The possible role of Coriolis forces in structuring large-scale sinuous patterns of submarine channel–levee systems

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Submarine channel–levee systems are among the largest sedimentary structures on the ocean floor. These channels have a sinuous pattern and are the main conduits for turbidity currents to transport sediment to the deep ocean. Recent observations have shown that their sinuosity decreases strongly with latitude, with high-latitude channels being much straighter than similar channels near the Equator. One possible explanation is that Coriolis forces laterally deflect turbidity currents so that at high Northern latitudes both the density interface and the downstream velocity maximum are deflected to the right-hand side of the channel (looking downstream). The shift in the velocity field can change the locations of erosion and deposition and introduce an asymmetry between left- and right-turning bends. The importance of Coriolis forces is defined by two Rossby numbers, $R_{RW} = U/Wf$ and $R_{RR} = U/Rf$, where $U$ is the mean downstream velocity, $W$ is the width of the channel, $R$ is the radius of curvature and $f$ is the Coriolis parameter. In a bending channel, the density interface is flat when $R_{RR} \sim -1$, and Coriolis forces start to shift the velocity maximum when $|R_{RW}| < 5$. We review recent experimental and field observations and describe how Coriolis forces could lead to straighter channels at high latitudes.
1. Introduction

Submarine channel systems are formed by the sediment transport associated with large-scale turbidity currents flowing out of submarine canyons on the continental margin. These channels have a striking sinuous pattern and are significant morphological features on the ocean floor [1]. At high latitudes, Coriolis forces will influence the gravity currents within these submarine channels owing to the very large length scales of these submarine channels [2,3]. Recently, Peakall et al. [4] showed that the sinuosity of submarine channels decreases with latitude. Their study of 31 large-scale submarine channel–levee systems found that at high latitudes channel–levee systems have much lower sinuosity and are almost straight, while near the Equator channel–levee systems are highly sinuous. In addition to differences in slope and sediment type, one of the possible explanations suggested by Peakall et al. [4] for this relationship is that at high latitudes Coriolis forces systematically change the dynamics of turbidity currents.

The development of sinuosity in a submarine channel is usually thought to occur by a coupling between the locations of high velocity in a turbidity current, the locations of erosion and deposition and the channel curvature. Sinuosity will increase in channels where there is a positive feedback between erosion and the location of maximum velocity, as occurs when centrifugal forces deflect gravity currents to the edge of a bend apex, leading to increased erosion near the outside of bends and an increase in curvature. In modelling the development of sinuosity, bank erosion and migration are often treated with a semi-empirical model that assumes a linear relationship between excess near-bank velocity and channel migration with an empirically derived erosion coefficient [5,6]. In this type of model, the lateral migration rate $\zeta(s)$ along the channel axis $s$ has the form $\zeta(s) = E_0(s)u_b(s)$, where $E_0$ is an empirical erosion coefficient (which depends on the specific sediment properties) and $u_b$ is the near-bank velocity excess, defined as the difference between the near-bank velocities and the reach-averaged value. Furthermore, in this type of model, it is usually assumed that $u_b$ is only a function of the local curvature of the channel [6], so that the lateral migration speed is proportional to and is in phase (or has a small lag) with the local curvature. This implicitly assumes that only centrifugal forces are important in determining the velocity structure in the channel.

Numerous oceanographic observations have shown that Coriolis forces can be important in determining the velocity structure of gravity currents that flow in wide channels at high latitudes [7,8]. As the velocity and turbulence structures within dense saline gravity currents are very similar to those of turbidity currents [9], it seems reasonable to assume that large-scale turbidity currents in wide channels will respond in the same fashion. One strong impact of Coriolis forces is to laterally shift the downstream velocity maximum, which would change the near-bank velocity excess $u_b$ in a large turbidity current at high latitudes. This would mean that $u_b$ is a function of Coriolis forces as well as centrifugal forces. If this were the case, then the lateral migration rate $\zeta(s)$ will change, and there might no longer be a positive feedback between curvature and the erosion rate. Recent laboratory experiments by Cossu et al. [10] and Cossu & Wells [3] have used a rotating platform to investigate gravity currents in sinuous channels. Compared with the non-rotating case, these experiments have shown that Coriolis forces can significantly shift the lateral location of the downstream velocity maximum, and hence change the near-bank velocity excess. In addition, Coriolis forces also tilt the upper density interface, change the secondary circulation of the flow and slow the current down. In light of these recent developments in understanding the flow structure of gravity currents in large-scale submarine channels, it is time to revisit our understanding on how the internal velocity structure of high-latitude turbidity currents could also be influenced by Coriolis forces.

In this paper, we review recent theory and experimental observations of the flow structures of gravity currents in sinuous channels and discuss how Coriolis forces introduce a lateral asymmetry into the velocity field. We start by reviewing the pertinent geological observations of sinuosity in channel–levee systems, which show that the sinuosity varies with latitude. We then describe how Coriolis and centrifugal forces determine the velocity structure within a channelized turbidity current. A series of recent experiments are reviewed that show how Coriolis forces can
change the spatial patterns of erosion and deposition within a channel. We finish with a discussion of how the experimental observations of lateral asymmetries in both flow structure and patterns of erosion and deposition could explain recent field observations of a latitudinal dependence of sinuosity of submarine channel systems.

