Flood and tides trigger longest measured sediment flow that accelerates for thousand kilometers into deep-sea

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Abstract

Here we document for the first time how major rivers connect directly to the deep-sea, by analysing the longest runout sediment flows (of any type) yet measured in action. These seafloor turbidity currents originated from the Congo River-mouth, with one flow travelling >1,130 km whilst accelerating from 5.2 to 8.0 m/s. In one year, these turbidity currents eroded 1-2 km$^3$ of sediment from just one submarine canyon, equivalent to 14-28% of the annual global-flux from rivers. It was known earthquakes trigger canyon-flushing flows. We show major river-floods also generate canyon-flushing flows, primed by rapid sediment-accumulation at the river-mouth, but triggered by spring tides weeks to months after the flood. This is also the first field-confirmation that turbidity currents which erode can self-accelerate, thereby travelling much further. These observations explain highly-efficient organic carbon transfer, and have important implications for hazards to seabed cables, or how terrestrial climate change impacts the deep-sea.

Introduction

Flows of sediment that move along the seabed (called turbidity currents) form the largest sediment accumulations, deepest canyons and longest channel systems on Earth$^{1,2,3}$. The scale of individual turbidity currents can also be exceptionally large (Table 1). For example, an earthquake-triggered turbidity current that occurred in 1929 in the NW Atlantic carried over 200 km$^3$ of sediment, and ran out for >800 km, at speeds of up to 19 m/s$^{4,5}$. This single turbidity current carried over 20 times the annual sediment flux from all of the world's rivers$^6$, and its volume exceeded the largest documented subaerial landslide in the last ~350,000 years$^7$. It was previously thought that directly measuring powerful turbidity currents that reached the deep-sea was impractical$^8$. However, here we describe direct monitoring of deep-sea turbidity currents in the Congo Canyon offshore West Africa$^9$, whose timing was captured by an array of seabed moorings and seabed telecommunication cable breaks (Figs. 1 and 2). On January 14-16th 2020, one of these flows travelled for over 1,130 km from the mouth of the Congo River, measured along the sinuous axis of the submarine Congo Canyon and Channel (Fig. 1). This is the longest runout sediment-driven flow yet measured in action on our planet, with a runout distance exceeding that of the 1929 NE Atlantic turbidity current$^4$, and longest known terrestrial debris flow$^{10}$, snow avalanche$^{11}$ or volcanic pyroclastic flow$^{12}$ (Table 1). Two further long runout turbidity currents broke seabed telecommunication cables again on March 9th 2020 and 28-29th April 2021 (Supplementary Table 1), whilst the mooring array recorded twelve slower and shorter runout turbidity currents within the upper canyon during a ~4 month period in 2019-20 (Fig. 2).
Table 1
Comparison of sediment volumes and runout distances for 2019-20 Congo Canyon turbidity currents and those from other individual events or global fluxes.

| Sediment flux and runout distance of individual events | Sediment Volume Transported (km$^3$) | Runout Distance (km) |
|-------------------------------------------------------|-------------------------------------|----------------------|
| **Congo Canyon Turbidity Currents in 2019-20 (this study)** | 1-2 km$^3$ | > 1,130 km |
| Grand Banks turbidity current in 1929, N.E. Atlantic. | > 200 km$^3$ | > 800 km |
| Mt St Helens landslide in 1980: largest historical landslide | 2.8 km$^3$ | 22.5 km |
| Largest snow avalanches | 0.01 km$^3$ | <3-5 km |
| AD184 Taupo pyroclastic flows - largest volcanic pyroclastic flows in last 2,000 years | 30 km$^3$ | < 90 km |
| Longest terrestrial lahar or debris flows in last century | - | < 90 km |
| Sediment flux by turbidity currents to deep sea after M$_w$9.1 Tōhoku earthquake | 0.2 km$^3$ | 200-500 km |
| Sediment flux by turbidity currents to deep sea after M$_w$7.8 Kaikōura earthquake | 0.94 km$^3$ | > 700 km |

**Global Annual sediment Fluxes**

| Sediment Volume |
|-----------------|
| Rivers | ~7 km$^3$ per year* |
| Sediment settling from surface ocean | ~21 km$^3$ per year* |
| Dust transport from land to oceans | ~0.3 km$^3$ per year* |
| Glacial sediment transport (present day) | ~ 0.4 km$^3$ per year* |

* based on average sediment density of ~2,600 kg/m$^3$

The scale of turbidity currents ensures that the sediment-mass carried by these flows rivals that of any other process on Earth$^{1,13}$, including rivers$^6$ or glaciers, or settling from the surface ocean$^{14}$ (Table 1).
Turbidity currents are thus important for a wide variety of reasons. For example, turbidity currents play a globally significant role in terrestrial organic carbon burial\textsuperscript{15} that affects atmospheric CO\textsubscript{2} levels on long time scales, and other global geochemical cycles. It was once thought that terrestrial organic carbon was incinerated primarily on continental shelves\textsuperscript{16}. More recent studies\textsuperscript{15,17} proposed that transfer and burial of terrestrial organic carbon in the deep-sea by turbidity currents could be highly efficient, based on similarities in organic carbon abundances, compositions and ages within sediment samples collected from river-mouths and deep-seafloor. However, these studies\textsuperscript{15,17} did not document how such efficient sediment and organic carbon transfer actually occurred. Here, we use novel direct observations to explain why transfer of sediment and associated organic carbon from rivers to the deep-sea can be so efficient. Organic carbon forms the basis for most seafloor food webs, and rapid and sustained deposition of organic-rich sediment by turbidity currents can creates distinct ecosystems, such as at the end of the Congo system\textsuperscript{18,19}. These sometimes very powerful flows can also scour life from floors of submarine canyons\textsuperscript{20}, and this study therefore also illustrates how turbidity currents affect deep-sea life in disparate ways.

