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Plio-Pleistocene imprint of natural climate cycles in marine sediments

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ABSTRACT

The response of Earth to natural climate cyclicity is written in marine sediments. The Earth is a complex system, as is climate change determined by various modes, frequency of cycles, forcings, boundary conditions, thresholds, and tipping elements. Oceans act as climate change buffers, and marine sediments provide archives of climate conditions in the Earth´s history. To read climate records they must be well-dated, well-calibrated and analysed at high-resolution. Reconstructions of past climates are based on climate variables such as atmospheric composition, temperature, salinity, ocean productivity and wind, the nature and quality which are of the utmost importance. Once the palaeoclimate and palaeoceanographic proxy-variables of past events are well documented, the best results of modelling and validation, and future predictions can be obtained from climate models. Neither the mechanisms for abrupt climate changes at orbital, millennial and multi-decadal time scales nor the origin, rhythms and stability of cyclicity are as yet fully understood. Possible sources of cyclicity are either natural in the form of internal ocean-atmosphere-land interactions or external radioactive forcing such as solar irradiance and volcanic activity, or else anthropogenic. Coupling with stochastic resonance is also very probable.

I provide here, an overview of the cyclicity affecting the Earth on various time scales focussing upon the Plio-Pleistocene and Holocene epochs, together with a compilation of some of the key questions under debate, and a number of representative works that illustrate cyclicity in marine sediments.

Key words: cyclicity, millennial-scale, multi-decadal-scale, orbital-scale, Pliocene-Pleistocene

Impronta de la ciclicidad climática natural en sedimentos marinos durante el Plio-Pleistoceno

RESUMEN

La respuesta de la Tierra a la ciclicidad natural del clima se encuentra inscrita en los sedimentos marinos. La Tierra es un sistema complejo, en el que el cambio climático viene determinado por varios modos, frecuencia de sus ciclos, causas, condiciones de contorno, puntos irreversibles y elementos de no retorno. Los océanos amortiguan el cambio climático, y preservan en los sedimentos marinos las condiciones climáticas de la historia terrestre. Para su lectura es necesario que los registros estén bien datados, calibrados y analizados a alta resolución. Las reconstrucciones climáticas del pasado se basan en indicadores climáticos, tales como la composición atmosférica, temperatura, salinidad, productividad oceánica y viento, cuya naturaleza y calidad son cruciales. La calidad de los indicadores de paleoclima y paleoceanografía garantiza buenos resultados derivados de la modelización y su validación, y del rigor de las predicciones a partir de los modelos climáticos. Los mecanismos que rigen los cambios climáticos a escala orbital, milenaria y multi-decadal no se comprenden en la actualidad en su totalidad, como tampoco se conoce del todo el origen, ritmo y estabilidad de los ciclos. El origen de la ciclicidad climática puede ser natural (interacciones internas entre atmósfera-océano-continente o efecto externo de la radioactividad tal como la irradiancia solar y la actividad volcánica) o antropogénica. Hay que añadir además una alternativa y probable resonancia estocástica.

El presente trabajo aporta una visión de la ciclicidad que afecta a la Tierra, a varias escalas temporales, y contempla las épocas del Plioceno, Pleistoceno y Holoceno. Se recopilan algunas de las cuestiones clave que necesitan una mayor perseverancia para su entendimiento y se enumeran trabajos científicos representativos de ciclicidad registrada en el ámbito marino.

Palabras clave: ciclicidad, milenaria, multi-decadal, orbital, Plioceno-Pleistoceno

VERSION ABREVIADA EN CASTELLANO

Introducción

En la naturaleza abundan los fenómenos que se rigen conforme a patrones repetitivos de cambios climáticos abruptos. Entre ellos podrían destacarse: el punto alcanzado por las concentraciones de CO_2 en el que la biosfera y el océano son aún capaces de actuar como sumideros disminuyendo sus niveles en la atmosfera; el crecimiento y colapso alternativo de los glaciares desde el inicio del Pleistoceno (2,6 My) según la insolación en las altas latitudes; el calentamiento rápido del Polo Sur cuando del Polo Norte súbitamente se desprenden témpanos de hielo y cesa la circulación termohalina (CTH); y la magnitud de eventos extremos de inundaciones o sequías acorde con la circulación atmosférica.

Los sedimentos marinos muestran la impronta de la ciclicidad natural orbital (ciclos de 400 000 años (ka), 100 ka, 41 ka y 21 ka) y las respuestas a los cambios climáticos impuestos al sistema Tierra. Aún cuando el origen de estos ciclos no es del todo conocido, han sido considerados orígenes externos y más regulares (cambios de los parámetros orbitales de la Tierra, conocidos como de Milankovitch) e internos y menos regulares (dinámica de los glaciares, CTH, ciclo del carbono, etc). La localización de los mecanismos inductores no es exclusiva de la latitud. Se ha demostrado que la eccentricidad (400 y 100 ka) rige los períodos glaciales, con procesos focalizados en latitudes altas, aún cuando la oblicuidad (41 ka) es la frecuencia dominante del volumen de hielo en los polos (Shackleton, 2000; Paillard y Parrenin, 2004). El CO_2 parece jugar un papel importante en esta discrepancia, aunque no resulta fácil cuantificar los limites de sensibilidad del clima y los umbrales de las transiciones de CO_2 hacia un calentamiento (Knutti y Hegerl, 2008), dada la incertidumbre en relación al papel de la circulación oceánica en el ciclo del carbono, como afecta el almacenamiento de C a los ciclos, o los niveles de saturación de CO_2 que impulsan a un cambio del modo de funcionamiento del sistema. Cuando la insolación disminuye en las latitudes altas (Berger, 1978) (Fig. 1), la precesión (21 ka) refuerza la estacionalidad en las latitudes bajas, supeditando los vientos Alíseos y los Monzones, que a su vez influyen en la circulación oceánica ecuatorial, tropical y de las latitudes subtropicales (deMenocal et al.*, 1993; Chapman y Maslin, 1999). Sin embargo, no es del todo conocido el impacto de los cambios climáticos tropicales en el Atlántico Norte (Rosenthal* et al.*, 2003; Oppo* et al.*, 2003).*

Las series de paleo-datos integran los mecanismos de inducción y retroalimentación de la ciclicidad climática, y sus procesos, además de revelar el posible impacto antropogénico en la variabilidad climática natural (Soon y Baliunas, 2003), los cuales parecen estar cambiando los ciclos de larga duración. Los modelos climáticos son frecuentemente usados para simular la complejidad de las respuestas climáticas del sistema (Alverson et al.*, 2003). El análisis de registros de ciclicidad requiere precaución en relación a su extensión y resolución temporal, sobretodo si abarcan cambios del último siglo y se utilizan para realizar predicciones futuras.*

En este artículo se enfocan diferentes ciclicidades y sus orígenes y se enumeran estudios clave y/o representativos en los que claramente se refleja la impronta de la ciclicidad en sedimentos del fondo oceánico.

Variabilidad orbital (10^5)

Edades glaciales

Los cambios de los parámetros orbitales (Milankovitch) aportan ciclicidades naturales con frecuencias de 400, 100, 41 y 21 ka.

El enfriamiento general del Plioceno desemboca en la Glaciación del Hemisferio Norte (GHN) con desarrollo de glaciares a partir de 2,6 Ma, que marca el inicio del Pleistoceno (Fig. 2). A lo largo de este destacan otras dos transiciones abruptas, acaecidas hace 1,4 Ma y hace 1 Ma, la última de las cuales es denominada Transición del Pleistoceno Medio (TPM) (Lisiecki y Raymo, 2007). Este registro Plio-Pleistoceno revela una curva general en forma de sierra con oscilaciones que son de gran amplitud de variaciones de temperatura, de nivel del mar y de concentraciones de CO_2 y así como de metano en la atmosfera, correspondientes a los períodos glaciales e interglaciales (GI) del Pleistoceno (Fig. 1). La forma de las oscilaciones es asimétrica, debido a que la construcción de los glaciares tarda 80 ka en producirse y las desglaciaciones son muy rápidas del orden de 10 ka (Lisiecki y Raymo, 2007).

Entre las causas de la GHN se encuentran el cambio de la posición de los continentes, el levantamiento tectónico, la creación de suelo oceánico, la circulación oceánica profunda, la reducción de CO_2 atmosférico y la insolación. La TPM puede deberse a formación y estabilización de los glaciares, cambios en los márgenes continentales afectados por procesos de (des)glaciación, y/o aumento de los umbrales de insolación.

