Foreword

The amplitude of future global warming induced by human activity (Figure 1.1) remains largely uncertain, in part because of large uncertainties that concern the natural climatic modes of variability. From this point of view, the last glacial period that was marked by harsh, rapid and high-amplitude climatic variability (i.e. the Heinrich-Dansgaard/Oeschger events, H-DO variability, Figure 1.2) offers the opportunity to decipher how the climate dynamics evolved at the centennial timescale or less.

It is generally accepted that the H-DO variability is highly sensitive to the North Atlantic thermohaline circulation (Ganopolski and Rahmstorf, 2001, Figure 1.2), and may further remotely control the monsoon dynamics (Figure 1.2) as well as the intermediate water mass circulation (i.e. see Behl and Kennett, 1996 for the Northeast Pacific). The global impact of the H-DO variability implies the existence of climatic teleconnections (Vidal and Arz, 2004) that further requires a mapping effort of rapid climatic changes during the last glacial period.

In this PhD I have reconstructed the surface and intermediate-depth hydrological variability during the Marine Isotope Stage 3 (MIS3) at a centennial resolution. The two sediment cores that I have studied (MD02-2529, Eastern Equatorial Pacific EEP, 1600m water depth and MD02-2508, Northeastern tropical Pacific, 600m water depth) will help to:

- Better constrain the role of the tropics on rapid climatic changes
- Decipher the how the climatic connections between the North Atlantic area and the EEP are set up
- Study how the Pacific oceanic circulation at intermediate depth responded to rapid climate changes

The first part of this PhD will introduce the modern climatology, the methodology and the state of the art of rapid climatic changes over the last glacial period.

The second part is focused on the surface hydrological variability of the EEP region, using planktonic foraminifera oxygen isotopes and Mg/Ca ratios.

The third chapter will present benthic foraminifera stable isotopes measurements off and within the present-day Oxygen Minimum Zone (OMZ) area.

CHAPTER 1 – INTRODUCTION

1. Present-day climatology and oceanography

1.1. Dynamics of the atmosphere

1.1.1. General atmospheric circulation

The general atmospheric circulation is composed of 3 main convective cells (Figure 1.3). At low latitudes, the insolation maxima provoke deep atmospheric convection resulting in large amounts of rainfall at the Intertropical Convergence Zone (ITCZ). Seasonnal migrations of the solar zenith between both tropics induce northward and southward migrations of the ITCZ during the boreal summer and winter, respectively (Figure 1.4).

1.1.2. The tropics and monsoonal activity

The deep atmospheric convection occurs mainly above the Western Equatorial Pacific region (WEP), the Tropical Africa and the Central and South America (Figure 1.5). In the tropical Pacific, the wind divergence at the top of the troposphere in the Western Pacific, the eastward direction and the wind convergence in the southeastern Pacific describe the upper part of the Walker circulation (Figure 1.5).

1.2. Surface oceanic circulation and ocean/atmosphere interactions

1.2.1. Surface oceanic circulation

The surface waters generally circulate around the subtropical gyres (Figure 1.6). At middle latitudes, the western boundary currents redistribute heat toward high latitudes while the eastern sides of oceanic basins are marked by coastal upwelling and intense primary productivity.

At low latitudes, the trade winds induce the westward flow of the North Equatorial and South Equatorial Currents (NEC and SEC), between which countercurrents circulate estward (Figure 1.6).

1.2.2. The ENSO variability

Under normal conditions, the trade winds act to accumulate warm waters in the WEP and induce the thermocline shallowing on the eastern side of the tropical Pacific (Figure 1.7), leading to wet and dry conditions on the western and southeastern sides of the tropical Pacific, respectively (Figure 1.5, 1.7).

With a periodicity ranging from 3 to 7 years the trade winds weaken and induce the eastward advection of warm waters initially located in the WEP, together with the eastward advection of the WEP atmospheric convection site and the thermocline flattening (Figure 1.7).