Turbidity currents are also important geohazards\textsuperscript{21}. In particular, they break seabed telecommunications cable networks that now carry over 99\% of intercontinental data traffic\textsuperscript{22}, which underpin the global internet and many other aspects of our daily lives worldwide\textsuperscript{23}. The January 2020 flow described here broke both telecommunication cables (Figs. 1 and 2) connecting to West Africa, causing the internet to slow significantly from Nigeria to South Africa\textsuperscript{9}, and these cables were broken again by turbidity currents in March 2020, and April 2021 (Supplementary Table 1), including during coronavirus (CoV-19) related lockdown when internet bandwidth was particularly critical. These cables had not been damaged by turbidity currents in the previous 18 years. Understanding why these cables broke in 2020 and 2021 is crucial for assessing the hazard to submarine cables and other seabed infrastructure. This paper will also address why turbidity currents broke some cables, but left intervening cables intact\textsuperscript{9} (Figs. 1 and 2), as seen in other locations worldwide\textsuperscript{24,25}. It has been proposed that turbidity current deposits (called turbidites) can provide long term records of other major hazards, including earthquakes, typhoons or river floods\textsuperscript{26–28}. Such records are potentially valuable, as they extend further back in time than most records on land. This study provides the most detailed information yet on how long runout turbidity currents are related to river floods, and how floods are recorded in the deep-sea.

Despite their importance, there are remarkably few direct measurements from turbidity currents, ensuring they are poorly understood\textsuperscript{1}. This is a stark contrast to far more numerous and widespread direct measurements from other major sediment transport processes\textsuperscript{6,14,29}. Recent pioneering work has shown how short runout (< \textasciitilde 50 km) turbidity currents can be monitored in shallow water, typically using moorings with sensors, such as acoustic Doppler current profilers (ADCPs) that measure profiles of flow velocity and sediment backscatter\textsuperscript{30–35}. However, detailed monitoring is still only available for turbidity currents at <10 sites worldwide, all in water depths of <2 km\textsuperscript{30–35}. Previously there were no detailed direct measurements from turbidity currents that ran out for >50 km, which flush submarine canyons and
dominate longer-term sediment transfer. This situation ensured that fundamental questions remain. For example, previous studies showed that major earthquakes can sometimes trigger canyon-flushing turbidity currents that carry very large amounts of sediment\textsuperscript{4,20}. However, it was not clear if river floods could also generate such large canyon-flushing events, and therefore how major rivers are connected by turbidity currents to the deep-sea. It was also theorised that turbidity currents might potentially behave in a very different way to rivers; as turbidity currents that erode the seabed could become denser and faster, and erode yet more sediment and become even denser, causing turbidity currents to self-accelerate or ‘ignite’\textsuperscript{36}. However, sustained ignition was yet to be documented clearly in submarine flows\textsuperscript{35}, and it was unclear what factors determined whether it occurred.

\section*{Aims}

Here we present the most detailed measurements yet from turbidity current in the deep (2-5 km) sea, which combines information from cable breaks with that from 11 moorings along a 900 km length of the Congo Canyon and Channel\textsuperscript{9} (Fig. 1). The overall aim of this contribution is to understand how turbidity currents can connect major river mouths to the deep-sea. To do this, we address two specific questions. First, how are unusually powerful and long runout turbidity currents initiated that flush submarine canyons, and what controls their timing and frequency? In particular, how are flows linked to major river floods and tidal cycles. Second, how do turbidity currents then behave, and why do some flows accelerate and runout much further than others? Answers to these questions underpin a generalised model for how turbidity currents transfer globally significant sediment volumes from major rivers to the deep-sea. Finally we outline the wider implications of this study, for efficiency of organic carbon transfer to the deep-sea\textsuperscript{15,16}, predicting future hazards to seabed telecommunication cable networks\textsuperscript{9,22,23}, and how future climate or land-use changes may impact the deep-sea.

\section*{Study Area}

The head of the Congo Submarine Canyon lies within the estuary of the Congo River (Fig. 1d), which has the second largest water discharge and fifth largest particulate organic carbon export of any river\textsuperscript{5}. The canyon incises deeply into the continental shelf and slope, before transitioning in a less-deeply incised conduit termed a submarine channel\textsuperscript{37,38} (Fig. 1a-c). The channel terminates at a water depth of \textasciitilde 4,800 m, beyond which there is an area of sediment deposition termed a lobe\textsuperscript{37,39}. Previous deposit-based studies suggest that long-term sediment transfer through the canyon and channel is efficient, with \textasciitilde 30\% of the total sediment mass located in lobe deposits\textsuperscript{40}. Exceptionally rapid deposition of organic carbon-rich (3-4\% TOC) sediment of mainly terrestrial origin (70-90\%) leads to efficient organic carbon burial on the lobe\textsuperscript{41}, with methane-rich fluids due to diagenesis of this organic matter leading to unusual chemosynthesis-based ecosystems\textsuperscript{18,19}.

