CHAPTER 1

Introduction and summary of investigation

1.1. Milankovitch theory of ice-ages

The Milankovitch theory of the ice ages holds that astronomical perturbations in the Earth’s orbit and axis are responsible for glaciations by influencing climate through changes in the seasonal and latitudinal distribution of incoming solar radiation; this theory is now generally accepted by the geological community. It was Adhémar [1842] who first suggested that ice ages might be astronomically controlled, only 5 years after Agassiz presented his Ice Age theory in [1838]. In [1864] Croll elaborated the initial theory and formulated the relationship between astronomically variables and ice ages. Using formulas of the French astronomer Leverrier, he calculated curves for past changes in eccentricity 1 and precession 2 and suggested that cold winters were critical for the initiation of an ice age. However, he also remarked that astronomical forcing is too small to directly control glacial cycles and suggested that an internal amplifying mechanism within the climate system is needed as positive feedback.

Sixty years after Croll, Köppen and Wegener [1924] presented an alternative ice age theory, based on solar irradiance curves calculated by the Serbian astronomer Milankovitch. In contrast to Croll, who assumed that winter insolation is critical for glaciation, they assumed that low summer insolation would initiate ice growth. In [1941] Milankovitch further elaborated this early work and calculated the incoming solar radiation on top of the atmosphere of different latitudes taking into account the changes in precession, obliquity 3 and eccentricity. He stated that summer insolation at 65°N triggered the ice ages and predicted that ice age cycles are dominated by the 41-kyr cyclicity.

With the advance of magnetostratigraphy, and radio- and stable isotope analysis in the 60’s, acceptance of the Milankovitch theory was pushed forward. In addition, new coring techniques resulted in the recovery of long and continuous cores. The break-

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1 Eccentricity is a measure of the degree of elongation of the Earth’s orbit and varies between nearly zero (circular orbit) and 0.06 (slightly elliptical) with main periods of 400,000 and around 100,000 years

2 Axial precession is the slow movement of the rotation axis around a circular path with one revolution completed every 26,000 years. Due to the opposite movement of the eccentric orbit itself, the precession of the equinoxes also called climatic precession completes one full cycle in about 21,000 years. Climatic precession is modulated by eccentricity.

3 Obliquity describes the angle between the Earth’s axis of rotation and the orbital plane and varies between 22° and 25° with a main period of 41,000 years.
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through in accepting the Milankovitch theory came from the finding of spectral peaks in ice volume proxy ($\delta^{18}O$) records that matched exactly with the predicted Milankovitch frequencies, indicating a clear relationship between glacial-interglacial driven ice volume changes and the astronomical parameters [Hays et al., 1976]. Comparison with simple ice sheet model indicated that there is a connection between ice volume and orbital obliquity and precession, thereby confirming that glacial-interglacial variations are driven by orbital forcing with fixed leads and lags [Imbrie and Imbrie 1980; Imbrie et al., 1984]. This recognition led to the construction of an astronomically tuned timescale (SPECMAP) for the past ~800 kyr, which has been used as a template for dating deep marine late Pleistocene oxygen isotope records ever since [Imbrie et al., 1984].

In contrast to what was predicted by Milankovitch, $\delta^{18}O$ records of the late Pleistocene proved to be dominated by a 100 kyr ice age cycle, suggesting a relation of global climate change with eccentricity. It is generally accepted that the amount of the global annual insolation perturbation associated with the (100 kyr) eccentricity cycle is insufficient to cause a climate change on ice-age magnitude and, hence, that it is more likely that the strong 100-kyr eccentricity cycle observed in the $\delta^{18}O$ spectrum arises from a nonlinear transfer of power from the precession band [Imbrie et al., 1984; Hagelberg et al., 1991]. Alternative models propose that the glacial-interglacial fluctuations are a consequence of nonlinear internal interactions in a highly complex system [Saltzman and Sutera 1984] and that ice volume fluctuations are modulated rather than driven by orbital variations. Finally, it has been proposed that the 100-kyr cycle is related to changes in orbital inclination rather than to changes in eccentricity [Muller and MacDonald 1995]. Evidently, the quasi periodic fluctuations within the various components of the climate system such as variations in CO$_2$, ocean circulation, surface and deep water temperature are phase-locked to insolation changes due to the 100-kyr cycle.

