Observations of long-duration episodic bottom currents in the Middle America Trench: Evidence for tidally initiated turbidity flows

by

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Abstract

Benthic flow in the Middle America Trench off the Pacific coast of Costa Rica is examined using time series from a single-point acoustic current meter moored 21 m above bottom at 4386 m depth at the southern end of the trench from November 2005 to April 2007. In addition to significant (~ 0.1 ms\(^{-1}\)) tidal currents, the instrument recorded a series of twelve, episodic northwestward along-trench flow events of roughly monthly duration. Event velocities often exceeded 0.25 ms\(^{-1}\) and were contemporary with enhanced acoustic backscatter intensity. Events ended with a rapid (< 1 day) reversal to southeastward flow and reduced backscatter. Seafloor temperature records from two nearby Ocean Drilling Program (ODP) borehole observatory sites reveal that the flow events were accompanied by a steady rise in bottom water temperature. Temperatures dropped abruptly to background values at the end of each event. The event timing generally tracked the envelope of the tidal current modulation. Based on the November 2002 to February 2009 borehole observatory temperature records, the events had a mean duration of 40(±20) days and were separated by a between-event interlude of 30(±25) days. Findings indicate that the episodic flows were likely rotationally modified, autosuspending turbidity currents initiated by tidal current resuspension of sediments above the shoaling trench floor to the southeast of the mooring site. Suspended particles in the turbidity currents are estimated to range from 0.0003 to 0.006% of the current by volume. Results suggest that tidally induced turbidity currents may be common to steep, well-mixed regions of the deep ocean adjacent to sediment rich continental margins.
1. Introduction

The Middle America Trench is a 2750 km long, 25 km wide, maximum 6669 m deep, northwest trending depression in the eastern Pacific crust formed by subduction of the Cocos Plate beneath the continental margin of Mexico and Middle America (Figure 1). At its southern end, the trench shoals to the southeast where it is partially blocked by the ~3300 m-deep sill adjacent to Fisher Seamount. The sill (herein, the “Fisher Sill”) isolates the main portion of the trench from a 100 km long, ~3700 m deep enclosed basin further to the southeast. Aside from historical survey data which reveal that the bottom waters of the region are extremely well mixed (see Section 2), little is known about oceanic conditions within the ~700-m-high confines of the southern trench.

Although well mixed, the deep waters of the trench are certainly not static. This is evident from the roughly monthly duration, ~0.01 °C bottom water warming episodes recorded at Ocean Drilling Program (ODP) borehole observatories installed at Sites 1253 and 1255 in the trench off Costa Rica, roughly 90 km to the northwest of the Fisher Sill (Davis and Villinger, 2007; Figure 1). A plausible explanation for these events is that they are associated with gravity currents cascading down the relatively steep (~1°) slope of the trench at the observatory sites. Cascading of dense water occurs when anomalous temperature and salinity conditions develop in the upper ocean along continental margins (see review by Ivanov et al., 2004) and when dense bottom water constrained behind sills in deep ocean passages, such as the Denmark Strait between Iceland and Greenland, overflow into the adjoining ocean (Käse et al., 2003; Tanhua et al., 2005). Sediment laden turbidity
currents and their tell-tale turbidite deposits are common occurrences along the slopes and canyons of oceanic continental margins (see review by Meiburg and Kneller, 2009).

Despite their ubiquity, turbidity currents are rarely measured directly. In addition to their intermittency, the currents typically destroy any instrumentation in their path; recorded sequences of underwater cable breaks still provide some of the best information on turbidity current velocity in the deep ocean (Simpson, 1997). Xu et al. (2004) appear to be the first to record in-situ velocity profiles of oceanic turbidity currents successfully.

Supported by bottom temperature and transmissometer data, the authors used upward-looking ADCPs moored at three locations at depths of 1450, 2837 and 3223 m to identify four turbidity current events along the axis of Monterey Canyon off southern California. Two of the current events observed over the one-year study period appear to have been storm-generated; none was seismically generated. Flows were confined to the bottom 50 m of the water column, attained hourly-average speeds ranging from 0.5 to 2 ms\(^{-1}\), and persisted for several hours. As with all in-situ events, the turbidity currents reported for Monterey Canyon were highly intermittent and relatively short-lived, in marked contrast to the quasi-cyclic, long-duration events reported here for the Middle America Trench.

To test our proposition that the bottom-water temperature events reported earlier for the southeastern Middle America Trench resulted from turbidity currents, we took advantage of a visit to the area by the German R.V. Sonne in November 2005 to deploy a Nortek Aquadopp acoustic current meter on the seafloor within a kilometer of borehole Sites 1253 and 1255 (Figure 1). The current meter recorded data from 17 November 2005 until its
battery failed on 21 April 2007. In this study, we combine the 1.4-year current meter time series with the longer 6.2-year temperature records from the two ODP sites to examine bottom currents and associated changes in water properties within the trench up to the time of the mooring recovery in February 2009. These data, supported by historical CTD profiles, are shown to be consistent with tidally modulated gravity currents descending along the trench axis from as far to the southeast as Fisher Sill. Results provide the first ever near-bottom flow measurements in the trench and strong evidence that tidal currents may be a major forcing mechanism for deep ocean turbidity currents.

2. Observations

2.1 Water property structure

A limited number of Conductivity-Temperature-depth (CTD) profiles for the southeastern trench are available within the World Ocean Database 2005 Geographically Sorted Data (http://www.nodc.noaa.gov/OC5/WOD05/data05geo.html). Profiles collected nearest the study area (Figure 1) consist of two Neil Brown Mark IIIB CTD casts from May 1989 by the United States Research Vessel (R.V.) Moana Wave. These profiles (Figures 2a,b), as well as profiles collected further to the northwest by the German research vessels Sonne and Meteor several years later (Figures 2c,d), reveal that the potential temperature, salinity, and potential density of the bottom waters are uniform to within ±0.01 °C, ±0.0005, and ±0.001 kg m⁻³, respectively. We located several other profiles for the region but many had abrupt offsets and high-frequency noise similar to those in Figure 2d, which put into question the reliability of these particular profiles.
The near uniform salinity below roughly 3300 m depth in the mid-trench CTD profiles (Figures 2a and 2c) means that any changes in potential density are primarily due to changes in potential temperature. At the time of these particular profiles, there was relatively warm and highly stratified water above ~2900 m depth overlying a series of partially mixed layers extending to the seafloor. These layers included a ~100 m thick benthic boundary layer and a relatively warm, and near homogeneous, layer between 3300 and 3850 depth whose upper boundary coincides with the depth of Fisher Sill and topographically confining outer wall of the trench (Figure 1).

2.2 Current meter time series

The 2 MHz single-point Nortek acoustic current meter (ACM) was deployed in an upward-looking configuration on 14 November 2005 and landed near the middle of the trench in 4386 m of water, roughly 0.72 km northwest of ODP Borehole Site 1253 (Figure 1; Table 1). The ACM recorded three-dimensional current velocity, three-beam acoustic backscatter intensity, pressure, and temperature at an elevation of 21 m above bottom every 15 minutes based on a 1-Hz sampling rate and 2-min burst-averaging period. Currents were measured in earth coordinates based on an ensonified water volume within a radius of a few meters of the three acoustic transducers. The instrument was recovered by the DSV Alvin from the R.V. Atlantis in February 2009 and, with the exception of two missing data points, functioned flawlessly until its battery failed on 21 April 2007. According to the data, sensor resolutions were ±0.005 ms\(^{-1}\) for velocity, ±0.01 °C for temperature, ±2 counts for backscatter, and ±0.013 m for depth. The depth resolution is roughly 0.0003% of full scale and is based on a background density of 1027.744 kg m\(^{-3}\) from the CTD data; the
backscatter resolution is about 0.90 db based on Nortek’s specification of 0.40 to 0.47 db/count (Lohrmann, 2001).

We used linear interpolation to fill in the two missing 15-min values that occurred part way through the 523-day velocity time series. The current direction was then corrected for local magnetic declination and the current vectors rotated from a north and east reference frame to a principal component reference frame in which horizontal velocity components $u$, $v$ are in the northeast (cross-trench; 45° T) and northwest (along-trench; 315° T) directions, respectively. Vertical velocity, $w$, is positive in the upward direction. As indicated in Table 2, horizontal currents were strongest in the along-trench direction and reached 15-min average speeds of up to 0.3 ms$^{-1}$ toward the northwest. Vertical velocities were also strong and commonly exceeded the instrument resolution of 0.005 ms$^{-1}$. The acoustic backscatter intensity had a range of 25 counts (~11 db) superimposed on a background value of about 40 counts, with no suggestion of an acoustic noise threshold. Backscatter from the three beams are nearly identical so that only the beam-1 record has been examined. Because of the low (0.01 °C) resolution, temperatures from the ACM have not been used except for establishing absolute near-bottom temperatures.