Past work along the Congo Canyon produced some of the first measurements from turbidity currents, albeit with less-detailed sensors\textsuperscript{38,42}, or at just one site in the upper canyon\textsuperscript{31-33}. Initially, current meters recorded velocities at a single height above the seabed, at three sites along the canyon-channel\textsuperscript{38,42}. 
These measurements were averaged over an hour, and flow velocities reached up to ~1 m/s, before moorings broke. This work documented transit speeds between moorings that decreased from 3.5 to 0.7 m/s. Subsequently, moored-ADCPs were used to record more detailed (every ~30 sec) velocity profiles through flows in the upper canyon in 2010-13. ADCPs recorded flows travelling at up to ~3.5 m/s, and led to a new view of turbidity current structure, where the faster frontal part to the flow outran the trailing body, causing flows to stretch. However, no previous study had deployed ADCP-moorings at multiple sites extending from upper canyon to the deep-sea, as occurred during this project in 2019-2020 (Figs. 1 and 2). Eleven ADCP-moorings were deployed at depths of 1,650 to 5,000 m (Fig. 1), with each mooring containing one or more downward-looking ADCPs, located 30 to 150 m above the seabed.

Results

Initial causes of powerful and very long run-out turbidity currents

A series of 12 flows restricted to the upper canyon were recorded by ADCP-moorings between September 2019 and early January 2020 (Fig. 2), causing three moorings to break. A much longer and more powerful flow then occurred on 14-16th January 2020, breaking the eight remaining moorings and two seabed telecommunication cables in a sequence from shallower to deeper water (Fig. 2; Supplementary Tables 1 and 2). Data from 9 of 11 ADCP-moorings were recovered successfully, despite considerable challenges as surfaced moorings drifted across the sea-surface, amid CoV-19 related lockdowns. Further cable breaks due to turbidity currents occurred on March 9th 2020, and April 28-29th 2021 (Supplementary Table 1). There had been no cable breaks in the preceding ~18 years, despite one or more cables being present in the canyon during this period (Supplementary Table 1), suggesting that the three cable-breaking turbidity currents in 2020-2021 were unusually powerful.

None of the turbidity currents recorded by the ADCPs or cable breaks coincided with earthquakes, and there is no clear relation to offshore wave heights (Supplementary Material). However, these cable breaking flows are associated with the largest floods of the Congo River since the early 1960's, and they occurred after an 18 year period without cable-breaks or comparable floods. A 1-in-50 year flood occurred with a peak discharge of ~70,883 m³ at Kinshasa on December 21st 2019 (Fig. 4), with the flood peak most likely arriving ~2-4 days later at the river-mouth estuary. The first cable-breaking flow occurred on January 14-16th, two weeks after the flood peak when river discharge was high, and the arrival times of this turbidity current were captured by eight ADCP-moorings just before they broke. The second cable-breaking flow on March 9th 2020, occurred 10 weeks after the flood peak whilst river discharge was much lower (Fig. 3b). A second major (1-in-20 year) flood occurred the following year, with a peak discharge of 67,210 m³ in Kinshasa on December 13th 2020. This was followed by a third cable-breaking flow on April 28-29th 2021, some 4.5 months after the December 2020 flood. However,
there were significant time delays between the flood peaks and the cable-breaking flows, with all three cable-breaking flows coinciding with subsequent spring tides (Fig. 4). It appears that floods supplied large amounts of sediment that primed the river mouth to produce powerful and long runout flows (Fig. 3), which were triggered finally at spring tides (Fig. 4).

**Subsequent flow behaviour**

Changes in turbidity current transit (front) speeds, and flow behaviour, are documented by arrival times at ADCP-moorings and cable breaks. These data show that the front of the January 14-16th turbidity current progressively accelerated as it ran out for over 1,130 km (Fig. 5a). The flow front initially moved at 5.0-5.2 m/s for its first 500 km, before reaching a velocity of 8.2 m/s over 1,000 km from source, albeit with a small decrease in front speed between ~880 and 1,000 km (Fig. 5a).

A further 13 flows were recorded by ADCP-moorings between September 2019 and January 2020 (Figs. 2 and 5). Twelve of these flows terminated in the upper canyon, and these events had front velocities of <4 m/s (Fig. 5a). One flow on January 5-15th travelled for >800 km, initially with a front speed of 4.4 m/s, but this flow decelerated to speeds of <1 m/s in deep-water, and terminated before the final mooring (Fig. 5a). Cable breaks on 28-29th April 2021 recorded a long runout flow travelling at 4.0 m/s, although no ADCP-moorings remained to capture this event in detail (Fig. 2). Thus a broad pattern emerges; flows with initial front speed exceeding 4 m/s ran out for long distances (>1,000 km), and accelerated if their initial speed was ≥5.0 m/s. In contrast, initially slower (<4 m/s) moving flows decelerated and ran out for 200-800 km (Figs. 2 and 3).

**Associated seafloor erosion**

Time-lapse seafloor surveys of the Congo Canyon and Channel in September 2019 and October 2020 show that ~1.04 km\(^3\) was eroded from resurveyed reaches of the upper canyon and deep-water channel (Fig. 7). The resurveyed reaches comprise only ~50% of the total canyon-channel length (Fig. 1a), so the total amount of eroded seafloor sediment may be ~2 km\(^3\). This is an exceptionally large amount of sediment. For comparison, the total annual sediment flux from all of the world’s rivers is ~7 km\(^3\) (Table 1). The unusually powerful and long runout turbidity currents in January and March 2020 presumably caused this erosion. The amount of sediment eroded along the flow pathway most likely greatly exceeds that initially within the flow, as the eroded volume is ~35-70 times the average annual sediment supply from the Congo River (0.028 km\(^3\)).