Las edades de las transiciones son cruciales a la hora de defender ciclicidades y en concreto para el intervalo Plio-Pleistoceno se han establecido tres cronoestratigrafías: la SPECMAP de Imbrie et al. *(1984) y Raymo (1997); la PISO-1500RPI de Channel* et al. *(2008; 2009) y la LR04 de Lisiecki y Raymo (2005).*

Mecanismos y Ciclicidad

Elbikki y Rial (2001) exponen en una revisión exhaustiva que la hipótesis de Milankovitch (Hays et al.*, 1976) mantiene su valor, y que el clima responde de manera linear a las frecuencias de Milankovitch. Sin embargo, Shackleton (2000) ha demostrado que el ciclo de los 100 ka se encuentra en fase con el C atmosférico, la temperatura del aire en la Antártida y el agua profunda, mientras que el volumen de hielo obedece a una frecuencia de 41 ka, desfasada en 6-14 ka de los anteriores. Paillard (2001) también enuncia posibles debilidades de la teoría astronómica clásica, incapaz de explicar cambios climáticos abruptos o la ausencia de cambios orbitales significativos, como la persistencia del ciclo de 100 ka, la transición del ciclo de 41 ka a 100 ka en la TPM, o el estadio isotópico marino (MIS en inglés)-11. A esto, Elbikki y Rial (2001) añaden la amplitud de los ciclos GI de 100 ka y la ausencia del ciclo de 400 ka en los últimos 1,2 Ma. Igualmente, se apuntan como nuevos componentes con potencialidad para influir en los cambios de la ciclicidad las concentraciones de CO_2, la productividad oceánica del Polo Sur, o la circulación profunda (Paillard, 2001). En la última década, varios estudios han demostrado que los cambios climáticos a escala orbital que afectan al Ecuador y a los Trópicos pueden haberse generado en altas latitudes (100 ka y 41 ka) pero también por procesos típicos de bajas latitudes como los Monzones (ciclo de 21 ka) (deMenocal, 1993; Leuschner y Sirocko, 2003; Tjallingil* et al.*, 2008).*

Son muchos los trabajos que confirman las interacciones entre las ciclicidades orbitales y que están basados en estudios de multi-indicadores (ej. Charles et al.*, 2010; Martrat* et al.*, 2004; Hernández-Almeida* et al.*, 2012; Tzedakis* et al.*, 2004; deMenocal* et al.*, 1993; Larrasoaña* et al.*, 2003; Abrantes, 2003; Tiedemann y Mix, 2007).*

Variabilidad milenaria (10^3)

Estadios glaciales

Los cambios climáticos abruptos tienen su mejor expresión en los eventos Dansgaard-Oeschger (DO) y Heinrich (HE) (Dansgaard et al.*, 1993; Johnsen* et al.*, 1992) que irrumpen en el período entre los 110 y 10 ka. Se trata de oscilaciones emparejadas que reflejan condiciones extremas de temperatura, con variaciones en el Polo Norte de 10ºC/100 años (EPICA project members, 2006; Rousseau* et al.*, 2006). El patrón de ciclicidad identificado inicialmente en el hielo glaciar se repite en los sedimentos del fondo oceánico de todo el Planeta (Bond* et al.*, 1997; revisión por Voelker* et al.*, 2002) (Fig. 3). Y aunque inicialmente se detectaron en el MIS-3, de nivel de mar intermedio (McManus* et al.*, 1999; Schulz, 2002; Ganopolsky y Rahmstorf, 2002), se han encontrado también en los estadios estrictamente glaciales como los MIS-6, 8, 10, 12 (ej. McManus* et al.*, 1999; de Abreu* et al.*, 2003; Siddall* et al.*, 2007; Margani* et al.*, 2010).*

Mecanismos y Ciclicidad

Los DO y HE son parte integral del balance térmico bipolar, que produce una respuesta asimétrica entre los dos hemisferios (Broecker, 1994; Blunier et al.*, 1998; figura 1 de Clark* et al.*, 2007). La mayoría de las modelizaciones que soportan esta hipótesis requieren una descarga súbita de agua helada procedente del deshielo de los glaciares del Atlántico Norte, que obliga a una reorganización de la circulación oceánica termohalina (AMOC en inglés, Circulación Meridional de Retorno del Atlántico) que oscila entre dos extremos desde el cese completo de su corriente en los HE hasta su restablecimiento en los estadios más cálidos (IS, interestadiales) (Sarnthein* et al.*, 1995; Stocker y Wright, 1991; Fanning y Weaver, 1997; Manabe y Stouffer, 1997; Alley* et al.*, 1999; Sakai y Peltier, 1999; Ganopolski y Rahmstorf, 2001). El cese de la formación de agua profunda en el Atlántico Norte (en los HE), evita que Groenlandia se enfríe en exceso, por lo que la Antártida se calienta y transfiere calor al Polo Norte (Clark* et al.*, 2002; Alley* et al.*, 2007; Stenni* et al.*, 2010; Severinghaus, 2009). Entre los posibles mecanismos generadores de los DO y HE se cuentan el transporte de calor oceánico a través del Ecuador, la sincronización hielo-océano debido a los cambios del nivel del mar, la inestabilidad de los márgenes continentales que sufrieron procesos de des(glaciación) y el calentamiento subsuperficial (revisión por Schmittner* et al.*, 2007). La transmisión de los cambios climáticos que se producen en el Atlántico Norte hacia el Ecuador es muy rápida, afectando la intensidad de los vientos Alíseos y Monzones, la expansión y migración del cinturón de la Zona de Convergencia Intertropical (ZCIT), y la variación de las temperaturas y oxigenación del océano Pacífico (ej. Timmermann y Goosse, 2004; Zhang y Delworth, 2005).*

El ciclo de 1.47 ka (Groots y Stuiver, 1997; Bond y Lotti, 1995; Mayewski et al.*, 1997; Rahmstorf, 2003) es el más publicado para los DO durante el intervalo glacial de 110-10 ka. Los HE, que engloban varias parejas de DO, ocurren cada 7 ka (ej. Clark* et al.*, 2007), configurando los ciclos de Bond (Bond* et al.*, 1993) (Fig. 3), que no deben confundirse con las oscilaciones de similar frecuencia pero mucho menor amplitud del Holoceno (Bond* et al.*, 1997). El origen de esta ciclicidad se ha explicado tanto por factores naturales internos (estabilidad de los glaciares y ciclo hidrológico) como externos (insolación orbital) (Rial y Yang, 2007), además de por la superposición de otros dos períodos de 87 y 210 años en un sistema no-lineal (Braun* et al.*, 2005), o una resonancia estocástica que justifica elementos periódicos de eventos climáticos abruptos cada 1.47 ka ("el reloj" de Rahmstorf, 2003).*

Existe una colección enorme de trabajos que manifiesta y valida resultados de modelos climáticos, con registros de diferentes indicadores biogeoquímicos en los sedimentos marinos (ej. Bond et al.*, 1993; Grousset* et al.*, 1993; Lebreiro* et al.*, 1996; van Kreveld* et al.*, 1996; Little* et al.*, 1997; Vidal* et al.*, 1997; Vidal* et al.*, 1998; Kennett* et al.*, 2000; Cacho* et al.*, 2000; Shackleton* et al.*, 2000; Kanfoush* et al.*, 2000; Peterson* et al.*, 2000; Grousset* et al.*, 2001; Pailler y Bard, 2002; Elliot* et al.*, 2002; de Abreu* et al.*, 2003; Hendy y Kennett, 2003; Moreno* et al.*, 2004; Sierro* et al.*, 2005; Voelker* et al.*, 2006; Skinner y Elderfield, 2007; Saikku* et al.*, 2009).*

Holoceno

El Holoceno muestra oscilaciones de menor amplitud que los estadios glaciales (revisión por Mayewski, 2004), aunque existe una periodicidad marcadamente similar a los períodos anteriores. Su frecuencia apunta también a un valor de 1,470 ka (Bond et al.*, 1997; 2001), atribuida por la mayoría de los autores a una contribución solar y oceánica. Algunos análisis espectrales no convergen sin embargo en un único valor. Debret* et al. *(2007) separa dos picos de 1 y 2 ka y 1,5 ka, asignados independientemente a un origen solar y/o oceánico, respectivamente. Otros autores encuentran recurrencias en torno a 900 años (Schulz y Paul, 2000) o múltiples frecuencias de diferente significación estadística (Sarnthein* et al.*, 2003).*

Variabilidad multi-decadal (10^1-10^2)

Las oscilaciones climáticas de período corto controlan, por ejemplo, precipitaciones, inundaciones, sequías, huracanes, o la productividad pesquera costera y oceánica, con un impacto importante en la sociedad y en la economía.

Existen varios modos de variabilidad multi-decadal bien identificados en el sistema climático actual, unos de ámbito global como la de El Niño-Oscilación del Sur (ENSO en sus siglas en inglés; Gershunov y Barnett, 1998; Enfield et al.*, 2001), la Oscilación del Atlántico Norte (NAO; Hurrell, 1995), y la Oscilación Multi-decadal Atlántica (AMO; Kerr, 2000; Enfield* et al.*, 2001), y otros más regionales como la Oscilación Decadal del Pacífico (PDO; Mantua* et al., 1997; *NPO; Gershunov y Barnett, 1998), la Oscilación del Ártico (AO; Ambaun* et al.*, 2001; Marshall* et al.*, 2001), o el Modo Anular del Sur (SAM; Kidson, 1988; Arblaster y Meehl, 2006). Estos son índices que representan la variación de fenómenos atmosféricos de temperatura y presión, dependientes de datos instrumentales, y por tanto con una extensión temporal limitada a los últimos 150 años. Afortunadamente esta variabilidad de alta frecuencia queda registrada, entre otros archivos, en los sedimentos marinos (Fig. 4), alargando su escala temporal hacia el pasado, lo que permite la validación y calibración de los datos y afianza la robustez de las series climáticas.*

Mecanismos y Ciclicidad

La ENSO (cálida) condiciona el clima del Pacífico Norte y del Atlántico Norte, siendo inversamente relacionada con los Monzones de la India (débil) (Kumar et al.*, 1999). Además presenta una ciclicidad de 3-7 años (Dong y Sutton, 2002) e intervalos especialmente intensos como los de 1982–83 y 1997–98 (Wolter y Timlin, 1998). La NAO muestra una amplitud máxima de presión sobre Islandia y las Azores, y repercute en los Vientos del Oeste a través del Atlántico Norte hacia Europa (Hurrell, 1995; 2001; 2003; Rodwell* et al.*, 1999). Posee una periodicidad de 2-4 (u 8) años (Cook* et al.*, 2002). La AMO crea anomalías de temperatura en el Atlántico Norte, de modo que valores positivos se correlacionan con temperaturas más altas, menos precipitaciones y en consecuencia períodos de sequía (Kerr, 2000; Feng* et al.*, 2009). La AMO muestra un patrón más homogéneo que la NAO. El análisis espectral apunta a frecuencias de 11 años (Lohmann* et al.*, 2004), 70 años (Schlesinger y Ramankutty, 1994; Delworth y Mann, 2000; Andronova y Schlesinger, 2000), o el ciclo Gleissberg de irradiancia solar de 90 y 210 años (Ogurtsov* et al.*, 2002; Dergachev, 2004).*

