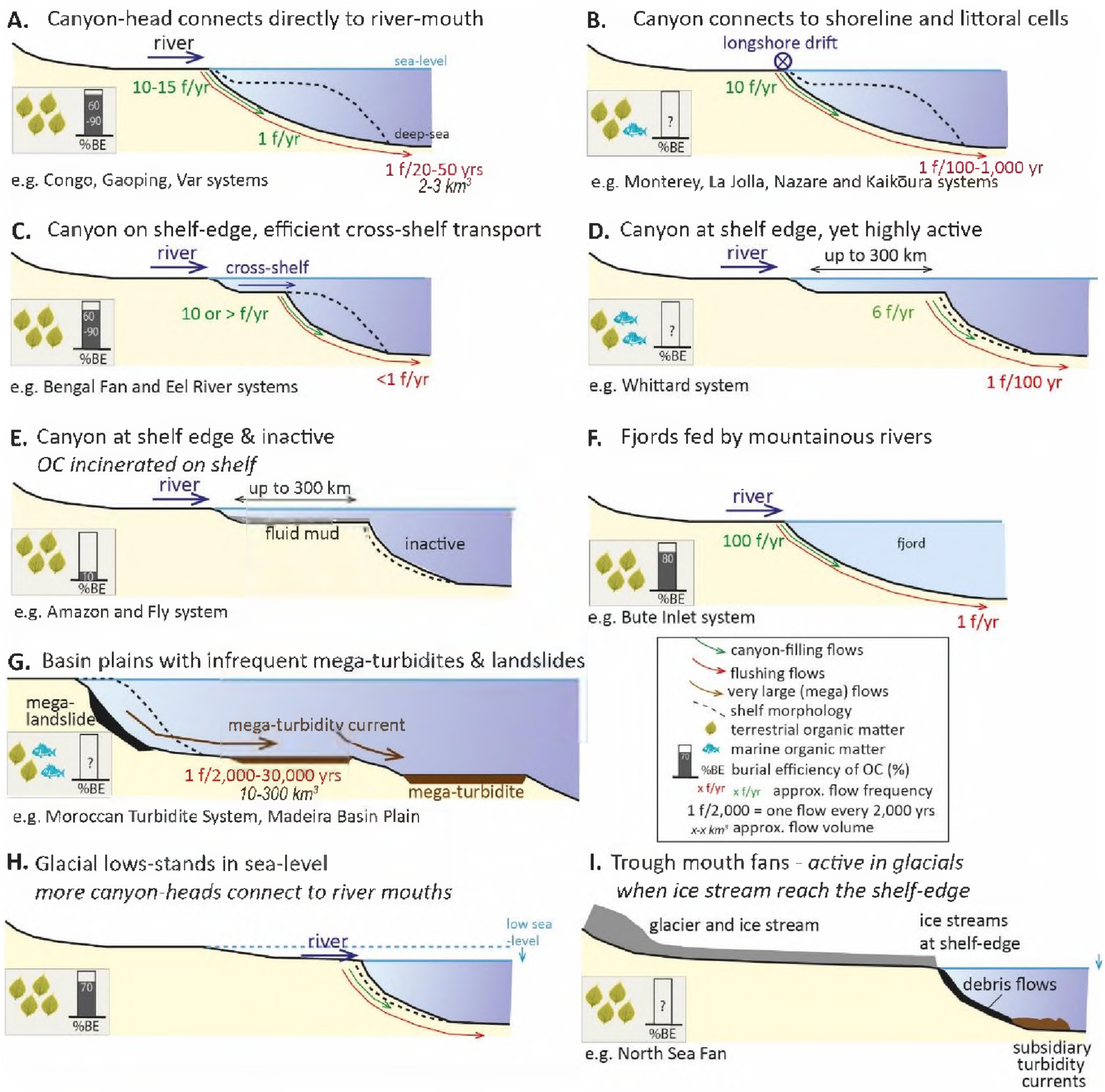


Figure 3. Sediment and organic carbon transfer by different types of turbidity current system. (a) Type 1: Submarine canyon-head connects directly to river-mouth. **(b)** Type 2: Submarine canyon connects to shore and fed by longshore drift. **(c)** Type 3: Submarine canyon only partially indents shelf, but sediment still reaches it from rivers. **(d)** Type 4: Submarine canyon restricted to shelf edge, yet still partly active. **(e)** Type 5: Submarine canyon at shelf-edge, and assumed to be inactive. **(f)** Type 6: Fjords where river-mouth feed directly into deep-water. **(g)** Type 7: Mega-landslides and abyssal plains - infrequent but very large turbidity currents. **(h)** Glacial lowstand when all rivers connect to canyon heads – as in type 1. **(i).** Trough-mouth fan active during a glacial lowstand.