**Discussion**

Here we discuss the first detailed direct measurements from turbidity currents in the deep (> 2 km) sea. These unique measurements show how sediment can be transferred efficiently from a major river mouth to water depths of ~5 km, by the longest runout sediment flows (of any type) yet measured in action on Earth.
It was previously known that major earthquakes could generate long runout turbidity currents that transfer very large volumes of sediment to the deep-sea\textsuperscript{4,20}. However, here we document directly for the first time that major river floods also generate extremely large turbidity currents that flush submarine canyons. Indeed, the turbidity currents that flushed the Congo Canyon-Channel in January and March 2020 eroded \(~1\text{-}2\) km\textsuperscript{3} of sediment from the seabed. This volume is equivalent to 14\text{-}28\% of the global annual sediment flux from all rivers\textsuperscript{6}, and it was carried down a single submarine canyon-channel, probably by just two turbidity currents (Fig. 2). The 1929 event in the NW Atlantic\textsuperscript{4} involved a much larger sediment volume (>200 km\textsuperscript{3}), but the amount of sediment carried by the flood-related events in Congo Canyon rivals or exceeds other canyon-flushing flows due to earthquakes, such as those offshore New Zealand in 2016 (~1 km\textsuperscript{3}; M\textsubscript{w} 6.8 Kaikōura earthquake\textsuperscript{20}) or Japan in 2011 (0.2 km\textsuperscript{3}; M\textsubscript{w} 9.1 Tōhoku earthquake\textsuperscript{44}). The turbidity currents in 2020 and 2021 that flushed the Congo Canyon-Channel were linked to two river floods with recurrence intervals of 20 and 50 years\textsuperscript{43}. This flood recurrence interval is significantly shorter than recurrence intervals of major earthquakes (100\text{-}300 years) that were previously proposed to trigger canyon-flushing events elsewhere\textsuperscript{20,44\textendash}48.

Turbidity currents that flushed the Congo Canyon were initiated by a combination of floods and spring tides. Past work has shown how elevated river discharge and tides can combine to generate much shorter runout (1\text{-}50 km) turbidity currents offshore from smaller rivers\textsuperscript{30,49\textendash}51. However, this is the first study to show that floods and tides generate far larger turbidity currents offshore from one of the world's largest rivers, and in an estuarine setting. This suggests that floods and tides may trigger turbidity currents in a wider range of settings than previously thought, which then transfer globally significant sediment volumes.

A notable observation is that delays of several weeks to months can occur between an initial river flood and turbidity currents that flush the Congo Canyon (Fig. 3). Previous work has documented significant delays between river floods and associated turbidity currents, but only for hours\textsuperscript{50} to days\textsuperscript{24,25}, not weeks to months. Moreover, older cable breaks (1883 to 1937) in the Congo Canyon indicate that clusters of cable breaks may occur after one or more years of elevated river discharge\textsuperscript{9} (Supplementary Fig. 2). This suggests that the Congo Estuary can store flood sediment for up to several months, and maybe years, and thus act as an efficient 'capacitor', before eventually releasing sediment in one or more long-runout turbidity currents.

Past work on how turbidity currents are generated by floods often focussed on a model in which the floodwater has enough sediment to become denser than seawater, so that the river-plume plunges to move directly along the seabed as a 'hyperpycnal flow'\textsuperscript{27,28,52}. However, this model can be ruled out for the turbidity currents that flushed the Congo Canyon, because of the significant delay between peak flood discharge and these submarine flows (Fig. 3). The Congo River also has relatively low suspended sediment concentrations, making it unlikely to trigger hyperpycnal flows\textsuperscript{53}. 

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However, two other models could explain how floods and spring tides combine to generate these canyon-flushing flows. In the first model, major floods drive large amounts of sand-dominated bedload across the submarine canyon head (‘x’ in Figure 1d). This causes the canyon-lip to prograde rapidly, and then collapse, thereby forming a powerful turbidity current\textsuperscript{30,50}. However, a significant time delay occurs between flood peaks and all three canyon-flushing flows (Figs. 3 and 4). Thus, although rapidly deposited flood-sediment may prime the canyon-head for failure, it must remain close to failure for weeks to months after the flood, until a minor perturbation associated with spring tides triggers final failure\textsuperscript{30,50}. Those perturbations might be due to expansion of gas bubbles in sediment\textsuperscript{54}, or increased bedload transport at a spring ebb tide\textsuperscript{55}.