Se ha recurrido a varios mecanismos para explicar las altas frecuencias de los ciclos de variabilidad multi-decadal, tanto de origen interno (CTH, acumulación de hielo-deshielo, vientos, migración latitudinal de la ZCIT, convección de aire tropical) (Delworth et al.*, 1993; 1997; Timmermann* et al.*, 1998; Delworth y Mann, 2000; Marshall* et al.*, 2001; Yu* et al.*, 2002; Latif* et al.*, 2004; Cheng* et al.*, 2004; Vellinga y Wu, 2004; Zhang y Delworth, 2005; Dai* et al.*, 2005; Knight* et al.*, 2005; Dima y Lohmann, 2007; Biastoch* et al.*, 2008), como de origen externo (irradiancia solar y erupciones volcánicas) (Ottera* et al.*, 2010), e incluso resonancia estocástica (Delworth y Greatbatch, 2000; Dima y Lohmann, 2007).*

La variabilidad climática multi-decadal (Fig. 3) queda plasmada en un número notable de publicaciones tanto como respuesta a cambios climáticos en el ámbito marino (ej. Sicre et al.*, 2008; Boessenkool* et al.*, 2007) como en el continental (ej. Bartels-Jonsdottir* et al.*, 2006; Lebreiro* et al.*, 2006; Alt-Epping* et al.*, 2009). El registro de cambios climáticos continentales en medio marino no es exclusivo de la escala multi-decadal, sino también de la milenaria (ej. Sánchez Goñi* et al.*, 2002; Jullien* et al.*, 2007; Lebreiro* et al.*, 2009; Romero* et al.*, 2011) y de la orbital (ej. Harris y Mix, 1999).*

Interacción entre diversos modos de variabilidad multi-decadal

Hay una interacción global entre los diversos modos de variabilidad multi-decadal puestos en evidencia, por ejemplo, en los siguientes trabajos: la AMO determina la variabilidad en el Pacífico Norte a través de los trópicos por medio de la ZCIT (Dong y Sutton, 2002; Zhang y Delworth, 2007; Dima y Lohmann, 2007); la ENSO impone sequía en el Pacífico Oeste, calor en el Norte de los Estados Unidos de América y humedad en el Sur, impidiendo el desarrollo de huracanes en el Atlántico. La ENSO intensa (El Niño) es consistente con una NPO positiva, asociada con una anomalía fría en el Pacífico Noroeste, y al revés para La Niña (fase contraria a El Niño) (Gershunov y Barnett, 1998).

Superposición de las diferentes escalas de variabilidad

La ciclos orbitales, milenarios y multi-decadales interaccionan, probablemente, porque el origen y mecanismos que producen sus ciclos son parcialmente comunes; por ejemplo, la CTH funciona y sufre cambios a escala orbital, milenaria y multi-decadal. El ciclo de 21 ka atraviesa los 2,6 Ma, del Plioceno al Pleistoceno, aún cuando se produce una transición del dominio del ciclo de 41 ka al de 100 ka (Becker et al.*, 2006). Los ciclos sub-orbitales y milenarios prevalecen no solo a lo largo de los períodos glaciales (McManus* et al.*, 1999; de Abreu* et al.*, 2003; Becker* et al.*, 2006; Margani* et al.*, 2010), sino también como sub-estadiales en los períodos interglaciales (McManus* et al.*, 1994; McManus* et al.*, 1999; Chapman* et al.*, 1999; Oppo* et al.*, 2001; Tzedakis* et al.*, 2004; Schaefer* et al.*, 2005; Desprat* et al.*, 2007; 2008). Además Tzedakis* et al. *(2004) sugieren que la duración de los Interglaciales pueda obedecer a la variabilidad milenaria, y Pena* et al. *(2008) a la multi-decadal de la ENSO. La migración del cinturón de la ZCIT opera de igual modo en la ENSO que en los HE (Leduc* et al.*, 2009). Las condiciones actuales de la ENSO se correlacionan también con las de los estadiales fríos de los DO en las latitudes altas, mientras La-Niña lo hacen con los interestadiales (Stott* et al.*, 2002), el Período Cálido Medieval (PCM) (Khider* et al.*, 2011) y el EIM5e (Pelejero* et al.*, 2003). La fase positiva de la NAO predomina a lo largo del PCM, mientras la fase negativa lo hace durante la Pequeña Edad del Hielo (Abrantes* et al.*, 2005; Trouet* et al.*, 2009).*

Inducción antropogénica en el cambio climático

No es de esperar que los modos de la variabilidad climática analizada permanezcan constantes en amplitud y frecuencia en el futuro (Alverson et al.*, 2003; Lorenz* et al.*, 2006; Koutavas* et al.*, 2006; Clement, 2000; Goosse* et al.*, 2006). Entre otras evidencias, podría apuntarse la contaminación atmosférica que altera el equilibrio de la irradiancia del Planeta (ej. Rayner* et al.*, 2003; Delworth* et al.*, 2007; Latif* et al.*, 2007), la probabilidad del cese de la CTH (Wood* et al.*, 2003), la expansión de la ZCIT (Koutavas* et al.*, 2006), o el aumento de la concentración de CO_2 que puede intensificar o debilitar los ciclos GI (Goodwin* et al.*, 2009; Lenton* et al.*, 2008).*

Conclusiones

Los sedimentos marinos aportan información sobre la ciclicidad climática natural impuesta al Planeta. Las series climáticas vienen revelando en sus análisis espectrales la alta probabilidad de que los diversos modos de variabilidad obedezcan a una combinación de mecanismos, que funcionan de modo similar y actúan a diferentes escalas. Conocer el porqué de los cambios de ciclicidad es crítico para su aplicación en predicciones climáticas futuras, así como para discernir el posible impacto antropogénico en la variabilidad.

Introduction

The discovery of abrupt climate changes occurring in accordance with different time scales and the need to explain them have introduced the concepts of exceeded critical thresholds, tipping points and hysteresis in relation to the recovery, stability, and continuity of climatic patterns of variability (Bradley *et al.*, 2003; Lenton *et al.*, 2008). Many phenomena contribute to repeatitious patterns of abrupt climate change in nature: CO_2 concentrations have reached points at which biosphere and ocean have still been able to sequester and lower atmospheric levels once more; ice-sheets have grown and declined since the onset of the Pleistocene (2.6 Myr) following high-latitude insolation changes; the south pole has warmed quickly while the north pole ice-sheets were dismantled into armadas of icebergs and the THC (thermohaline circulation) ceased; and the magnitude of river floods and droughts have reflected persistent atmospheric patterns. Marine sediments show the imprint of orbital (400-kyr-thousand of years, 100-kyr, 41-kyr, 21-kyr), millennial (1.5-kyr), multi-decadal (80-yr-years, 3-7 yr) cycles, and the palaeoclimate forcing responses. Although the origin of this cyclicity remains uncertain, many external forcings such as secular changes in the Earth orbital – Milankovitch´ parameters, where oscillatory modes are more regular, and internal forcings such as ice-sheet dynamics, THC circulation, and the carbon cycle, which are more irregular, have been proposed.

It is generally accepted that the eccentricity causing a 100-kyr cycle, drives the northern hemisphere ice ages and build-up of ice-sheets, but that the 41-kyr obliquity cycle is the dominant frequency in ice volume (Shackleton, 2000); CO_2 arose as the promoter of the 100-kyr signal (Shackleton, 2000; Paillard and Parrenin, 2004). Quantifying the limits of climate sensitivity and rates of CO_2 transients to warming is not easy however (Knutti and Hegerl, 2008), because of uncertainties about the role of ocean circulation in the carbon cycle, how carbon storage affects cycles, or the existence of a threshold level of CO_2 that switches to a different mode. When insolation decreases at high-latitudes (Berger, 1978), precession, a 21-kyr cycle strengthens seasonality at lower latitudes, driving trade winds and monsoons, which in turn influence equatorial, subtropical and mid-latitudinal oceanic processes (deMenocal *et al.*, 1993; Chapman and Maslin, 1999). Moisture and heat transferred polewards across the equator preconditions northern-hemisphere ice-sheet growth and water temperature changes (Ruddiman and McIntyre, 1981; Dahl *et al.*, 2005). Nevertheless, the impact of changes in the North Atlantic upon the climate in the tropics and vice-versa is not really understood (Rosenthal *et al.*, 2003; Oppo *et al.*, 2003).

Palaeo-data series integrate forcings and feedbacks and the processes operating on them. Palaeo-records also show natural forcing mechanisms prior to the anthropogenic forcing, allowing us to distinguish and calibrate the superimposition of human intervention in the variability (Soon and Baliunas, 2003). Models are useful tools, but have limited capability to represent accurately the true variability of complex climate-system responses (Alverson *et al.*, 2003). Analysing cyclicity requires prudence with regard to the length of records and time scales, particularly during the last century, where records aim for future predictions. It seems certain though that natural climate forcing is sensitive and vulnerable to anthropogenic activity in terms of future changes to long-lasting past cycles.

In this paper I offer an approach to different cyclicities and their origins, together with references to representative studies into marine sediments and their relationship with responses to climate systems.

Orbital variability (10^5)

Ice ages

Milankovitch cycles (Milankovitch, 1941) depend upon natural orbital oscillations of the Earth and the amount of insolation (incoming solar radiation it receives). Milankovitch cycles have three quasi-periodicities (ETP parameters) of about 100, 41 and 21 kyr; eccentricity (the Earth´s orbit around the Sun), obliquity or tilt (axial tilt of the Earth in relation to the plane of the ecliptic), and precession of the equinoxes (the rotation of the Earth´s axis, which impinges upon the seasons) (Fig. 1). Eccentricity may also be reflected in a long period of 400 kyr.