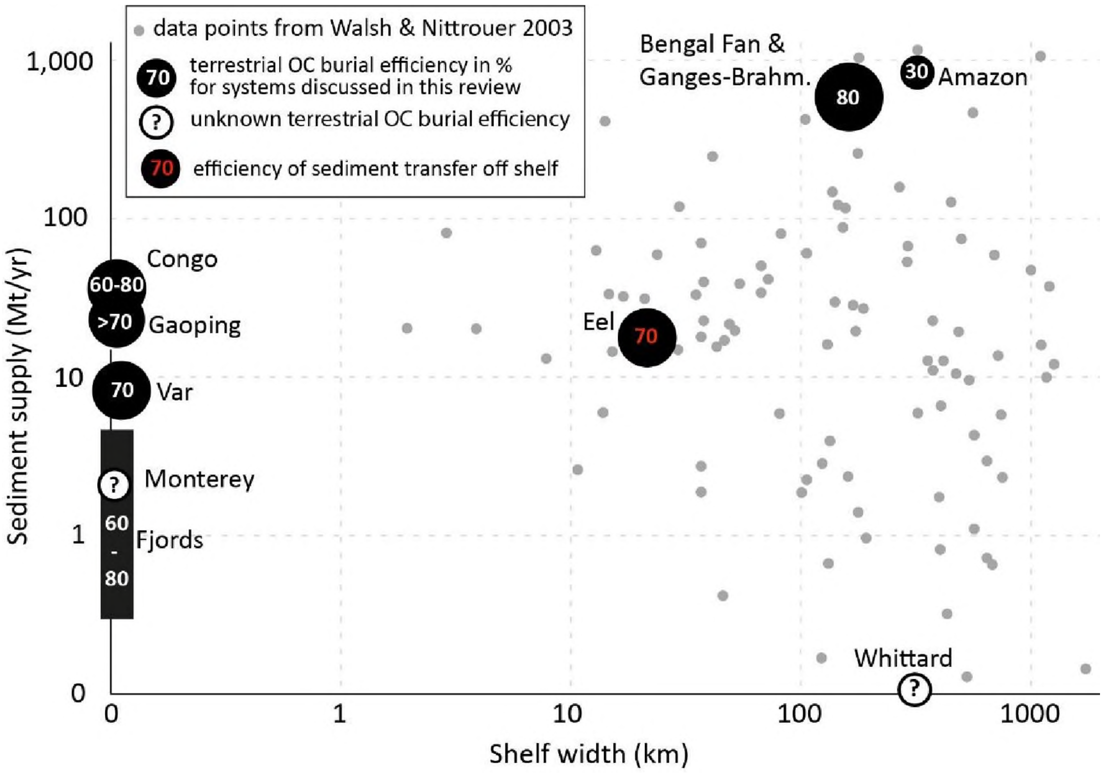


Figure 4. Relationship between efficiency of sediment transfer and terrestrial organic carbon burial, shelf width and magnitude of annual sediment supply from rivers or via longshore drift (e.g. to Monterey Canyon). Data on annual sediment fluxes from rivers and shelf width are from Walsh & Nittrouer (2003). Annual sediment flux into the head of Whittard Canyon is poorly known, but relatively low (Heijnen et al. 2022a). For Eel River and shelf, the fraction of riverine sediment that escapes the shelf on a decadal time-scale is shown, rather than estimated burial efficiency of OC.

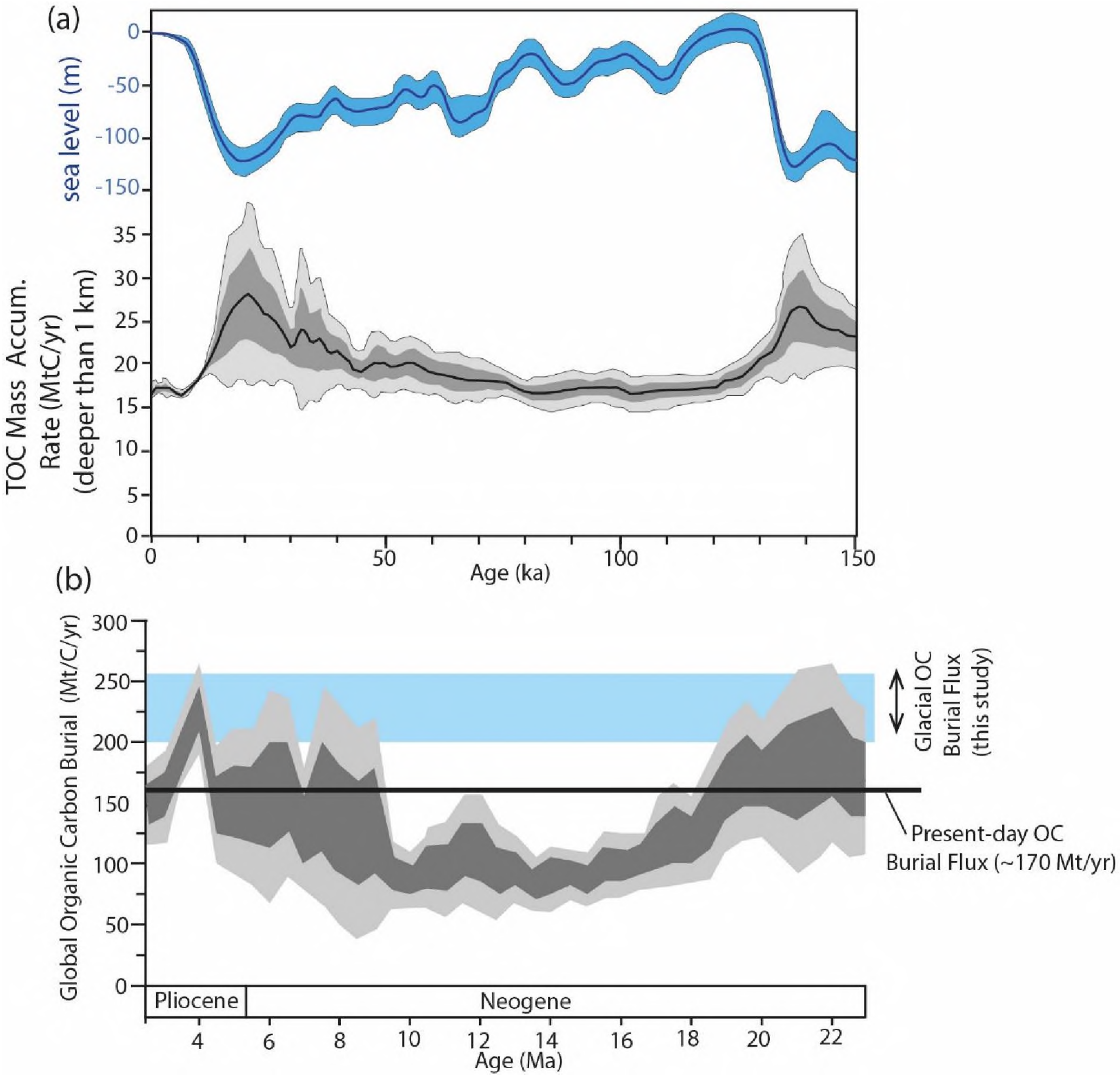


Figure 5. Changes in total organic carbon burial flux within marine sediments through time. Burial fluxes are calculated using seabed core databases, by analyses of TOC, mass accumulation rates and representative areas (biogeographic provinces). **(a)** Changes in total organic carbon burial flux in the deep-sea (> 1,000 m water depth) during glacial and interglacial periods (Cartapanis et al. 2016). However, submarine fans are not included within their seabed core database, suggesting that they may underestimate organic carbon burial fluxes. Here we estimate a global organic carbon burial flux during glacials of 200-265 MtC/yr, much of which will occur via turbidity currents on submarine fans at water depths of > 1,000 m. **(b)** Longer term changes in global organic carbon burial rates over the last ~23 Ma, from Li et al. (2023), who inferred that changes may have affected global climate.