2. Field observations of sinuous channel–levee systems

A typical channel–levee system is sketched in figure 1. Periodically turbidity currents flow down the submarine canyon to the sinuous channel–levee system on the ocean floor. The turbidity currents can be triggered by numerous mechanisms, such as sloping layers of sediment offshore of a large river mouth that become unstable owing to loading, underground gas release or seismic activity [11] or by sediment resuspension by wave action, tides or storms on the continental shelf. The length scales of sinuous channels can be very large (1000 km or more), such as the Zaire Fan system in West Africa [12] or the North Atlantic Mid-Ocean Channel (NAMOC) near eastern Canada [13]. Sinuous channels are usually contained within wide and deep levees. For instance, a study of 23 submarine channels found a mean channel width of 7.8 km and depth of 135 m [14]. The levees grow owing to continuous deposition of suspended load delivered by successive turbidity currents that transit the channel and spill over the channel margins along their entire length [15,16]. With time, the position of the channel will migrate, so there are typically many abandoned channels (figure 1). Further downstream, the channel geometry can disappear and turbidity currents spread out to form depositional lobes [1]. The sedimentary deposits associated with turbidity currents are known as turbidites. These deposits often contain significant deep-water hydrocarbon reservoirs and the resulting search by oil companies for rich drilling targets has motivated much of the recent field observations of submarine channel systems offshore from the Amazon, Mississippi and Niger deltas.

There is a striking difference in the planform geometry of the highly sinuous Amazon Channel and the much straighter NAMOC, as shown in figure 2a,b. The sinuosity is defined as the ratio of the along-stream length of a channel to the straight-line distance, so that the sinuosity is always greater than 1. The Amazon Channel has a maximum sinuosity of 2.6 in its mid-fan region at 3–7° N [19], comparable to other highly sinuous submarine channels found in equatorial regions such as on the Bengal, Indus and Mississippi Fans [1]. By contrast, the NAMOC at 53–59° N has a sinuosity of 1.01–1.05 [13], similar to channels in the Bering Sea that have a sinuosity of 1.05 at 55° N [1].
Figure 2. (a) Seismic image of the Amazon Fan at approximately 5° N. (Adapted from [17] with permission from Cambridge University Press.) The white arrow indicates the direction of flow. (b) Seismic image of the NAMOC at 60° N (courtesy David Piper). Note how much straighter the high-latitude channel is compared with the channel near the Equator. (c) Cross-section of NAMOC from Skene et al. [18], taken at a similar latitude to (b). (Reproduced with permission from John Wiley & Sons.) The right-hand side levee is higher than the left-hand side (looking upstream).

High-latitude channel–levee systems show distinct levee asymmetries, with the right-hand levee being higher than the left-hand levee in the Northern Hemisphere and vice versa in the Southern Hemisphere. This is owing to Coriolis forces deflecting the gravity current to the right-hand side in the Northern Hemisphere, so that overbanking flows predominantly form on the right-hand side and preferentially increase the levee height difference [20,21]. For instance, figure 2c shows the levee asymmetry in the NAMOC where levee differences are 65 m on average along a 950 km section [13]. In the Southern Hemisphere, the left-hand side levee is observed to be higher [22–24].

Coriolis forces arise owing to the Earth’s rotation and their importance upon gravity currents can be expressed by the non-dimensional Rossby number, defined as $Ro_W = U/fW$, where $U$ is the mean downstream velocity of the gravity current, $W$ is the channel width and $f = 2\Omega \sin \phi$ is the Coriolis parameter with $\Omega$ the Earth’s rotation rate and $\phi$ the latitude. Note that $f$ is positive in the Northern Hemisphere and negative in the Southern Hemisphere, so that the Rossby number changes sign. Coriolis forces begin to deflect gravity currents laterally when $|Ro_W| < 10$ [10]. At 45° N, the Coriolis parameter is $f = 10^{-4}$ s$^{-1}$, so, with a typical current velocity of $U = 1$ m s$^{-1}$, $Ro_W \sim 10$ when $W \sim 1$ km. As $f$ decreases near the Equator, channels must be very wide or the flow very slow for Rossby numbers to be low enough so that Coriolis forces are important.

Observations from Peakall et al. [4] of the peak sinuosity from 31 large-scale submarine channel–levee systems are plotted as a function of latitude in figure 3a. A strong latitudinal dependence of the peak sinuosity of submarine channels was found by Peakall et al. [4], with
Figure 3. (a) Relation between peak sinuosity and latitude. (Adapted from [4].) The dotted line represents a fitted curve to the data based on an exponential expression with a least-squares fit of $R^2 = 0.64$. (b) Relation between peak sinuosity and $|Ro_W|$. As channels are from the Northern and Southern Hemisphere, we plot absolute values. Am, Amazon Channel; Be, Bering Sea Channels; In, Indus Channel; NA, NAMOC; PIB, Pine Island Bay Channel; and Za, Zaire Channel. (Adapted from [25].)

Higher latitude systems (such as the NAMOC) having systematically lower peak sinuosity than their equatorial counterparts. Peakall et al. [4] attributed this latitudinal variation to a combination of the increases of Coriolis forces with latitude and changes in the nature of sediment supply and flow type. Variations in channel slope were also considered, but were found to be less statistically significant. It is important to note in figure 3a that the peak sinuosity is plotted for each channel–levee system, whereas the local sinuosity varies within a channel system.