General cooling in the Pliocene (Zachos *et al.*, 2001) resulted in the onset of the northern-hemisphere glaciation (NHG) with a growth of the ice-sheets beginning some 2.6 Myr ago (Pleistocene) (Fig. 2). During the Pleistocene two abrupt climate transitions took place, one at 1.4 Ma-million years and another around 1 Ma BP; this latter is called the mid-Pleistocene transition (MPT) (Lisiecki and Raymo, 2007). The Plio-Pleistocene reveals a saw-tooth curve, with changing variability (*cf.* Figure 4 in Lisiecki and Raymo, 2005; stacked benthic $\delta^{18}O$ record) into the Pleistocene Glacial-Interglacial (GI) oscillations, which record the highest amplitude in terms of global temperatures, sea-level, and greenhouse-gas parameters. Their shapes are highly asymmetric because the building-up of ice-sheets (glaciation) takes a very long time (~80 kyr) whilst deglaciation, on the other hand, is comparatively fast (~10 kyr) (Lisiecki and Raymo, 2007). The speed of deglaciation coincides with the rapid release of CO_2 into the atmosphere (Ruddiman and Raymo, 2003; De Saedeleer *et al.*, 2012).

Amid the causes triggering this major climate NHG change are variable continental positions, tectonic uplift, decreased rates of sea-floor spreading, deep ocean circulation, reduction in atmospheric CO_2 levels and insolation. Causes for the MPT are outlined in Lisiecki and Raymo (2007) and include ice-sheets formation and stabilization, changes in ice margins and an increase in insolation thresholds.

The timing of the major climate terminations is essential and three timescales are often used, all based upon the $\delta^{18}O$ of benthic foraminifera and tuned to an astronomical curve, where terminations are tightly linked to increases in summer 65°N radiation, ie. deglaciations or warming at high northern latitudes: SPECMAP (Imbrie *et al.*, 1984; Raymo, 1997), covering 800 kyr; PISO-1500 RPI, based on the geomagnetic palaeo-intensity (Channel *et al.*, 2008; 2009) for the last 1.5 Myr; and LR04 (Lisiecki and Raymo, 2005) for the Pliocene-Pleistocene (5.3 Myr).

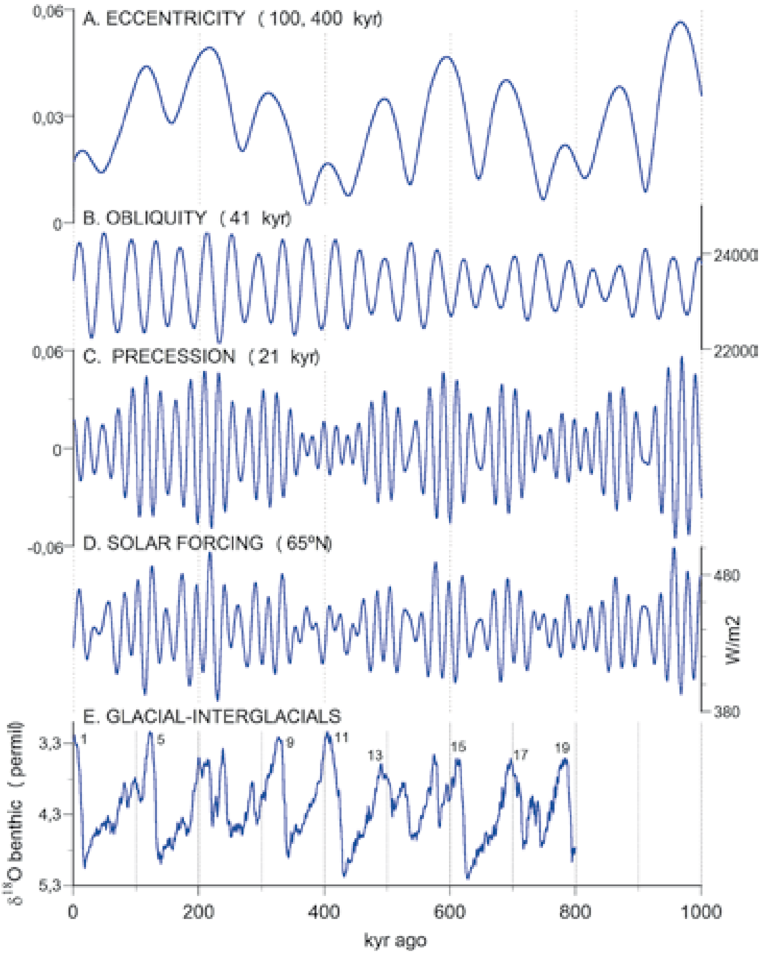

Figure 1. Natural orbital oscillations of the Earth (Milankovitch cycles) recorded in marine sediments. Periodicities are marked by the ETP parameters: (A) eccentricity (the Earth´s orbit around the Sun), (B) obliquity or tilt (the axial tilt of the Earth in relation to the plane of the ecliptic), and (C) precession (rotation of the Earth´s axis). (D) is solar forcing at 65ºN latitude, and (E) glacial-interglacial $\delta^{18}O$ stack in benthic foraminifera of the North Atlantic (Lisiecki and Raymo, 2005). Build with data available from NOAA/NGDC Paleoclimatology Program, Boulder CO, USA (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/), and IGBP PAGES/World Data Center for Paleoclimatology. Original references: Berger and Loutre (1991), and Lisiecki and Raymo (2005).

Figura 1. *Variabilidad orbital natural de la Tierra (ciclos de Milankovitch) registrados en los sedimentos marinos. Las periodicidades se identifican como ETP: (A) eccentricidad (órbita de la Tierra alrededor del Sol), (B) Oblicuidad (inclinación del plano axial de la Tierra en relación con la eclíptica del Sol), y (C) Precesión (rotación del eje de la Tierra). (D) es la Irradiancia solar y (E) Registro Glacial-Interglacial medio de $\delta^{18}O$ de foraminíferos bentónicos del Atlántico Norte (Lisiecki y Raymo, 2005). Datos disponibles en NOAA/NGDC Paleoclimatology Program, Boulder CO, USA (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/), o IGBP PAGES/World Data Center for Paleoclimatology, Referencias bibliográficas originales: Berger y Loutre (1991) y Lisiecki y Raymo (2005).*

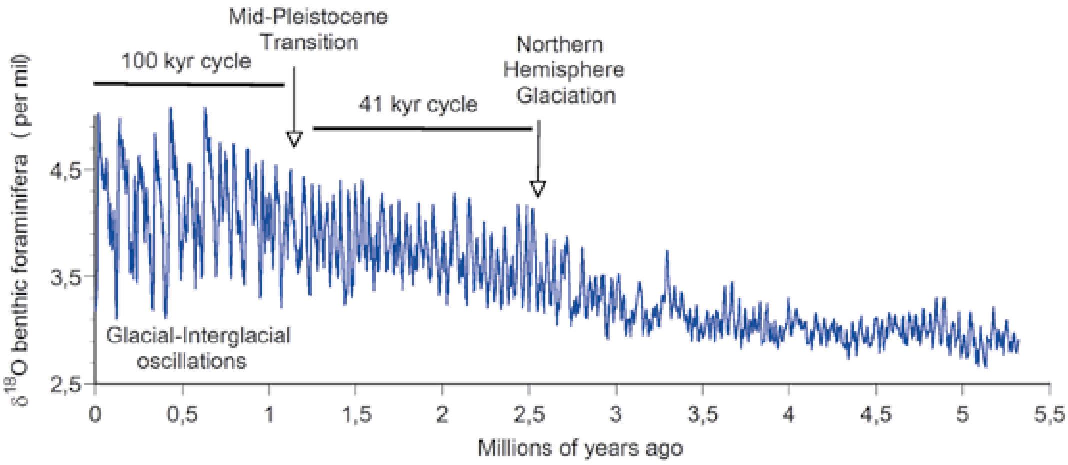

Figure 2. Past 5.5 Myr record of $\delta^{18}O$ in benthic foraminifera with obvious changes in cyclicity at the onset of the northern hemisphere glaciation (2.6 Ma) and the mid-Pleistocene transition (~1 Ma) towards the glacial/interglacial modes. Data available from NOAA/NGDC Paleoclimatology Program, Boulder CO, USA, or IGBP PAGES/World Data Center for Paleoclimatology. Original data from Lisiecki and Raymo (2005).

Figura 2. *Cambios de la ciclicidad para el intervalo del Plio-Pleistoceno (últimos 5,5 Ma) en los isótopos ($\delta^{18}O$) de foraminíferos bentónicos. El inicio de la Glaciación del Hemisferio Norte se produce hace 2,6 Ma. La Transición del Pleistoceno Medio ocurre hace ~1 Ma y da lugar al paso de una frecuencia dominante de 41 ka a otra de 100 ka, con las oscilaciones correspondientes a las Glaciaciones-Desglaciaciones bien marcadas. Datos disponibles en NOAA/NGDC Palaeoclimatology Program, Boulder CO, USA. Referencia bibliográfica original: Lisiecki y Raymo (2005).*

Mechanisms and cyclicity

It was always thought that the 100-kyr cycle represented the major component of northern-hemisphere ice volume changes. Since the mid 90´s, however, many authors have questioned this. In an exhaustive revision, Elbikki and Rial (2001) concluded that the Milankovitch hypothesis arisen by Hays *et al.* (1976) still holds good, the climate system responding non-linearly to all Milankovitch frequencies and the eccentricity signal bring deeply imbedded in the marine time-series data.

Shackleton (2000) emphasised the difficulty involved in explaining the predominant cycle in terms of orbital eccentricity (both small in amplitude and late in phase), and the non-linearity of the response of the ice-sheets to the 100-kyr period of orbital eccentricity when the precession dominated 65ºN summer insolation record is used as a forcing (model of Imbrie and Imbrie, 1980). He demonstrated that atmospheric carbon, air temperature (Vostok, Antarctica) and deep-water are in phase with orbital eccentricity (dominant 100-kyr period), while ice volume shows a dominant obliquity peak and lags the three previous variables by 5 to 14 kyr (*cf.* Figure 5 in Shackleton, 2000). Moreover, Shackleton infers that the influence of CO_2 concentration in the atmosphere generates the effect of orbital eccentricity. Elbikki and Rial (2001) reacted to the implied linearity of the system response to precession and obliquity, by claiming that Rial and Anaclerio (2000) had found obliquity to be non-linear. The problem of linearity versus non-linearity is still a moot point (*cf.* review by Elbikki and Rial, 2001). An additional issue, discussed by the same authors, is whether insolation is driven or considered independently in the models. In general, the models range from those that assume self-sustaining internal oscillations with no relation to insolation to those insolation-driven producing oscillations by non-linear coupling of higher frequency, or non-linear resonance.