A second model is that major river floods supply large amounts of fine-grained mud, which is then stored within the river-mouth estuary for weeks to months, before being released at spring tides (Supplementary Figure 4c and 5). This mud is initially dispersed via surface plumes\textsuperscript{56} (Fig. 1d), but settles onto the seabed across the entire estuary (Fig. 1d). Field observations (R. Nunny, \textit{pers. comm.}, 2021) from an extensive shallow water plateau upstream of Soyo (Supplementary Fig. 4a) show that a mud layer accumulates throughout the year (Fig. 5). During periods of elevated river discharge, and especially when spring ebb tides also occur, the freshwater plume touches-down across this shallow water plateau. This causes mud to be resuspended, forming highly-mobile fluid-mud layers\textsuperscript{57}, which can be several meters thick (Supplementary Figs. 4 and 5). These fluid-mud layers then drain into tributary canyon-heads, where they may either directly generate turbidity currents, or produce unstable deposits that fail to produce even larger turbidity currents (Supplementary Figs. 4 and 5). Near-bed estuarine circulation may also help to trap fine sediment in this second model\textsuperscript{58}. It is unclear which of these two models generated the canyon flushing turbidity currents in 2020 and 2021, as we lack suitably detailed observations of what occurred at the river-mouth, and the two models are not mutually exclusive.

To understand how turbidity currents transfer sediment from river-mouths to the deep-sea, we also need to understand why some turbidity currents increase in power and runout for exceptional distances into the deep-sea, whilst other flows terminate in shallow water. It has been theorised that turbidity currents which erode sediment become denser, and thus accelerate, causing increased erosion, and further acceleration (a process termed ‘ignition’\textsuperscript{36,59–60}). Alternatively, turbidity currents that deposit sediment decelerate, leading to further deposition (‘dissipation’). These positive feedbacks could produce thresholds in behaviour that depend on small differences in initial flow state\textsuperscript{36,59–60}. It has also been proposed that flows could achieve a near-uniform state in which erosion is balanced by sediment deposition, termed ‘autosuspension’\textsuperscript{36,59–60}. However, it was previously contentious whether ignition or autosuspension were reproduced in relatively slow laboratory-scale turbidity currents\textsuperscript{61–62}, and ignition had not been documented clearly in the field.

This is first study to document unambiguously that full-scale turbidity currents can ignite in the oceans, and that ignition can occur over exceptionally long (1,000 km) distances (Fig. 5a). This acceleration cannot be explained by changes in seabed gradient that decreases with distance, or narrowing of the
canyon-channel (Fig. 5b,c), and it is associated with very large (1-2 km³) volumes of seabed erosion. However, once flows erode and accelerate, it is important to understand how rapidly ignition occurs, and whether flows then tend towards a new equilibrium state. The rate at which the front of the January 2020 flow accelerated is relatively slow, as it took ~1,000 km to accelerate from 5.0 to 8.2 m/s, despite a very large amount (1-2 km³) of seabed erosion. Front speeds were sometimes relatively constant for long distances, suggesting a near-uniform frontal state. This near-equilibrium may arise if the mass of sediment eroded and incorporated into the dense frontal part of the flow (‘frontal cell’), is balanced by loss of comparable sediment-mass from the frontal cell into the slower-moving body (Fig. 5a). Local decreases and increases in front speed may be due to patchy seabed erosion.

Spatial changes in submarine turbidity current speeds have only been measured in detail at ~5 locations (Fig. 6) However, a comparison between these data suggests that a common pattern emerges for flows confined in canyons and channels, which may be a fundamental property of turbidity currents (Fig. 6). Flows with initial front speeds in excess of ~4 to 5 m/s tend to runout for longer distances. These flows either sustain speeds of 5-8 m/s (autosuspend), or accelerate from ~5 to 8 m/s (ignite), albeit it for variable distances of 30 to 1,100 km (Fig. 6). It is these flows that carry sediment and organic carbon much further and pose the greatest hazard. Conversely, flows in canyons and channels whose fronts travel at <4 m/s tend to decelerate and dissipate, as do initially faster flows (e.g. NW Atlantic turbidity current) which exit canyons and channels, and then decelerate markedly as they become unconfined and spread laterally.

Previous theory predicts that sediment grain size, and thus settling velocity, plays a key role in determining whether a turbidity current ignites or dissipates. Thus, a notable new result is that similar threshold initial front speeds (4.5 to 5 m/s) for ignition are observed in locations with very different grain sizes (Fig. 6). For example, the Congo Canyon is fed by a fine-grained and muddy river, and the canyon floor is often mud-dominated, whilst at the other end of the spectrum, Monterey Canyon is fed beach-sand via long-shore drift and has a sandy floor. It thus appears grain size is a weak control on flow speed needed for ignition. Previous theories for ignition are based on energy balances that often assume flows are dilute (<< 10% sediment volume), such that sediment grains settle individually, although settling may become hindered as sediment concentrations increase. An alternative model is proposed here (also see) in which faster turbidity current fronts comprise a dense (>20-40% volume) near-bed layer, in which grains do not settle individually, and which is weakly turbulent. Field evidence from Congo Canyon and elsewhere suggests faster (>4-5 m/s) turbidity currents contain such a dense near-bed layer at their front, whilst slower moving (<2-3 m/s) flows lack a dense layer. Behaviour of this dense layer may depend more on variations in excess pore pressures, or rates of sediment erosion from the bed, rather than the settling velocity of individual grains. Indeed, experiments show how substrate character and erosion processes can determine whether a dense sediment flow grows and accelerates, or dies out.
We now present a new generalised model for how turbidity currents transfer globally significant volumes of sediment from a major river to the deep-sea, through a submarine canyon (Fig. 8). Previous studies suggested that frequent and smaller turbidity currents deposit sediment within canyons, which are then flushed by much more infrequent and powerful flows, which occur every few thousand years and are most likely triggered by earthquakes. Here we show that numerous smaller flows infill the Congo Canyon; indeed these flows are active for 30% of the time in the upper canyon (Fig. 2a). Far more powerful and infrequent flushing events then excavate very large volumes (1-2 km$^3$) of sediment from the canyon-channel floor (Fig. 7). However, contrary to previous models, this study shows that canyon-flushing events can be triggered by major river floods as well as earthquakes, with clusters of multiple canyon-flushing events occurring after a single major flood over a period of weeks to months. Recurrence intervals for these major floods is 20-50 years, whilst previous work documented flushing events every few hundred to thousand years. It also appears that the amount of sediment carried into the deep-sea by a flushing event is comparable to that supplied by the Congo River between flushing events. The Congo River supplies ~43 Mt of sediment each year, so the volume of sediment (1-2 km$^3$) excavated by the 2019-20 canyon flushing flows is comparable to sediment supply from the river over the last ~35-70 years, assuming a density of ~1,500 kg/m$^3$ for eroded seabed material. Thus, although sediment is mainly stored for up to several decades in the upper canyon, it is then efficiently flushed beyond the canyon-channel into the deep-sea (Fig. 8).

