El Niño–Southern Oscillation signal associated with middle Holocene climate change in intercorrelated terrestrial and marine sediment cores, North Island, New Zealand

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ABSTRACT

A synchronous textural variation in intercorrelated, high-resolution sediment records from floodplain, continental-shelf, and continental-slope settings of the eastern North Island, New Zealand, provides evidence of increased storminess after ca. 4 ka. An upcore change in sediment texture reflects the transition to landsliding, which supplanted fluvial incision as the dominant mode of sediment production in the middle Holocene. This signal, which appears in all three records, indicates a regional response to external forcing and records the impact of an intensified atmospheric circulation marking the establishment of the contemporary climate that is strongly influenced by the El Niño–Southern Oscillation. The change in climate was a hemispheric event, and in the Southern Hemisphere its timing is confirmed by independent proxy records from elsewhere in New Zealand and the circum–South Pacific region.

Keywords: climate change, El Niño–Southern Oscillation, landsliding, New Zealand.

INTRODUCTION

Paleoenvironmental evidence suggests that the El Niño–Southern Oscillation (ENSO) was more subdued in the early to middle Holocene than it is today (Sandweiss et al., 1996; Rodbell et al., 1999; Clement et al., 2000; Tudhope et al., 2001). However, high-resolution proxy records that are of sufficient length to elucidate the development and date of the onset of modern ENSO variability are rare (Rodbell et al., 1999; Tudhope et al., 2001), and few well-dated records have been obtained from maritime regions beyond the tropical Pacific (Hellstrom et al., 1998). Located astride the boundary between the warm southwest Pacific and cold Southern Oceans, in a midlatitude region that is significant for ENSO teleconnections, New Zealand is well placed to record effects of large-scale climate change in the mostly maritime Southern Hemisphere (McGlone et al., 1993; Turney et al., 2003). In this paper we use evidence provided by changes in sediment particle size recorded in three intercorrelated cores from floodplain, continental-shelf, and continental-slope settings on the East Coast Continental Margin, North Island, New Zealand, to constrain the onset of modern ENSO variability. These high-resolution records are important, not only because of the good correlation between the terrestrial and marine environments, which helps obviate local environmental bias, but also because the observed signal of climate change is corroborated by proxy data from elsewhere in the circum–South Pacific region (Martin et al., 1993; Shulmeister and Lees, 1995; Domack et al., 2001; Rowe et al., 2002).

STUDY AREA

The East Coast Continental Margin is within the actively deforming Hikurangi Margin of the obliquely collisional Australian-Pacific plate boundary (Lewis and Pettinga, 1993). Specific suspended-sediment yields of the major rivers draining the region rank among the world's highest (Hicks et al., 2000). These elevated yields reflect high rates of tectonic uplift along the convergent plate boundary, erodible lithologies, eradication of the indigenous forest cover by European settlers, and a temperate but vigorous maritime climate, which is periodically disturbed by intense cyclonic storms of subtropical origin. Accordingly, the marine environment is dominated by high terrigenous inputs, and the thick sedimentary sequences preserved on the East Coast Continental Margin record the effects of perturbations to terrestrial conditions that occurred at various time scales (Foster and Carter, 1997; Wilmshurst et al., 1999; Carter et al., 2002).

CORE SITES

Three high-resolution records were obtained from a major terrestrial and two marine depocenters on the East Coast Continental Margin (Fig. 1A). Drill-core W4 was obtained from the Poverty Bay Flats floodplain, which was infilled by fine-grained alluvium deposited by the Waipaoa River after the last postglacial transgression (Brown, 1995). The W4 drill site at Waerengaahika (38°36.88′S, 177°55.97′E) is 9 km from the coast, midway between the maximum extent of the Holocene marine transgression of 7.1–6.8 ka and the 5 ka paleoshoreline. This location is now protected by artificial levees and was last flooded in 1948. Giant piston core MD972122 penetrated the actively subsiding middle shelf, where >35 m of terrigenous mud (biogenic $CaCO_3 < 5\%$), derived mainly from the Waipaoa River, has accumulated since the last postglacial transgression (Foster and Carter, 1997). Much of the terrigenous influx is confined on the shelf by the growing Lachlan and Ariel anticlines. The core site (38°48.67′S, 178°10.18′E) is between the two anticlines, at 55 m water depth. Giant piston core MD972121 penetrated a slope basin off southern Hawke Bay (40°22.93′S, 177°59.68′E) at 2314 m water depth. Sediment dispersal on the adjacent shelf is influenced by the northeastward-flowing Wairarapa Coastal Current (Fig. 1A), but sediment from northern sources, such as the Waipaoa River, is introduced to the slope by the southwest-flowing East Cape Current (Carter et al., 2002).