1.3. Thermohaline circulation and heat transfer

The thermohaline circulation is a key parameter that controls the global heat budget at the surface of the Earth (Figure 1.8). The intense evaporation in the Caribbean Sea and its removal from the Atlantic ocean by the atmospheric circulation at low latitudes increase the Sea Surface Salinity (SSS) of surface waters that feed the Gulf Stream, and ultimately favours the dip of surface waters in the Nordic Seas (Figure 1.9). The subsequent formation of the North Atlantic Deep Water (NADW) is globally compensated by the upwelling of deep waters in the Indian and Pacific Ocean, hence describing the “global conveyor belt” (Figure 1.10). The deep waters formation at high latitudes and their different pathways can be tracked by conservative or semi-conservative tracers such as salinity and phosphate concentrations (Figure 1.11).

In the deep Atlantic, the NADW flow southward and loose their specificity when they attain the Circumpolar Current (CCP), and are deflected toward the Indo-Pacific sector. The CCP redistribute the world ocean waters by the way of intermediate and bottom water masses formation (Figure 1.11), namely the Antarctic Intermediate Water (AAIW) and the Antarctic Bottom Water (AABW) that are formed at the polar frontal zone and at the edge of the Antarctic continent, respectively.

In the North Pacific sector, no deep water can be formed because of the low SSS. As a consequence, the North Pacific Intermediate Water (NPIW) only ventilates the upper 500m (Figure 1.11). The deep Pacific is mainly ventilated by the AABW that flow northward and return southward as Pacific Deep Water (PDW), that mainly consist in modified AABW (Figure 1.11). Between the PDW and the NPIW, the very sluggish ventilation induce an OMZ located at about 1000m depth in the North Pacific region (Figure 1.11). At low latitudes off California and Peru margins, intense OMZ also take place because of the combination of high primary productivity in the surface waters and sluggish ventilation between 300 and 1200m depth (Figure 1.11).

1.4. The EEP and Northeastern subtropical regions

The MD02-2529 (08°12.33’N, 84°07.32’W, 1619m depth) and MD02-2508 (23°27.91’N, 111°35.74’W, 606m depth) core location are presented in Figure 1.12.

1.4.1. Climatology and surface hydrology

1.4.1.1. The EEP: MD02-2529 coring site

The MD02-2529 was retrieved in the oceanic region situated beyond the Talamanca Cordillera, a geographical situation that prevents wind-induced upwelling in winter (Figure 1.13), and is under the influence of the North Equatorial Current (NEC) between December and April. The atmospheric circulation is modulated by the seasonnal migration of the ITCZ that brings large amounts of rainfall during the boreal summer (Figure 1.14), of which the half is brought from the Caribbean region. The eastward advection of the North Equatorial Countercurrent (NECC) that flows in the EEP region. Hence, the core MD02-2529 is ideally situated to monitor past changes of cross-isthmus water vapour transport that attains about 0.3Sv under present-day climatic conditions (Figure 1.15). The sharp halocline situated between 30 and 70m water depth separate the warm, low-salinity surface waters and the cold, high-salinity subsurface waters bathed in the Equatorial Undercurrent (EUC).

1.4.1.2. The EEP: MD02-2508 coring site

The MD02-2508 coring site is situated at the edge of the areas influenced by winter and summer monsoon regimes, and rainfall maxima coincide with the ITCZ northward migration during summer months (Figure 1.16). The cold California current and the warm Davidson current strongly influence the surface hydrology at the seasonal timescale (Figure 1.16).

1.4.1.3. Northeastern Pacific primary productivity

Wind-induced coastal upwelling during winter increase the primary productivity along the Baja California coast, and further South in the Tehuantepec Gulf, along the Nicarragua Margin and in the Panama Bight (Figure 1.17). During summer, the Costa Rica Dome induced by winds and surface currents also provide intense primary productivity from March to December in the EEP region (Figure 1.17).

1.4.1.4. ENSO impact on surface hydrology in the EEP

The ENSO variability does not have a significant impact on EEP SSS; positive SST anomalies of 1 to 2°C are recorded in the EEP region during El Niño years (Figure 1.18). The Costa Rica Dome is increased/decreased during cold/warm phases of the ENSO variability (Figure 1.19), inducing a strong decrease of primary productivity during El Niño years.