For analysis purposes, we generated several smoothed versions of the ACM time series (Figure 3): Hourly time series were produced using a 4-point running mean (box-car) filter followed by decimation to hourly values; daily and 10-day time series were generated using 30-hr and 240-hr Kaiser-Bessel low-pass filters, respectively (Emery and Thomson 2001). The 30-hr filter effectively removes tides and other “high-frequency” variations, while the
240-hr filter removes tides, inertial, and weather-band motions. Because of the considerable noise for short sampling intervals, the hourly vertical velocity is shown in the bottom panel of Figure 3b only.

2.3 Borehole observatory temperature time series

Two boreholes were drilled during ODP Leg 205 and instrumented with CORK hydrologic observatories with the primary goal of monitoring formation pressures and temperatures and sampling formation fluids in the subducting Cocos plate, the subduction thrust fault, and the overlying forearc prism (Morris et al., 2003; and Jannasch et al., 2003). ODP Hole 1253A is located at 4376 m depth on the landward side of the Middle America Trench, and Hole 1255A is about 0.7 km away at 4311 m depth, just landward of the subduction prism toe (Figure 1). Hourly samples of high resolution (±0.0005 ºC) internal instrument temperatures are available for these sites for over 2278 days, from 21 November 2002 to the time of the most recent data recovery on 15 February 2009. The wellhead instrument packages are positioned roughly 3 m above the seafloor.

The central part of the borehole records (Figure 4) coincided with the time of the ACM measurements (the full records are presented in Figure 10). Although temperature variations are similar at the two sites, the sensors were not calibrated prior to deployment. This led to a difference of 0.387 ºC between the deeper site 1253 record (mean = 1.993607 ºC) and the 65 m shallower site 1255 record (mean = 1.606962 ºC). Based on the mean temperature of 2.0 ºC from the calibrated current meter, the temperature for site 1253 is considered “absolute” and representative of the true bottom water temperature. As a
consequence, a correction of +0.377 °C has been applied to the site 1255 record, including an adjustment of -0.01 °C to compensate for the difference in adiabatic heating. Because of the weak contributions from salinity, temperature changes recorded at the ODP sites can be used to trace the source depth for bottom waters descending into the trench.

2.4 ACM and CORK seafloor pressure time series

The ACM bottom pressure time series (Figure 3d) consists primarily of tidal variations superimposed on a small upward trend near the end of the record. Without additional data, it is impossible to know if the pressure increase of ~0.7 m that began towards the end of the record was internal to the sensor or due to movement of the mooring anchor as a result of scouring by the currents or downslope motion of the underlying sediments. In addition to formation pressure, seafloor pressure was also recorded at the borehole observatories at a sampling interval of 10 minutes for the full 6.2 year observation period. These data augment those collected by the current meter but have not been used in our analyses.

2.5 Regional winds

Several studies (e.g. Dengler et al., 1984; Xu et al., 2004) have identified storms as triggering mechanisms for turbidity currents descending to the seafloor along steep continental margins. As there are no weather buoys in the general vicinity of the mooring site, we examined oceanic winds during the time of the current and temperature observations using the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) six-hourly Reanalysis-1 wind stress data for grid point 9°N, 86°W and the three-hourly North American Regional Reanalyses data from grid
8.6ºN, 86.1ºW (Kistler et al., 2001). Wind stress vectors were separated into alongshore and cross-shore components to conform to those for the current meter time series. Results for the six-hourly and three-hourly datasets are similar and show that the wind stress is strongest in winter and mainly directed cross-shore toward the southwest (Figure 5). In summer, the wind stress is also cross-shore but much weaker than in winter.

3. Analysis and results

Time series analysis methods have been used to examine variability in bottom water temperatures and flow structure in the trench, with focus on the detided (residual) velocity and its possible link to tidally-induced turbidity currents.

3.1 Spectra analysis

The time series records presented in Figures 3 and 4 reveal that bottom currents near the southern end of the trench consisted primarily of tidal motions (0.1 ms\(^{-1}\) peak-to-peak) superimposed on 0.15 to 0.25 ms\(^{-1}\) event-like flows having durations of weeks to months. Tidal currents were primarily along-trench and dominated by motions in the semidiurnal (M\(_2\), S\(_2\)) and diurnal (K\(_1\), O\(_1\)) frequency bands (Figure 6). Also evident were weaker, clockwise rotary, broadband motions with periods of around 2.5 days that were associated with “blue-shifted” near-inertial motions that would have propagated downward from the upper ocean (cf. Thomson et al., 1990; Garrett, 2001); the inertial period \(T = \frac{2\pi}{f_c} \approx 2.98\) days for the mooring site, where \(f_c\) is the Coriolis frequency. There is a gap in the spectral power at periods of around 4 days and spectra increase toward low frequencies, reaching maximum values over a broad frequency band with periods ranging from one month to a
year, the lowest frequency resolvable by the 16-month current meter records. The spectral peaks in the 5 to 10-day band are indicative of wind-forced variability in the “weather band” (cf. Cannon and Thomson, 1996).

Seafloor temperature, $T$, at the ODP borehole sites tracked the long-period variability in the current velocity but lacks the marked periodicity associated with the tides and other higher frequency motions. In contrast to the currents, temperature fluctuations at tidal frequencies were mainly confined to the semidiurnal band (Figure 7a). The spectral peak at around two months for the full 6.2 year borehole temperature records (Figure 7a) corresponds to the average time between event peaks. Coherence analysis of the temperature records for the two ODP sites reveals that the motions are highly coherent, with greatest coherence (> 99% confidence interval) at semidiurnal periods and periods longer than 3 days.

Spectra of the ACM acoustic backscatter records (Figure 7b) closely resemble those for the ODP temperature records. Again, tidal variations are mainly confined to the $M_2$ frequency band and there is no indication of persistent, relatively high energy motion within specific low frequency bands. Backscatter intensity is determined by the acoustic impedance presented by physical and biological scatterers in the water column (including turbulent velocity shear and density gradients), and by the signal-to-noise level (detection threshold) of the ACM transducers. If the turbulence is too weak, or the suspended particles too fine or weakly concentrated, the ACM will not be able to detect currents or variations in backscatter intensity. The size detection limit for individual scatterers is determined by the wavelength, $\lambda = c/f$, of the transducers, where $f$ is the transducer frequency and $c \approx 1500$
ms$^{-1}$ is the speed of sound in water. According to the manufacturer (Lohrmann, 2001), Nortek ACMs can detect individual particles with radius, $r$, as small as 5 $\mu$m provided there is no significant concentration of particles in the water column for which $r = \lambda/4\pi$ (roughly 60 $\mu$m for the 2 MHz Aquadopp current meter). Because we expect few biological scatters at 4400 m depth within the trench, the backscatter bursts observed during major flow events – combined with the fact that the instrument had no difficulty measuring currents using Doppler shifting of the drifting scatterers – indicates that the instrument was ensonifying suspended particles with radii as low as $\sim$10 $\mu$m.

3.2 Tidal analysis

We have used least squares harmonic analysis (Emery and Thomson, 2001) to examine the amplitude and phase relationships among the measured variables for different tidal bands (Table 3). Constituents K$_1$, M$_2$, MF, MSM, SSA and SA are representative of tidal motions within the diurnal, semidiurnal, fortnightly, monthly, semiannual, and annual frequency bands, respectively. The long-period tidal constituents were major contributors to the current variability in the trench and, as in most oceanic settings, would have involved both astronomical and non-astronomical forcing mechanisms. That astronomical tides account for $\sim$95% of the variance in the pressure signal but only about 20% of the variance in the current, temperature and backscatter intensity signals, confirms the strong contribution of the quasi-cyclic episodic flows to oceanic variability in the trench.

Temperature and pressure variations in the dominant M$_2$ tidal band were in-phase and led the currents by roughly 90°, indicating that maximum M$_2$ northwestward (flood) currents at
the mooring site occurred ~90° (3.1 hours) after M₂ high tide. The observation that peak bottom temperatures occur at the end of the M₂ southeastward (ebb) flow suggests that bottom water temperature generally *increased* northwestward along the deepening axis of the trench. This contrasts with variations at the longer duration annual cycle where temperature fluctuations lagged the currents by ~ 90° and were therefore associated with mean background temperatures that *decreased* northwestward in the trench. (This apparent paradox relates to the spatial excursions of the flow at the different time scales and the fact that M₂ oscillations occur throughout the observational period whereas the longer period oscillations only occur about 50% of the time.) In contrast to the temperature records, acoustic backscatter intensity lagged the M₂ and SA current velocity by ~90° and 30°, respectively, and was therefore greatest at the end of the flood.