In contrast, climate records of the late Pliocene and early Pleistocene are dominated by the obliquity cycle and it is generally accepted that glacial-interglacial cycles during the past 1–3 Ma are related to orbital obliquity [Shackleton et al., 1984; Ruddiman et al., 1986; Raymo et al., 1989] in agreement with Milankovitch’s predictions. However, it should be realised that the insolation curves of Milankovitch were calculated for the caloric half-year; this strengthens the obliquity signal relative to the same signal in peak summer (21 June – June/July) insolation curves [Berger et al., 1999; Raymo and Nisancioglu 2003].

1.2. Mediterranean sapropels

Although the Milankovitch theory is widely used to explain ice ages and associated climate changes at mid- to high-latitudes, it was shown that perturbations in the Earth orbit and rotational axis also exert a strong effect on low-latitude climate. However,
low-latitude insolation is dominated by precession in contrast to the obliquity-dominated insolation received at high-latitudes. For instance, low-latitude climate systems such as the monsoon are controlled by the seasonal distribution of incoming insolation received at low-latitudes, especially during summer.

A classical example of precession-dominated climate variability is the Mediterranean sapropel record [Hilgen 1991]. The regular and cyclic occurrence of sapropels (organic carbon rich intervals) has been associated with changes in river-runoff and circum-Mediterranean humidity [Rohling and Hilgen 1991], linked to intensified African monsoon circulation at times of minimum precession [Rossignol-Strick 1983; 1985]. Microfossil assemblages, pollen and stable isotope data have indicated that the principal climate variability in the precession band is related to changes in warm-wet and cold-dry conditions [Cita et al., 1977; Vergnaud-Grazzini et al., 1977; Rossignol-Strick 1983; 1997; Kallel et al., 2000]. Still, the precise mechanism behind sapropel formation in the Mediterranean is not fully understood. An ongoing point of discussion is whether the high C\textsubscript{org} concentrations observed in sapropels are primarily caused by enhanced preservation of organic matter during anoxic bottom water conditions or by increased surface water productivity and subsequent export of organic material to the deep sea. Clearly, sapropel formation is the result from the interplay of several processes of varying importance.

The occurrence of sapropels is related to periods of intensified monsoonal circulation associated with large precessional amplitudes. Since precession is modulated by orbital eccentricity, sapropels occur in clusters associated with eccentricity maxima. Furthermore, alterations of thinner and thicker sapropels within a sapropel cluster indicate additional modulation by orbital obliquity [Lourens et al., 1996]. This modulation is still not fully understood but preliminary modelling studies indicate that obliquity might influence or modulate [Tuenter pers. comm.] the African monsoon system and thus (indirectly) influence the runoff into the Mediterranean.

Next to the precession-related occurrence of sapropels, obliquity-related variability in sea surface temperatures (SST) and ice volume is evidenced in planktonic foraminiferal assemblages and δ\textsuperscript{18}O throughout the past 1-3 Ma. These variations can be correlated to changes in ice volume and temperature known from North Atlantic records [Zachariasse et al., 1990; Lourens et al., 1992], implying a close relationship between Mediterranean and North Atlantic climate on a glacial-interglacial timescale throughout the late Pliocene and early Pleistocene. Thus, the Mediterranean climate record reveals variations that can be attributed to two different climate systems, namely the high-latitude North Atlantic and the low-latitude monsoonal system. The different spectral characteristics of the records further indicate that these climate systems were at least partially decoupled from one another.
1.3. Phase lags

It is generally assumed that sapropels lag the precession parameter by 3 kyr. This lag is based on the age difference between the AMS $^{14}$C-dated midpoint of the youngest Holocene sapropel, S1 (~8.5 kyr), and the correlative summer insolation maximum at 11.5 kyr [Lourens et al., 1996] suggested that this lag could be related to a ~3 kyr time lag of maximum summer temperature ($T_{\text{max}}$) in northern Africa with respect to the precession parameter, as indicated by the outcome of an Energy Balance Model [Short and Mengel, 1986]. More recent modelling experiments revealed that $T_{\text{max}}$ at low-latitudes (15ºN) lags indeed the precession parameter, but that no time lag was observed between the African-Indian monsoon annual precipitation and the precession parameter [Tuenter et al., 2003]. This implies that either sapropel formation in the Mediterranean is not (only) linked to changes in African-Indian monsoon precipitation or that the time lag estimate for the S1 is an exception, being influenced by the deglaciation and Younger Dryas.