Paillard (2001) challenged the classical astronomical theory and suggested a new paradigma. He contested the sufficiency of linear and weakly linear systems to fully explain the dynamics of the 100-kyr cycles, introducing the concept of climate thresholds, encouraged by the increasing number of observations in the long term marine and ice records becoming available, such as the glacial 110-10-kyr abrupt switches, the changing patterns of long series of GI terminations and the atmospheric concentrations of carbon dioxide and methane. Paillard examined several pitfalls in the classical astronomical theory of palaeoclimate, which he identified as the "100-kyr problem" (although the main cyclicity in the palaeoclimatic record is close to 100-kyr, there are no significant orbitally induced changes in the radioactive forcing of the Earth within this frequency range), the "mid-Pleistocene transition problem" (i.e. the change from a 41-kyr to a 100-kyr dominant periodicity at about 1 Ma occurred without major changes in orbital forcing or in the Earth's configuration), and the "stage 11 problem" (the most prominent GI transition occured at a time of minimal orbital variations). Elbikki and Rial (2001) identified additional awkward issues: the wide amplitude of the 100-kyr ice age cycles; the variation in glacial cycle duration over the past 800 kyr; the absence of significant spectral power in the 400-kyr cycle over the past 1.2 Ma; and the presence of non-orbital spectral peaks in the climate record. Paillard (2001) outlines potential components of the climate system, such as atmospheric CO_2 concentration, Southern Ocean productivity, and global deep-water circulation that may play an important role in the climate cycles, apart from ice-sheets.

Many authors have tried to resolve these drawbacks, particularly during the last decade (*cf.* Benzi *et al.*, 1982; Muller and MacDonald, 1997; Ridgwell *et al.*, 1999; Tziperman and Gildor, 2003; Loutre and Berger, 2003; Paillard and Parrenin; 2004; EPICA community members, 2004; Berger *et al.*, 2005; Huybers, 2007; Luthi *et al.*, 2008; Loulergue *et al.*, 2008; Bintanja and van de Wal, 2008; De Saedeleer *et al.*, 2012). Lisiecki and Raymo (2005, 2007) examined the response to changes in $\delta^{18}O$ in benthic foraminifera in 57 marine records and found powerful obliquity (41-kyr) and precession (21-kyr) throughout the whole 5.3 Ma, but with increasing sensitivity to obliquity before 1.4 Ma, and precession after 2.6 Ma. Although 100-kyr cycles have been dominant for the last 0.8 Myr no abrupt climate transition was encountered in the obliquity and precession responses; new findings and differences that need further explanation. These authors state that GI cycles are orbitally forced and paced rather than self-sustained, as supported by Huybers (2007, 2009), which has served to arouse new controversy.

GI equatorial climate is controlled by both high-latitude forcing processes (dominant 100 and 41-kyr cycles), mainly during glacials, when North Atlantic SSTs are cold and enhance dust transport and arid conditions, but also by low-latitude precessional monsoon forcing (dominant 21-kyr cycles) during interglacials, particularly before 2.5 Myr BP (deMenocal, 1993; Leuschner and Sirocko, 2003; Tjallingil *et al.*, 2008).

Marine palaeo-climate data series

Apart from the key papers referred to above, other authors confirm the interaction of orbital cycles in multi-proxy series such as C and O gradients (Charles *et al.*, 2010); biomarkers (Martrat *et al.*, 2004); planktonic foraminifera (Hernández-Almeida *et al.*, 2012); and pollen (Tzedakis *et al.*, 2004). Precessional low-latitude orbital forcing at Atlantic, Mediterranean and Pacific Equatorial sites have been identified by their eolian and biogenic components (deMenocal *et al.*, 1993); terrigenous and magnetic sediment properties (Larrasoaña *et al.*, 2003); and diatoms and phytoliths (Abrantes, 2003; Tiedemann and Mix, 2007).

Millennial scale variability (10^3)

Glacial stages

Abrupt climate change finds its best defence in the so-called Dansgaard-Oeschger (DO) and Heinrich (HE) events in palaeoclimate records. DO events were first detected in Greenland ice-cores (Dansgaard *et al.*, 1993; Johnsen *et al.*, 1992) during the last glacial 110 – 10 kyr in a number of 25 paired oscillations known as Greenland stadials (GS) and interstadials (GIS) (EPICA project members, 2006; Rousseau *et al.*, 2006). Heinrich events (Heinrich, 1988) numbered H0 (Younger Dryas) to H6, from the most recent to the oldest (Bond *et al.*, 1997), bear witness to extremely cold conditions and occur between every packet of three DO events. DOs reflect a characteristic pattern of abrupt warming of approximately 10ºC (Greenland) into a interstadial (in decades) and more gradual cooling (in centuries) into severe stadials, though every event lasted for approximately 1 to 3 thousand years. Even though ice-core records were initially established as references, DO and HE events have been widely reported all over the North Atlantic in marine-sediment cores (eg. Fig. 3) with sufficient sedimentation rate and sample resolution (many compiled in Voelker *et al.*, 2002). These millennial-scale saw-tooth pulses seem to have occurred preferably during a period of intermediate global ice volume [marine isotope stage, (MIS)-3], between extremely cold glacial and warm interglacial modes (MIS 2-4) (McManus *et al.*, 1999; Schulz, 2002; Ganopolsky and Rahmstorf, 2002), and to some ex-

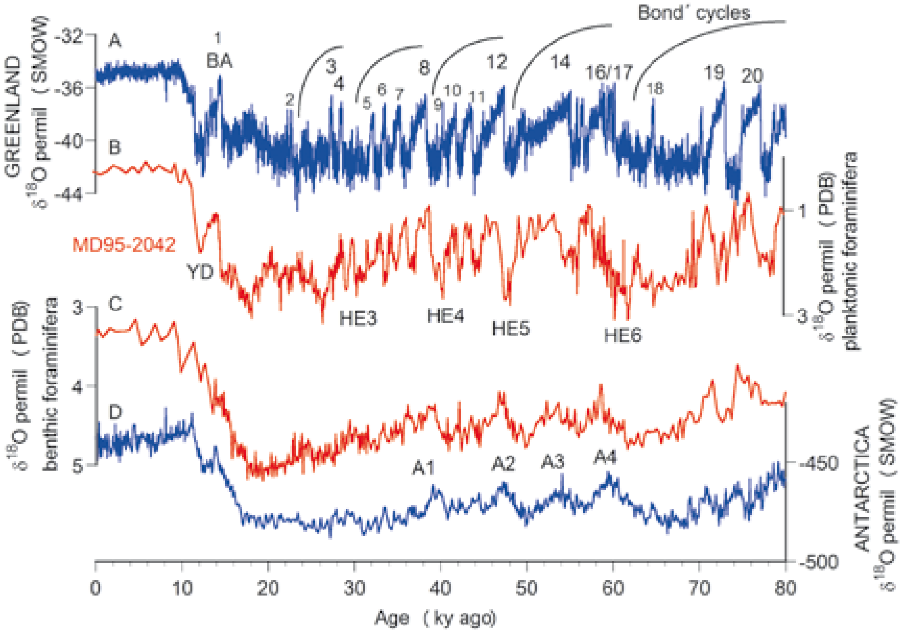

Figure 3. Millennial-scale abrupt climate variability (11-80 ka) of core site MD95-2042 (Shackleton *et al.*, 2000) on the North Atlantic, Portuguese Margin, rescaled to SFCP (Shackleton *et al.*, 2004), showing (B) planktonic and (C) benthic δ^{18}O isotopes. Correlation between marine sediments and ice-cores: (A) Greenland´ GRIP δ^{18}O (SMOW) isotopes (Johnsen *et al.*, 1992) and (D) Antarctica Vostok δ^{18}O (SMOW) isotopes (Jouzel *et al.*, 1999). Numbers 1-20 are Dansgaard-Oeschger climate oscillations, HE stands for Heinrich events, BA for Bolling-Allerod, YD for Younger Dryas, and A for Antarctica warm events (Blunier and Brook, 2001). Bond cycles shown by curved lines in Greenland´s profile (Bond *et al.*, 1993). Data available from www.esc.cam.ac.uk/pop/popdata/.

Figura 3. *Variabilidad climática milenaria de isótopos de O de foraminíferos planctónicos (B) y bentónicos (C), entre los 11 y 80 ka en el Atlántico Norte, en el testigo MD95-2042 del margen de Portugal (Shackleton* et al.*, 2000), corregido para la escala temporal SFCP por Shackleton* et al. *(2004). Correlación de registros de sedimentos marinos con hielo polar: δ^{18}O (SMOW) de la perforación GRIP de Groenlandia (Johnsen* et al.*, 1992) (A) y δ^{18}O (SMOW) de la Vostok de la Antártida (Jouzel* et al.*, 1999) (D). Los números de 1-20 indican oscilaciones climáticas Dansgaard-Oeschger, HE los eventos Heinrich, BA indica Bolling-Allerod, YD es el Younger Dryas, y A los episodios cálidos de la Antártida (Blunier y Brook, 2001), desfasados con los IS cálidos de Groenlandia. Los ciclos de Bond se encuentran representados en el registro (A) (Bond* et al.*, 1993). Todos los datos se encuentran disponibles en www.esc.cam.ac.uk/pop/popdata/.*

tent in other glacials such as MIS-6, 8, 10 and 12 (*cf.* McManus *et al.*, 1999; de Abreu *et al.*, 2003; Siddall *et al.*, 2007; Margani *et al.*, 2010).