### 3.3 Episodic flow events

Twelve distinct velocity events were recorded during the 15-month current meter observation period (Figure 3a). Although the events had basic similarities, no two events were the same. As illustrated by the representative events in Figures 3 and 8, each flow episode began with acceleration in the northwestward component of residual (detided) flow. The residual current then increased to peak hourly speeds of up to 0.3 ms⁻¹ (six times the typical maximum tidal current speed) several weeks to over a month after the start of the event. The current subsequently diminished before undergoing a rapid 180° reversal in direction at the end of the event. The ensuing southeastward flow persisted for several days to several weeks. Over the observation period, the flow events had a mean duration of 15
(+12) days, a mean interlude between events of 13(+12) days, and a time between peak event flow of 43(+17) days.

Each flow event was accompanied by an increase in seafloor temperature (Figure 8) beginning less than 1 day after the persistent acceleration of the northwesterly flow. Bottom-water temperatures peaked at around 0.01 °C above background several weeks after the start of the temperature event before abruptly returning to near background values of ~2 °C over a period of several hours at the end of the event. The timing of the rise in bottom water temperature at the start of each northwestward flow episode is difficult to resolve accurately, but where relatively abrupt increases occurred they began within an hour of one another at the two observatory sites. The drop in temperature at the termination of each event occurred commonly up to several hours to 1 day earlier at the trench Site 1253 than at Site 1255 located 0.7 km to the northeast (and 65 m shallower) just up the eastern wall of the trench. On several occasions, the temperature drop at Site 1255 was followed by a brief (< 5 day) return of warmer water that had maximum temperatures nearly identical to those immediately prior to the end of the event. This difference in response at the two borehole sites implies that the flow was likely highly three-dimensional, including the possibility of ambient bottom water intruding from the northwest along the oceanic side of the trench. The close correlation between the episodic velocity and temperature signals makes it possible to use the longer borehole temperature records as proxies for velocity events.
All major northwestward flow events were accompanied by an enhanced backscatter intensity signal (Figure 8). The start times of backscatter events were often delayed several days relative to the reversal to northwestward residual flow, and peak backscatter intensity observed during a particular flow event was not necessarily contemporaneous with the corresponding current or temperature peak. There were also occasions (e.g., Julian Day 716 to 724 in Figure 8b) when backscatter intensity increased during times of relatively weak southeastward flow. Therefore, unlike temperature, changes in backscatter intensity are not always well correlated with the duration and intensity of major flow events. Without additional information, it is not certain whether the strong backscatter signals observed during major events were due to increased turbulence, increased thermally induced density gradients, and/or increased concentrations of suspended particles. This uncertainty is inevitable, given the relatively small amplitude of the signals, with maximum amplitudes only about 40 times the instrument resolution.

Except for the first episodic event, the times of maximum northwestward along-axis velocity and maximum downward vertical velocity were simultaneous (Figure 9) and indicative of downslope residual currents at the southern end of the trench. The seafloor in the vicinity of the current meter mooring has a mean downslope gradient $\Delta h/h \sim 0.0126$ ($0.72^\circ$) which we compare with the “attack” angle $\theta_v = wv/(u^2 + v^2)$ of the 10-day low-pass filtered currents at the mooring site. For the six strongest northwestward flow events in Figure 9 with pronounced negative velocity, the residual current velocity 21 m above bottom had a mean (± standard error) downslope angle $\theta_v \sim 1.12 \pm 0.24^\circ$, corresponding to a very slight downward velocity angle of $0.3^\circ$ compared to the seafloor. For the
southeastward reverse flow, attack angles were slightly positive and parallel to the seafloor, within the margin of error.

3.4 ODP CORK bottom-water temperature events

As noted in the previous section, the hourly temperature signals at the two borehole sites were well synchronized, differing only at the ends of events when the temperature decrease at slope site 1255 lagged that at the basement site 1253 by as much as a day. A total of 33 temperature events were observed at the ODP sites during the period November 2002 to February 2009 (Figure 10). The events had a mean duration of 40(±20) days, a mean between-event interlude of 30(±25) days, and mean time between peak temperature events of 68(±29) days, roughly twice that for the shorter events observed during the current meter deployment. Thus, characteristic event durations and interludes for the full 6.2 year borehole temperature series were quasi-monthly while for the much shorter 1.4 year current events were quasi-fortnightly. Figure 10 further shows that the current measurements from late 2005 to early 2007 were collected during a period of weak temperature events, which may account for the shorter current velocity durations. As discussed in Section 3.3, the 33 temperature events are assumed to have been generated by a corresponding number of velocity events.

3.5 Time-frequency analysis

A multiple-filter method (Dziewonski et al., 1969) was used to examine temporal variations in the frequency content of the observed current, temperature and backscatter
signals. The method, which is similar to wavelet analysis (Emery and Thomson, 2001), applies a series of narrow-band, Gaussian filters with frequency response

\[ H_n(\omega) = e^{-\alpha \left( \frac{\omega - \omega_n}{\omega_e} \right)^2} \]  

(1)

that isolate specific center frequencies, \( \omega_n = 2\pi f_n \). Frequency resolution is controlled by the parameter \( \alpha \) such that the higher the value of \( \alpha \), the greater the resolution in frequency but the poorer the resolution in time (and vice versa). The Gaussian filters lead to matrices of signal amplitude and phase that have constant resolution on a log(\( \omega \)) scale. Plots of the complex signal amplitude (f-t diagrams) effectively identify oscillatory motions and how their energy changes as functions of frequency and time (cf. Rabinovich et al., 2006).

According to the f-t diagram for the along-axis component of velocity presented in Figure 11, there was marked flow variability in the semidiurnal, diurnal, fortnightly, and monthly tidal bands. Figure 11 reveals equally pronounced and slowly varying motions over broadband nontidal frequencies centered around periods of 60 and 120 days. The cause of these oscillations is uncertain but they may correspond to bimonthly and four-monthly variations arising from particular combinations of “quasi-fortnightly” flow events followed by “quasi-fortnightly” between-event interludes. For all of the frequency bands, including the predominant semidiurnal band, the amplitude of the velocity signal was not constant but increased and decreased over longer time scales. Modulation of the along-axis residual flow velocity in the lower frequency bands generally tracked modulation of the semidiurnal and diurnal tidal currents. The f-t diagrams for temperature for the time of the current velocity measurements (Figure 12) bear a close resemblance to the along-axis velocity except for
the reduced temperature variability in the diurnal and semidiurnal bands and increased energy in the inertial and weather bands. We also note that there was much greater low-frequency temperature variability during the second half of the record compared to the first half of the record. Somewhat similar results are obtained for acoustic backscatter time series which show distinct variability in the semidiurnal band, intermittent variability in the inertial and weather bands, and highly variable burst-like variability in the monthly to bimonthly bands.

As indicated by the $f$-$t$ plots for the full 6.2-year borehole temperatures records (Figure 12), bottom water intrusions in the trench underwent pronounced long-term variability within all major frequency bands. Peak, highly time-varying, “energy” occurred within broadband fortnightly, monthly, bi-monthly, four-monthly and quasi-semiannual frequency bands. Energy in these bands intensified and weakened throughout the record, with the most pronounced change associated with the rapid decrease in low-frequency variability over the one year period from early 2005 to early 2006 (the period of current meter observations). There was a comparatively weaker reduction in energy from late 2007 to the end of 2008. All of these bands were more or less present from the beginning of the record in 2002 until about the middle of 2005 but then faded from mid 2005 to late 2006. Higher energy levels then returned to most frequency bands.