The observed variation in maximum channel sinuosity is plotted as a function of the Rossby number in figure 3b. These data from Cossu & Wells [25] show a clear trend ($R^2 = 0.64$) with higher peak sinuosity in channels being associated with higher $|Ro_W|$. For instance, the channels with peak sinuosity less than 2 have a low value of mean $|Ro_W| = 4.96$ and vary between $0.39 < |Ro_W| < 13.71$, whereas the more sinuous channels, where peak sinuosity is greater than 2, have a much higher mean value of $|Ro_W| = 25.55$ and a range of $8.9 < |Ro_W| < 45.23$. The values of $Ro_W$ were calculated using the mean channel width and a mean velocity $U = 1 \text{ m s}^{-1}$, representing a typical mean velocity observed or inferred for numerous submarine channel systems [14,26,27]. The error bars indicate the range of $Ro_W$ for estimated flow velocities between 0.5 and 1.5 m s$^{-1}$. All the channels that have $|Ro_W| < 5$ have low sinuosity and are relatively wide and at high
Figure 4. (a) Schematic of a submarine channel–levees system, with a well-defined radius of curvature $R$, depth $H$ and width $W$. (b) Acoustic backscatter of a submarine channel cross-section showing an active turbidity current flowing around a bend and spilling over the levee. (Adapted from [29] and reproduced with permission from John Wiley & Sons.) (c) A sketch of a turbidity current in a sinuous channel at low latitudes, where centrifugal forces lead to overbanking flows downstream of the bend apices. (d) In very high Northern latitudes, the Coriolis forces will strongly deflect the turbidity current to the right-hand side (looking downstream).

Latitudes [25]. By contrast, narrow and highly sinuous submarine channels at low latitudes such as the Zaire [12], Amazon [19] or the Indus Channel [1] all have $|RoW| > 8$. The correlation of low peak sinuosity with low Rossby number and high peak sinuosity with high Rossby number supports the hypothesis of Peakall et al. [4] that Coriolis forces could be one of the key controls for significantly lower sinuosity at high latitudes. They also noted that some of the changes in sinuosity could be due to differences in slope and sediment type. In addition, it should be made clear that it is not only the latitude that determines whether Rossby numbers are low and hence Coriolis forces are important, but also the channel geometry and flow velocity. An example (not plotted) that emphasizes the importance of Rossby number rather than latitude is a highly sinuous and narrow channel at $51^\circ$ N in British Columbia [28]. The flow velocity was of the order of $3 \text{ m s}^{-1}$, the width $W = 100 \text{ m}$, radius of curvature $R = 1000 \text{ m}$ and $f = 1.13 \times 10^{-4} \text{ s}^{-1}$. In this case, $RoW = 256$, consistent with the grouping of other highly sinuous channels in figure 3b, despite the relatively high latitude.

The geometry of a sinuous channel is sketched in figure 4a, where there is a well-defined radius of curvature $R$, depth $H$ and width $W$. Figure 4b shows an acoustic backscatter image of a turbidity current in a submarine channel in cross-section, as it flows around a bend [29]. In this channel, the centrifugal forces dominate and strongly tilt the interface so that it spills over the higher outside levee. A turbidity current in a sinuous channel at low latitudes is sketched in figure 4c, where there is a tilt of the upper interface towards the outside of the bends. In successive bends, the sign of the tilt alternates and the highest levee will alternate between the right-hand side and the left-hand side. In very high Northern latitudes, the Coriolis forces will strongly deflect the turbidity current to the right-hand side of the channel looking downstream, as shown in figure 4d. In the left-turning bend, Coriolis and centrifugal forces act together and lead to overbanking flows. In the right-turning bend, the Coriolis and centrifugal forces act in opposite directions so that the interface is flatter, and overbanking flows may be suppressed. In this case, the right-hand side
levee is higher than that of the left-hand side, as in the NAMOC channel [13] and the Monterey Deep-Sea Fan Channel [21].

There are a number of observations that emphasize the role of Coriolis forces on depositional asymmetries of sediment-laden gravity currents. For instance, in high-latitude lakes and fjords sediment deposition patterns document a strong deflection of turbidity currents by Coriolis forces, so that sediment layers are thicker on the right-hand side (looking downstream) in the Northern Hemisphere [30] and on the left-hand side in the Southern Hemisphere [31]. In addition, Coriolis forces are known to shift the locations of erosion and depositional patterns in large estuarine flows. For instance, Schramkowski & de Swart [32] and Valle-Levinson et al. [33] both show how Coriolis forces shift the circulation patterns in a large estuary and change the morphodynamic evolution of the system. Contourite drifts formed by oceanographic contour currents also display a strong influence of Coriolis forces [34]. Akhmetzhanov et al. [35] document a number of striking examples where there are lateral asymmetries of erosion and deposition driven by saline gravity currents in the Gulf of Cadiz and near the Faeroe Bank Channel. In most of the sandy channels that they studied, erosion preferentially occurred on the right-hand side of the mean flow direction, and deposition to the left-hand side, consistent with the shift in velocity maxima sketched in figure 4d.

Direct observational evidence for the influence of Coriolis forces upon the velocity structure of turbidity currents has also been seen in two recent field studies in right- and left-turning channel bends. Observations were made at 41°N of a dense current flowing in a left-turning channel in the Black Sea [27] and at 35°N in a right-turning channel flowing into a large reservoir in the Yellow River [36]. In both cases, the latitude, width, velocity and radius of curvature of the channels are similar. The striking difference is that in the right-turning channel in the Yellow River the Coriolis forces and centrifugal forces oppose one another and the density interface is nearly flat (similar to the second bend in figure 4d), whereas in the left-turning channel bend in the Black Sea the Coriolis forces and centrifugal forces act together to result in a super-elevated density interface, similar to the first bend in figure 4d. These observations will be discussed in more detail after reviewing the existing theory of Coriolis forces upon gravity currents.