By adopting an in phase relationship between circum Mediterranean humidity and insolation [Lourens et al., 2001] showed that the obliquity-related time lag for the Mediterranean humidity proxy Ti/Al is in the same order of that for precession, i.e. 150 ± 300 years. This observation is confirmed by the modelling work of Tuenter et al. [2005], who observed an in phase relationship between the annual precipitation in the African-Indian monsoon and the obliquity parameter. These outcomes differ significantly from the results of Clemens et al. [1996], who observed phase lags between the Asian monsoon and the precession and obliquity parameters of 6 kyr and 13.4 kyr, respectively, during the late Pleistocene. These phase relations are very different to those observed from the ice volume records [Imbrie and Imbrie, 1980], suggesting that parts of the low-latitude climate system are decoupled from the high latitude glacial history. Finally, they suggested that these phase relations are not constant but varied over time in response to the global distribution of the polar ice cap(s).

1.4. Sub-Milankovitch variations

The recovery of the long ice cores from the Greenland ice sheet indicated that the Earth’s climate and system was extremely unstable throughout the past 150 kyr undergoing rapid changes in the order of a few thousand years [Dansgaard et al., 1984]. Distinct oscillations in air temperature above Greenland, termed Dansgaard-Oeschger (D-O) cycles, culminated in large-scale ice rafting events known as Heinrich (H) events [Heinrich, 1988; Bond, 1992; Broecker, 1992; Bond et al., 1993; Dansgaard et al., 1993; Bond et al., 1999]. These oscillations that are associated with a major reorganisation of North Atlantic SST and the global thermohaline circulation are recorded in sedimentary records throughout the North Atlantic and the leading hypothesis links the cold phases of the D-O cycles and H events to a collapse of the ice sheets, resulting in the injection of large volumes of meltwater to source regions of North Atlantic Deep Water.
(NADW) formation. Subsequently, lowered surface water salinities lead to a reduction of the deep convection and hence a slowdown of the global thermohaline circulation (THC) [Broecker 1997].