4. Discussion

The episodic flows recorded at the southern end of the Middle America Trench are suggestive of gravity currents descending a sloping bottom in a deep ambient fluid (cf.
Chapter 11 of *Simpson, 1997; Cenedese et al., 2004*). However, in marked contrast to most observed gravity currents, the flow events recorded in the trench were gradually accelerating, quasi-cyclic, and highly protracted. Consequently, the driving mechanism (or mechanisms) must also have been gradually developing, quasi-cyclic, and long-lived. Moreover, for the events to be gravity currents, rather than some form of amplified baroclinic oscillations within the water column itself, the negative buoyancy associated with the elevated water temperatures of the episodic flows would need to have been over-compensated by increased salinity or sediment loading (or a combination of both). The lack of salinity data is problematic and makes it difficult to choose between the two sources for increased density. Nor do the acoustic backscatter data help distinguish between mechanisms since salinity-driven gravity currents can cause increased backscatter through turbulent resuspension of the bottom sediments. Autosuspension, in which turbulent motion in the turbidity current helps to maintain and potentially enhance the particle suspension, is also possible for both types of density-generation mechanisms. *Simpson (1997)* also alludes to highly erosive flow velocities and sediment concentrations in which “… the turbidity current is said to ‘ignite’, that is, it accelerates and entrains sediments, attaining the catastrophic state.”

4.1 The case for turbidity currents

The observed episodic flows combined acceleration of the northwestward residual current velocity with increases in bottom temperature and near-bottom acoustic backscatter intensity. Temperature generally rose throughout the flow event or reached a constant value immediately following the peak current velocity. Backscatter intensity typically peaked
near the time of maximum velocity. These observations, together with the high Reynolds numbers

\[ R_e = \frac{UL}{\nu} \approx 5.9 \times 10^6 \]  

(2)

of the flow, are indicative of turbulent, particle laden currents advecting warmer water downslope from a source region to the southeast of the mooring site (here, \( U \sim 0.1 \) ms\(^{-1}\) is a characteristic flow speed, \( L \sim 100 \) m a minimum length scale, and \( \nu = 1.7 \times 10^{-6} \) m\(^2\)s\(^{-1}\) the kinetic viscosity). Based on the \(-1.6^\circ\text{C}\) near-isothermal potential temperatures recorded by the CTDs at bottom depths throughout the study region (e.g., Figure 2), it is reasonable to assume that water descending into the trench during an event originated much higher in the water column. To account for the episodic seafloor temperature anomalies of \(-0.01^\circ\text{C}\), the warmer water must have originated from as high as 1000 m above the mooring. From this we conclude that the observed events were gravity currents with sufficiently large concentrations of suspended particles (or salt) to overcome the thermal component of buoyancy. Because temperature is a tracer for water mass movement, the greater the temperature anomaly recorded at the borehole sites, the shallower the source depth for the gravity current. Those events for which temperature increased throughout an event were likely those for which the source region shoaled with time. Water temperature at the crest of the Fisher Sill appears to determine the maximum thermal anomalies at the borehole sites. Water originating any shallower in the water column would have been from depths with much greater temperature gradient (Figure 2) and hence would be more likely to produce much greater seafloor temperature anomalies than observed. In the case of sediment-driven gravity currents initiated by turbulent bottom currents, the process could be occurring over the entire length of the trench to the southeast of the study region (Figure
13). In contrast, salinity-driven gravity currents require a source of “high” salinity water, which would limit the process to cross-sill water exchange with Fisher Basin located 100 km to the southeast of the mooring site. This would require a source for high salinity water in the basin.

With no observational constraints other than the CTD data, we cannot immediately rule out salinity as a possible driving mechanism for the gravity currents. Specifically, a salinity increase of only 0.0005 can compensate for the density anomalies of -0.001 kgm$^{-3}$ associated with the observed 0.01 °C increases in water temperature. A small salinity increase of only 0.001, for example, would then be sufficient to initiate a gravity flow. A major difficulty with this interpretation is that observed salinity in the region is uniform to 0.0005 within the lower 1000 m of the water column and shows no evidence for the ~0.001 salinity anomalies needed to drive gravity currents. At depths shallower than 1000 mab, salinity decreases rapidly upwards and cannot be a source for high salinity water. This leaves Fisher Basin itself as the only immediate source for warm salty water. Although the basin is isolated to the southeast by the shallow ~2000 m deep Cocos Ridge and a shallow 1500 m deep sill (Figure 1b), it is feasible that the geothermal heating, accompanied by local convective bottom-water mixing and entrainment, could cause the deep waters in the basin to rise. This process could then draw in saltier water from the west (assuming that such water exists at these shallow depths), similar to the mechanism proposed by Gargett (1988) for the Panama Basin. The uplift of relatively warm salty water to sill depth in the Fisher Basin, combined with an estuarine-type exchange process during times of relatively weak tidal mixing over the sill (cf. Griffin and LeBlond, 1990; Masson and Cummins,
2000), could then lead to the cascade of warmer, but saltier and hence more dense, water down the northern slope of the Fisher Sill into the trench.

A drawback to this mechanism is that the geothermal heating and entrainment mechanism is a slow process (given the 300 m depth of Fisher Basin) and is unlikely to account for the needed fortnightly to monthly recharge rates. Moreover, unlike the case for the Panama Basin, there is no deep gap in the basin walls that would permit water to be drawn in at depth. In addition, if there is estuarine-like exchange taking place over the sill, gravity currents would be expected to form during times of neap tides when tidal mixing over the sill would be weakest. However, as discussed in the next section, our data imply that the exchange occurred during times of spring tides when tidal mixing is highest. This would have weakened the density contrast and caused the dense inflow to intrude at intermediate depths, rather than to the depth of the current meter mooring.

We therefore conclude that our findings are more consistent with autosuspending turbidity currents initiated by tidally modulated resuspension of bottom sediments. Although resuspended sediments could be entering the trench from the adjacent Cocos Plate or continental margin, it is more likely that resuspension was focused over the shoaling trench floor northwest of the Fisher Sill (Figure 13). Spillage of sediment-enriched water over the sill from Fisher Basin is a possibility, but this can only add to water of more local origin. Based on the nature of the initial segments of the events and the lag time between flow initiation and the arrival of water having a Fisher Sill temperature signature, results suggest a distributed source.
4.2 Simple flow dynamics

Ignoring friction and Coriolis effects, the linearized along-axis ($y$) momentum balance and hydrostatic equation can be written in incremental form as

$$\frac{\Delta v}{\Delta t} \approx -\frac{1}{\rho_o} \frac{\Delta p}{\Delta y} \tag{3a}$$

$$\Delta p \approx g \rho \Delta z \tag{3b}$$

where $v$ is the velocity in the $y$-direction, $p$ is the pressure, $g$ is the acceleration of gravity, and $\rho$ and $\rho_o$ are the turbidity-modified and background water densities, respectively.

Substituting (3b) into (3a) and rearranging, we obtain

$$\Delta v \approx g \frac{\Delta \rho}{\rho_o} \frac{\Delta z}{\Delta y} T \tag{4}$$

where $\Delta v$ represents the change in velocity over time $T$ for a fluid layer with reduced gravity $g' = g \frac{\Delta \rho}{\rho_o}$ and bottom slope $S = \Delta z / \Delta y$. Assuming that the flow accelerated over a fortnight ($T = 15$ days), had a bulk density anomaly $\Delta \rho = 0.001 \text{ kgm}^{-3}$ above ambient (the minimal density difference detectable by CTDs between the turbidity current and the background density $\rho_o \approx 1027.744 \text{ kgm}^{-3}$), and that $S \approx 0.01$, corresponding to the average slope between Fisher Sill and the mooring site (insert, Figure 1), we obtain

$$\Delta v \geq 0.11 \text{ ms}^{-1}$$

which is consistent with our observations.

The above result can be compared with the laboratory results of Benjamin (1968) and Britter and Linden (1980) whereby the gravity current head advances downslope at speed
\[ V_f = (1.5 \pm 0.2) \left( g'Q \right)^{1/3} \approx \sqrt{2} (g'h)^{1/2} \] (5)

determined by the volume flux per unit width, \( Q = HU \), and front height, \( h \). Here, \( V_f \) is independent of slope angle within the range 5 to 90° and only becomes sensitive to slope when the current enters near horizontal bottom segments of the experimental tank (Simpson 1997). If we assume that the gravity current had a thickness \( H \sim 250 \) m (the approximate relief of the deeper portion of the trench and the thickness of the well defined bottom layer in Figure 2) and increase \( g' \) to only twice the minimal value needed to overcome the thermal buoyancy, we obtain

\[ V_f \geq 1.5 \left( 500 \times 10^{-6} \right)^{1/3} \sim 0.12 \text{ ms}^{-1} \]

which is again consistent with the event velocities observed within the trench despite the low seafloor slope angles of around 1° to the northwest of the Fisher Sill.