Table 1. Estimates of global amount and efficiency of organic carbon burial in seabed sediments (i) in present day sea-level high-stand, and (ii) in glacial low-stand in sea-level (see text for derivations).

Present day (interglacial high stand in sea-level)				
Study	Terrestrial total particulate organic carbon (POC) supplied by rivers (MtC/yr)	Terrestrial POC global burial efficiency (%) in marine sediment Total OC (*Biospheric OC*)	Terrestrial POC global burial flux (MtC/yr) in marine sediment Total OC (*Biospheric OC*)	Total POC (terrestrial & marine OC) burial flux in marine sediments (MtC/yr)
Berner (1982, 1989)				~130
Hedges et al. (1997)		10-30 %		~160
Burdige (2005, 2007)	170-200	14-30 %	40-80	~170 [(a)]
Schlünz & Schneider (2000)	460 (for both POC & DOC)	10 %	46	
Blair & Aller (2012)	170-200	20-44 %		
Galy et al. (2015)	200 *(157 biospheric)*			
Hilton & West (2020).	200-300 [(b)]	10-30 %	40-80	~170 [(a)]
This study	200 *(157 biospheric)*	**31-45 %** ***(28-51 %)***	**62-90** [(e)] ***(44-80)*** [(e)]	**152-220** [(a)]
Glacial low-stand in sea-level				
Cartapanis et al. 2016		50 %	27 (only >1 km water depth)	
This study		**60-80 %** ***(60-80 %)***	**130-175** [(c)] ***(103-138)***	**200-265** [(c,d)]

(a) Assuming that the burial flux of marine organic carbon remains at 90-130 Mt/yr from Hilton and West (2020), but note that Burdige (2007) cites a significantly higher value of ~310 Mt/yr for the present day flux of marine OC that is buried.

(b) Also based on Li et al. (2021).

(c) Includes ~10-15 Mt/yr of terrestrial organic carbon buried globally within glacial trough mouth fans, and assumes that global supply of terrestrial organic carbon does not change from glacial to present day, nor does fraction that is biospheric.

(d) To allow comparison, assumes burial of marine organic carbon does not change from glacial to present day.

(e) Assumes a global TOC flux of 200 MtC/yr, and a biospheric flux that is 79% of 200 MtC/yr (i.e. 157 MtC/yr).

Supplementary Material

Method used to estimate revised global burial efficiencies and fluxes of terrestrial organic carbon

Here we provide further information on the methods used to calculate revised burial efficiencies and mass fluxes of terrestrial organic carbon (Supplementary Table 1).

We first consider the present-day period, before providing revised estimates for glacial periods.

Global terrestrial organic carbon supply from rivers: It is assumed that the total rate of supply of terrestrial particulate organic carbon from rivers to the oceans is currently 200 MtC/yr (Galy et al. 2015). This value is derived using a near-linear relationship that is observed between sediment yield ($Mt/yr/km^2$) and organic carbon yield ($Mt/yr/km^2$). Using the global average sediment yield, it was then possible to derive the global average total organic carbon (TOC) yield. This terrestrial TOC yield can then be multiplied by the surface area of continents to produce a global terrestrial TOC mass flux from rivers to oceans (Galy et al. 2015).

It is also assumed that 79% of this global terrestrial organic carbon flux from rivers (i.e. ~157 MtC/yr) is biospheric carbon, and thus contributes to drawdown of atmospheric pCO_2. This value of 79% is again based on the data base and analysis of Galy et al. (2015).

Note that Hilton & West (2020) and Li et al. (2022) recently proposed that the global mass flux of terrestrial TOC from rivers to the ocean is 200-300 MtC/yr, which is higher than the value of 200 MtC/yr from Galy et al. (2015). We prefer to use the value of 200 MtC/yr from Galy et al. (2015) because our estimated values of TOC and OC_{bio} mass fluxes from the Ganges-Brahmaputra, Congo, Amazon and Fly Rivers were derived using the same method by Galy et al. (2015) as this global terrestrial TOC flux of 200 MtC/yr. However, Supplementary Table 2 provides a re-analysis using the same workflow as below that is based on an alternative global terrestrial TOC flux of 200-300 MtC/yr. It results in a global burial efficiency of TOC of 28-45% (rather than 31-45%; Supplementary Table 1), and a global burial efficiency of 25-51% for biospheric OC (rather than 28-51%).

Subdivision of turbidity current systems: We then compiled information from a series of individual river and linked submarine-fan systems, or wider areas. They are the (i) Ganges-Brahmaputra River and Bengal Submarine Fan, (ii) Congo River and Congo Submarine Fan, (iii) Oceania that is mainly characterised by small mountainous rivers, (iv) fjords, and (v) the combined Amazon and Fly Rivers and offshore areas. For each of these systems or areas, we calculated the input flux from rivers of terrestrial total organic carbon (TOC) and its biospheric component (OC_{bio}) (e.g. using values in Galy et al. 2015). A final category of 'all other locations' was used to capture the remaining flux of TOC or OC_{bio}, once the previous fluxes had all been subtracted from global estimates. The various fluxes calculated for each individual site or category of system were then converted to a percentage of global supply of TOC or OC_{bio} from rivers.

This percentage of the global amount of organic carbon supplied was then multiplied by the burial efficiency assigned to that particular system, with the burial efficiency representing the ratio of the burial flux to the supply flux. This produced a percentage of the global organic carbon supply that is buried within each system, and this was calculated for both TOC or OC_{bio} (Supplementary Table 1).

The various percentages of global organic carbon supply that are buried in each system are then summed to calculate a cumulative global burial efficiency. This is done for both TOC and $OC_{bio.}$

The values of organic carbon flux supplied from rivers, and burial efficiencies of this organic carbon within marine sediment, used for each location were derived in the following ways.