1.4.2. Intermediate-depth hydrology

The MD02-2508 and MD02-2529 core were retrieved within and below the present-day OMZ, respectively (Figure 1.20, 1.21). During the last glacial period, the MD02-2508 may have been under the influence of the OMZ, the NPIW and the AAIW while the MD02-2529 may have been under the influence of the OMZ, the PDW and the AAIW.

CHAPTER 2 – SEA SURFACE HYDROLOGY IN PANAMA BASIN

2.3. SST variability

The general $U^{k'}_{37}$ SST features are strongly decoupled from the DO-like SSS variability (Figure 2.10). However, at the millennial timescale, SST variations with amplitudes lower than 1°C are observed (i.e. variations of amplitudes comparable with the uncertainty range), with minima and maxima occurring during interstadials and stadials, respectively. Because these shifts seem to be systematic (see Figure 2.10), this kind of variability may be linked to some extent with a coupling between the monsoon intensity and the SST. One possible explanation would be that during periods of strong summer monsoon, increases in cloud cover may have lowered the SST, as it has already been proposed to explain EEP SST lowering during the LGM (Koutavas et al., 2003). It has already been demonstrated that the cloud cover has a strong impact on the present-day EEP SST, and is responsible for the SST drop during summer months (see Figure 1.14e). Therefore, it is reasonable to interpret these millennial-scale low-amplitude SST shifts in terms of nebulosity above the studied site.

The SST fluctuations are also marked by amplitudes of 2 to 3°C at Milankovitch timescale: especially between 5 and 20 ky BP and between 40 and 70 ky BP, the EEP SST seem to follow the summer insolation changes (Figure 2.13a). Modelling studies have shown that Milankovitch forcing could have been responsible for long-term ENSO-like dynamics within the tropical Pacific: when in insolation is minimal in the North Equatorial Pacific (Figure 2.13a) and maximal in the South Equatorial Pacific (Figure 2.13b), then the SST across the tropics tends to become more uniform and hence favour El-Niño conditions (Figure 2.13c, Clement et al., 1999). The Southeast Brazil is very sensitive to the ENSO variability : during El-Niño, increased rainfall are recorded (Silvestri, 2004). The $\delta^{18}O$ record of the Brazilian speleothem indicate that periods of rainfall maxima were concomitant with times of increased Nino3 index (see Figure 2.13b and 2.13c), and may suggest that some ENSO-like variability could have been responsible for these precipitation changes in Southeast Brazil. On the other hand, the 2 to 3°C SST variations recorded in MD02-2529 at the Milankovitch timescale rather suggest that the ENSO dynamics was not responsible for the EEP SST variations, since Nino3 index maxima are rather linked to SST minima in MD02-2529. Then, it appears unlikely that an ENSO-like variability was responsible for the EEP SST variations at the Milankovitch timescale, as it has previously been proposed (Clement et al., 1999; Koutavas et al., 2002). However, the relationship between summer insolation and EEP SST remains problematic for the 25-35 ky time interval, indicating that some contribution of high-latitude climatic changes at the glacial-interglacial timescale could have played a significant role on the EEP SST changes.

CHAPTER 3 – EASTERN PACIFIC HYDROLOGY AT INTERMEDIATE DEPTHS

2.2. Eastern Pacific intermediate water masses modes of circulation related to the MIS3 rapid climatic changes

2.2.1. Intermediate and deep Pacific ventilation changes deduced from benthic foraminifera $\delta^{13}C$ measurements

The present-day North Pacific surface waters are not enough salty to induce any deep-water formation within the North Pacific region (Emile-Geay et al., 2003), and an efficient oceanic ventilation in the North Pacific is only achieved in the upper 500m. It has been emphasized by benthic foraminifera $\delta^{18}O$ and $\delta^{13}C$ measurements across the termination 1 that a northern source for Pacific deep waters was unlikely (Keigwin, 1987). For the MIS3, the few high-resolution records of benthic foraminifera $\delta^{13}C$ available for the Pacific Ocean indicate greater oceanic ventilation rates during the Heinrich events, i.e. concomitant with the Antarctic warm events (see Figures 3.9 and 3.10).