4.3 Time varying forcing

The nominal fortnightly and monthly variations in observed event velocity and temperature, together with their associated bi-monthly and four-monthly spectral peaks, imply that forcing of the turbidity flows is tied to long period variations in the dissipation of tidal mechanical energy, \( \tau_{tide} \cdot V_{tide} \), where \( V_{tide} \) is the magnitude of the tidal velocity and \( \tau_{tide} \sim \rho V_{tide}^2 \) is the bottom stress due to the tidal currents. The integrated effect of this mechanical energy dissipation can be expressed through the cube-root-mean-cubed (CRMC) tidal velocity

\[
\text{CRMC} = \left( V_{tide}^3 \right)^{1/3}
\] (7)
where brackets denote a time average (Griffin and LeBlond, 1990). Previous studies have used CRMC to account for long period tidal variations in estuarine exchange processes in coastal tidal channels (Griffin and LeBlond, 1990; Masson and Cummins, 2000; Masson, 2002; Thomson et al., 2007). In the present case, variations in CRMC are related to the occurrence and intensity of the residual flow events, such that the greater the turbulent kinetic energy dissipation (higher CRMC), the stronger and more prolonged the turbidity flow event. Assuming that the tidal currents are barotropic and aligned parallel to the adjacent continental margin, continuity requires that we adjust the tidal current velocity for shoaling depths to the south of the mooring site. Subsequently, we have amplified the observed tidal currents by a factor of 1.33, corresponding to the ratio of the mooring depth (4400 m) to the sill depth (3300 m). We further assume that the phasing of the tidal currents at the mooring site is representative of tidal phasing throughout the study region.

Figure 14 indicates that there is a sufficiently close relationship between CRMC maxima and the timing and intensity of the velocity-temperature events to support the proposition that tidal currents are an initiating mechanism for the gravity flows at the southern end of the trench. Although most CRMC maxima were linked to a northwestward acceleration in the residual bottom current and increased bottom temperatures, not all maxima yielded major flow events. We, therefore, speculate that turbidity currents were initiated only when the amplitude and/or duration of the tidal motions exceeded some threshold value or after the bottom waters in the trench were sufficiently well “preconditioned” (i.e., had reduced density) for gravity currents to penetrate to the trench floor. Although gravity currents could possibly have been initiated during all CRMC maxima, many of these flows may not
have had sufficient negative buoyancy to penetrate to the deeper portions of the trench and may therefore have separated from the seafloor at some intermediate depths during descent from the southeastern end of the trench (cf., Sparks et al., 1993). Only when the density of the bottom water become sufficiently low through diffusion and mixing processes from earlier events do the turbidity currents descend to the observatory site and beyond.

4.4 Rotational effects

As noted in the previous sections, advancing turbidity currents characterized by abrupt temperature “fronts” were recorded at both borehole sites nearly simultaneously. On the other hand, the rapid reversal of the flow and intrusion of cold sediment-free water from the northwest at the end of an event was recorded at the mooring and borehole Site 1253 typically about a day before Site 1255. Both characteristics can be attributed to Coriolis effects which are directed to the right of the direction of residual flow in the Northern Hemisphere. For the northwestward flowing turbidity current, the Rossby number

$$R_o = \frac{V}{f_c L} = \frac{0.1 \text{m/s}}{(3.9 \times 10^{-6} \text{s}^{-1} \times 10^4 \text{m})} \approx 2.6$$

is indicative of moderate rotational effects (here, $L = 10$ km is the scale width for the trench, $f_c = 2\Omega \sin(\text{latitude}) \approx 2.28 \times 10^{-5}$ s$^{-1}$ is the local Coriolis parameter, and $\Omega = 0.72921 \times 10^{-4}$ s$^{-1}$ is Earth’s rate of rotation). As a result, we expect gravity flows entering the trench were in quasi-geostrophic balance and significantly affected by rotational effects. For the slower reversed flows, $R_o \sim 1$, so that the flows were even more dominated by rotational effects. To illustrate the Coriolis effects on the two oppositely directed flows, it is
instructive to consider how the currents would have been confined to a radius of curvature, $r$, given by

$$r = \frac{1}{f_c} (g'H)^{1/2}$$

(9)

where $g' \approx 10^{-4}$ ms$^{-2}$ and $H$ the height of the intruding flow. Assuming a representative gravity current thickness $H \approx 250$ m and a smaller thickness of 100 m for the initial stages of the southeastward reversed flow, we obtain the e-folding scale

$$r \approx 7 \text{ km (northwestward turbidity current)},$$

$$\approx 4 \text{ km (southeastward reversed flow)}.$$

In the case of the turbidity current, the radius is comparable with the width of the trench, and therefore consistent with simultaneous temperature increases at both ODP sites. On the other hand, the start of the southeastward reversed flow would have been more confined to the southwestern side of the trench, resulting in a delayed response along the northeastern side of the trench.

4.5 Supercritical flow

The characteristics of the density-driven flows in the trench are expected to differ according to whether the internal Froude number

$$F_r = \frac{V}{\sqrt{g'H}}$$

(10)

was greater or less than unity. Based on laboratory studies (Cenedese et al., 2004), subcritical density currents ($F_r < 1$) display laminar flow behaviour, with a constant thickness behind the advancing head, while supercritical currents ($F_r > 1$) give rise to wavelike motions on the interface between the gravity current and the overlying water.
column. The small obstruction across the path of the gravity current 24 km southeast of the mooring site (Figure 1) may also have been responsible for generating oscillations on the flow. With a typical event velocity $V \sim 0.1 \text{ ms}^{-1}$ and a relatively high reduced gravity, $g' \sim 10^{-4} \text{ m s}^{-2}$ ($\Delta \rho/\rho_o \sim 0.01/1027$), the threshold for supercritical flow requires only that the thickness, $H$, of the turbidity current be less than 1000 m. This condition is likely met since this elevation exceeds both the height of the Fisher sill above the current meter mooring and the depth of the homogeneous layer in the trench. Because $V$ and $g' H$ can change in unison during the evolution of a density current, it is possible that flow events observed in the trench were supercritical throughout much of their existence. Turbulent mixing and wave-like structure associated with supercritical flow might account for the disruptive high-frequency disturbances and low-frequency oscillations commonly observed in the property records during major events (cf. the current velocity “noise” in the upper panel of Figure 8a starting around day 637).

4.6 Suspended particle fraction and size

To estimate the minimum sediment load needed to drive the turbidity currents, we let $\rho_o$, $\rho_1$, and $\rho_2$ be densities of the background fluid, the interstitial fluid in which the particles are suspended, and the suspended particles, respectively ($\rho_2 < \rho_1 < \rho_o$). Turbidity flow is driven by the difference in density between the bulk density of the suspension

$$\rho(\phi) = \rho_2 \phi + (1 - \phi) \rho_1$$

(11)
and the density of the ambient fluid, $\rho_o$, where the volume fraction, $\phi$, occupied by the particles is then

$$\phi = \frac{\rho(\phi) - \rho_i}{\rho_2 - \rho_1}$$

(0 < $\phi$ << 1). From CTD records, $\rho_o = 1027.744$ kgm$^{-3}$ is representative of the background water density in the trench.

Major intrusive flow events had temperature anomalies of $\sim 0.01$ °C, corresponding to a density decrease $\Delta \rho = -0.001$ kg m$^{-3}$, so that the interstitial fluid density $\rho_i \approx \rho_o + \Delta \rho = 1027.743$ kgm$^{-3}$. Measurements on cores collected at ODP Site 1040 (co-located with Site 1255) yielded surface-sediment grain densities, $\rho_2$, of 2600 (±50) kgm$^{-3}$ (Kimura et al. 1997). Using this, and assuming that the bulk density $\rho(\phi)$ of the turbidity current exceeded the ambient water density by a multiple of $|\Delta \rho| = 0.001$ kgm$^{-3}$ (the minimal density difference resolvable by the CTDs), we find that $\phi$ must be at least 0.0003%. An upper bound to $\phi$ can be found using a mean turbidity velocity $V \approx (g' h)^{1/2}$, which for $V \sim 0.1$ ms$^{-1}$ and $h > 100$ m, we obtain $|\Delta \rho/\rho|<0.01$, whereby $\phi \sim 0.006\%$ or less. Higher densities and particle volume fractions are possible, but based on the highly qualitative information provided by the acoustic backscatter data, no additional constraints are available. Given the small number required, it is likely that the flows are driven by low concentrations of suspended material relative to ones reported by Meiburg and Kneller (2009) of 0.1% to 7%.
Although more appropriate to the end of a turbidity flow event when the strong, particle-resuspending turbulent motions have greatly diminished, we can use Stokes terminal settling velocity, $V_s$, for weak laminar flows to derive an upper limit for the minimum particle radii,

$$r = \left[ \frac{9 \mu}{2g (\rho_2 - \rho)} \right]^{1/2}$$

suspended within the turbidity current; here, $\mu = \rho \nu = 1.787 \times 10^{-3} \text{ Pas}$ (at 0 C) is the dynamic viscosity in Pascal seconds ($1 \text{ Pa} = 1 \text{ Nm}^{-2}$) and $\rho_2 - \rho$ is the density contrast between the particles and the bulk fluid density. The terminal Stokes velocity is estimated from

$$V_s = H / T$$

where $H \leq 500 \text{ m}$ is the maximum likely thickness of the turbidity current and $T \leq 15 \text{ days}$ is the minimal time for all particles in the current to settle to the bottom once the turbulent motions of the event have diminished. For want of a better approach, we estimated $T$ from rough approximations of the time it took the backscatter intensity in Figure 3c to return to background levels following a major event. As indicated by Table 4, estimates of $r$ are typically in the range of 10 to 40 $\mu$m, which is consistent with the range of particle sizes for local silt- and diatom-bearing sediments (Kimura et al., 1997; Morris et al., 2003) and the minimum particle radii of $5\mu$m detectable by the Nortek ACM (Lohrmann, 2001)