The development of sinuosity in submarine channels is usually attributed to erosion occurring at the outside bends and deposition occurring near the inside of the bends, so that with time the bend curvature increases [17]. In the absence of strong Coriolis forces, the sediment will be eroded on the outer bank upstream of the bend and deposited on the inner bank downstream of the bend as inner accretion packages [28, 37, 38]. Subsequent growth of lateral accretion packages (LAPs) on alternating sides of the channel continuously increases their sinuosity. The exact location of the erosion and deposition of sediments is partially set by the secondary (cross-channel) circulation dynamics driven by centrifugal forces, as well as changes in the lateral location of the downstream velocity maximum. In very wide channels, Coriolis forces can also strongly deflect the lateral location of the velocity maximum, change the secondary circulation and will shift the location of erosion and deposition in channelized turbidity currents. Some of these changes in circulation are illustrated in figure 4d, and the following sections will elaborate on how the lateral shift in the velocity maximum by Coriolis forces could provide a mechanism to explain the observed low-sinuosity channels at high latitudes in figure 2a.

3. Modelling the response of gravity currents to Coriolis forces

On the rotating Earth, the Coriolis force acts on any moving object. The magnitude of this acceleration is expressed as the cross product of the horizontal velocity vector with the rotation vector, \( \frac{d\mathbf{U}}{dt} = -2\Omega \times \mathbf{U} \). The resulting force is always at 90° to the direction of the flow and depends upon the speed of the current and the Coriolis parameter \( f \). The acceleration in the y-direction is \( \frac{du}{dt} = -fv \) and in the x-direction \( \frac{dv}{dt} = fu \). As \( f \) changes sign between the Northern and Southern Hemispheres, the direction of the Coriolis force also changes with the hemisphere. There is no Coriolis force for a non-moving object \( (u = v = 0) \) or at the Equator where \( f = 0 \).
One of the most important consequences of a constant force at right angles to the direction of movement is that, in the absence of friction, objects would follow a circular path [39]. Such a circular trajectory will be completed in a period of \(2\pi/\omega\), which is 17 h at 45° N, and the inertial radius is given by

\[R_{\text{int}} = \frac{U}{\omega}.\tag{3.1}\]

When this length scale is smaller than the radius of curvature \(R\) of a sinuous channel, Coriolis forces will be larger than centrifugal forces, and Coriolis forces will deflect the velocity core to the right-hand side of a curved channel in the Northern Hemisphere. The length scale \(R_{\text{int}}\) decreases with latitude; for example, an object with velocity of 1 m s\(^{-1}\) at 45° N where \(\omega \sim 10^{-4}\) s\(^{-1}\) would move in a circle of radius 10 km, at 10° N, \(R_{\text{int}} \sim 40\) km, while at 60° N, \(R_{\text{int}} \sim 8\) km. For comparison, the NAMOC at 53–59° N has radius of curvature between 15 and 30 km [13], so that \(R_{\text{int}} \ll R\). At low latitudes, it is usually the case that \(R_{\text{int}} \gg R\), and hence centrifugal forces would dominate, such as in the sinuous channels of the Amazon where \(R \sim 1\) km [19].

The cross-channel tilt (\(dh/dy\)) of the upper interface of the turbidity current shown in figure 4d can be determined from the momentum balance across the channel as

\[g' \frac{dh}{dy} = \omega \frac{U^2}{R},\tag{3.2}\]

where \(U\) is the mean downstream velocity [21]. The radius of curvature \(R\) is defined as positive when the bend is to the left (looking downstream), so that the force is in the same direction as the Coriolis force in the Northern Hemisphere. Bends turning to the right have negative \(R\) [3]. The slope \(dh/dy\) then depends upon the sign of both \(\omega\) and \(R\).

Equation (3.2) can also be written in terms of the local channel curvature, as in eqn (2.13) in Imran et al. [17].

Rearranging equation (3.2) gives an equation for the interface slope whereby

\[\frac{dh}{dy} = Fr^2 \left( \frac{\omega h}{U} + \frac{h}{R} \right), \quad \text{where } Fr^2 = \frac{U^2}{g'h},\tag{3.3}\]

and \(h\) is the depth of the gravity current. The difference in height of the interface across the channel is related to the slope as \(\Delta h = W \frac{dh}{dy}\), which can then be written in terms of the Rossby number and the Froude number \(Fr\) as

\[\frac{\Delta h}{h} = Fr^2 \left( \frac{1}{Ro_W} + \frac{W}{R} \right)\tag{3.4}\]

In a straight channel there is no centrifugal term (\(W/R = 0\)), the tilt of the interface will scale as \(\Delta h/h = Fr^2/Ro_W\). As the influence of friction, density stratification or internal circulation is neglected in this derivation, the above scaling of (3.4) is only approximate. A more general form is

\[\frac{\Delta h}{h} = Fr^2 \left( \frac{A}{Ro_W} + B \frac{W}{R} \right),\tag{3.5}\]

where the constants \(A\) and \(B\) are of the order of 1 and must be determined experimentally.

The important parameter \(Fr^2/Ro_W\) in (3.4) shows a key difference between a river and a gravity current flowing in the same width channel. For the same velocity, both will experience the same Coriolis forces and hence have the same \(Ro_W\), but the Froude numbers will be much lower in the river owing to the high density difference between the air and water. Hence, \(\Delta h/h\) owing to either Coriolis or centrifugal forces is generally of orders of magnitude greater for a gravity current in a bend than in a river of the same scale.