To explain higher ventilation rates in the PDW in Northeastern Pacific during Heinrich events (see core W8709A-13PC, Figure 3.10), it has been proposed that the PDW could be influenced by greater ventilation “from below” (i.e. influenced by the underlying AABW) or “from up above” (i.e. influenced by the intermediate-depth waters of the Northeast Pacific) (Lund and Mix, 1998). To constrain the modes of millennial-scale PDW ventilation changes at 3000m depth, it is useful to compare the $\delta^{13}C$ record of core W8709A-13PC with records of lower depth within the same region (i.e. the sediment cores from the “California borderlands”, retrieved at 1400-1800m water depth). During the MIS3, the California borderlands $\delta^{13}C$ records of benthic foraminifera indicate that the water masses $\delta^{13}C_{DIC}$ remained lower than at W8709A-13PC coring site (Figure 3.11), suggesting that an influence “from up above” is unlikely to explain positive $\delta^{13}C$ shits recorded by the W8709A-13PC $\delta^{13}C$ record during Heinrich events. Instead, it appears reasonable to explain greater ventilation rates of the PDW by enhanced AABW formation during Heinrich events, i.e. at times of Antarctic warm events. At least two distinct mechanisms could potentially explain a greater AABW formation during Antarctic warm events. Firstly, the poleward migration of westerly winds belts could have enhanced upwelling at the Antarctic divergence during Antarctic warm events, and consequently could have led to enhanced AAIW and AABW formation at these times (Toggweiler et al., 2006). Secondly, the geothermal heating of the abyssal seafloor may have modified the bottom water density (e.g. as proposed by Adkins et al., 2005), of which the influence on deep oceanic circulation (thought to be particularly crucial for the Pacific Ocean) has recently been reconsidered from modelling studies (Emile-Geay and Madec, under revision).

Whatever which process is involved in the AAIW and AABW formation, the Pacific modes of circulation have influenced the ventilation as far as at MD02-2529 coring site during Heinrich events, either through the influence of AAIW or through the influence of greater southward flowing PDW (cf. Article#3). On the other hand, an overall reduction of the oceanic ventilation rates within the Pacific Ocean may have led to the southward expansion of the particularly low $\delta^{13}C_{DIC}$ water masses initially situated off California bordelands (cf. Article#3).

In order to feed synchronously the AAIW and the AABW, it is necessary to enhance upwelling of nutrient-rich deep waters at the Antarctic divergence within the Circumpolar Ocean (see e.g. Sarmiento et al., 2004). The modelling experiments of Toggweiler et al., 2006 indicate that the poleward migrations of the westerlies belt during Antarctic warms may favour the upwelling at the Antarctic divergence, and may further play a crucial role on atmospheric CO_2. This process is also consistent with higher AAIW and AABW water masses formation recorded at times of Heinrich events in other modelling experiments (see Figure 3.10 for paleo data; Marchal et al., 1998 and Schulte et al., 1999 for modelling experiments).

Paleoproductivity indicators in the Pacific sector of Austral Ocean indicate productivity maxima during Heinrich events (Sachs and Anderson, 2005). To explain these productivity maxima, the authors have mentioned two possible mechanisms: either an upwelling increase in the Southern Ocean sector that bring iron to surface waters and hence fertilizes the whole Southern Ocean, or increased Southern Ocean surface water stratification to increase the exposition to light of marine algae (Sachs and Anderson, 2005). The authors then stated that large uncertainties remained on how the Southern was altered at times of Heinrich events.

In the Southern Ocean, upwelling regions (that control sea-air CO_2 exchange) and AAIW and South Pacific Mode Waters (SPMW) formation sites (preferential zones for biological productivity export) are distinct (see Marinov et al., 2006). However, the correspondence between Antarctic warms and (1) atmospheric CO_2 concentrations (Indermuhle et al., 2000) and (2) increases in AAIW (Pahnke et al., 2005) and in SPMW (Robinson et al., 2006) suggest that productivity increases in the Southern Ocean during Antarctic warms were controlled by upwelling increases at the Antarctic divergence (and, as a consequence, linked to increases in AAIW and SPMW production) instead of increases in surface waters stratification.