In the Antarctic ice-cores for the same time period of MIS 4-2 oscillations depict less abrupt changes and more squarer shapes (*cf.* Figure 4 in Shackleton *et al.*, 2000). Inter-pole comparison of the Greenland DO-HE sequence pattern with the Antarctica counterparts (EPICA, 2006) (Fig. 3), reveals three important features: 1) rapid cooling and warming in Greenland; 2) the absence of rapid warmings in the Antarctic; and 3) the north and south poles out-of-phase, linked with the meridional overturning circulation (MOC) and atmospheric circulation.

Mechanisms

The ocean MOC, termed earlier THC or "the great conveyor belt" (Broecker, 1991; reviews in Alley, 2007 and Lozier, 2010), is an important component of the Earth´s climatic system. The MOC can be defined as a "system of surface and deep currents encompassing all ocean basins. It transports large amounts of water, heat, salt, carbon, nutrients and other substances around the globe, and connects the surface ocean and atmosphere with the huge reservoir of the deep sea" (Schmittner *et al.*, 2007).

The idea that fresh water discharged into the North Atlantic leads to the reorganization of oceanic circulation and heat transport coupled with atmospheric changes was championed by Broecker (1994; Alley, 2007, and references herein), and has been greatly expanded upon since then. Theoretical models have shown that only a small perturbation (weak freshwater forcing) is required to trigger abrupt changes in the MOC (Stocker and Wright, 1991; Fanning and Weaver, 1997; Manabe and Stouffer, 1997; Sakai and Peltier, 1999; Ganopolski and Rahmstorf, 2001), and so the key issue revolves around finding the mechanisms that influence the NA freshwater budget. Atmospheric response to North Atlantic oceanic change is very rapid, affecting the strength of the trade winds and upwelling, the migration of intertropical convergence zone (ITCZ), the intensity of the Asian monsoon and temperatures and ventilation in the North Pacific (*cf.* Timmermann and Goosse, 2004; Zhang and Delworth, 2005).

Hundreds of coupled ocean-atmospheric models of different complexity give the response of ocean circulation to freshwater and temperature forcing and generally imply the existence of thresholds and hysteresis in the strength of the MOC (*cf.* review in Rahmstorf *et al.*, 2005). The climate system exhibits multiple modes of operation between the two extremes of MOC-on and MOC-off. The mode switches vary depending upon the place and strength of sinking cold, and dense water: 1) in the modern ocean (Holocene-style interglacial) the NADW at high-latitudes sinks to great depths with intense overturning, 2) in the glacial ocean, reduced sinking to intermediate depths occurs at lower latitudes; and 3) at HE, there is no sinking water and overturning collapses (Sarnthein *et al.*, 1995; Alley *et al.*, 1999; Rahmstorf, 2002; Stocker, 2002). For a large freshwater input, involving a substantial release of icebergs such as that observed in the North Atlantic during HE, deep-water formation is temporarily switched off, causing no great cooling in Greenland, but warming in Antarctica, with heat transmitted to the northern hemisphere.

Inter-hemispheric synchronization of ice records between Greenland and Antarctica, which is decisive to an understanding of the role of global ocean circulation, has been reliably achieved on the basis of based on atmospheric gas concentrations (Bender *et al.*, 1994; Blunier and Brook, 2001; Blunier *et al.*, 2007). The resulting picture synchronises maximum HE cooling in Greenland with maximum warming in Antarctica. Furthermore, during the last deglaciation, the northern Oldest Dryas – Bolling/Allerod – Younger Dryas sequence matches up with warming Antarctic Cold Reversal – warming in the southern hemisphere (Blunnier *et al.*, 1997; Stenni *et al.*, 2001; Clark el al., 2002), which is clearly out-of-phase. There is also a one-to-one coupling of inter-hemispheric climate events with changes in the overturning of strength and heat transport (Skinner *et al.*, 2007). These observations support the bipolar see-saw climatic model, which is fairly well established nowadays (*cf.* Clark *et al.*, 2002; Alley *et al.*, 2007; Severinghaus, 2009; Stenni *et al.*, 2010) based on the THC and the conveyor belt paradigma (Broecker, 1998; Stocker, 1998; Alley *et al.*, 1999). The basic mechanism assumes that the shutting-off of THC triggers rapid cooling in the north and warming in the south, because heat is no longer transported northward. The rate of deep-water formation and perturbation of the THC is responsible for millennial scale events. DO and HE events are, therefore, an integral part of the thermal bipolar seesaw balance that produces the asymmetric response between the hemispheres (Blunier *et al.*, 1998; figure 1 of Clark *et al.*, 2007). Among the possible mechanisms that may trigger DO-HE events are cross-equatorial ocean heat transport, coupled ice-ocean due to sealevel changes, and ice-shelf instability and subsurface warming (*cf.* review by Schmittner *et al.*, 2007).

Given chronostratigraphic uncertainties, signs of phasing beyond synchrony are even more complex to resolve. It is important though to decipher which pole leads rapid climate change. Steig and Alley (2002) claim that only 50% of the Greenland-Antarctica behaviour is in antiphase, and is particularly in phase during cooling. Although most authors validate the see-saw model in their works, it is not yet clear whether the North dials the South (*cf.* Hinnov *et al.*, 2002; Stocker, 2000; Ganopolski and Rahmstorf, 2001; Stocker and Johnsen, 2003; Schmittner *et al.*, 2003; Knutti *et al.*, 2004), or viceversa (*cf.* Bender *et al.*, 1994; Charles *et al.*, 1996; Blunier *et al.*, 1997; Knorr and Lohmann, 2003; Huybers, 2004). Or perhaps it remains an ambiguous, unsolved question (Skinner *et al.*, 2007).

Cyclicity

The cycle of 1470-kyr deduced from the ice-cores by Groots and Stuiver (1997) seems to be regular and reliable for DO events during the 110-10-kyr glacial period (Bond and Lotti, 1995; Mayewski *et al.*, 1997; Rahmstorf, 2003), and is strongly imprinted in marine cores.

A long-term cooling trend that envelopes around three DO oscillations and concludes in an extreme stadial, an HE event, is named a Bond cycle (Bond *et al.*, 1993); the following cycle begins abruptly with an outstandingly warm interglacial (Fig. 3). HEs occur approximately every 7 kyr (*cf.* Clark *et al.*, 2007). But still spectral analysis often fails to notice any clear periodicity, possibly due to imprecise time scales (Alley, 2007).

Internal forcing of the periodicity of abrupt climate events such as DOs and HEs remains uncertain, mainly because of the complex interaction between the stability of ice-sheets and the hydrological cycle (precipitation, run-off, iceberg discharge). Some authors have suggested that external forcing such as orbital insolation might influence the timing of abrupt DO climate changes through frequency (or phase) modulation (Rial and Yang, 2007). Braun *et al.* (2005) go even further and claim the reproduction of DO events in absence of the 1.5-kyr cycle in the forcing and spectrum because this number represents the superimposition of two freshwater cycles with shorter periods of 87 and 210 yrs in a non-linear system.

Some models, on the other hand, assumed a stochastic resonance mechanism to explain periodic elements of abrupt climatic events. Rahmstorf (2003) claims that DOs are discrete events paced by a regular 1470-kyr cycle (the clock) rather than being cycles themselves. Using a simple event-detection algorithm, this period falls into the 95% confidence interval. The presence of other secondary maxima at 3 and 4.5-kyr in noise amplitude in the Greenland ice-core data suggests that the stochastic resonance variability in the glacial climate is suboptimal for triggering events of time evolution, amplitude, special pattern and interspike intervals such as DO events (Ganopolski and Rahmstorf, 2002). The authors outline, however, that stochastic resonance would be limited to switches between deep-water production sites rather than thermo-haline on-off regimes. If a stochastic system does exist, given its regularity its origin must be outside the Earth´s system because oscillatory modes within the Earth are more irregular.

The cause of periodic oscillation remains uncertain, but weak internal signals of noise and periodic forcing possibly combine to cause transitions when the phase of the periodic forcing is favourable (Alley *et al.*, 2001). Rial and Yang (2007) add that in nature, DOs could result from a combination of convection, turbulence and stochastic resonance.

Marine palaeo-climate data series

The connection between ice and the ocean surface was made in the North Atlantic by Bond *et al.* (1993), later recognised together in the surface- and deep-ocean at one site in the Iberian margin by Shackleton *et al.* (2000), and further verified by Saikku *et al.* (2009) in the Pacific.

A huge number of studies have resorted to different proxy-variables and generated a collection of marine data-sets in which the Earth´s system clearly responds to millennial cyclicity. Many authors have validated ocean-atmospheric models and integrated real observations and simulations in an attempt to improve future predictions regarding climate change, among whom are: Grousset *et al.*, 1993; Lebreiro *et al.*, 1996; van Kreveld *et al.*, 1996; Little *et al.*, 1997; Vidal *et al.*, 1997; Vidal *et al.*, 1998; Kennett *et al.*, 2000; Cacho *et al.*, 2000; Shackleton *et al.*, 2000; Kanfoush *et al.*, 2000; Peterson *et al.*, 2000; Grousset *et al.*, 2001; Pailler and Bard, 2002; Elliot *et al.*, 2002; de Abreu *et al.*, 2003; Hendy and Kennett, 2003; Moreno *et al.*, 2004; Sierro *et al.*, 2005; Voelker *et al.*, 2006; Skinner and Elderfield, 2007; or Saikku *et al.*, 2009.