Figure 1.0: Lithology of Monte San Nicola section (SN) in comparison with the ATNTS2004 and lithology of ODP Site 967. For a detailed description of the section see Rio et al. [1994]. Individual sapropels of sapropel clusters A and B [coding after Verhallen 1987; Zijderveld et al., 1991] are labelled in the photograph of SN. Thick black and grey bars at the right hand side of the photograph indicate stratigraphic positions (scale bar lower right corner) of sapropels based on field observations, while the thin bars indicate positions of sapropels as assumed from the photograph. Stipple lines indicate correlation to the lithology of the Monte de Singa section that was incorporated in the ATNTS2004 [Lourens et al., 2004]. Additionally, marine isotope stages (MIS) 110, 108 and 100-96 are indicated in the lithology of SN and by peak occurrences of *Neogloboquadrina atlantica* (green shaded) at Singa [Lourens et al., 1992]. The ATNTS2004 shows the sapropel occurrences, polarity, chron and stages in relation to the La04$_{(11)}$ 65°N summer insolation curve. Insolation maxima correlating to sapropels are labelled according to the i-cycle coding and ages (kyr) are indicated on the right axis [Lourens et al., 1996]. The yellow shaded area indicates the interval of MIS101-95 at Singa and Site 967, respectively. Ti/Al, colour reflectance and lithology of ODP Leg 160 Site 967 (composite) are plotted versus meter composite depth (mcd), after Sakamoto et al. [1998]. I-cycle codes are indicated on the left and sapropel codes of Kroon et al. [1998] on the right. Sapropels A5, B1, Bx and B2 are indicated in addition.
However, climate fluctuations associated with the D-O cycles and H events are not restricted to the North Atlantic region but have been found in climate archives all over the world [Leuschner and Sirocko 2000; Voelker et al., 2002]. The forcing mechanism behind the high-frequency climate variations is uncertain and the debate generally distinguishes between internal forcing mechanisms, such as ice sheet oscillations forced by the interaction of large ice sheets with the underlying bedrock [MacAyeal 1993; Alley and MacAyeal 1994], and external forcing mechanisms, such as variations in solar output [Van Geel et al., 1999; Perry and Hsu 2000; Bond et al., 2001], periodic tidal motions of the Earth and Moon [Keeling and Whorf 2000] amplified in the presence of large ice sheets, non-linear response as harmonics or combination tones of the main orbital cycles [Pestiaux et al., 1988; Hagelberg et al., 1994; Ortiz et al., 1999], or simply the twice-yearly overhead passage of the sun across the equator [Short and Mengel 1986; Short et al., 1991]. Especially the latter two forcing mechanism suggests that millennial-scale climate variability could be driven by low-latitude rather than by high-latitude climate; the processes involved include strong atmosphere-ocean feedbacks, such as changes in the equatorial wind system equivalent to long-term changes in El Niño - Southern Oscillation (ENSO), changes in the intensity of the Inter Tropical Convergence Zone (ITCZ) or monsoon variability [Stott et al., 2002].
Figure 1.3: Frequency analysis of ODP Site 967 colour reflectance a) in the depth (70-83 mcd) and b) in the time (2.2-2.7 Ma) domain. Shaded intervals/labels mark important frequencies/periods and stipple lines indicate 80%, 90%, 95% and 99% significance levels.
The Plio-Pleistocene climate record

Most of these studies concentrated on the time interval in which ice-age cycles were dominated by the 100 kyr pacing, and then in particular on the last 150,000 years. Since the origin of these 100-kyr ice-age cycles is still hotly debated, it is probably more straightforward to study the relationship between millennial-scale climate variability and primary Milankovitch forcing during the obliquity-controlled ice ages of the late Pliocene or early Pleistocene. The presence of D-O and H-like fluctuations at times without major Northern Hemisphere ice sheets during the smaller obliquity-dominated glacial cycles of the late Pliocene - middle Pleistocene [Raymo et al., 1998; McIntyre et al., 2001], or climate fluctuations with similar spacing as D-O and H-oscillations at

Figure 1.4: Normalised colour reflectance (L*) data of Site 967 with superimposed filter (stippled line) versus depth. Numbers indicate central frequency and bandwidth (1/m) and corresponding periodicity (kyr; in brackets) of the applied filter.
times before 2.7 Ma [Ortiz et al., 1999; Kleiven et al., 2002; Steenink et al., 2003] indicate that such high-frequency climate fluctuations are consistently present in Earth’s climate history. Yet, interpretation of these records is not always straightforward, either because of the poor stratigraphic control or the lack of detailed correlations with the open ocean record.

