Supplemental Material: Annu. Rev. Mar. Sci. 2024. 16.
https://doi.org/10.1146/annurev-marine-032223-103626
The Global Turbidity Current Pump and Its Implications for Organic Carbon Cycling
Talling, Hage, Baker, Bianchi, Hilton, and Maier

Supplemental 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 (Supplemental 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, Supplemental 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%; Supplemental 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} (Supplemental 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% (Supplemental 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 Supplemental Table 1).

Sediment fluxes: Estimates of sediment fluxes are also given in Supplemental 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 Supplemental 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 OC 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 OC 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.

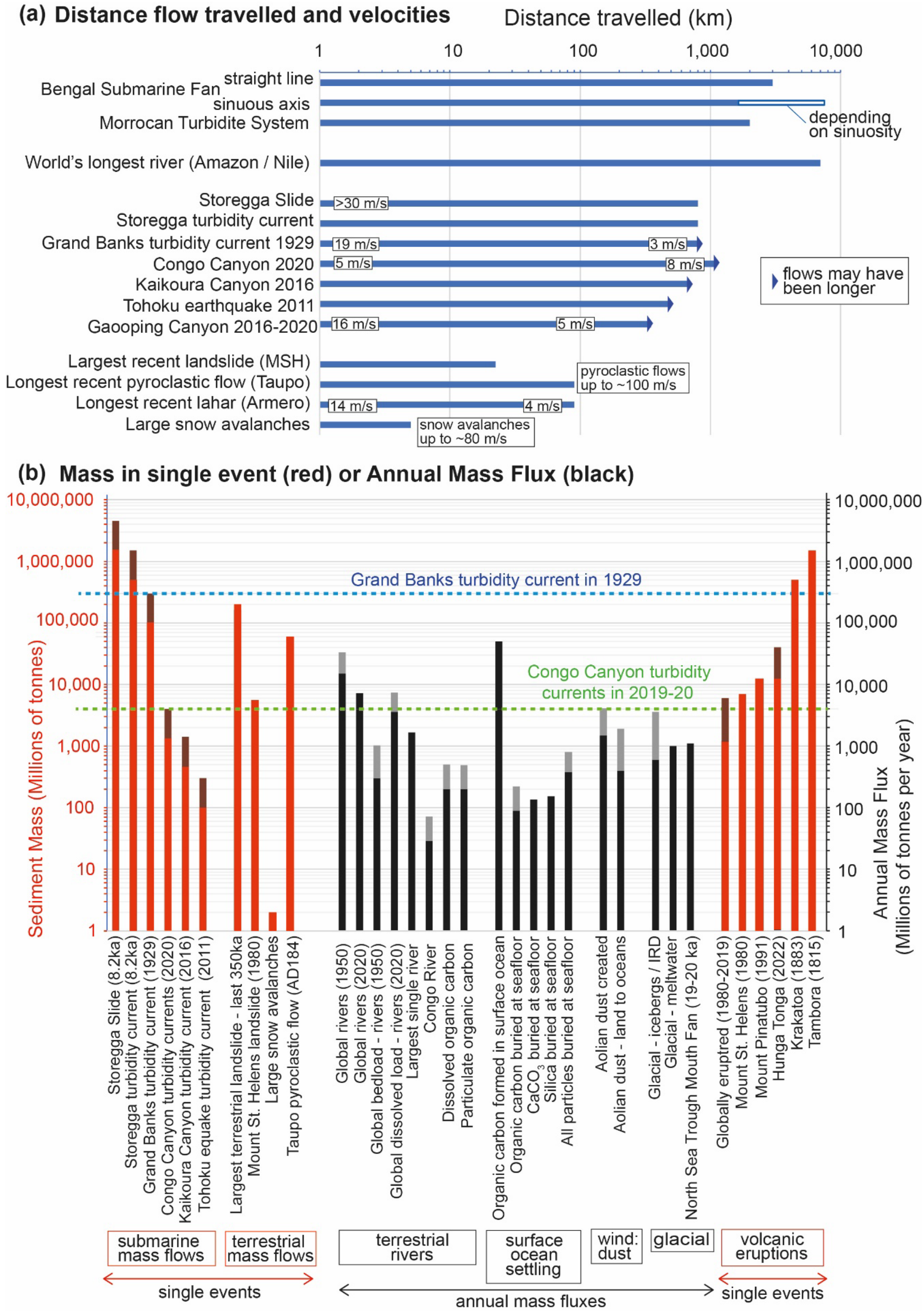
Total burial flux of both marine and terrestrial organic carbon can also be estimated, assuming that the rate of marine organic carbon burial on the seabed (90-130 Mt/year) does not change between glacials and the modern day (Table 1). Again this assumption may not hold in detail, but it illustrates how variable terrestrial organic burial efficiencies may affect the total amount of organic carbon that is buried. If the rate of terrestrial OC burial in marine sediment during glacial periods (130-175 Mt/year) and the rate of marine OC burial (90-130 Mt/yr) are summed, this leads to a combined burial of TOC during glacial periods of 220-305 Mt/yr (Table 1; Fig. 5).

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 220-305 MtC/yr in glacials; Table 1).

Supplemental 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	-



Supplemental 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. Supplemental Table 1 provide further information and lists source literature used for the distances, speeds, masses or annual mass fluxes that are quoted.

SUPPLEMENTAL REFERENCES

Pierson TC, Janda RJ, Thouret J-C., Borrero C. 1990. Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. *Jour. Volc. Geotherm. Res*. 41:17–66.

Korup O, Clague JJ, Hermanns RL, Hewitt K, Strom AL. Weidinger JT. 2007. Giant landslides, topography, and erosion. *Earth Planet. Sci. Letts* 261:578–589.

Shearer P, McClung D. 2006. The avalanche handbook (3rd edn), 288 pp. (Mountineers Books, Seattle.

Wilson CJN. 1985. The Taupo Eruption, New Zealand: II. The Taupo Ignimbrite. *Trans. R. Soc. Land. A* 314:229–310.

Koziorowska K, Kulinski K, Pempkowiak J. 2018. Comparison of the burial rate estimation methods of organic and inorganic carbon and quantification of carbon burial in two high Arctic fjords. *Oceanologia* 60:405–418.

Zaborska A, Wlodarska-Kowalczuk M, Legeżyńska J, Jankowska E, Winogradow A, Deja K. 2018. Sedimentary organic matter sources, benthic consumption and burial in West Spitsbergen fjords – signs of maturing of Arctic fjordic systems? *J. Mar. Syst.* 180:112–123.

Berg S, Jivcov S, Kusch S, Kuhn K, White D, Bohrmann G, Melles M, Rethemeyer J. 2021. Increased petrogenic and biospheric organic carbon burial in sub-Antarctic fjord sediments in response to recent glacier retreat. *Limnol. Oceanogr.* 66:4347–4362

Smeaton C, Hunt CA, Turrell WR, Austin WEN. 2021. Marine sedimentary carbon stocks of the United Kingdom’s exclusive economic zone. *Front. Earth Sci.* 9.

Sepúlveda J, Pantoja S, Hughen KA. 2011. Sources and distribution of organic matter in northern Patagonia fjords, Chile (44 – 47S): A multi-tracer approach for carbon cycling assessment. *Cont. Shelf Res.* 31: 315–329.