TOC and OC_{bio} fluxes from Ganges Brahmaputra, Congo and Amazon-Fly Rivers: Values of TOC and OC_{bio} annual fluxes were taken from Galy et al. (2015) for the Ganges-Brahmaputra River (3.63 Mt TOC/yr and 3.34 Mt OC_{bio} /yr), Congo River (2.00 Mt TOC /yr & 1.96 Mt OC_{bio} /yr), and combined Amazon-Fly Rivers (12.54 Mt TOC/yr and 11.66 Mt OC_{bio} /yr).

These fluxes of TOC and OC_{bio} were then compared to their total global fluxes calculated using the same method by Galy et al. (2015), which are 200 MtC/yr for TOC and 157 MtC/yr for OC_{bio}. This allowed us to calculate the percentages of global fluxes that are represented by the local fluxes.

Burial efficiency for Bengal Fan: A burial efficiency of 80-90% was assigned to this system, following Galy et al. (2007), who inferred that burial of terrestrial organic carbon was 'highly efficient' in this system. Their conclusion was based on very similar TOC abundances and ages in sediment samples from the Ganges-Brahmaputra River-mouth and deep-sea cores in the Bengal Submarine Fan. We chose not to assign a maximum burial efficiency of exactly 100%, as some organic carbon is likely remineralised offshore, despite the high efficiency of burial (Blair & Aller 2012; Baudin et al. 2020).

Burial efficiency for Congo Fan: A burial efficiency of 60-90% was assigned to this system. It lies at the upper range of burial efficiency estimates of 33-69% by Baudin et al. (2020). However, almost 50% of the Congo River sediment flux remained unaccounted for in the budget of Baudin et al. (2020), emphasising uncertainties in that OC budget. More importantly, recent flow monitoring suggests that close to 100% of riverine sediment is flushed into the deep sea over time scales of ~20-50 years (Azpiroz-Zabala et al. 2017; Simmons et al. 2020; Talling et al. 2022). Thus, it seems likely that the burial efficiency may be higher than that estimated by Baudin et al. (2020) as efficient sediment transfer is also likely to be linked to efficient carbon burial.

Burial Efficiency in the Amazon and Fly Systems: We use a burial efficiency of ~30% for both of these systems, following the summary of Blair and Aller (2012; their figure 9). This burial efficiency reflects the observation that much of the organic carbon is remineralised as it is reworked by highly mobile mud layers on the continental shelf (Aller, 1998; Aller and Blair, 2006).

TOC and OC_{bio} fluxes from rivers in Oceania: Past work has used two methods for calculating organic carbon fluxes from rivers in Oceania (Kao et al. 2014, Bao et al. 2015). They both start with TOC (1.8 MtC/yr) and OC_{bio} (0.5 MtC/yr) fluxes calculated for the island of Taiwan (Kao et al. 2014, Bao et al. 2015). These organic carbon fluxes from Taiwan are then be scaled up to those from the whole of Oceania in two different ways.

First, it can be assumed that the average abundance of TOC or OC_{bio} is the same in sediment reaching the ocean from Taiwan, and that reaching the ocean from the rest of Oceania. Using a total sediment flux for Taiwan of 384 Mt/yr, and a terrestrial TOC flux of 1.8 Mt/yr, this gives a TOC fraction of 0.47% in the sediment. A similar calculation derives an OC_{bio} fraction in Taiwanese river sediment of 0.13%. These abundances of TOC and OC_{bio} carbon in Taiwanese river sediment are then assumed to be the same as those in the ~7,000 Mt/yr of sediment originating across Oceania (Milliman & Farnsworth 2011; Bao et al. 2015). This method derives a terrestrial TOC flux of 32.8 MtC/yr, and OC_{bio} flux of 9.1 MtC/yr, for the mainly small and mountainous rivers within Oceania.

A second method assumes that the average yield of TOC in Taiwan (MtC/yr/km^2) is similar to the average yield for all of Oceania. The area of Taiwan is 3.6 x 10^4 km^2, whilst the area of Oceania is ~2.7 x 10^6 km^2. This method produces a much higher estimate for the total flux of TOC (134.3 MtC/yr), or a OC_{bio} flux of 37.2 MtC/yr, from all of Oceania's rivers. The estimate of 134.3 MtC/yr of total terrestrial organic carbon flux from Oceania rivers seems high, as it is ~67% of the global flux used here for all rivers (i.e. 200 Mt/yr; Galy et al., 2015). We therefore prefer to use the lower value of 32.8 MtC/yr derived via the first method for the flux of terrestrial TOC from Oceania's rivers. We thus divide global TOC fluxes of 200 MtC/yr by a local flux of 32.8 MtC/yr to get the fraction of global TOC supply coming from rivers in Oceania (i.e. 16.4%). We use 8-40 MtC/yr for the flux of OC_{bio} from Oceania's rivers, which is the range of values advocated by Kao et al. (2014) and Bao et al. (2015). These values of 8-40 MtC/yr for OC_{bio} supply from Oceania rivers are then compared to global value of 157 MtC/yr (Galy et al. 2015) when calculating the fractions of the global OC_{bio} flux that is supplied by rivers in Oceania. (i.e. 5.1% to 25.5%).

Burial efficiency for Oceania: A terrestrial organic carbon burial efficiency of 60-90% in marine sediments was assigned to areas offshore Oceania, which is based on estimates of >70% by Kao et al. (2014) from sites around Taiwan. It is likely that highly episodic delivery of large amounts of sediment and OC, sometimes in floods with high enough sediment concentrations to plunge as offshore hyperpycnal flows (Mulder et al. 2003, Liu et al. 2012, Kao et al. 2014), will favour high burial efficiencies in offshore sediments. A lower bound of 60% (rather than 70%) is used for burial efficiencies, as some system in Oceania may not be quite as efficient as those around Taiwan (Kao et al. 2014).

TOC and* OC_{bio} *fluxes for fjords: A total amount of organic carbon buried in fjords (18 Mt/yr) is derived by Smith et al. (2015) using two different methods. The first method uses an average organic carbon mass accumulation rate (OC MAR), derived from analysis of a seabed core database from a variety of fjords, and the cumulative area of fjords globally. A second method uses estimates of the total flux of sediment deposited in fjords (813 Mt/yr) and the average TOC within fjord sediment (2.6 %). Both of these methods then assume that ~80% of the total terrestrial organic carbon that was originally supplied to fjords is then buried, so that fjords were originally supplied by 22.5 MtC/yr of terrestrial TOC from rivers globally.