Late Pliocene to early Pleistocene Mediterranean successions are well suited to study millennial-scale climate variations since they contain both obliquity-controlled glacial-interglacial cycles and precession-related sapropels; the latter allow astronomical tuning, thus providing an excellent age control. Furthermore, variations on a D-O and H-scale are observed in the glacial-interglacial cycles of the central Mediterranean marine land-based sections (field observations) and in eastern Mediterranean ODP Leg 160 records throughout the past 2-3 Ma [Shipboard data Sakamoto et al., 1998] (Figure 1.1). Fast variations in the sedimentary properties can be correlated basin-wide, suggesting a common (climate) mechanism operating on Milankovitch to sub-Milankovitch timescales (field observations) and in eastern Mediterranean ODP Leg 160 records throughout the past 2-3 Ma (Figure 1.2). Preliminary spectral analysis of the long Site 967 colour record (69.64-89.73 mcd; Shipboard data) indicates cyclic colour changes with wavelengths of \( \sim 60 \) cm, 27-30 cm, 17-15 cm and \( \sim 10 \) cm, being significant above the 90% level (Figure 1.3a). Clearly, the variation at 60 cm is related to the occurrence of sapropels at Site 967 (Figure 1.1) and, hence, corresponds to the precession frequency. Subsequently, frequencies in the depth domain translate into periodicities in the time domain at semi-precession (30 cm), quart-precession (15 cm) and some periodicity \( \sim 3.5 \) kyr (10 cm). Filter outputs of these frequencies generally show larger amplitudes in sapropel intervals (Figure 1.4). Variations at a semi-precession period are not very clear in these intervals and might present an artefact due to small colour variations in between sapropels or shoulders on top of sapropels. Variations with wavelengths of 15cm (corresponding to the quart precession) and 10 cm are present in the entire record. These 10 and 15 cm cycles make up most of the sub-Milankovitch scale colour changes observed in the glacial. In sapropel intervals, two 15 cm or three 10 cm cycles fit into a single sapropel. Frequency analysis in the time domain of the Site 967 colour variations [age model of Lourens et al., 2001], confirms that changes in sediment colour occur with periods of 21 kyr, (10 kyr), 6-5 kyr and 3.5 kyr above the 80% confidence limit (Figure 1.3b).

Preliminary frequency analysis on the magnetic susceptibility record of San Nicola indicates concentration of variance with wavelengths of 357, 175, 102, 45, 30 and 26

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4 ODP Site 967 shipboard colour reflectance data and preliminary magnetic susceptibility data of SN and Singa. See Chapter 6 for a more detailed description of methods and data.

5 Frequency analysis is carried out using the REDFIT computational program of Schulz and Mudelsee [2002].

6 Filtering was carried out using a Gaussian filter with central frequency provided by Paillard et al., [1996].
cm above the 80% significance level (Figure 1.5). Filtering of the low frequency signal centred at 0.0028 cycles/cm (i.e. with a period of 357 cm) indicates that this frequency corresponds to the obliquity cycle (Figure 1.6). Subsequently, the observed variations in the depth domain translate into periodicities in the time domain of 41, 19, 11, 5, 3.4 and 2.9 kyr, with wavelengths around 30 cm (~3 kyr) corresponding to the smallest-scale (low amplitude) changes in the magnetic susceptibility record of San Nicola.

1.5. Marine oxygen isotope stages 101-95

Visual inspection of Monte San Nicola (SN) and Site 967 indicates that the interval between the A and B sapropel clusters (i.e. ~2.5 Ma) is perfectly suitable for high-resolution studies of climate variations at Milankovitch to sub-Milankovitch time scales (Figure 1.1). Precession amplitude is low in this time interval due to a minimum in the 400-kyr eccentricity and, consequently, sediments in the central and eastern Mediterranean reflect obliquity-related glacial-interglacial variations rather than precession cycles. Earlier studies indicated that these dark-light alternations on a metre scale in-between the A5 sapropel (base Gelasian) and the B sapropel cluster reflect glacial cycles MIS100, MIS98 and MIS96 [Zachariasse et al., 1990], three of the most prominent glacial cycles that occurred shortly after the onset of major Northern Hemisphere glaciations [Ruddiman et al., 1986; Raymo et al., 1989]. Within the dark glacial stages, light-coloured centimetre-thick bands are visible indicating variability at sub-orbital scale superimposed on the obliquity related variation. Evidence for
occasional massive discharge of icebergs during these first full glacial cycles with a similar spacing as Mediterranean colour reflectance variations comes from the colour variations in the core photographs of North Atlantic DSDP sites (Figure 1.7) and ice rafted debris (IRD) records [Raymo et al., 1992; Carter and Raymo 1999]. Rapid changes in the size of the continental ice-sheets at that time are confirmed by major shifts in benthic foraminiferal oxygen isotope records [Raymo et al., 1989; Raymo et al., 1992].