4.7 Heat flux estimates

It is instructive to estimate the thermal contribution of the turbidity flows based on the time-integrated product of the northwestward residual current velocity and its associated
temperature anomalies. The strong bias in northwesterly flow results in a cumulative advective flux directed to the northwest of roughly $0.6 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$. This results in an average advected heat flux at the position of the current meter of roughly $0.4 \text{ W m}^{-2}$, which is large relative to the local geothermal flux ($\approx 0.1 \text{ Wm}^{-2}$ from lithosphere that is 20 Ma in age), but which integrates with time to a total heat flow of only $\sim 1 \text{ MW}$ even if turbidity-driven flows span the full cross-section of the confined trench relief ($\approx 2.5 \text{ km}^2$; cf. Figure 15). This represents a small heat input to the long section of the trench stretching to the northwest, and it is small even relative to the geothermal heat flow into Fisher Basin of roughly 100 MW. This means that we cannot use the heat budget for the region to rule out overspill from Fisher Basin, driven by geothermal heating and periodic tidal forcing in the basin, as a contributing factor to the observed episodic currents.

4.8 Possible impact of winds

The differences between the CRMC and event time series presented in Figure 14 again suggest that tidal current modulation may not be the only mechanism effecting long-term changes in the turbidity currents. Variations in CRMC alone cannot account for the intense and long-lived (50-day) event that occurred from mid January to late February 2007. We therefore compared the timing and intensity of the velocity records in the trench with wind-stress data obtained from Reanalysis and North American Reanalysis grid points closest to the study region. Greatest wind activity appears to be associated with the cross-shore component of the wind from late fall to early spring (Figure 5). However, with the exception of the major storm from mid January to the end of February 2007, there is no apparent correlation with regional winds. The coincidence of a major turbidity current with
the 2007 wind event may be a coincidence, or it may indicate that intense wind systems with a strong cross-shore component of wind stress may ultimately influence the strength and duration of turbidity currents at the southeastern end of the trench.

5. Summary and Conclusions

In this study, we have combined time series records from a moored acoustic current meter with seafloor temperature records from nearby ODP borehole sites 1253 and 1255 to examine the long-term benthic flow dynamics and water property variability at the southern end of the Middle America Trench. The November 2005 to April 2007 current meter data provide the first-ever long-term time series of bottom currents and high frequency (2 MHz) acoustic backscatter intensity for this region. The November 2002 to February 2009 borehole observatory records provide some of longest seafloor temperature records in the World Ocean. Findings reveal that flow variability 21 m above bottom was dominated by order 0.1 m/s, predominantly semidiurnal tidal currents superimposed on long-lived, 0.15 to 0.30 m/s gravity currents that intermittently transported anomalously warm (~0.01 °C) water to the northwest along the deepening axis of the trench. Strong downward velocities accompanied all but the first major flow event, indicating that the downslope turbidity currents were flowing at a slight downward angle of 0.3° relative to the seafloor. In the case of the first recorded flow event in late 2005, the gravity current was tilted upward relative to the horizontal, suggesting that the core of the turbidity current had begun to lift from the seafloor upslope of the mooring site. The interludes between events were dominated by equally long-lived, but considerably weaker southeastward along-trench residual currents that paralleled the seafloor. Although the timing and intensity of the twelve episodic current
events observed during the November 2005 to April 2007 mooring period were highly variable, the events had an underlying periodicity that mimicked (albeit, not perfectly) long period modulation of the semidiurnal tidal currents.

After being initiated by the tidal currents, the gravity currents began as weak downslope flows (Figure 15a) but then intensified as the tidal motions continued to resuspend sediment into the overlying water column (Figure 15b). The more intense and protracted the tidally induced turbulent resuspension, the greater the possible along-axis extent of the source region. Once speeds exceeded a critical speed of about 0.15 m s⁻¹, it is likely that the currents began to scour the seafloor. This further increases the bulk density of the flow and leads to erosive turbidity currents (cf., Simpson, 1997) which may be responsible for accelerating the currents to the maximum observed speeds of around 0.3 m s⁻¹. The more vigorous the initial tidal currents, the greater the initial suspended sediment concentrations and the greater the likelihood that resuspension augmented the evolution of the turbidity flow.

For extreme mixing events, for which temperature anomalies were as high as 0.012 °C, the source region must have extended to the ~3300 m depth of the Fisher Sill, but no shallower. This depth threshold marks the base of a comparatively rapid upward increase in temperature so that water originating much shallower than the sill depth would have produced much higher borehole temperature anomalies than observed. As tidal currents weakened, the sediment load and autosuspension would have diminished, and turbidity currents weakened. Eventually, there would have been insufficient sediment in the current...
to counter its thermal buoyancy. The loss of sediment, combined with the elevated
temperature of the turbidity current relative to the ambient water, may then have led to
decreased negative buoyancy and to detachment of the current from the seafloor (cf. Sparks
et al., 1993). This in turn would have caused a reversal in the along-axis baroclinic pressure
gradient such that colder, relatively sediment-free water lying northwest of the mooring site
would have pushed southeastward beneath the weakening gravity current (Figure 15c). We
believe that it was this southward intruding current (Figure 15d) that explains the abrupt
return of borehole temperatures to their pre-event values at the end of a flow event, as well
as the delayed temperature response at the more northeastern borehole Site 1255. The short-
lived return of higher temperatures that sometimes occurred at Site 1255 following the end
of an event were likely due to interaction of the weakening turbidity current and
strengthening counter-flow. However, other factors such as wave-like oscillations in the
gravity current and cross-axis variations in flow structure cannot be ruled out.

The close relationship between the episodic residual currents and the coincident
temperature records from the ODP borehole sites has enabled us to extrapolate our findings
on flow behavior to the entire 6.2-year borehole observation period. Based on the 33 major
temperature events observed during the temperature recording period, a new gravity current
event was triggered, on average, 30(±25) days after the end of the previous flow event and,
once initiated, persisted for a mean period of 40(±20) days. The time between peak flows
was 68(±29) days. These times are a factor of two greater than times obtained for the
shorter current meter observation period, a period dominated by anomalously weak
temperature and gravity current events. When examined in the frequency-time domain, the
“energy” of the tidally modulated, episodic flows was found to be highest at periods of around 30, 60 and 120 days, corresponding to multiples of the fundamental fortnightly period.