It is then assumed that 60% of organic carbon supplied to and buried in fjords is terrestrial in origin, with the remaining 40% being marine (Cui et al. 2016; Smeaton & Austin, 2022). This leads to a global mass flux of 13.5 MtC/yr (i.e. 60% of 22.5 MtC/yr) of TOC from rivers to fjords. This leads to the assumption that 6.8% (i.e. 13.5/200 MtC/yr) of the global supply of terrestrial TOC by rivers to the oceans is provided to fjords.

It is then assumed that ~90% of the organic carbon supplied to rivers is biospheric in origin, with the remainder being petrogenic (Koziorowska et al. 2018; Zaborska et al. 2018; Bianchi et al. 2020). Thus, the global mass flux of OC_{bio} supplied from rivers to fjords is 12.2 Mt/yr (i.e. 90% of 13.5 MtC/yr), which is equivalent to 7.8% (12.2/157 MtC/yr) of the global OC_{bio} flux from rivers to the oceans.

Burial efficiency in fjords: Burial efficiencies within individual fjords can vary from 28% to 98% (Bianchi et al. 2020). Globally, about 20% of organic carbon that reaches the ocean from rivers is petrogenic (Galy et al. 2015). However, a value of 60-80% is a reasonable global average, as supported by work on average values in Scottish fjords (Smeaton et al. 2021) or Chilean fjords (Sepulveda et al. 2005). The value of 80% used by Smith et al. (2015) lies at the upper boundary of this range. It is thus assumed the fraction of petrogenic carbon (OC_{petro}) reaching fjords is somewhat below the global average of 20% for all rivers (Galy et al. 2015). However, it is noted that the petrogenic fraction of organic carbon within fjords can vary substantially, such as due to variation in the bedrock eroded within mountainous hinterlands (Bianchi et al. 2020; Berg et al. 2021). This set of assumptions leads to an estimate of 12.2 MtC/yr of OC_{bio} (i.e. 90% of 13.5 MtC/yr) is supplied to fjords globally.

TOC and OC_{bio} fluxes in all other rivers: A final category comprises all other rivers, which are not in the previous categories. The amounts of TOC and OC_{bio} supplied by all other rivers to the ocean is derived as follows. The cumulative total fluxes for all of the previous categories were calculated, and then subtracted from global estimates of 200 MtC/yr for TOC supply from rivers, and 157 MtC/yr for OC_{bio} supply, as derived by Galy et al. (2015).

Burial efficiency in all other rivers: A range of burial efficiency offshore from 'all other rivers' were explored with values of 30%, 20% and 10% (Supplementary Table 1). This range was chosen because previous studies (Table 1) have proposed global average burial efficiencies of 10-30%. However, we then felt that average burial efficiencies of 20 or 30% were most likely within the 'all other rivers' category, and they underpin the revised burial efficiencies cited in Table 1 and the paper's abstract. However, if an average burial efficiency of 10% is assumed for 'all other rivers' then revised global average burial efficiencies become 24-45% for TOC and 20-51% for OC_{bio} (see Supplementary Table 1).

Sediment fluxes: Estimates of sediment fluxes are also given in Supplementary Table 1. They are derived from Milliman & Farnsworth (2011) for the Ganges Brahmaputra, Congo, Amazon and Fly Rivers, and from Milliman & Syvitski (2021) for Oceania, and Smith et al. (2015) for fjords. Values for 'all other rivers' assume that total global sediment flux is 15,000 to 18,000 Mt/yr (Milliman & Fahnsworth, 2000). Those calculating do not include a recent decrease in global river sediment flux since 1950 proposed by Syvitski et al. (2021), due to factors including dams and reservoirs.

Additional assumptions used in Supplementary Table 1: The calculations outlined above lead to a revised global burial efficiency of terrestrial TOC of 31-45%, and OC_{bio} of 28-51% (Table 1). Those burial efficiencies were then turned into global annual fluxes of TOC and OC_{bio} in the following way (Table 1). The burial efficiency of TOC (31-45%; Table 1) was multiplied by the annual flux of TOC from rivers (200 MtC/yr; Galy et al. 2015), which gives a terrestrial TOC burial mass flux of 62-90 MtC/yr. Similarly, the terrestrial OC_{bio} burial efficiency (28-51%; Table 1) was multiplied by the global flux of OC_{bio} from rivers of 157 MtC/yr (Galy et al. 2015), which gives a terrestrial OC_{bio} burial mass flux of 44-80 MtC/yr.

It was then assumed that about 90-130 MtC/y of marine organic carbon is buried on the seabed each year (Burdige, 2005, 2007; Blair & Aller, 2012; Hilton & West, 2020). This amount of marine carbon was then added to previous estimates of terrestrial organic carbon buried on the seabed, to derive a total burial flux of organic carbon of 152-220 MtC/yr (i.e. [62-90] + [90-130] MtC/yr).

Burial efficiency and fluxes during glacial periods with low stands in sea-level

It was assumed that global burial efficiency of terrestrial organic carbon (TOC) will increase significantly to values of 60-80% during low-stands in sea-level. This increase arises because almost all river mouths will connect directly to submarine canyon-heads during low-stands, when the coastline is located around the edge of the continental shelf. Thus, almost all of the ~9,500 canyons on the seafloor will be highly active, including those now linked directly to the Amazon, Nile and Mississippi Rivers. Burial efficiencies of >60 to 80% characterise modern rivers that connect to submarine canyon heads, such as in the Congo Fan, Bengal Fan and Gaoping Canyon systems. Thus, it is reasonable to attribute a 60-80% burial efficiency as a global average for glacial periods.

This assumption of 60-80% burial efficiency then leads to global terrestrial TOC burial flux of 120-160 MtC/yr (i.e. 60-80% of 200 MtC/yr), and OC_{bio} burial fluxes of 94-127 MtC/yr (i.e. 60-80% of 157 MtC/yr).

An additional 10-15 MtC/yr of TOC is also assumed to be buried in trough mouth fans fed by ice streams that extend across the shelf, as in the North Sea Fan (Nygard et al. 2007). This gives a cumulative TOC mass flux of 130-175 MtC/yr that is buried in marine sediments during glacials.