This new understanding of how river mouths are connected to the deep-sea by turbidity currents (Fig. 8) explains why organic carbon transfer and burial can be highly efficient. Fresh organic carbon from major floods can reside in the river-mouth for only a few weeks or months before being flushed into the deep-sea, together with a far larger volume of organic carbon from canyon-filling deposits that accumulated over several decades. The supply of organic carbon by turbidity currents can also have profound impacts on seabed life. For example, distinctive chemosynthesis-based ecosystems occur on the lobe fed by the canyon-channel, where sediments rich in (mainly terrestrial) organic-carbon are rapidly buried. This new study illustrates how large amounts of organic-matter-rich sediment are delivered episodically to this lobe. It also emphasises how turbidity currents physically disturb benthic fauna, as tens of meters of sediment may be removed locally along the canyon-channel floor (Fig. 7).

Seabed telecommunications cables now carry >99% of global data, underpinning daily lives. Cable routes are generally chosen to avoid submarine canyons, but this is not always possible, such that ~2.8% of global cables involve canyon crossings. Cable-breaking flows in this study are associated with exceptional floods along the Congo River, and these floods may thus provide an early warning of elevated risks to cables. This elevated risk may persist for a significant period after the flood peak, and a single major flood can generate multiple cable-breaking flows (Fig. 8). A key decision for cable routing is how far offshore the cable should be located from the river-mouth. The overall frequency of turbidity currents decreases strongly with distance as initially slower events dissipate within the upper canyon. However, the January 2020 event also shows how infrequent and longer runout turbidity currents may self-accelerate with distance (Fig. 5). Thus, only for larger and more infrequent flows, there may be an
increased hazard to cables located further offshore, as they will experience the fastest flow-front speeds in such events.

This study indicates turbidity currents with frontal speeds in excess of ~5.5-6 m/s (Fig. 5a) are needed to damage cables, and this is broadly consistent with information from cable breaks elsewhere\(^2\) (Fig. 6). However, a notable observation is that although some cables broke in the January and March 2020 and April 2021 flows, other cables survived despite being impacted by turbidity currents with similar front speeds (Figs. 3 and 5; Supplementary Table 1). Thus, there are local conditions that can prevent a cable from breaking, whilst neighbouring cables break. This in turn suggests there may be ways to route cables in more advantageous positions to reduce cable breaks. Time-lapse surveys may provide an explanation for why some cables break, whilst others do not. These surveys show that seabed erosion during turbidity currents is very patchy, over distances of just a few kilometres (Fig. 7). In particular, deep (20-40 m) erosion may be associated with knickpoints\(^6\),\(^7\), defined as zones of locally steeper gradients along the canyon or channel floor (Fig. 7), and such localised deep erosion will tend to undermine cables and cause breaks or faults\(^9\).

It has previously been suggested that turbidity current deposits (turbidites) may provide a record of major floods\(^2\), which could be valuable if it goes further back in time than records on land. This study confirms that major river floods can indeed be recorded by deposits of unusually powerful and long runout turbidity currents, although a single major flood can generate multiple turbidity current deposits. The best submarine record of major floods is located near the end of the canyon-channel system, as smaller-scale turbidity currents complicate the flood-record closer to the river-mouth (Fig. 8).

Finally, this study provides the clearest evidence yet that river floods can directly and rapidly impact the deep-sea\(^2\), weeks to months after a flood. Climate change is predicted to produce a more active hydrological cycle, with global changes to flood frequencies\(^4\),\(^6\). Future changes in Congo River discharge are uncertain but potentially significant\(^6\). Here we show how such changes in terrestrial climate and river-flood frequency may affect how organic carbon is flushed into the deep-sea, associated functioning of deep-sea flood webs, and hazards faced by seafloor cables. Dam construction, deforestation and changes in land-use can also substantially affect sediment flux to river-mouths\(^6\),\(^7\), and this too may change the frequency of turbidity currents. This study of the longest runout sediment flow yet measured in action thus illustrates why changes affecting terrestrial continents may also have significant impacts for the deep-sea.
much larger turbidity current occurred on January 14-16th 2020 (Fig. 2). The remaining eight moorings surfaced on January 14-16th due to this exceptionally powerful cable-breaking flow (Fig. 2). Nine of the 11 moorings were then eventually recovered via emergency vessel charters.