As illustrated by Figure 13, we consider increased sediment loading the principal mechanism offsetting the thermal buoyancy of the northwestward flowing gravity currents. For salinity to be a major driving force, there would need to be a shallow source of high salinity water accessible to the deep Fisher Basin located about 100 km “upstream” from the mooring site. There would then need to be a low-frequency exchange mechanism – such as the tidally modulated estuarine circulation exchange observed in silled coastal tidal channels or a wind-forced “sloshing” of the bottom water in the basin – that would allow this denser water to periodically spill across the sill and flow northwestward down the face of the sill. Although not impossible, this model also requires rapid (fortnightly to monthly) recharging of the basin water mass. We know of no source of high salinity water over the relatively shallow Cocos Ridge to the west of the basin. Moreover, tidally modulated estuarine-like exchange, similar to that observed within silled fjords, is not supported by observation. In particular, formation of the gravity currents typically occurred at times of maximum tidal mixing, as represented by estimates of the turbulent tidal velocity parameter CRMC for the mooring site. A delayed response, corresponding to the time it takes mixing effects to propagate from the sill to the mooring site (which for events originating near the sill could be as long as 12 days at typical flow speeds of 0.1 ms\(^{-1}\)) might account for some of the timing mismatch between CRMC and peak event velocity.
In summary, our findings lead us to conclude that the gravity currents observed at the southern end of the Middle America Trench were rotationally modified turbidity currents initiated by tidal current oscillations over the rapidly shoaling region to the southeast of the mooring site. Such motions may be common to the deep subduction zone trenches found adjacent to the continental margins of the World Ocean and may be especially ubiquitous to offshore regions, such as that off Costa Rica, which provide a supply of sediments from coastal rivers and unstable continental slopes. Sediment contributions from extreme winter storm winds and autosuspension – whereby the particles are kept in suspension by the turbulent motions of the advancing flow – may also contribute to the strength and longevity of the turbidity flow in the deep homogeneous waters of the trench. The abrupt flow reversals and temperature drops that mark the end of an event are possibly associated with reversed along-axis density gradients formed when suspended particles settle out of the weakening and increasingly buoyant turbidity flow. Buoyancy-induced uplift of “aging” turbidity currents near the end of an event may account for the anomalous behaviour of the first measured episodic flow event. Based on borehole sediment density profiles and simple flow dynamics, suspended particles in the turbidity current are estimated to occupy between 0.0003 and 0.003% of the volume of the current. Because the waters of the trench have nearly constant density, extremely low resuspended bottom sediment concentrations of only a few parts per million are required to initiate the formation of gravity currents at the shoaling region at the southeastern end of the trench.

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**Figure captions**

*Figure 1.* The Middle America Trench off the Pacific coast of Central America. (a) Topographic map showing the trench, Fisher Seamount (FS), Leg 2005 ODP region (see inset), and instrument locations. The star denotes location of the moored acoustic current meter (ACM) and the red diamond the location of ODP Borehole sites 1253 and 1255. Inverted triangles denote locations for the CTD profiles presented in Figure 2; (b) water depth along the axis (thelweg) of the trench and adjoining regions, beginning at the Cocos Ridge to the southeast (see inset). “Fisher Sill” is our designation for the sill adjacent to the seamount; “Fisher Basin” refers to the basin located to the southeast of the sill.

*Figure 2:* CTD profiles of potential temperature (black), salinity (blue), and potential density (red) collected in the southern Middle America Trench. (a) *Moana Wave* Station 6, 10 May 1989; (b) *Moana Wave* Station 7, 9 May 1989; *Sonne* Station 5, 28 April 2002; and (d) *Meteor* Station 54-1 on 14 August 2002. Station locations are shown in Figure 1 and their position is listed in each panel. Archived profile data can be found at the following website: [http://www.nodc.noaa.gov/OC5/WOD05/data05geo.html](http://www.nodc.noaa.gov/OC5/WOD05/data05geo.html).

*Figure 3a:* Time series of the cross-axis ($u$) and along-axis ($v$) components of velocity (red and black, respectively) from the Aquadopp acoustic current meter (ACM) moored 21 mab in the southern Middle America Trench from 14 November 2005 to 21 April 2007. The top panel shows the daily mean (30-hr low-pass filtered) time series for the entire record; bottom panel shows hourly data for a selected segment of the full record (see shaded area in
Figure 3b: Time series of the vertical component of velocity ($w$) from the Aquadopp acoustic current meter (ACM) moored 21 mab in the southern Middle America Trench from 14 November 2005 to 21 April 2007. The top panel shows the daily mean (30-hr low-pass filtered) time series for the entire record; bottom panel shows hourly data for a selected segment of the full record (see shaded area in top panel). The top panel also includes the 10-day low-pass filtered record. Note the change in vertical scale between panels. Time axis is shown as Julian Days since the start of 2005. Year and month are also displayed.

Figure 3c: Time series of the acoustic backscatter intensity (Beam 1) from the Aquadopp acoustic current meter (ACM) moored 21 mab in the southern Middle America Trench from 14 November 2005 to 21 April 2007. The top panel shows the daily mean (30-hr low-pass filtered) time series for the entire record; bottom panel shows hourly data for a selected segment of the full record (see shaded area in top panel). Time axis is shown as Julian Days since the start of 2005. Year and month are also displayed. Arrows denote start and end of episodic events.

Figure 3d: Time series of pressure from the Aquadopp acoustic current meter (ACM) moored 21 mab in the southern Middle America Trench from 14 November 2005 to 21 April 2007. The top panel shows the daily mean (30-hr low-pass filtered) time series for the entire record; bottom panel shows hourly data for a selected segment of the full record (see...
shaded area in top panel). Note the change in vertical axis between panels. Time axis is shown as Julian Days since the start of 2005. Year and month are also displayed. Arrows denote start and end of episodic events.

**Figures 4.** High resolution (0.001 °C) hourly seafloor temperature records from ODP borehole observatory sites 1253 and 1255 for the current meter observation period 14 November 2005 to 21 April 2007. (a) Full daily mean records; and (b) expanded segments of hourly data for the event centered at Julian Day 570. Red lines denote data for Site 1253; blue denotes Site 1255. Note changes in vertical scales. The 1255 temperature record has been calibrated using the temperature record from site 1253. The time axis is in Julian Days since the start of 2005. Year and month are also displayed. Arrows denote start and end of episodic events.

**Figure 5.** Low-pass (10-day) filtered along-axis current velocity (v; black) at the mooring site versus the cross-shore component of wind stress (τ; red) for a nearby NCEP/NCAR reanalysis site. The major protracted flow event in early 2007 coincided with a strong offshore wind event along the coast of Central America. The time axis is shown as Julian Days since the start of 2005. Year and month are also displayed.

**Figure 6.** Clockwise (CW) and counterclockwise (CCW) rotary current velocity spectra for the Middle America Trench mooring. Currents are rectilinear when CW and CCW spectra are equal; polarized CW near-inertial motions are observed near a period of 2.5 days.
Spectra have 10 degrees of freedom (DOF) and are based on 50% overlapping record segments of $N = 4096$ hours in a total record of $NT = 12,564$ hours.

**Figure 7.** Spectrum of hourly time series for (a) the borehole temperature record at Site 1253 for the full borehole observation period November 2002 to February 2009; and (b) the acoustic backscatter intensity for beam 1 for the ACM observation period November 2005 to April 2007. Spectrum of the temperature record for Site 1255 are nearly identical to those in (a). Temperature spectra for the shorter current observation period closely resemble those in (a) but lack the resolution at low frequencies.

**Figure 8a.** Hourly time series of along-trench current velocity ($v$), acoustic backscatter intensity (BS), and borehole temperature for Site 1253 spanning the moderate event starting on Julian Day 626. The time axis is shown as Julian Days since the start of 2005. Year and month are also displayed. Arrows denote approximate start time of the episodic events.

**Figure 8b.** Hourly time series of along-trench current velocity ($v$), acoustic backscatter intensity (BS), and borehole temperature for Site 1253 spanning the relatively strong, protracted event starting around Julian Day 742. The time axis is shown as Julian Days since the start of 2005. Year and month are also displayed. Arrows denote approximate start time of the episodic events.

**Figure 9.** Low-pass filtered 10-day time series of along-axis velocity ($v$; black) and vertical velocity ($w$; red) for the current meter mooring period 14 November 2005 to 21 April 2007.
The vertical velocity scale is inverted so that it matches that of the horizontal velocity. The record mean vertical velocity was subtracted from the time series prior to filtering. The time axis is in Julian Days since the start of 2005. Year and month are also displayed.

*Figure 10.* Hourly time series of seafloor temperature records from Borehole Sites (a) 1253 and (b) 1255 for the full ODP borehole observation period 21 November 2002 to 15 February 2009. The temperature record for site 1255 has been corrected by +0.377 °C using the “absolute” temperature record from site 1253. Time axis is in Julian Days since the start of 2002.

*Figure 11.* Frequency-time (f-t) diagram for the along-trench (v) component of velocity for the current meter mooring period 14 November 2005 to 21 April 2007. Red (blue) denotes times and frequencies with high (low) flow variability. Time is in days since the start of the record on 14 November 2005. Frequency is in cycles per hour (cph).

*Figure 12.* Frequency-time (f-t) diagram for seafloor temperature for borehole site 1253 for the full 6.2 year borehole observation period 21 November 2002 to 15 February 2009. Red (blue) denotes times and frequencies with high (low) temperature variability. Time is in years and frequency in cycles per hour (cph).