The terrestrial TOC burial flux is seafloor sediments during glacials (130-175 MtC/yr) is thus roughly twice that estimated at the modern day (62-90 MtC/yr; Table 1). Note that this estimate of terrestrial TOC and OC_{bio} burial flux assumes rate of organic carbon supply by rivers do not change from present-day to glacials. This assumption is unlikely to hold, but it allows the effects of variable burial fluxes to be easily understood.

Total burial flux of both marine and terrestrial organic carbon can also be estimated, assuming that the rate of marine organic carbon burial on the seabed does not change between glacials and the modern day (Table 1). Again this assumption may not hold in detail, but it illustrates how variable terrestrial organic burial efficiencies may affect the total amount of organic carbon that is buried.

Cartapannis et al. (2016) previously assumed that terrestrial organic carbon burial efficiencies may be ~50% during glacial periods. They used seabed cores from water depths of > 1,000 m to estimate the combined burial flux of both marine and terrestrial carbon (Fig. 5b). However, their seabed core data-base excluded submarine fans, and deltas and other locations on the continental shelf. Thus, they derived a much lower global burial flux of total organic carbon (~17 MtC/yr at present day and 27 MtC/yr in glacials) than our estimate of (152-220 MtC/yr at present day and 200-265 MtC/yr in glacials; Table 1).

Supplementary Table 1. Revised burial efficiencies for individual systems and types of system, assuming a global terrestrial TOC mass flux of 200 MtC/yr from Galy et al. (2015).

assumed Burial Efficiency of 'all other rivers' = 30%

place	sed supply	Terrestrial total & biosp OC mass flux (MtC/yr)	% global terrest. OC supply - min	% global terrest. OC supply - max	% global biopsheric OC supply - min	% global biopsheric OC supply - max	Burial efficiency (%) min	Burial efficiency (%) max	TOC min	TOC max	total biosp min	total biosph max	
Ga ges-Br maputra	1600	3.63 (3.34 biospheric)	1.8	1.8	2.1	2.1	0.80	0.90	1.44	1.62	1.68	1.89	
Congo River	53 150	2.00 (1.96 biospheric)	1	1	1.2	1.2	0.60	0.90	0.6	0.90	0.72	1.08	
Oceania Rivers	~7,000	32.8-(134.3*) (8-40 biospheric)	16.4	16.4	5.1	25.5	0.60	0.90	9.84	14.76	3.06	22.95	
Fiords	813	13.5 (12.2 biospheric)	6.8	6.8	7.8	7.8	0.60	0.80	4.08	5.44	4.68	6.24	
Amazon and Fly	930	12.54 (11.66 biospheric)	6.3	6.3	7.4	7.4	0.30	0.30	1.89	1.89	2.22	2.22	
all others	4,500-7,500	135.5 (116.8 biospheric)	67.7	67.7	76.4	56	0.30	0.30	20.31	20.31	22.92	16.80	
									38.16	**44.92**	**35.28**	**51.18**	**Burial efficiency %**
		* value is not used (as 67% global TOC flux)	assumes 200 Mt/yr total OC from rivers			assumes 157 Mt/yr biospheric OC from rivers				30%>> 38% 45%		30%>> 35%-51%	

assumed Burial Efficiency of 'all other rivers' = 20%

place	sed supply	Terrestrial total & biosp OC mass flux (MtC/yr)	% global terrest. OC supply - min	% global terrest. OC supply - max	% global biopsheric OC supply - min	% global biopsheric OC supply - max	Burial efficiency (%) min	Burial efficiency (%) max	TOC min	TOC max	total biosp min	total biosph max	
Ganges-Brahmaputra	1600	3.63 (3.34 biospheric)	1.8	1.8	2.1	2.1	0.80	0.90	1.44	1.62	1.68	1.89	
Congo River	53-150	2.00 (1.96 biospheric)	1	1	1.2	1.2	0.60	0.90	0.6	0.90	0.72	1.08	
Oceania Rivers	~7,000	31.8-(134.3*) (8-40 biospheric)	16.4	16.4	5.1	25.5	0.60	0.90	9.84	14.76	3.06	22.95	
Fiords	813	13.5 (12.2 biospheric)	6.8	6.8	7.8	7.8	0.60	0.80	4.08	5.44	4.68	6.24	
Amazon and Fly	930	12.54 (11.66 biospheric)	6.3	6.3	7.4	7.4	0.30	0.30	1.89	1.89	2.22	2.22	
all others	4,500-7,500	135.5 (116.8 biospheric)	67.7	67.7	76.4	56	0.20	0.20	13.54	13.54	15.38	11.20	
									31.39	**38.15**	**27.64**	**45.58**	**Burial efficiency %**
		* value is not used (as 67% global TOC flux)	assumes 200 Mt/yr total OC from rivers			assumes 157 Mt/yr biospheric OC from rivers				20% >> 31% to 38%		20% >> 28% to 45%	

assumed Burial Efficiency of 'all other rivers' = 10%

place	sed supply	Terrestrial total & biosp OC mass flux (MtC/yr)	% global terrest. OC supply - min	% global terrest. OC supply - max	% global biopsheric OC supply - min	% global biopsheric OC supply - max	Burial efficiency (%) min	Burial efficiency (%) max	TOC min	TOC max	total biosp min	total biosph max	
Ganges-Brahmaputra	1600	3.63 (3.34 biospheric)	1.8	1.8	2.1	2.1	0.80	0.90	1.44	1.62	1.68	1.89	
Congo River	53 150	2.00 (1.96 biospheric)	1	1	1.2	1.2	0.60	0.90	0.6	0.90	0.72	1.08	
Oceania Rivers	~7,000	32.8-(134.3*) (8-40 biospheric)	16.4	16.4	5.1	25.5	0.60	0.90	9.84	14.76	3.06	22.95	
Fiords	813	13.5 (12.2 biospheric)	6.8	6.8	7.8	7.8	0.60	0.80	4.08	5.44	4.68	6.24	
Amazon and Fly	930	12.54 (11.66 biospheric)	6.3	6.3	7.4	7.4	0.30	0.30	1.89	1.89	2.22	2.22	
all others	4,500-7,500	135.5 (116.8 biospheric)	67.7	67.7	76.4	56	0.10	0.10	6.77	6.77	7.64	5.60	
									24.62	**31.38**	**20**	**39.98**	**Burial efficiency %**
		* value is not used (as 67% global TOC flux)	assumes 200 Mt/yr total OC from rivers			assumes 157 Mt/yr biospheric OC from rivers				10% >> 25%-31%		10% >> 20%-40%	