**Arrival times of turbidity currents at moorings and cables**

The arrival times of turbidity currents at ADCP-moorings were defined using the time series of velocity profiles recorded by 75, 300 and 600 kHz ADCPs every 11-to-45 seconds (Supplementary Table 2). The arrival times of turbidity currents were marked by an abrupt increase in near bed velocities above ambient values of ~0.3 m/s. The timing of faults on submarine telecommunication cables were also used to define turbidity current arrival times (Supplementary Table 1), and this assumes the cables were damaged by the arrival of the flow front. Cable breaks were recorded to the nearest minute.

**Flow front (transit) speeds between moorings or cables**

The speed of the flow front between moorings or cables was calculated by dividing the distance between sites and the difference in arrival times. Distances were measured along the floor of the canyon-channel using bathymetric survey data.

**Time at which turbidity currents are triggered**

The first mooring is located ~80 km from the river mouth (Fig. 1). It was thus assumed that turbidity currents originated at the mouth of the Congo River, and that the flow speed from the river mouth to the first mooring was the same as that between the first and second moorings. For faster moving turbidity currents with speeds over 2-3 m/s between the first two moorings, the uncertainty of when the flow originated is likely to be less than a few hours (i.e. the time taken for the flow to travel 80 km at speeds of >4 m/s). Thus, although the original times of these turbidity currents cannot be reliably compared to individual low and high tides, those times can be compared to longer term cycles of spring and neap tides. Uncertainties in the time taken by flows to travel from the river mouth to the first mooring site are much larger for slow moving flows, and may be several days for flows travelling at <1 m/s (and see Supplementary Information). Thus it is more challenging to determine if these slower moving flows are also triggered by spring-neap tidal cycles, and they too cannot be linked to individual low or high tides.

**River discharge**

The timing of turbidity currents was compared to fluctuations in water discharge from the Congo River at the Kinshasa gauging station43 (Fig. 3), located ~400 km from the river mouth, as measured by the Règie des Voies Fluviales (RVF) at Kinshasa, Democratic Republic of Congo.

**Tidal elevations at the river mouth**

Daily tidal data (Fig. 4) were obtained for Santo Antonio do Zaire near the port of Soyo, at the Congo River mouth (Fig. 1a).

**Time-lapse seafloor surveys and eroded volumes**
Swath multibeam surveys of seafloor bathymetry were collected in September 2019 and October 2020 using a Kongsberg EM122 (1° x 1°) system operating at 12 kHz for two areas (Fig. 1a). Highest resolution data was generated by setting the swath width to the narrowest setting (45° from the nadir), and having large overlaps between adjacent swaths. Sound velocity profiles (SVPs) were taken through the water column at the start of most surveys, and a second SVP was performed halfway through some longer survey. The first area of repeat surveys was along the upper canyon in Angolan waters, whilst the second area was the deeper-water channel in international waters (Fig. 1a). The accuracy of these sounding data were <0.3-0.5% of the water depth.

The multibeam bathymetric data were processed in CARIS HIPS and SIPS and corrected for the ship's motion and for differences in sound velocity in the water column (using SVP data), before being gridded with a horizontal grid cell resolution of 5-15 m that depended on water depth. A bathymetric difference map was then produced by subtracting October 2020 bathymetric data from September 2019 bathymetric data. The total volume of eroded sediment was determined from the sum of the (negative) vertical difference in elevation for each grid cell. This value for the difference in seabed elevation at each grid cell was multiplied by the grid cell area, and then summed, to derive the volume of eroded sediment. The eroded volume of 1.0 km$^3$ was derived only from the canyon and channel floors in the two areas that were repeat surveyed in September 2019 and October 2020. This ensured that areas with the largest likely errors due to steep topography (i.e. the canyon walls) were not included. The first area comprises the upper Congo Canyon, whilst the second area is located along the distal deep-sea channel (see Fig. 1a). The calculations of eroded sediment volumes did not include the lobe, beyond the end of the deep-sea channel.

Data Availability

Data supporting the findings of this study are available within the Supplementary Data files.

Declarations

AUTHOR CONTRIBUTIONS

PJT wrote the manuscript, assisted by MB and EP, and with comments from all of the authors. PJT, MLB, EP, RSJ, MSH, SH, SMS, MH, CJH, SR, CM, RA and AF collected data on research cruises in 2019 and 2020. MJBC, DP, MAC, MU helped to design the field experiment. DW and AG assisted with cable fault data. RS, MAT, GB, RN provided information on river discharge and processes. CC and RF led the Angola project component. AG and CP assisted with bathymetric survey, whilst RB and JN assisted with data analysis.

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Figure 1

Location map of oceanographic moorings and telecommunication cables that recorded turbidity currents in 2019-21 in the Congo Canyon and Channel, offshore from the mouth of the Congo River in West Africa.