In a curved channel, the interface of the gravity current will be flat (\(dh/dy = 0\)) at the bend apex when Coriolis forces and centrifugal forces balance, which occurs in (3.4) when \(Ro_W = -W/R\) for
a bend to the right in the Northern Hemisphere. This condition can be rewritten in terms of a Rossby number defined as

$$R_{OR} = \frac{U}{fR} = -1,$$  \hspace{1cm} (3.6)

which is the ratio of centrifugal to Coriolis forces at the bend. $R_{OR}$ will be positive or negative depending upon whether the forces are in the same direction or not. The balance is illustrated in figure 4$d$, where in the first left-turning bend the interface is superelevated, but in the right-turning bend the interface is flat. $R_{OR}$ could also be defined in terms of the radius of curvature and the inertial radius derived in (3.1) as $|R_{OR}| = R_{int}/R$.

In figure 3$b$, $|R_{OW}| < 5$ could be used as a threshold to suggest when the sinuosity of submarine channels might be strongly influenced by Coriolis forces. Although there is a paucity of data on the radius of curvature of submarine channels, data in Clark & Pickering [1] suggest that a typical range is $1.5 < W/R < 10$. This empirical criterion that low-sinuosity channels always occur when $|R_{OW}| < 5$ is then broadly consistent with the stronger threshold $|R_{OR}| < 1$, whereby a gravity current is strongly influenced by Coriolis forces.

Even flows where $|R_{OR}|$ is of the order of 1 will experience some asymmetry between left- and right-turning bends. The fraction of the total force in a bend that is owing to Coriolis forces is expressed by the ratio

$$\frac{fU}{U^2/|R| + fU} = \frac{1}{1 + |R_{OR}|}.$$  \hspace{1cm} (3.7)

Without Coriolis forces ($|R_{OR}| \gg 1$) this ratio will equal 0. When $|R_{OR}| = 1$, the forces balance and Coriolis accounts for 50% of the total. For $|R_{OR}| = 3$, Coriolis forces are responsible for 25% of the total and only reach 10% when $|R_{OR}| = 9$. Thus for flows where $|R_{OR}|$ is of the order of 1, Coriolis forces will lead to significant asymmetries in interface tilt between successive bends.

In addition to tilting the interface, increasing Coriolis forces will also reduce the downstream velocity of gravity currents. This has been shown in numerous laboratory and oceanographic studies where a geostrophically adjusted gravity current is found to move at slower speeds than a non-rotating current [7,10,40–42]. The theory of Cossu et al. [10] considers the force balance between Coriolis forces, bottom friction and pressure gradient in a 1.5-layer system in a straight rectangular channel of width $W$, which slopes downwards at angle $s$ to the horizontal. In this case, the momentum equations can be written as

$$-fv = -g's - v_E \frac{\partial^2 u}{\partial z^2},$$ \hspace{1cm} (3.8a)

and

$$fu = -g' \frac{dh}{dy} - v_E \frac{\partial^2 v}{\partial z^2},$$ \hspace{1cm} (3.8b)

where $u$ and $v$ are the velocity in the along and across-channel directions, $v_E$ is the eddy viscosity and $h(y)$ is the thickness of the dense layer. Note that (3.8b) is similar to (3.2) in that the interface slope is a function of the along-channel velocity, but now includes the viscous term that leads to Ekman boundary layers. There is no centrifugal term as they consider a straight channel. These equations are solved in Cossu et al. [10] and a numerical solution is given for the mean downstream geostrophic velocity, which decreases with increasing $R_{OW}$. They also show that the inclusion of an Ekman boundary layer leads to differences with (3.3) for the values of $\Delta h$; and they find $\Delta h/h = 1.5 F^2/R_{OW}$, i.e. a value of $A = 1.5$ in (3.5).

4. Laboratory observations of gravity currents

(a) Methods

The use of laboratory experiments is motivated by the difficulty in directly observing episodic turbidity currents that occur at great depth in the ocean. Laboratory models are much smaller than natural channels, so dynamical similarity is achieved by matching the Froude and Rossby...
numbers. This means that the experimental rotation rate is much faster than the Earth’s rotation in order to achieve the low Rossby numbers typical of large-scale, high-latitude gravity currents. In laboratory experiments, the Reynolds number cannot be matched; instead, researchers aim to have fully turbulent flows with Reynolds number greater than 2000.

Results from experiments with three different channel models were used by Cossu et al. [10] and Cossu & Wells [3] to understand the flow structure, erosion and deposition patterns in submarine channels. In all cases, a dense fluid was pumped into the submerged channel model placed within a rectangular tank (figure 5a). All three channels had a constant, rectangular cross-section of 10 cm but varied in sinuosity between 1, 1.03 and 1.09, as sketched in figure 5b–d. The downstream and across-stream velocity data were recorded in the apex of the left-turning channel bend using a Metflow Ultrasonic Doppler Velocity Profiler and a Nortek Vectrino II Acoustic Doppler Velocimeter. Reynolds numbers were between 2000 and 7000, guaranteeing

Figure 5. (a) A side view of the experiments; (b–d) planform views of the three channel models used. In channel (c), the sediment thickness was measured in an area of 0.6 × 0.25 m as shown by the red dashed box. In channel (d), the photographs of sediment deposition are of an area of 0.9 × 0.4 m, as shown by the red dashed box.
that the flows were turbulent. The tank was rotated so that Coriolis parameters were between $-0.5 < f < +0.5 \text{ rad s}^{-1}$. Before the experiment began, the tank had to be spun up for at least 30 min. This represents several Ekman pumping time scales [39], guaranteeing solid body rotation of the water.