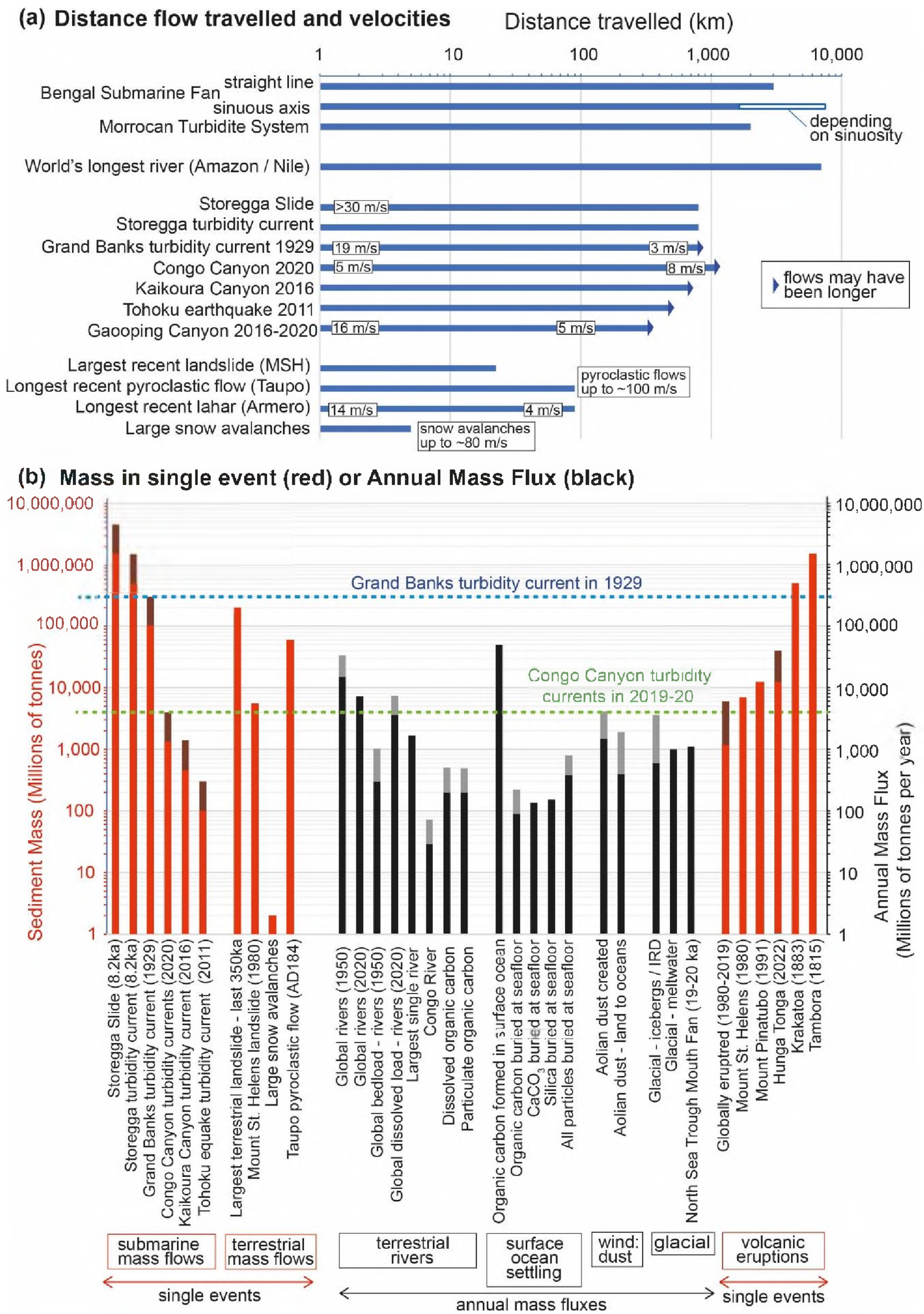
Supplementary Table 2. Revised burial efficiencies for individual systems and types of system, assuming a global terrestrial TOC mass flux of 200-300 MtC/yr from Hilton & West (2020) and Li et al. (2022).