ANALYTICAL METHODS AND CORE PROPERTIES

Sediment particle size in cores W4 and MD972122 was determined at 0.03 m intervals by using a CILAS 1064 laser granulometer, following dispersion by $(NaPO_3)_6$ and ultrasound. Samples obtained at either 0.02 or 0.1 m intervals from MD972121 were analyzed by using a Sedigraph 5100. The error of mean values is ± 0.6 μm for the granulometer and ± 0.5 μm for the Sedigraph. To help discriminate between erosion processes, we measured a variety of environmental magnetic parameters for core MD972122 by using a computer-controlled superconducting rock

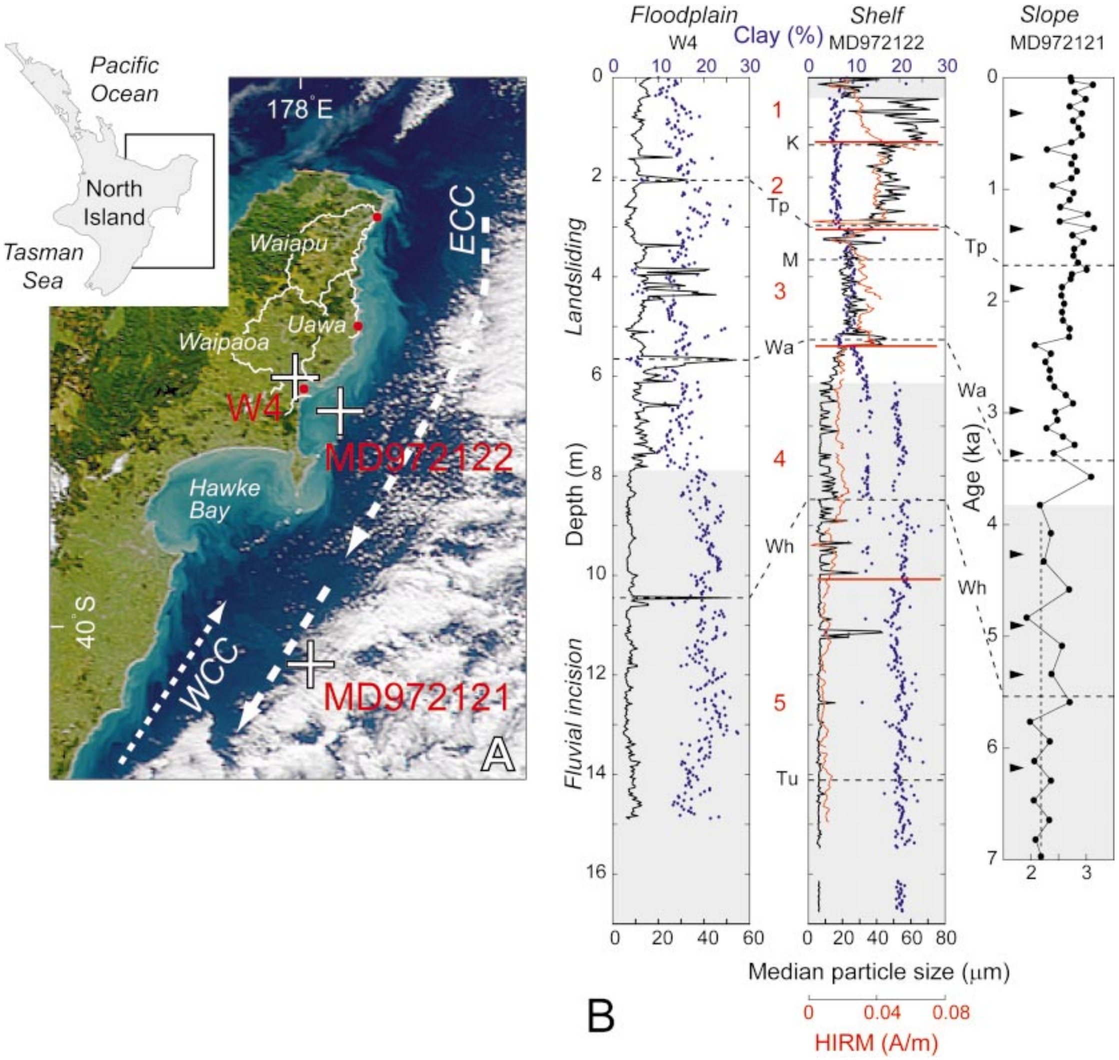

Figure 1. A: Sea-viewing wide field-of-view sensor (SeaWiFS) image of East Coast Continental Margin, New Zealand (4 June 2000), showing core sites (W4, MD972122, and MD972121), major drainage basins, and primary elements of surface circulation (ECC—East Cape Current; WCC—Wairarapa Coastal Current). Turbidity of coastal waters results from series of small floods between 31 May and 6 June, when Waipaoa, Waiapu, and Uawa Rivers (mouths marked by red dots) collectively discharged ~1.2 Mt of suspended sediment. B: Intercorrelation and downcore variations in sediment texture in cores W4 (floodplain), MD972122 (shelf), MD972121 (slope), and hard isothermal remanent magnetization (HIRM) in core MD972122 (solid horizontal red lines and lettering delimit magnetozones 1–5). Shading denotes periods when fluvial incision was dominant erosion process. Solid blue dots indicate clay percentage in W4 and MD972122 (periodic influxes of coarse sediment, released by landsliding, with reduced clay content create double line of dots in magnetozone 4). Dashed vertical line indicates mean for all early Holocene samples (*N* = 25) from MD972121 analyzed by Carter et al. (2002), and arrowheads mark timing of major seismic events on East Coast Continental Margin. Dashed horizontal lines indicate locations of tephra: K—Kaharoa, 0.665 ka; Tp—Taupo, 1.718 ka; M—Mapara, 2.12 ka; Wa—Waimihia, 3.47 ka; Wh—Whakatane, 5.58 ka; Tu—Tuhua, 6.97 ka. Ages are given in calendar years; ages at intermediate depths are estimated by linear interpolation.