Additionally, the colour reflectance data of ODP Site 967 indicates further, that MIS100, 98 and 96 are not equally thick but show an alternating thick, thin, thick pattern. This alternation points towards a modulation of the obliquity-related glacial

![Figure 1.6: Normalised magnetic susceptibility data of San Nicola with superimposed filter (stipple line) versus depth. All data are plotted on the same scales. Numbers indicate central frequency and bandwidth (1/m) and corresponding periodicity (kyr; in brackets) of the applied filter.](image)
signature, possibly by the (400-kyr) eccentricity signal. Additionally, sub-Milankovitch variability is more clearly observed in the thick stages MIS100 and MIS96.

1.6. Summary of investigations
The selected time interval and sections should shed new light on the following fundamental research questions: Are sub-Milankovitch frequencies present in the late Pliocene with frequencies similar to those observed in the late Pleistocene and, if so, is the climate mechanism comparable (Chapter 2)? What is the relationship of these signals with high latitude and low latitude climate (Chapters 3 and 4)? Are the phase relations of the different climate components with respect to the primary forcing frequencies (obliquity and precession) constant within the studied interval and are they comparable with those of the Pleistocene (Chapter 5)? What is the role of sub-Milankovitch variability on the time lags of climate change on Milankovitch scales? And, finally, is it possible to couple the observed sub-Milankovitch variations with primary Milankovitch frequencies (Chapter 6)?

To answer these questions, the interval of MIS101-99 was studied at high resolution (~400 years) in the marine land-based section of Monte San Nicola (Sicily/Italy) and ODP Leg 160 Site 967 by means of foraminiferal assemblages, stable isotopes (ice volume) and CaCO$_3$. This study was carried out to get first insight into Mediterranean climate variability operating on a Milankovitch to sub-Milankovitch time scale in the late Pliocene (Chapter 2). Obliquity-controlled glacial variability is clearly reflected in the oxygen isotope records of planktonic and benthic foraminifera, which depict a saw-
tooth asymmetry with superimposed stadial-interstadial variability in MIS100: in total two stadials (100.3 and 100.5) and three interstadials (100.2, 100.4 and 100.6) are recognised. Both $\delta^{18}O$ and SST lag orbital obliquity by ~6 kyr. Sea surface temperature (SST) estimates derived from changes in planktonic foraminiferal assemblages also indicate cooling cycles with saw-tooth asymmetry, confirming stadial-interstadial type of climate variability similar in duration and nature as the open ocean Bond-cycles of the late Pleistocene. Furthermore, the abundance pattern of Neogloboquadrina atlantica, a cold water planktonic foraminifer, indicates episodes of low SST with an even shorter duration (1.5-3 kyr) during MIS100. Cold episodes are associated with high abundances of the benthic foraminifer Triarina angulosa indicating that these episodes were characterised by increased deep ventilation caused by intensive mixing and deep convection. This scenario is analogous with observations in the western Mediterranean during the late Pleistocene [Cacho et al., 1999; 2001] and a similar mechanism has been proposed: Low SST associated with increased deep water formation during stadials are related to a) a direct influence of cold Atlantic surface waters entering the Mediterranean, and b) a more indirect connection with the Atlantic system, which probably extended further into the Mediterranean due to weakened monsoonal circulation at times of minimum (400-kyr) eccentricity. Discrepant conditions are found during cycle i-244, when a low salinity surface layer associated with a deep chlorophyll maximum (DCM) points to the influence of precession-related climate variability.

The absence of high-frequency variations in the $\delta^{18}O$ of Site 967 suggests that the eastern part of the Mediterranean was either decoupled from or not sensitive to North Atlantic climate forcing. However, colour reflectance records show similar millennial-scale variability in the eastern and the central Mediterranean. Comparison of these variations with the Ti/Al (a proxy for circum-Mediterranean humidity/aridity) record of ODP Site 969 [data Wehausen 1999] indicates a relationship between sedimentary properties (colour reflection, $\text{CaCO}_3$), African dust deposition (Ti/Al) and cold intervals ($\delta^{18}O$), suggesting a linkage between high- and low-latitude climate. The proxy data of the Mediterranean indicate that high-frequency climate change is highly complex due to the interaction of climate variations on different timescales.