Saline gravity currents were used in many experiments as they serve as a good analogue to low-concentration sediment currents [43]. The non-rotating flows ($f = 0 \text{ rad s}^{-1}$, $Ro_W = \infty$) had a vertically averaged velocity of $U = 0.052 \text{ m s}^{-1}$ and $U = 0.04 \text{ m s}^{-1}$ and a mean thickness of $h = 0.06 \pm 0.005 \text{ m}$. The Froude numbers of $Fr = 0.58 \pm 0.2$ and $Fr = 0.52 \pm 0.15$ and Reynolds numbers of approximately 3000 are similar to comparable experiments with turbulent gravity currents [16,44].

Depositional experiments were performed by Cossu & Wells [25] in the curved channel shown in figure 5d. To monitor depositional patterns, approximately 10 particle-laden flows were conducted using silicon carbide with a mean diameter of 30 $\mu$m. The average flow height was 0.04 m and a vertically averaged flow velocity of 0.025 m s$^{-1}$ yielded a Froude number in the range of $Fr = 0.25–0.4$ and a turbulent flow with a Reynolds number of approximately 2000. The areas of deposition in the channel were identified from photographs taken from a height of 1.5 m above the tank.

Erosional experiments were performed in the sinuous channel shown in figure 5c. In these experiments, saline fluid with density of 1025 kg m$^{-3}$ was discharged at 1 l s$^{-1}$ for 180 s to produce a gravity current with a thickness of 9 cm. The mean downstream velocity was 75 mm s$^{-1}$ so that the Froude numbers were $Fr = 0.9 \pm 0.15$ and the flow was turbulent with a Reynolds number of approximately 7000. An erodible bed of thickness of 2 ± 0.5 cm was made with low-density plastic sediment (Opti-Blast Abrasive T-5 Acrylic) with density of 1150–1190 kg m$^{-3}$ and mean diameter of 400 $\mu$m (similar to [44]). Changes in bed thickness were measured with an array of 12 Seatek 2 MHz ultrasonic acoustic transducers mounted on a traversing frame. The spatial locations of erosion and deposition were determined from differences in the topography measured before and after the passage of the saline density current, while the table was rotating.

(b) Results

Coriolis forces lead to a tilt of the upper density interface of a gravity current, as shown in photographs looking upstream in a straight channel (figure 6a–c). For the case without rotation ($Ro_W \sim \infty$), the density interface is flat (figure 6b), whereas for small values of $Ro_W = \pm 0.83$ there is a significant deflection of the density interface (figure 6a,c). The measured secondary across-stream circulation patterns are plotted in figure 6d–f and sketched in 6g–i. In the non-rotating experiment, there is a helicoidal flow with two adjacent flow cells (figure 6e). For strongly rotating flows, the secondary circulation is dominated by Ekman boundary layers in figure 6d–f, for $Ro_W = \pm 2.4$ [10].

The mean downstream velocities in the straight channel decrease with increasing rotation rates as the downstream velocity is now controlled by a geostrophic balance between the lateral pressure gradient, Ekman boundary layers and Coriolis forces [10]. The data are plotted in figure 7 against the theory incorporating Ekman dynamics, in terms of the Froude and Rossby numbers. The experiments show that, for all absolute values of the Rossby numbers less than 10, the velocity is significantly reduced. For a given slope and density contrast, the Coriolis parameter plays a strong role in determining the velocity. Thus, the use of only slope and Froude number to estimate the flow dynamics [45] will be limited to turbidity currents with large Rossby numbers.

Flow structures in a channel bend are shown in figure 8, where the channel model of figure 5d is used. Without rotation, the density interface slopes up towards the outer bend owing to the centrifugal acceleration (figure 8b), similar to Keevil et al. [46] and Straub et al. [16]. When Coriolis and centrifugal forces act together, the tilt of the interface increases (figure 8a), and when they oppose the interface can tilt towards the inner bend (figure 8c). Changes in the density interface (figure 8a–c) correlate with the observed locations of the downstream locus of velocity maximum.
Figure 6. Circulation in the straight channel. (a–c) Photographs showing the deflection of the interface for $Ro_W = 0.83$, $Ro_W = \infty$ (no rotation) and $Ro_W = -0.83$. The perspective is looking upstream and hence a deflection to the left-hand side means a deflection to the right-hand side from the downstream perspective. The white lines represent the interface slope based upon an average of many photographs. (d–f) The measured across-stream velocities (looking upstream) for $Ro_W = 2.4$, $Ro_W = \infty$ and $Ro_W = -2.4$. (g–i) A sketch of the sense of circulation for high Northern latitudes, the Equator and high Southern latitudes. (Adapted from [10].)

Figure 7. The dependence of the Froude number (normalized velocity) upon Rossby number in a straight channel. The values of $Ro_W$ and $Fr$ are based on the observed mean geostrophic velocity of the gravity current. The solid line shows the Froude number based upon the theoretical geostrophic velocity $U$, and the dashed line is the non-rotating value. (Adapted from [10].)

$U_{\text{max}}$ shown in figure 8d–f. The secondary circulation also changes significantly in figure 8g–i, as described in Cossu & Wells [3].