2.2.2. Modes of ventilation within and in the vicinity of OMZ areas

At OMZ depths, no epibenthic foraminifera were present in MD02-2508 core, and endobenthic foraminifera do not represent the $\delta^{13}C$ of DIC (cf. Article#3). However, it has been proposed that the endobenthic foraminifera $\delta^{18}O$ responded to intermediate-sea temperatures variations, in relation with rapid ventilation shifts (Hendy and Kennett, 2003). In the following I will compare *U. peregrina* $\delta^{18}O$ results to the ones of Santa Barbara Basin.

This comparison requires the construction of a common timescale to eventually discuss the rapid hydrological changes. For this, the MD02-2508 density data and the Santa Barbara Basin record of planktonic foraminifera –both records that strongly vary with a DO-like pacing- were synchronized with respect to the GISP2 timescale (Figure 3.14). In Figure 3.15, the benthic $\delta^{18}O$ record of benthic foraminifera measured on the Santa Barbara Basin sedimentary sequence is compared to the ones of MD02-2508 and of MD02-2529. On the contrary of the Santa Barbara Basin record, MD02-2508 and MD02-2529 records are rather marked by “triangular-shaped” variations that mimic Antarctic temperatures, even if some abrupt shifts are also observed. Hendy and Kennett, 2003 have proposed that the Santa Barbara Basin benthic $\delta^{18}O$ record was likely to reflect temperature changes at coring site, with a probable influence of a Southern “warm” component during interstadials, with a likely superimposed influence of the sill. Nevertheless, this kind of variability that is not systematically recorded in MD02-2508 (i.e. by where the Santa Barbara Basin Southern water mass component necessarily passes by) could be questioned by MD02-2508 results.

However, recent Antarctic temperatures results from the EDML drilling site have revealed a one-to-one coupling between Greenland DO variability and their corresponding Antarctic events that lead Greenland events by a few centuries. If a tropical hypothesis for the Santa Barbara Basin intermediate depth origin is real, then the MD02-2508 record that rather mimics an “Antarctic-like origin” does not necessarily refute the hypothesis of Hendy and Kennett, 2003. However, the age model uncertainties and the time resolution at the end of MIS3 do not permit to unambiguously constrain the hydrological variability at MD02-2508 coring site, that also may have been under the influence of different water masses than those recorded in Santa Barbara Basin when the sill depth is taken into account.

In the Article#3, it has been proposed that the $\delta^{18}O$ record of *C. wuellerstorfi* could have been influenced by salinity variations at MD02-2529 coring site. The relatively good correspondence between the EDML record and the $\delta^{18}O$ record of *C. wuellerstorfi* may indicate that the water masses influencing the MD02-2529 coring site during Antarctic warms were less salty than those of the California Borderlands, situated further North. This result suggests strong salinity gradients in the Northeastern Pacific region at about 1500m water depth. This result is somehow coherent with the pore water measurements that indicate that during the LGM the water mass stratification was controlled by salinity rather than by temperature, as it is observed today (Adkins et al., 2002).

CONCLUSION AND PERSPECTIVES

The hydrological parameters reconstruction of surface and intermediate waters in the Eastern Pacific region led to the identification of several paleoceanographical processes at the millennial timescale during the MIS3. These processes have implications for the modes of climatic connections between the atmospheric circulation at low latitudes and climatic variations in the North Atlantic region, as well as for the oceanic circulation at intermediate depth in the Eastern Pacific region, and potentially at a global scale.

The SSS reconstruction has permitted to show that the ITCZ dynamics, analogous to the present-day seasonal variability, is the main factor that influences rainfall variations in the EEP region. This result one supplementary evidence for latitudinal migrations of the ITCZ at the DO timescale, already detected in tropical regions. For the first time, two important aspects of the low latitudes atmospheric dynamics were identified:

- MD02-2529 core location and its SSS recorded at the DO timescale have allowed constraining past changes in cross-isthmus water vapour transport that were enhanced during interstadials and lowered during stadials. Tese modes of atmospheric connection between the Atlantic and the Pacific allowed identifying a positive feedback on abrupt climatic changes at the DO timescale that potentially could regulate the Atlantic salt budget. During interstadials, increased water vapour transport lead to North Atlantic SSS increases, hence favouring the NADW formation (Figure 4.1). During stadials, the southward migration of the ITCZ led to the orogenic blocking of water vapour transport by the Andes that recirculate within the Atlantic Ocean via the Amazon Basin drainage (Figure 4.1).