The relationship between high-frequency climate changes observed in the Mediterranean during MIS101-95 and high latitude climate variability are investigated in Chapter 3. This is done by comparing the Mediterranean $\delta^{18}O$ and N. atlantica records with high resolution $\delta^{18}O$, $\delta^{13}C$, N. atlantica and ice rafted debris (IRD) records from Atlantic DSDP Leg 94 Site 607 and ODP Leg 162 Site 981. For this purpose, the highly accurate timescale of Site 967 is exported to the Atlantic using the benthic oxygen isotope record for correlation. The comparison reveals that millennial-scale cooling cycles in the Mediterranean are also found in the Atlantic, where they are
accompanied by episodes of intensive ice rafting. Depleted $\delta^{13}C$ during IRD episodes indicates a coupling of changes in the global thermohaline circulation with North Atlantic ice rafting history, as observed during late Pleistocene HE and D-O events.

Again, an exception occurs during MIS100.3 (i-244) when sea surface water warming at Site 607 evidenced by the presence of *Globorotalia menardii*, a sub-tropical planktonic foraminifera, is accompanied by a restart in deep water circulation. It remains unclear whether the associated depletion in benthic $\delta^{18}O$ indicates a warming of the deeper water as well. In the studied time interval, two additional influxes of *G. menardii* are closely related to precession minima as well, pointing to the interference of precession-related (low?) climate variability and obliquity-controlled glacial-interglacial cycles.

Nonetheless, the results unambiguously demonstrate that the Bond cycles and associated Heinrich events are an intrinsic part of the climate system throughout the late Pliocene and Pleistocene notwithstanding the transition from dominant 41-kyr to 100-kyr controlled glacial cycles.

The role of precession-related climate variability in the Mediterranean and the possible relationship between a low latitude (dust) climate component and high latitude climate change during MIS100 is further evaluated in Chapter 4. For this purpose, bulk sediment geochemical and grain size data are produced with the same temporal resolution as the SST and $\delta^{18}O$ records.

The chemical data indicate that environmental conditions during MIS100 were too weak for sapropel formation, which is in agreement with the reduced precession amplitude at that time as a consequence of minimum eccentricity. However, the development of a DCM during i-244 as proposed in Chapter 2 is to be expected. The chemical data further indicates that sediments at San Nicola present a two component mixing system with biogenic carbonates and aluminosilicates as end members. The relative contribution of these two components changes predominantly at glacial-interglacial (obliquity) scale. Superimposed on the glacial-interglacial variability are precession-related variations in dust deposition and basin-wide short-term (1.5-4.5 kyr) variations in dust and CaCO$_3$, which are probably related to episodes of enhanced dust delivery from the African continent amplified during maximum precession and minimum obliquity. These dust episodes in the Mediterranean are time equivalent to north Atlantic IRD events, suggesting a relationship between low-latitude dust variability and high-latitude ice rafting during MIS100.

In Chapter 5 phase relations between benthic $\delta^{18}O$ and obliquity are separately investigated for the glacial stages MIS100, MIS98 and MIS96. For this purpose, the $\delta^{18}O_{benthos}$ of Site 967 was extended throughout MIS95 and subsequently decomposed into an ice volume and a Northern Hemisphere annual air temperature component by using the coupled model of Northern Hemisphere ice sheets and ocean temperatures.
developed by Bintanja et al. [2005]. This model allows to accurately extract the ice volume and temperature component from the $\delta^{18}O$ at a given time interval. Advantage of using Site 967 is that its timescale is independent of glacial-interglacial variability; the age model has been developed by correlating the Ti/Al record to the La04$_{0,1}$, summer insolation time series at 65$^\circ$N assuming an in phase relationship [Lourens et al., 2001].