place	sed supply	Terrestrial total & biosp. OC mass flux (MtC/yr)	% global terrest. OC supply - min	% global terrest. OC supply - max	% global biospheric OC supply - min	% global biospheric OC supply - max	Burial efficiency (%) min	Burial efficiency (%) max	TOC min	TOC max	total biosp min	total biosph max	
			assumed Burial Efficiency of 'all other rivers' = 30%										
Ganges-Brahmaputra	1600	3.63 (3.34 biospheric)	1.2	1.8	1.4	2.1	0.80	0.90	0.96	1.62	1.12	1.89	
Congo River	53-150	2.00 (1.36 biospheric)	0.7	1	0.8	1.2	0.60	0.90	0.42	0.90	0.48	1.08	
Oceania Rivers	~7 000	32.8-[134.3*] (8-40 biospheric)	10.9	16.4	3.4	25.5	0.60	0.90	6.54	14.76	2.04	22.95	
Fjords	813	13.5 (12.2 biospheric)	4.5	6.8	5.2	7.8	0.60	0.80	2.7	5.44	3.12	6.24	
Amazon and Fly	930	12.54 (11.36 biospheric)	4.2	6.3	4.9	7.4	0.30	0.30	1.26	1.89	1.47	2.22	
all others	4,500-7,500	135.5 (116.8 biospheric)	78.5	67.7	84.3	56	0.30	0.30	23.55	20.31	25.29	16.80	
									35.43	44.91	33.52	51.18	Burial efficiency %
		* value is not used (as 67% global TOC flux)	assumes 200-300 Mt/yr total OC from rivers			assumes 157-237 Mt/yr biospheric OC from rivers				30%>> 35%-45%		30%>> 34%-51%	
			assumed Burial Efficiency of 'all other rivers' = 20%										
Ganges-Brahmaputra	1600	3.63 (3.34 biospheric)	1.2	1.8	1.4	2.1	0.80	0.90	0.96	1.62	1.12	1.89	
Congo River	53-150	2.00 (1.36 biospheric)	0.7	1	0.8	1.2	0.60	0.90	0.42	0.90	0.48	1.08	
Oceania Rivers	~7 000	32.8-[134.3*] (8-40 biospheric)	10.9	16.4	3.4	25.5	0.60	0.90	6.54	14.76	2.04	22.95	
Fjords	813	13.5 (12.2 biospheric)	4.5	6.8	5.2	7.8	0.60	0.80	2.7	5.44	3.12	6.24	
Amazon and Fly	930	12.54 (11.36 biospheric)	4.2	6.3	4.9	7.4	0.30	0.30	1.26	1.89	1.47	2.22	
all others	4,500-7,500	135.5 (116.8 biospheric)	78.5	67.7	84.3	56	0.20	0.20	15.7	13.54	16.86	11.20	
									27.58	38.15	25.09	45.58	Burial efficiency %
		* value is not used (as 67% global TOC flux)	assumes 200-300 Mt/yr total OC from rivers			assumes 157-237 Mt/yr biospheric OC from rivers				20% >> 28% to 38%		20% >> 25% to 46%	
			assumed Burial Efficiency of 'all other rivers' = 10%										
Ganges-Brahmaputra	1600	3.63 (3.34 biospheric)	1.2	1.8	1.4	2.1	0.80	0.90	0.96	1.62	1.12	1.89	
Congo River	53-150	2.00 (1.36 biospheric)	0.7	1	0.8	1.2	0.60	0.90	0.42	0.90	0.48	1.08	
Oceania Rivers	~7 000	32.8-[134.3*] (8-40 biospheric)	10.9	16.4	3.4	25.5	0.60	0.90	6.54	14.76	2.04	22.95	
Fjords	813	13.5 (12.2 biospheric)	4.5	6.8	5.2	7.8	0.60	0.80	2.7	5.44	3.12	6.24	
Amazon and Fly	930	12.54 (11.36 biospheric)	4.2	6.3	4.9	7.4	0.30	0.30	1.26	1.89	1.47	2.22	
all others	4,500-7,500	135.5 (116.8 biospheric)	78.5	67.7	84.3	56	0.10	0.10	7.85	6.77	8.43	5.60	
									19.73	31.38	16.66	39.98	Burial efficiency %
		* value is not used (as 67% global TOC flux)	assumes 200-300 Mt/yr total OC from rivers			assumes 157-237 Mt/yr biospheric OC from rivers				10% >> 20%-31%		10% >> 17%-40%	

Supplementary Table 3: Comparison of sediment volumes and mass fluxes carried by turbidity currents and other important global sediment transport processes ('pumps'), showing turbidity currents are one of the most important sediment pumps on Earth.

Sediment volume/mass and runout distance of individual events	*Sediment Volume Transported (km^3)*	*Runout Distance (km)*
Congo Canyon Turbidity Currents in 2019-20 (Talling et al. 2022)	~2.675 km^3 ++ (1,338 - 2,675 Mt)**	> 1,130 km
Grand Banks turbidity current in 1929, N.W. Atlantic (Piper et al. 1999).	>200 km^3 (100,000 - 200,000 Mt)**	> 800 km
Sediment flux by turbidity currents to deep-sea after M_w9.1 Tōhoku earthquake (Kioka et al. 2019).	0.2 km^3	200-500 km
Sediment flux by turbidity currents to deep-sea after M_w7.8 Kaikōura earthquake (Mountjoy et al. 2018).	0.94 km^3	> 700 km
Mt St Helens landslide in 1980: largest historical landslide (Korup et al. 2007).	2.8 km^3	22.5 km
Largest snow avalanches (Schearer & McClung 2006).	0.01 km^3	<3-5 km
AD184 Taupo pyroclastic flows - largest volcanic pyroclastic flows in last 2,000 years (Wilson 1985).	30 km^3	< 90 km
Longest terrestrial lahar or debris flows in last century (Pierson 1990).	-	< 90 km
Global or Local Annual Sediment Fluxes	*Sediment Mass*	
Congo River - suspended sediment load (Milliman & Fahnsworth 2011)	~29-43 Mt/yr	-
Rivers (suspended sediment load): modern-day (2010) (Syvitski et al. 2022) Rivers (suspended sediment load): pre-Anthropocene (Milliman & Fahnsworth, 2011) Rivers (bedload - but very poorly known): modern day (Milliman & Fahnsworth 2011, Syvitski et al. 2022) Rivers (dissolved load) pre-Anthropocene & modern day (Milliman & Fahnsworth 2011, Sytvitski et al. 2022).	~7,200 Mt/yr ~15-18,000 Mt/yr ~720 - 300 Mt/yr ~3,600-3,800 Mt/yr	- - - -
Sediment settling from surface ocean (Burdige, 2005, 2007).	~54,600 Mt/yr	-

.....but sediment that reaches seabed (Burdige 2005, 2007).	~2,960 Mt/yr	-
Aeolian dust transport from land to oceans (Jickells et al. 2005, Syvitski et al. 2022).	~1,500 Mt/yr	-
Glacial transport (icebergs and meltwater): modern day (Raiswell et al. 2008; Hasholt et al. 2022; Syvitski et al. 2021)	~ 4,000 Mt/yr	-



Supplementary Figure 1. Comparison between turbidity currents and various other major global sediment transfer processes, showing turbidity current are one of the most important sediment transfer processes ('pumps') on Earth. (a) Distance that flows travel (km) and their velocities (m/s).

(b) Mass of sediment carried by individual events (in red), and as annual sediment mass fluxes (in black), with uncertainties as grey additional bars. The sediment mass carried by the Grand Banks turbidity current in 1929 (blue dotted line; Piper et al. 1999) and Congo Canyon turbidity currents in 2020 (green dotted line; Talling et al. 2022) are indicated. Supplementary Table 1 provide further information and lists source literature used for the distances, speeds, masses or annual mass fluxes that are quoted.

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