Observations of the density interface slopes from 32 experiments in a straight and a sinuous channel (with $W/R \sim 0.28$) are summarized in figure 9. The interface slopes are calculated from fits to photographic images, as shown by the white lines in figures 6a–c and 8a–c. The main result...
Figure 8. (a–c) Photographs of the lateral tilt of the density interface in the bend apex for various $Ro_R$. The white lines represent the interface slope based upon an average of many photographs. (d–f) Corresponding distribution of the downstream velocity core in the bend apex. (g–i) Across-stream velocities in the bend apex. All images are looking upstream. (Adapted from [3].)

Figure 9. Relationship between $Fr^2/Ro_W$ and the lateral tilt of the interface $\Delta h/h$ for different rotation rates, channel slopes and for sinuous and straight channel sections. In the straight channel, the data collapse to a line where $\Delta h/h = 1.5 Fr^2/Ro_W$.

of figure 9 is that the data for $\Delta h/h$ plotted against $Fr^2/Ro_W$ for all 32 experiments collapse well to the dashed and solid lines, which have a slope of 1.5. An empirical relationship to data in figure 9 is $\Delta h/h = Fr^2(1.5/Ro_W + 3.75 W/R)$, i.e. coefficients of $A = 1.5$ and $B = 3.75$ in equation (3.5). This scaling is also consistent with a more complex theory including Ekman boundary layers for a straight channel, where Cossu et al. [10] predicted that the interface slope should scale as $\Delta h/h = 1.5 Fr^2/Ro_W$. These observations in figure 9 are similar to the non-rotating
experiments of Straub et al. [16], who also found that the scaling of Komar [21] in equation (3.4) underestimated the observed superelevation at channel bend apices by a factor of 2–3, implying $B = 2–3$.

Depositional patterns of the sediment-laden and erosional flows are shown in figure 10, for similar Rossby numbers as used for the gravity current experiments in figures 6 and 8. The observed locus of $U_{\text{max}}$ is marked by a dashed line in figure 10a–c and is inferred from seven velocity measurements made 1 cm above the bed. The measurements at the bend apex are shown in figure 8d–f, and additional measurements were made at locations upstream and downstream of the bend apex shown in figure 10a–c. Without rotation ($Ro_R = \infty$), the locus alternates between left-turning and right-turning bends, as observed in other non-rotating experiments [16,44,46]. However, with low Rossby numbers the location of $U_{\text{max}}$ is now restricted to either the right-hand side or left-hand side of the channel depending upon the sense of rotation.

Observations of depositional flows in figure 10d–f show a strong influence of Coriolis forces. For non-rotating depositional currents (large $Ro_R$), the flow deposits cover the entire channel (figure 10b), with low-sedimentation areas occurring downstream of the inside of the channel bend [25]. This pattern is in agreement with other non-rotating depositional turbidity currents [16,47] and numerical models [48] where deposition occurs predominantly, where the flow is superelevated and the suspended sediment concentration is the largest. By contrast, for small $Ro_R$ the sedimentation occurs mainly on either the right-hand side (figure 10d) or left-hand side (figure 10f), where the velocity core is located [25].

There is a consistent shift in the location of erosion with the changes of the Coriolis parameter in figure 10g–i. In the non-rotating experiment of figure 10h, the erosion of sediment is greatest at upstream of the bend on the outer bank and deposition is greatest at downstream of the bend on the inner bank, concurrent with previous laboratory experiments [44,49] and field observations [28,38]. When the Rossby number is small, centrifugal forces become smaller than Coriolis forces and the location of the velocity core is restricted to one side of the channel, leading to erosion predominantly on only one side of the channel (figure 10g,i).

5. Discussion and conclusion

A number of experimental and field observations demonstrate that Coriolis forces are important for the internal flow structure of gravity currents. This is mostly evident in the control of the position of the downstream velocity core, and secondarily in the tilt of the upper density interface and the reduction in speed. Experimental observations with sediments also show that Coriolis forces lead to an asymmetry in the locations of erosion and deposition between the left-hand side and right-hand side of the channels. The lateral location of the velocity maximum is often invoked as the most important flow feature for the evolution of submarine channel systems, with the development of channel sinuosity being tied to a feedback between erosion and channel curvature [5,6]. If Coriolis forces lead to an asymmetry in locations of erosion between left- and right-turning bends and so decouple the location of maximum curvature from maximum erosion, then there may be a reduction in the development of sinuosity in wide high-latitude channel systems. This asymmetry between left- and right-turning channel bends is a possible mechanism to explain the observations of Peakall et al. [4] that less sinuous channels usually occur at high latitude.

The new data in figure 9 compare well with the observations of interface tilt from the left-turning channel in the Black Sea [27] and the right-turning channel in the Yellow River [36]. In the Black Sea channel, $W = 850 \text{ m}$, $U = 0.7 \text{ m s}^{-1}$, $R = 8000 \text{ m}$ and $f = +0.95 \times 10^{-4} \text{ s}^{-1}$, so that $Ro_R = +0.87$, $Ro_W = +8.7$ and $W/R = 0.1$. The Froude number was estimated at $Fr = 0.41$, so that $F_r^2/R_{0W} = 0.02$. The observed interfacial tilt in the Black Sea is approximately 10–15 m in the 20–25 m deep channel, so that $\Delta h/h \sim 0.4–0.75$, consistent with the experimental results in figure 9 for $W/R = 0.28$, where observations are between 0.4 < $\Delta h/h < 0.7$. In the Yellow River channel, $W = 500 \text{ m}$, $R = -2250 \text{ m}$, $f = +0.83 \times 10^{-4} \text{ s}^{-1}$ and $U = 0.2–0.3 \text{ m s}^{-1}$, so that $Ro_R = -1.6$ to $-1.1$, $Ro_W = +4.8$ to $+7.2$ and $W/R = -0.2$. The Froude number was estimated as a supercritical value.
Figure 10. (a–c) Location of the locus of maximum velocity is shown by a dashed line, based upon observations made by an acoustic Doppler velocimeter 1 cm above the base at the seven locations shown. (d–f) Photographs of sedimentation areas from suspension-fallout-dominated gravity currents in the channel model. (Adapted from [25].) The grey shades indicate areas of deposition with a thickness of less than 5 mm, and the white shades represent the channel floor, e.g. zones of no deposition. (g–i) Changes in bed thickness after the passage of a saline gravity current ($Re \sim 7000$) for a slightly less sinuous channel at similar Rossby numbers. In both images, the dashed line represents the observed locus of the downstream velocity maximum. The channels have the same widths, and the areas of the measurements are sketched in figure 5c,d.