magnetometer. A saturation isothermal remanent magnetization (SIRM) was imparted twice (in a 900 mT field) to U-channel samples from each 1.5-m-long section of core by using an impulse magnetizer. After measurement of SIRM, each section was then reversed, a 300 mT field applied twice, and the magnetization measured at 0.01 m intervals. End measurements (0.04 m) were ignored, because they were affected by the length of the sensor-response function (Weeks et al., 1993). Here we use the hard isothermal remanent magnetization (HIRM), which is a measure of the concentration of weakly magnetic, high-coercivity minerals, such as hematite and/or goethite, that are characteristic of oxic weathering environments (King and Channell, 1991). The HIRM signature is a sensitive indicator of soil loss, because high-coercivity minerals are not abundant in the local bedrock. Throughout MD972122 the sediments are brown, suggesting that oxic conditions were maintained during deposition and that early-diagenetic iron and sulfate reduction have not altered the magnetic mineral assemblage. Intensities of magnetization used to calculate HIRM are six orders of magnitude above the noise level of the magnetometer and are reproducible to within ±1%.

The MD972122 stratigraphy is constrained by six tephra (Fig. 1B), correlated with dated terrestrial counterparts on the basis of mineralogy and glass chemistry. As determined from the ^{210}Pb activity profile, the top 0.5 m of MD972122 postdates A.D. 1890. Three tephra occur in W4 and MD972121 (Fig. 1B), and the latter core also has a detailed stable oxygen isotope and radiocarbon stratigraphy (Carter et al., 2002). The textural differences between the three environments are substantially greater than the analytical errors; the sediment in all three cores coarsens upward with frequent particle-size fluctuations, and in MD972122, the corresponding HIRM variations delimit 5 magnetozones (Fig. 1B).