Climate biogeochemical proxies operate in the same way for long-lived GIs than short-lived inter/stadials climate changes because ocean-circulation patterns are common irrespective of time scales. The THC is behind the orbital and millennial scales. Becker *et al.* (2006) maintain that the 21-kyr and millennial cycles prevailed around 2.5 Ma BP despite the transition from the 41-kyr-dominated glacial cycles of the late Pliocene to the 100-kyr cycles of the late Pleistocene. Suborbital and millennial scale cycles are pervasive not only throughout glacials (McManus *et al.*, 1999; de Abreu *et al.*, 2003; Becker *et al.*, 2006; Margani *et al.*, 2010), but also during substadials of interglacial stages (McManus *et al.*, 1994; McManus *et al.*, 1999; Chapman *et al.*, 1999; Oppo *et al.*, 2001;Tzedakis *et al.*, 2004; Schaefer *et al.*, 2005; Desprat *et al.*, 2007; 2008). Persistent 1-3-kyr cycles throughout MIS 5-7-9-11-13 support the development of this type of cyclicity in the absence of large ice-sheets, emphasizing that other factors apart from ice volume, such as ocean-ice interactions and mid- and deep-water play an important role in amplifying the suborbital signal in any ocean (Oppo *et al.*, 2001). What also emerges is that although the broad timing of interglacials is consistent with orbital theory their specific duration may be dictated by millennial variability (Tzedakis *et al.*, 2004).

Holocene stage

Relatively less abrupt climatic events than that of last glacial period also happened worldwide during the Holocene (last 11.5 cal kyr BP) (*cf.* review by Mayewski, 2004); the common 1 470-kyr cycle emerges throughout its marine palaeoclimate records (Bond *et al.*, 1997). In the Holocene, the term Bond cycle is often used for the periodicity of ~1.5 kyr after Bond *et al.* (1997) in which ice-rafted quartz and red-stained grains appear in marine sediments, creating confusion with the last glacial terminology of the 7-kyr-Bond cycle (referred to above).

The origin of the ~1.5-kyr pacing in the Holocene is far from consensual, although a large number of authors cite solar effects and the MOC as being the most probable origins of this variability (*cf.* review by Mayewski, 2004). Debret *et al.* (2007), applying wavelet analysis (WA), which is appropriate for non-stationary variability, demonstrated that during the Holocene combined forcing mechanisms with variable contribution over time would account for the observed oscillations. Solar forcing would explain the 1-kyr and 2-kyr cycles and oceanic forcing the 1.5-kyr cycle, arguing against Bond and co-authors´s interpretation of solar output governing the quasi-periodic 1.5-kyr cycle (2001), because this signal can be split into the 1-kyr and 2.5-kyr cycles by Fourier transform Blackmann-Tuckey and WA. Palaeoclimate proxies studied in marine sediments suggest a signal close to the 1.5-kyr (Bianchi and McCave, 1999; Chapman and Shackleton, 2000; Giraudeau *et al.*, 2000), which probably contains a relative combination of both of the previous forcing mechanisms, or others (atmospheric NAO, Giraudeau *et al.* 2000; current intensity, Bianchi and McCave, 1999; geomagnetic field, St-Onge *et al.*, 2003). WA also shows that the 2.5-kyr cycle is continuous throughout the Holocene whilst ~1.5-kyr cycle dominates the record before it.

Ganopolski and Rahmstorf (2001) followed the presence of the ~1.5-kyr period throughout the Holocene but its signature is very weak because it is not amplified by the ocean circulation instability typical of glacial times. Schulz and Paul (2002) report a significant, recurrent 900-yr harmonic signal component in the Holocene variability; they suggest that climate cycles can be described as damped oscillations, triggered by cooling events at 8.3 ka and 4.7 ka, with an underlying mechanism behind that might transit from the glacial to the Holocene. Many other authors (c*f.* Sarnthein *et al.*, 2003) have put forward multiple periodicities of variable significance.

Centennial and multi-decadal scale variability (10^1-10^2)

Short-term oscillations of multi-decadal (30-80 yr), decadal (8-12-yr), and interannual (<8-yr) variability have been forcing responses in rainfall, river floods, droughts, hurricanes, coastal upwelling and ocean productivity, and sea level, among others, and have therefore had a great ecological and socioeconomic impact on climate changes at the human scale.

Several modes of variability have been established for the modern climate system, such as those of global impact like El Niño-southern oscillation (ENSO) (Gershunov and Barnett, 1998; Enfield *et al.*, 2001), the North Atlantic oscillation (NAO) (Hurrell, 1995), the Atlantic multi-decadal oscillation (AMO) (Kerr, 2000; Enfield *et al.*, 2001), and other more regional ones, such as the Pacific Decadal oscillation (PDO) (Mantua *et al.*, 1997) also known as the North Pacific oscillation (NPO) (Gershunov and Barnett, 1998), the Arctic oscillation (AO) (Ambaun *et al.*, 2001; Marshall *et al.*, 2001), and the southern annular mode (SAM) (Kidson, 1988; Arblaster and Meehl, 2006). These indices are atmospheric temperature and pressure phenomena defined in instrumental climate and weather data, and therefore their records are limited to instrumental coverage over about the last 150 years. Fortunately these high-frequency modes are also archived in longer-term multi-decadal to centennial scale data series such as historical documents, tree rings, shell rings, ice-cores and corals, as well as varved sediments in lakes and sediments in marine environments (Fig. 4), thus extending the records back in time, and allowing the assessment, calibration, and robustness of multi-decadal variability.

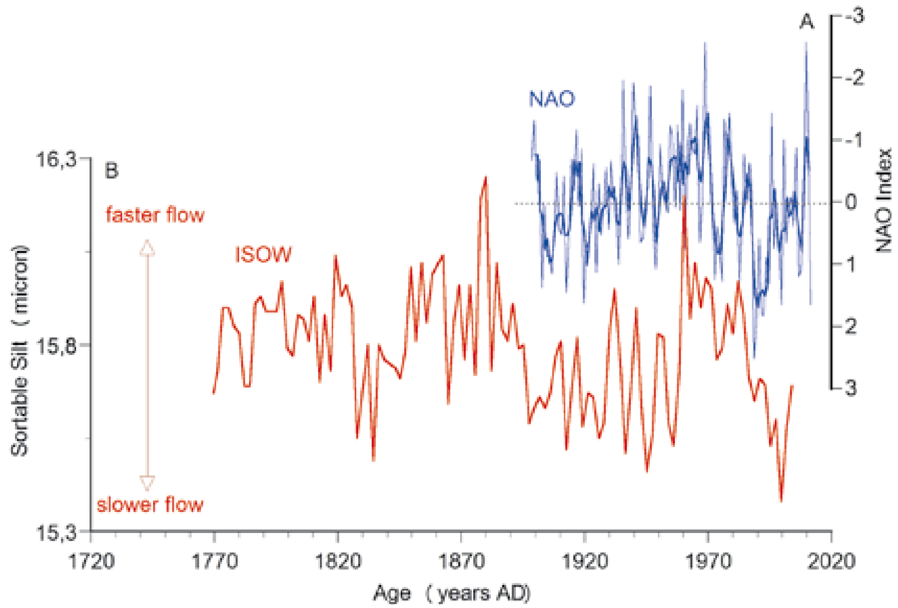

Figure 4. Multi-decadal scale climate variability. (A) North Atlantic oscillation Index-winter (Hurrell, 2003), and (B) deep-ocean flow speed (sortable-silt proxy used for changes in Iceland-Scotland overflow water, ISOW) on the eastern flank of the Reykjanes Ridge (core RAPID-21-12B) for the last 230 years. NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (2003), and Sortable Silt from NOAA/NGDC Palaeoclimatology Program, Boulder CO, USA. Original reference: Boessenkool *et al.* (2007).

Figura 4. *Variabilidad climática multi-decadal. (A) Índice de la Oscilación del Atlántico Norte para los meses de invierno (Hurrell, 2003), y (B) velocidad de la corriente Iceland-Scotland Overflow Water (ISOW), obtenida por medio del* Sortable Silt*, en el testigo RAPID-21-12B, situado en el flanco este de la Cordillera de Reykjanes, durante los últimos 230 años. Las curvas muestran una notable correlación entre la fase negativa de la NAO y una mayor velocidad del flujo de la ISOW. Datos del Index de la NAO tomados de la Climate Analysis Section, NCAR, Boulder, USA, Hurrell (2003), y* Sortable Silt *de la NOAA/NGDC Palaeoclimatology Program, Boulder CO, USA. Referencia bibliográfica original: Boessenkool* et al. (2007).

Mechanisms and cyclicity

ENSO interdecadal variability has a strong impact on the climates of North Pacific and North Atlantic. Typical El Niño-events show low pressure over the northeast Pacific, dry northwest and wet southwest. The (warm) ENSO is inversely related to the (weak) Indian summer monsoon (Kumar *et al.*, 1999). Lags in ENSO and the monsoons have also been investigated (Webster and Yang, 1992). The basic physics of the ENSO cycle is reasonably well known (Tudhope and Collins, 2003), although some aspects remain poorly understood. The ENSO varies considerably in strength and frequency, it was particularly strong, for example, in 1982–83 and again in 1997–98 (Wolter and Timlin, 1998). Its cyclicity tends to be one of 3 to 7 years (Dong and Sutton, 2002).

NAO is associated with changes in the surface westerlies across the North Atlantic towards Europe. The NAO index is determined from the difference in sea-level pressure between winters with larger values than 1 and -1 (Hurrell, 1995; 2001; Rodwell *et al.*, 1999). A positive phase is associated with strong westerly winds over the subpolar gyre, leading to enhanced ocean-to-atmosphere heat fluxes. The wider amplitudes of NAO occur at the subpolar (Iceland) and tropical (Azores) North Atlantic. An up-to-date compilation can be found in Hurrell *et al.* (2003). The NAO has a periodicity of 2 to 4 (or 8) years (Cook *et al.*, 2002).