of 1.06–1.32, so that $Fr^2/RoW = 0.15–0.363$. The fact that $Ro_R$ is close to $-1$ suggests that the interface in the Yellow River channel is close to the condition described by equation (3.5), where centrifugal and Coriolis forces balance and indeed the interface was observed to be nearly flat.
at the right-turning bend apex. The difference in interface tilt between the left- and right-turning bends is a striking manifestation of the importance of Coriolis forces in these large-scale flows.

A summary of the deposition and erosional patterns in channel systems is presented in figure 11. When Coriolis forces dominate in depositional suspension fallout flows, the formation of deposition on alternating sides of the channel downstream of bends (as shown in figure 11b) is restricted. Instead, deposition occurs most strongly where the bulk of the flow is located, which is now on the same side both upstream and downstream of bend apices (figure 11a,c). Both the secondary flow field and the tilt of the interface depend upon Coriolis forces, which will promote levee height asymmetries. As pointed out by Amos et al. [44], there is unlikely to be any increase in channel sinuosity for suspension fallout flows. The dashed lines represent the possible evolution of these channels, which might migrate laterally when Coriolis forces are dominant. In figure 11e, we sketch the classic evolution of bedload-dominated flows in submarine channels, in the absence of strong Coriolis forces. Sediment will be eroded on the outer bank upstream of the bend (blue shading) and deposited on the inner bank downstream of the bend as inner accretion packages (red shading). There is a subsequent growth of LAPs on alternating sides of the channel which increases the sinuosity [44], as indicated by the dashed lines in

**Figure 11.** (a–c) A sketch of how deposition patterns change with increases in Coriolis forces for a suspension-fallout-dominated flow. (d–f) A conceptual model of how erosion and depositional patterns could shift with increases in Coriolis forces in a bedload-dominated flow. The possible evolution of the channel boundaries is marked with a dashed line.
However, when Coriolis forces control bedload-dominated flows, erosion no longer occurs preferentially on the outside of bends, and transport processes suggest little potential for increases in channel sinuosity (figure 11d–f). In addition, there may be a lateral migration of the entire channel system, e.g. to the right-hand side in the Northern Hemisphere and to the left-hand side in the Southern Hemisphere. Most importantly, figure 11d–f represents a conceptual model which suggests that flow asymmetries owing to Coriolis forces change intrachannel deposits. This supports the hypothesis of Peakall et al. [4], who found a good correlation between high-latitude channels and low-sinuosity planform geometries in submarine channels.

While the experimental observations have clearly shown how Coriolis forces lead to a strong asymmetry in the flow between left- and right-turning bends, more work remains to fully test the hypothesis that Coriolis forces are the main control on the observed latitudinal variation of channel sinuosity. One strong test would be to investigate stratigraphic records of channel–levee systems at high latitude with low $Ro_W$, and determine whether the evolution of sinuosity is consistent with our sketch in figure 11. Another approach would be to formally take into account the influence of Coriolis forces on deflecting the locus of velocity maximum, so that the lateral migration term $\zeta(s)$ is no longer directly coupled to channel curvature for flows with low $Ro_R$.

Much of the mathematics needed to model the locus of velocity maximum has already been presented by Imran et al. [17], where their non-dimensionalization of the Coriolis parameter is $f^* = 2/\gamma Ro_W$. In terms of the influence of Coriolis forces, Imran et al. [17] only discuss how these strongly influence the slope of the density interface. Hence, future work should investigate how the evolution of channel sinuosity depends explicitly upon $Ro_R$.

We emphasize that other factors such as slope, sediment type and flow power of gravity currents will have important controls on sinuosity in submarine channels [4,50]. The role of these factors has been further discussed in Peakall et al. [4,51] and Sylvester et al. [52]. Slope shows only a weak influence on global changes in channel meandering in comparison with Coriolis forces [51] and should not be neglected. Sediment and flow type depend not only on climate-driven factors that underlie latitudinal variations but also on hinterland geology and tectonics settings [4,53], which in turn are independent of latitude. In conclusion, sediment type and flow variation vary with latitude but it has been suggested that Coriolis forces are the dominant driver for low-sinuosity channels at high latitudes [4,25]. Models similar in form to that described by Imran et al. [17] are fairly idealized. A full descriptive model of how channel sinuosity develops should take into account Coriolis forces, the sediment load, the substrate type, the cross-sectional channel shape and time dependence of the turbidity currents. For example, an advanced model was introduced by Janocko et al. [49] but it still neglects Coriolis effects. Thus, a globally applicable, full descriptive model remains a challenging prospect for the future.

References


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