*Figure 13.* Cartoon showing the tidally-initiated generation of turbidity currents in the southern Middle America Trench.
**Figure 14.** Along-axis current velocity ($v$; red) versus the CRMC parameter (black) for selected time averaging periods (a) 7 days; and (b) 20 days. Time axis is shown as Julian Days since the start of 2005 and as year and month.

**Figure 15.** Conceptual model of the cross-trench structure of along-trench turbidity currents for the four main stages of flow development: (a) start of a northwestward flow event; (b) peak downslope flow; (c) loss of buoyancy in the turbidity current and beginning of southeastward intrusion of the reversed flow on the western side of the trench; and (d) fully developed reversed flow to the southeast. The tilt due to Coriolis forcing has been exaggerated for plotting purposes.
List of Tables

Table 1. Locations and times of the Aquadopp ACM and ODP borehole temperature measurements. Also listed are locations for two nearby historical CTD profiles. The ACM recorded temperature, acoustic backscatter intensity, pressure, and three-dimensional velocity at intervals ($\Delta t$) of 15 min; the borehole sensors measured seafloor temperature at 60-min intervals. The ACM and ODP records have durations of 523.5 and 2277.9 days, respectively. Elevations are in meters above bottom (mab).

<table>
<thead>
<tr>
<th>Item</th>
<th>Location</th>
<th>Depth (m)</th>
<th>Start UTC</th>
<th>End UTC</th>
<th>$\Delta t$ (min)</th>
<th>Elevation (mab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACM</td>
<td>9º 39.04’ N</td>
<td>4365</td>
<td>0026</td>
<td>1230</td>
<td>15</td>
<td>21</td>
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<td></td>
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<td>ODP 1253</td>
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<td>1900</td>
<td>1800</td>
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<td>15 Feb 09</td>
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<tr>
<td>ODP 1255</td>
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<td>4311</td>
<td>2000</td>
<td>1700</td>
<td>60</td>
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<td>15 Feb 09</td>
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<tr>
<td>CTD</td>
<td>9º 37.2’ N</td>
<td>3924</td>
<td>10 May 89</td>
<td>10 May 89</td>
<td>NA</td>
<td>full water column</td>
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<tr>
<td></td>
<td>86º 15.7’ W</td>
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<tr>
<td>CTD</td>
<td>9º 48.8’ N</td>
<td>4193</td>
<td>28 April 02</td>
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<td>NA</td>
<td>full water column</td>
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<td>86º 16.3’ W</td>
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</tbody>
</table>
Table 2. Statistical properties of the 15-min ACM and 60-min ODP borehole time series.

Velocity components $u, v, w$ are in the northeastward, northwestward, and upward directions, respectively. BS denotes the acoustic backscatter intensity (for which a change of 1 “count” corresponds to a change of ~ 0.45 db), $P$ is the pressure, and $T_{ACM}$ the in situ temperature from the ACM; $T_{1253}$ and $T_{1255}$ are seafloor temperatures at borehole sites 1253 and 1255. The corrected borehole record $T_{1255}^* = T_{1255} + 0.377 \, ^\circ\text{C}$ (see text).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Mean</th>
<th>Median</th>
<th>Max</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>0</td>
<td>0.0645</td>
<td>0.0510</td>
<td>0.2740</td>
<td>0.04818</td>
</tr>
<tr>
<td>$u$ (m/s)</td>
<td>-0.0622</td>
<td>0.0031</td>
<td>0.0028</td>
<td>0.0658</td>
<td>0.01378</td>
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<tr>
<td>$v$ (m/s)</td>
<td>-0.2135</td>
<td>0.0186</td>
<td>0.0035</td>
<td>0.2892</td>
<td>0.08165</td>
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<tr>
<td>$w$ (m/s)</td>
<td>-0.0500</td>
<td>-0.0025</td>
<td>-0.0020</td>
<td>0.0420</td>
<td>0.0107</td>
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<tr>
<td>BS (counts)</td>
<td>37</td>
<td>44.69</td>
<td>44</td>
<td>62</td>
<td>2.87</td>
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<tr>
<td>$P$ (m)</td>
<td>4370.76</td>
<td>4372.38</td>
<td>4372.37</td>
<td>4374.52</td>
<td>0.68</td>
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<tr>
<td>$T_{ACM}$ (°C)</td>
<td>2.0300</td>
<td>2.0350</td>
<td>2.0300</td>
<td>2.0500</td>
<td>0.0050</td>
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<tr>
<td>$T_{1253}$ (°C)</td>
<td>1.9904</td>
<td>1.9936</td>
<td>1.9932</td>
<td>2.0009</td>
<td>0.0019</td>
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<tr>
<td>$T_{1255}$ (°C)</td>
<td>1.6032</td>
<td>1.6069</td>
<td>1.6064</td>
<td>1.6150</td>
<td>0.0021</td>
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<tr>
<td>$T_{1255}^*$ (°C)</td>
<td>1.9802</td>
<td>1.9839</td>
<td>1.9834</td>
<td>1.9920</td>
<td>0.0021</td>
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</tbody>
</table>
Table 3. Harmonic constituents (amplitude, phase) for the major tidal bands based on hourly time series records. The last row gives the percentage of the signal variance in each band explained by the full suite of derivable tidal constituents. Because the tidal current ellipses for all major constituents closely parallel the axis of the trench, the tidal ellipse orientations are not included in the table.

<table>
<thead>
<tr>
<th>Variable</th>
<th>T1253 (°C, °)</th>
<th>T1255 (°C, °)</th>
<th>P (m, °)</th>
<th>U (cm/s, °)</th>
<th>BS (count, °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA solar annual</td>
<td>0.0003, 46.0</td>
<td>0.0002, 14.2</td>
<td>0.0826, 45.2</td>
<td>0.014, 304.7</td>
<td>1.447, 331.6</td>
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<tr>
<td>SSA solar semi-annual</td>
<td>0.0011, 276.9</td>
<td>0.0012, 276.0</td>
<td>0.0575, 355.1</td>
<td>0.038, 134.8</td>
<td>0.458, 311.4</td>
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<tr>
<td>MSM monthly</td>
<td>0.0003, 76.4</td>
<td>0.0003, 68.0</td>
<td>0.0106, 297.8</td>
<td>0.014, 272.2</td>
<td>0.196, 50.6</td>
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<tr>
<td>MF fortnightly</td>
<td>0.0002, 227.5</td>
<td>0.0002, 217.4</td>
<td>0.0219, 24.2</td>
<td>0.005, 350.5</td>
<td>0.220, 250.4</td>
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<tr>
<td>K1 diurnal</td>
<td>0.0001, 25.6</td>
<td>0.0001, 51.5</td>
<td>0.0970, 79.4</td>
<td>0.007, 111.2</td>
<td>0.014, 93.8</td>
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<tr>
<td>M2 semidiurnal</td>
<td>0.0001, 247.8</td>
<td>0.0001, 244.3</td>
<td>0.9012, 242.7</td>
<td>0.027, 348.1</td>
<td>0.093, 86.9</td>
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<td>% tidal</td>
<td>18.6</td>
<td>18.2</td>
<td>94.7</td>
<td>20.4</td>
<td>14.0</td>
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</table>
Table 4: Estimated suspended particle radius, $r$, for water density $\rho = 1027.743$ kgm$^{-3}$, dynamic viscosity $\mu = 1.787 \times 10^{-3}$ Pas (at 0 °C), and Stokes settling velocity $V_{stokes} = H/T$, where $T$ is the time for all suspended particles to settle to the bottom from an elevation $H$.

<table>
<thead>
<tr>
<th>Particle density $\rho_2$ (kgm$^{-3}$)</th>
<th>Layer thickness, $H$ (m)</th>
<th>Radius $r$ (microns) for different sediment settling times, $T$</th>
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</thead>
<tbody>
<tr>
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<tr>
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<td>19</td>
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<td>1850</td>
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<td>1850</td>
<td>200</td>
<td>21</td>
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<tr>
<td>1850</td>
<td>500</td>
<td>33</td>
</tr>
</tbody>
</table>
10-day mean time series $v,w$ (inverted)

Along-axis velocity (m/s)

Vertical velocity (m/s)

2005

2006

2007

Julian Day (2005)
(a) CRMC

Daily mean v-component of velocity (m/s)

1 Jan 1 July 1 Jan

(b) CRMC Tidal Velocity (m/s)

Daily mean v-component of velocity (m/s)

2006

1 Jan 1 July 2007

Julian Day (2005)