LINKING EROSION AND CLIMATE

The effect of major paleoseismic events on the East Coast Continental Margin is subsumed within the record of storm-generated landslide activity, and individual events cannot be recognized in the terrigenous flux record for the lower continental slope (Fig. 1B; Carter et al., 2002). Therefore, we link the observed variations in sediment texture and in HIRM to a change in the dominant erosional process and perturbations of the vegetation cover affecting slope stability in source areas. These changes are translated to depositional sinks and recorded in the sediment cores. The fundamental geomorphic processes involved are fluvial incision (including gully erosion) into bedrock and landsliding (Hicks et al., 2000). On the continental shelf, for example, we expect the transition from an incisive to a diffusive erosion regime to be signaled by the influx of coarser, more texturally variable sediment containing increased concentrations of high-coercivity minerals. Farther from land, spikes associated with the influx of sediment generated by landsliding are attenuated, and in the deep ocean the transition is manifested as a general coarsening of the fine hemipelagic load.

Hillslope evolution is tied to incision through regrading by landsliding or other mass failures, and plucking and abrasion are the primary erosion processes involved in river incision of jointed rock. The debris assemblage produced by the abrasive wear of blocks released by plucking, and of bedrock, is predominantly fine grained. Fine-grained sediment is also supplied by the deep-seated earthflows that were responsible for most hillslope adjustment in some headwater tributaries (Gage and Black, 1971). By contrast, the soil mantle contains little clay because the parent materials have not been extensively weathered (Preston and Crozier, 1999). Thus, landsliding releases a heterogeneous mass of relatively coarse grained soil and regolith to river channels and increases the rate of influx to sediment reservoirs, including the increased concentrations of high-coercivity minerals that are responsible for the HIRM signature (cf. Turner, 1997; Gomez et al., 1999). Today, significant landsliding occurs on 18° or steeper hillslopes during storms with rainfall of 150–200 mm in 72 h (Reid and Page, 2002). The effect of large storms influences the suspended-sediment record for ~3 yr (Hicks et al., 2000). However, gully erosion generates prodigious quantities of mud and fine sand and is the dominant mode of sediment production (Gage and Black, 1971; Hicks et al., 2000).

The rate of downcutting in the Waipaoa River basin varied throughout the Holocene, but the major phase ended by ca. 5.58 ka (Brown, 1995; Berryman et al., 2000). Initially, the amount of sediment contributed by incision, and augmented by earthflow activity, apparently exceeded that produced by landsliding. In the lower part of MD972122 (magnetozones 4 and 5), the influence of landsliding is manifested as occasional influxes (spikes) of coarse sediment, with a reduced clay content, superimposed on the fine-grained signature of incision and earthflow activity (Fig. 1B). However, the process of regrading oversteepened hillslopes by landsliding gradually became more important (magnetozone 4) and eventually dominated (magnetozone 3) under the indigenous forest cover (cf. Crozier et al., 1992; Eden and Page, 1998). The result was that the sediment supply coarsened. Volcanic eruptions and wildfires that disturbed the vegetation cover (Wilmshurst et al., 1999), and lowered the threshold for hillslope erosion by landsliding and scour by surface runoff, amplified the coarsening trend (magnetozones 3 and 2). Localized clearances initiated by Polynesian settlers from ca. 700 B.P. onward and the regional deforestation implemented by their European counterparts also contributed to sediment coarsening. Deforestation triggered the modern phase of gully erosion (magnetozone 1). The landscape remained prone to landsliding, but for the past ~70 yr sediment produced by gully erosion has dominated the MD972122 core because the amount of sediment produced during high-frequency, low-magnitude rainstorms far outweighs contributions from low-frequency, high-magnitude (landslide inducing) events (Hicks et al., 2000). The pronounced reductions in median particle size from 59.5 ± 11.8 μm to 23.2 ± 8.7 μm and in HIRM (in magnetozone 1) near the top of MD972122 (Fig. 1B) represent the response to European deforestation of the basin headwaters and the associated switch in process dominance, from landsliding to gully erosion (Gage and Black, 1971). This response is the reverse of what occurred ca. 4 ka. Prior to ca. 4 ka, fluvial incision generated predominantly fine-grained, low-coercivity sediment. The subsequent shift to a landslide-dominated erosional regime generated a supply of coarser, high-coercivity sediment that dominated the sedimentary package.