- At MD02-2520 core location, there is no ENSO impact on rainfall changes, suggesting that SSS changes do not reflect an ENSO-like variability. On the other hand, the comparison between precipitation changes at MD02-2529 coring site and other paleoclimatic records situated in the western tropical Pacific allow identifying the spatial distribution of precipitation changes at the DO timescale. This result implies that the ITCZ dynamics, analogous to the present-day seasonal migrations of the ITCZ, could not be explained by an ENSO-like variability in the Eastern Pacific. Moreover, the persistence of millennial-scale ITCZ changes during the LGM when the DO variability is not observed at high latitudes indicate that the ITCZ dynamics does not passively respond to high latitudes climatic changes, suggesting that the low latitudes atmospheric dynamics may play some active role on rapid climatic changes.

In response to rapid climatic changes, the intermediate depth ventilation changes in the Eastern Pacific area and its associated OMZ dynamics allow constraining the modes of operation of the ocean-atmosphere coupling implied in rapid climatic changes. One major difficulty in interpreting the carbon isotopic signature of benthic foraminifera within the OMZ is to characterize which hydrological processes generate them (productivity vs. ventilation).

The $\delta^{18}O$ and the $\delta^{13}C$ records of benthic foraminifera measured on cores MD02-2529 and MD02-2508 coupled to proxies of organic matter supply to the seafloor indicate that while the $\delta^{13}C$ of *C. wuellerstorfi* records the $\delta^{13}C_{DIC}$, the $\delta^{13}C$ of *U. peregrina* neither reflects the organic matter remineralisation nor the $\delta^{13}C_{DIC}$ of bottom waters, and that $\delta^{18}O$ variations of ~2‰ recorded by *C. wuellerstorfi* are linked to salinity variations.

To understand how ventilation changes at intermediate depth evolved in the studied area, the $\delta^{13}C$ of *C. wuellerstorfi* has been compared to other records. It appears that the oceanic water masses circulation at water depth deeper than ~1500m have fluctuated synchronously in the whole Pacific Ocean: all the available high-resolution benthic records point to increased ventilation during the Antarctic warm events, i.e. at times of Heinrich events (Figure 4.2). Within the present-day OMZ, it is more difficult to constrain unambiguously how the oceanic circulation evolved at the millennial timescale from the $\delta^{18}O$ of benthic foraminifera only (Figure 4.2).

Some key points remain to be explained by further analysis:

- A mapping effort of sedimentary processes would better constrain the spatial and temporal variability of precipitation changes in relation with rapid climatic variations. Continental material supply may be quantified by coupling XRF analysis and ICP-OES/MS measurements. This kind of analysis may help to characterize variations in erosion and continental transport, and hence to document e.g. temporal variations of precipitation regimes across the tropical Pacific, particularly by comparing the eastern and the western sides of the tropical Pacific.

- It is also necessary to better characterize the ENSO dynamics, e.g. by studying the subsurface hydrology at MD02-2529 coring site, where the temperature at the base of the thermocline is highly sensitive to the ENSO dynamics (Figure 4.3). One way to capture the ENSO dynamics within welldefined time intervals (Holocene, LGM, stadials, interstadials) would be to measure repeatedly the $\delta^{18}O$ on one single test of the thermocline-dwelling species *N. dutertrei* within one sample (see Koutavas et al., 2006). This work, already started in CEREGE has to be coupled with Mg/Ca measurements and tested for sites particularly sensitive to the ENSO variability, as e.g. the Galapagos archipelago situated in the NINO3 zone.

- The respective contributions of productivity and ventilation for rapid OMZ changes have to be deciphered by comparing different independent proxies. One way to circumvent this problem may be to compare productivity indicators to trace elements sensitive to redox conditions such as Mo, Cd or U. This type of analysis has also to be performed on sediment cores retrieved at different depths in order to eventually detect variations in the extension of the OMZ and/or its migrations in depth.