The modelling results show global sea level changes in the order of 60-70 m during MIS101-95, indicating that the deep water temperature component has been underestimated in earlier studies of sea level estimates for the late Pliocene. During glacials, Northern Hemisphere annual air temperatures are reduced by $\sim$12°C as compared to interglacials showing superimposed (stadial-interstadial) variations of up to 4-6°C (MIS96). Spectral analysis of the $\delta^{18}O$ and its derivatives global ice volume and Northern Hemisphere annual air temperature reveals strong peaks at $\sim$80, 41 and 28 kyr and, remarkably, no variance in the precession band. Filtered 41-kyr components of the different proxies show a 5-8 kyr lag with respect to obliquity. However, the time lag increases during MIS100 and MIS96 and decreases during MIS98 by $\sim$5 kyr, respectively, if the 80-kyr and 28-kyr components are included in the reconstructed signals. Evidence for nonlinear interactions between obliquity and eccentricity to explain the 80-kyr and 28-kyr components is ambiguous. Instead, the 80 kyr (and 28 kyr) is probably caused by the nonlinear behaviour of ice sheets to obliquity forcing by internal dynamics. In particular the existence of a significant large ice cap during MIS99 may largely explain the occurrence of these frequencies as sidebands.

In Chapter 6 spectral analysis is applied to the different records (SST and ice volume and African dust) of Mediterranean climate. Oxygen isotope and sediment property data of San Nicola and Site 967 record climate relationships during MIS98 and MIS96 that are comparable to those observed during MIS100 (Chapters 2, 3 and 4), i.e. low latitude dust episodes as recorded by the colour reflectance (CR) and magnetic susceptibility (MS) can be linked with cooling cycles in the Mediterranean and the North Atlantic, and with North Atlantic ice rafting history. Spectral analysis indicates however, that these climate systems might have operated on slightly different time scales: On a Milankovitch-scale, spectra of the oxygen isotope records are dominated by 80, 41 and 28 kyr periodicities, which is in agreement with global ice volume and Northern Hemisphere annual air temperature in that interval (Chapter 5). Only the spectra of $\delta^{18}O_{\text{G.upper}}$ indicate variance at the precession period, reflecting a local sea surface salinity/temperature component. The CR and MS spectra indicate a much stronger precession component but they differ significantly from one site to the other. These differences may be explained by the shortness of the records and, probably more importantly, differences in the glacial-interglacial signature of the individual sites and the strength of the precessional signal. Spectra of these records are more similar in the sub-Milankovitch range, showing concentration of variance around 6-7 kyr close to periodicities resulting from harmonics and combinations tones of the primary
precession components. Comparison with the power spectrum of a curve constructed by taking the difference between the strongest temperature maximum (T_{\text{max}}) and the strongest minimum (T_{\text{min}}) in the annual cycle at the equator indicates that differential heating related to the orbital configuration may explain the observed climate variability recorded by the MS and CR at SN and Site 967. Such a model would be in agreement with a (stationary) periodic climate signal as observed in the sediment property records of SN and Site 967. However, a link with primary precession may be considered less likely in view of the reduced precessional amplitude as a consequence of minimum eccentricity at that time.

On the contrary, spacing of δ^{18}O subcycles, which represent the most prominent feature on a sub-Milankovitch scale in the δ^{18}O record of the investigated time interval (see also Chapter 2), vary from one glacial to the other between 7 and 9 kyr, with the length of the cycles being related to the length of the glacial. Wavelet analysis indicates that both intensities and frequencies of the climate signal change through time, explaining the relatively broad peak in the power spectrum around 7-9 kyr. Such a non-stationary behaviour points towards nonlinear components either in the recording mechanism, the climate response or the forcing itself. Such nonlinear components could arise from frequency modulation of the primary eccentricity, obliquity and precession cycle or from internal ice sheet dynamics. An example of frequency modulation is presented for the Northern Hemisphere annual air temperature (T_{\text{air}}), a derivative of the δ^{18}O_{\text{benthos}} of Site 967, which shows the presence of a 8 kyr or ~12 kyr component being modulated by a ~70 kyr periodicity. This example is more in agreement with the model proposed by McIntyre and Molfino [1996], who related zonal wind-driven divergence in the equatorial Atlantic with a periodicity of ~8.4 kyr to nonlinear interaction between precession and an anomalous short eccentricity periodicity. However, our data also clearly indicate that more work has to be done to unravel the enigmas of sub-Milankovitch variability in the climate system.