Textural shifts in the shelf sediment after ca. 4 ka are replicated on the floodplain and in the deep ocean (Fig. 1B). Rather than an internal (local) mechanism, the spatial extent of the shifts indicates a regional response to external forcing. At that time there was also a marked decline in the rate of terrigenous mass accumulation on the continental shelf (from 4.8 to 2.1 $g \cdot cm^{-2} \cdot yr^{-1}$) and slope. In MD972121, the reduction in the terrigenous flux is associated with more effective sediment retention on the continental shelf following a climate-forced change in shelf circulation (Carter et al., 2002). Accordingly, we associate the upcore coarsening and more frequent shifts in particle size in cores W4 and MD972122 with a middle Holocene climate change and the transition to a landslide-dominated sediment supply.

The East Coast Continental Margin is in the lee of the prevailing westerly weather systems; therefore, high-intensity storms of subtropical or Southern Ocean origin are important components of the local climate (Gordon, 1986; Salinger and Mullan, 1999). Rainfall is higher than average during La Niña years, when warm air masses from the north and east reach New Zealand more frequently (McGlone et al., 1992). ENSO is also associated with increased storminess (Sinclair, 2002) and large-magnitude rainstorms that generate landsliding (Eden and Page, 1998). During an ENSO cycle, landsliding may be amplified by drought- and fire-affected degradation of the vegetation cover in El Niño years (cf. Wilmshurst et al., 1999). Although total precipitation may have been higher (Gordon, 1986), rainstorms of sufficient magnitude to generate landslides probably were not a persistent feature of the ameliorating early Holocene climate, when seasonality effects were damped, and the ENSO was weaker (Rodbell et al., 1999; Clement et al., 2000; Tudhope et al., 2001). Once the atmospheric circulation pattern in the Southern Hemisphere intensified in the middle Holocene and the modern Walker Circulation with embedded ENSO became established, the frequency of storms large enough to induce landsliding increased. In New Zealand, confirmation that a fundamental change in climate occurred ca. 4 ka is provided by a positive excursion in the $\delta^{18}O$ speleothem record from caves in the northwest South Island (Hellstrom et al., 1998) and by variations in peat-bog surface wetness in the southeast South Island (McGlone and Wilmshurst, 1999). Elsewhere in the circum–South Pacific region, rising lake levels in the Andes (Martin et al., 1993; Rowe et al., 2002), a change in effective-precipitation status in northern Australia (Shulmeister and Lees, 1995), and an increase in Antarctic ice-rafted debris in Palmer Deep sediments (Domack et al., 2001) have also been attributed to a climate shift ca. 4 ka.

CONCLUSIONS

The middle Holocene change in climate, inferred from intercorrelated terrestrial and marine sediment cores from the New Zealand East Coast Continental Margin, is associated with an intensification of the atmospheric circulation marking the establishment of the contemporary ENSO-dominated climatic regime. This change was a hemispheric event, and in the Southern Hemisphere its timing is confirmed by independent proxy records from elsewhere in the circum–South Pacific region. Teleconnections across the Pacific region are features of the ENSO, and may be linked to climate variations in Antarctica (Vincent, 1994). The interaction should be manifested from ca. 4 ka, when paleoenvironmental evidence from low and mid-latitudes suggests an intensification of the Circumpolar Westerly Vortex, Walker Circulation, and ENSO (Shulmeister and Lees, 1995; Hellstrom et al., 1998). In high latitudes, greater ice-rafted debris production is consistent with increased storminess in the middle Holocene and is linked to a large-scale atmospheric change, such as variation in the intensity of westerly winds (Smith et al., 1999; Domack et al., 2001). Moreover, widespread and synchronous middle Holocene climate change throughout the Southern Hemisphere supports the hypothesis that the present atmospheric circulation pattern is the outcome of orbitally driven changes in the tropical Pacific Ocean (Shulmeister, 1999; Clement et al., 2000).

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