(a) Map of the entire array with mooring (e.g. M1 or A2) and cable (e.g. WACS) names. Red dotted lines
indicate areas where time-lapse bathymetric surveys were collected in September 2019 and October 2020. (b & c) Detailed map of the upper submarine canyon, and deep-water submarine channel, with locations in (a). (d) The head of the Congo Submarine Canyon lies within the estuary forming the mouth of the Congo River, with the river producing a surface plume of sediment that extends offshore. Landsat 8 image on 02-03-2015 with superimposed bathymetric contour at 20 m, 100 m, 200 m, and 400 m from UK Admiralty Chart 658. The main submarine canyon head (x), a shallow-water plateau off Soyo (y), and tributary canyon heads (z) are indicated.
Figure 2

Timing and runout distance of turbidity currents measured from September 2019 to January 2020 along the Congo Canyon and Channel system. (a) ADCP time series of velocities measured at mooring M9, showing occurrence of turbidity currents. (b) Plot of event timing against distance from Congo River mouth, as measured along the sinuous canyon-channel axis. Red vertical lines denote flow events, and indicate their runout distances, with the most powerful January 14-16th event in bold. Dotted horizontal lines denote a mooring site or submarine cable. The times of mooring deployment are shown, together with when moorings or cables broke due to turbidity currents. Two moorings (M4 and A3) were not recovered (‘NR’); flow timings at these two sites are derived from when mooring reached the ocean surface, and an assumed rise rate of 150 m/min (as seen during earlier work).
Figure 3
Figure 4

Cable breaking turbidity currents coincide with spring tides. (a) Time series of velocity profiles recorded by an ADCP at mooring site A2 in 2019-20 (Fig. 1), with warmer colours indicating turbidity currents. Superimpose are the arrival timings of long-runout, cable-breaking turbidity currents on January 14th and March 9th 2020 (red lines), and slower moving flows restricted to the upper canyon (thin black lines). (b) Time series of daily maximum tidal range, and daily lowest low tide, at Soyo in the estuary at the mouth
of the Congo River. (c) Box and whisker plots showing median, first and second quartiles of daily tidal range values for (i) all days in which ADCP-moorings were in the Congo Canyon in 2019-2020, (ii) days on which turbidity currents occurred at the ADCP moorings, (iii) days on which no turbidity currents occurred at ADCP moorings, and (iv) days on which the five fastest non-cable breaking flows occurred at ADCP moorings. Each box and whisker plot shows the median tidal range (x), tidal ranges on given days (o), and the 95% percentile of the distribution of tidal ranges for specified days (•). Stars indicate the maximum daily tidal range for the days on which the 3 cable-breaking flows occurred on January 14-16th and March 9th 2020, and April 28-29th 2021. (d) Time series of daily tidal coefficients at river mouth (Soyo) showing times of three cable-breaking turbidity currents (red stars), and peak of major river floods (blue arrows). The larger the tidal coefficient, the greater the tidal range. Period in which ADCP-moorings deployed shown by yellow box.

Figure 5

Changes in turbidity current front (transit) speed with distance along the Congo Fan system, compared to changes in long profile, gradient and width. (a) Changes in front speed with distance from Congo River mouth for all turbidity currents recorded in 2019-20. Flow speeds are derived from submarine cable breaks, and arrival times at moored ADCPs. Distances are measured along the sinuous floor of the Congo Canyon-Channel. Seabed cable are shown by vertical dashed lines, and ADCP-mooring (e.g. M7) sites are shown by red arrows and vertical dashed lines. Speeds of individual turbidity currents in 2019-2020 are shown by different coloured lines. The figure also includes the speed of the April 28-29th 2021 turbidity current between cable breaks (Supplementary Table 1), and the speed of a turbidity current between moorings in 200442. Flows with front speeds >4-5 m/s (grey box) tend to self-accelerate or sustain those front speeds over long distance, whilst flows with front speeds < 4 m/s tend to decelerate and dissipate. (b) Changes in water depth and (c) seafloor gradient with distance along the floor of the canyon-channel. (d) Changes in canyon-channel width with distance measured at crests of confining levees or first terrace.
Figure 6

Changes in turbidity current front (transit) velocity with distance for flows that are confined in canyon and channels, from the four locations worldwide where such data are currently available. These field sites are (a) the Congo Canyon-Channel (this study), (b) Monterey Canyon offshore California $^{34,35}$, (c) Gaoping Canyon offshore Taiwan$^{24,25}$, and (d) Bute Inlet in British Columbia, Canada $^{62,63}$. Data from individual flows are shown by different coloured lines and dots. Front velocities are average values between
moorings or cables that are broken, and distances are from the coast or river mouth. Data from Monterey Canyon also includes internal flows speeds measured by ADCPs at the closest mooring to shore (black box) \(^{34,35}\). Flows in Monterey Canyon and But Inlet contain a much higher fraction of sand compared to the muddy turbidity currents originating from the Congo River\(^{34,35,37}\). Flows with front speeds faster than 4-5 m/s (grey box) tend to runout much further, and maintain or increase their front speeds over longer distances than flows with initially slower front speeds.
Figure 7

Generalised model for how the turbidity current pump operates from river mouths to the deep sea, showing flow timing and frequency, and spatial behaviour and evolution. (A) Schematic profile along a generalised submarine canyon-channel from the river mouth to deep-sea. Numerous smaller-scale turbidity currents that infill the canyon (in blue). Much more infrequent, powerful and longer runout turbidity currents then erode the sediment infill from the smaller flows, and flush the canyon (in red). (B and C) Time series (vertical axis) showing a sequence of smaller canyon filling flows (in blue) and larger canyon flushing flows (in red), based on this study of the Congo system. Part B shows canyon filling and flushing flows over a ~2 year period, together with river floods and tidal cycles. Canyon flushing flows occur 2 weeks to 5 months after major floods (Fig. 3), and coincide with spring tides (Fig. 4). Part C shows a longer 100 year period in with canyon flushing flows are associated with major floods occurring every 20-50 years.

Figure 8

Supplementary Files
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