The AMO is marked by a persistent, long-term pattern of alternations of warm and cold sea surface temperature (SST) anomalies in the North Atlantic basin and is more properly defined as the first rotated empirical orthogonal function (EOF) of the non-ENSO global SST field (Mestas-Nuñez and Enfield, 2001). Although this mode shows maximum amplitudes in the Atlantic basin, it also includes a positively correlated multi-decadal oscillation in the North Pacific (Minobe, 1997). During warm (cold) phases, the entire North Atlantic ocean shows positive (negative) SST anomalies, meaning less precipitation and consequent droughts (Kerr, 2000; Feng *et al.*, 2009). The AMO has been reconstructed for the last few centuries (Gray *et al.*, 2004; Mann and Park, 1995) as well as being identified in several proxy records (Shabalova and Weber, 1999; Stocker and Mysak, 1992; Mann *et al.*, 1995; Delworth and Mann, 2000; Lohmann *et al.*, 2004). It shows a more homogeneous pattern than the NAO, with positive or negative anomalies spanning the whole North Atlantic. Spectral analyses of climatic time-series show a significant peak at around 70-yr (Schlesinger and Ramankutty, 1994; Delworth and Mann, 2000), as well as around the 90-yr and 210-yr bands of the Gleissberg solar irradiance cycle (Ogurtsov et al., 2002; Dergachev, 2004) and the 11-yr cycle (Lohmann et al., 2004).

Several mechanisms both internal and external have been identified to explain these high-frequency cycles such as the THC, sea ice switches, melting ice, wind, latitudinal shifts in the ITCZ and tropical air convection, or solar irradiance and volcanic eruptions, apart from stochastic drivers.

Most coupled atmosphere-ocean models involve THC fluctuations as the internal driver of multi-decadal variability in the Atlantic ocean (Delworth *et al.,* 1993; 1997; Timmermann *et al.,* 1998; Delworth and Mann, 2000; Marshall *et al.*, 2001; Latif *et al.*, 2004; Cheng *et al.*, 2004; Dai *et al.*, 2005; Knight *et al.*, 2005). A strong (weak) Atlantic MOC leads to a warm (cold) AMO phase. In a simulation by Timmermann *et al.* (2005) the THC shutdown in the North Atlantic accompanied a reduction in variability in the ENSO because of a deepening of the mean zonal tropical Pacific thermocline. Biastoch *et al.* (2008) have suggested that the dynamics of the Agulhas leakage at the southern tip of Africa contributes to the MOC signal in the sub- and tropical Atlantic at a similar magnitude to that of the northern source in their influence on multi-decadal variability.

In their model to reproduce MOC multi-decadal variability Vellinga and Wu (2004) lay emphasis upon air-sea coupling, where a stronger MOC during a warmer phase in the Atlantic provoked a northerly shift in the ITCZ and fresher water input to the tropical North Atlantic. Yu *et al.* (2002) and others focussed on the impact of surface heat flux and wind stress in the Indian Ocean on the ENSO cycle over the Indo-Pacific Ocean region. Dima and Lohmann (2007) introduced the sea-ice response to wind forcing, with a thermo-haline circulation adjustment to freshwater forcing, the SST response to it, oceanic adjustment in the North Pacific and the time scale of the associated multi-decadal cycle. Both these latter authors and Delworth and Greatbatch (2000) state however that given the decadal-scale memory of a two-component atmosphere–ocean system, a stochastic forcing applied to the THC would also suffice to yield multi-decadal periodic climatic evolution, regardeless of sea-ice dynamics.

Meanwhile, Schlesinger and Ramankutty (1994) proposed that the AMO is probably internally driven by deterministic processes, an idea supported by the numerical experiments of Andronova and Schlesinger (2000), who produced 70-yr cycles not generated by external forcing. Ottera *et al.* (2010), however, evoked other externally imposed mechanisms such as natural climate changes in solar irradiance and volcanic eruptions, which affect the amount of radiation transmitted, reflected and absorbed by the atmosphere, as forcings to drive phasing of northern hemisphere atmospheric circulation and multi-decadal variability in the THC. Solar modulation has also been proposed by Ogi *et al.* (2003), Ogurtsov *et al.* (2002), or Lohmann *et al.* (2004) among others.

Overall, mechanisms proposed among others by Delworth *et al.* (1993, 1997, 2006), Timmermann *et al.* (1998), Timmermann and Goosse (2004), Vellinga and Wu (2004), Zhang and Delworth (2005), Jungclaus *et al.* (2005), Zhang and Vallis (2006) and Dima and Lohmann (2007), share common features including THC variations, ocean–atmosphere interactions, North Pacific manifestations, and hemispheric atmospheric variations.

Marine palaeo-climate data series

Some additional cases, not already mentioned, where marine series record multi-decadal variability, are clearly those to the north of Iceland, where SST concurs with bottom currents in the North Atlantic and titanium series in the Cariaco Basin, which are in turn connected with low-latitude ITCZ changes over the last 4.5 kyr (Sicre *et al.*, 2008); or the correlation shown by Boessenkool *et al.* (2007) between more vigorous Iceland-Scotland overflow water (ISOW) and a negative NAO index for the last 230 years (Fig. 3), with its implications for the Atlantic MOC (AMOC).

Furthermore, continental climate is also reflected in marine- sediment cyclicity according to their pollen, coastal diatoms, biomarkers, eolian and riverine components, on a centennial scale (*cf.* Bartels-Jonsdottir *et al.*, 2006; Lebreiro *et al.*, 2006; Alt-Epping *et al.*, 2009). But marine sites recording land-sea link variability are also common on millennial (*cf.* Sánchez Goñi *et al.*, 2002; Jullien *et al.*, 2007; Lebreiro *et al.*, 2009; Romero *et al.*, 2011), and orbital (*cf.* Harris and Mix, 1999) scales.

Connection between all modes of multi- and decadal variability

Are therefore all decadal variability modes connected? What is the role of the MOC in connecting modes of decadal timescales? Is sea ice in the North Atlantic linked with the ITCZ?

Attempts to answer questions about interaction between the various modes of short-term variability are contained in many works. Zhang and Delworth (2007) questioned the influence of the AMO upon North Pacific variability modes such as the PDO, and used a climate model to simulate an ensemble-mean that suppresses North Pacific variability and internally generated ENSO teleconnections, but did show the AMO forcing North Pacific multi-decadal variability. ENSO events, on the contrary, impose dry conditions in the western Pacific, warmer than average conditions in the northern United States and wetter than average conditions to the south, suppressing hurricane development in the Atlantic. Climatic anomalies tend to be weak and spatially incoherent during low North Pacific oscillation (NPO)–El Niño and high NPO–La Niña winters; typical El Niño patterns are strong and consistent during the high phase of the NPO, associated with an anomalous cold northwestern Pacific, and vice-versa during La Niña (Gershunov and Barnett, 1998).

Dima and Lohmann (2007) and Dong and Sutton (2002) summarize how the multi-decadal signal is transferred from the Atlantic to the Pacific through the Tropics (Dima and Lohmann, 2004) via the ITCZ. Furthermore, by means of atmospheric teleconnections it is transmitted from the tropics to the North Pacific (Seager *et al.*, 2001). Here it is amplified by a local positive feedback resulting from ocean–atmosphere interactions, with a delay of several years (Peng and Robinson, 2001; Wu *et al.*, 2003). Nevertheless, the mid/high-latitude atmosphere in the northern hemisphere can also be involved in transferring the multidecadal signal from the Atlantic to the Pacific basin.

Overlap with other time-scales

As seen above, orbital and millennial cyclicities often interact. The same is true for the millennial and multidecadal cycles according to many types of overlapping mode, some of which are mentioned here.

Analogous to DO cycles, modern ENSO conditions correlate with millennial-scale stadials at high-latitudes, whereas La Niña conditions correlate with interstadials (Stott *et al.*, 2002). Similarly, more frequent long-term extreme NAO positive (negative) phases have been found to have influenced the mediaeval warm period (MWP) and little ice age (LIA) periods (*cf.* Abrantes *et al.*, 2005; Trouet *et al.*, 2009), and La Niña-events were more frequent during the MWP (Khider *et al.*, 2011) and MIS5e (Pelejero *et al.*, 2003).

Positive and negative NAOs are dominant in two different phases within HEs in the mid-latitude Atlantic (Naughton *et al.*, 2009). In the tropical latitudes, on the other hand, ITCZ southern shifts coherent with rainfall changes on a millennial HE scale challenge analogous present-day ENSO variability (Leduc *et al.*, 2009). In the same vein as these latter authors, Visser *et al.* (2003) also stress the importance of the tropical Pacific region in driving orbital rather than millennial GI cycles, although in a way similar to that in which the ENSO regulates poleward heat and water vapour fluxes. Pena *et al.* (2008) emphasise the relevance of ENSO-like dynamics on the causes of glacial terminations.

Climate change and anthropogenic forcing – changes in cyclicity?

There is no reason to expect that the modes of climate variability will remain constant in frequency and amplitude in the future (*cf.* Alverson *et al.*, 2003; Lorenz *et al.*, 2006; Koutavas *et al.*, 2006; Clement, 2000; Goosse *et al.*, 2006). We still know little about their centres of action or impact and about how these modes may have developed in the past under different boundary conditions. Atmospheric pollution has altered the radioactive balance of the Earth, making the MOC and anthropogenic forcings to the SST in the Atlantic during the 20th century, for example, difficult to discern (*cf.* Rayner *et al.*, 2003; Delworth *et al.*, 2007; Latif *et al.*, 2007).

Wood et al. (2003) comment about the evolution of the AMOC, writing, "Rapid or irreversible THC shutdown is considered a low-probability (but high-impact) outcome; some climate models of intermediate complexity do show the possibility of such events. The question of the future of the THC is beset with conceptual, modelling and observational uncertainties". Koutavas *et al.* (2006) demonstrated the importance of the position of the ITCZ in modulating the ENSO to influence its future evolution conditioned by changes in atmospheric patterns.

As far as the relationship between CO_2, carbon ocean storage and its chemical partitioning in the sea water are concerned, Goodwin et al. (2009) find that radioactive forcing of the climate is more sensitive to carbon perturbations now than at any time during the last 400 kyr. Therefore, detecting the proximity of some tipping points implies an early warning of system changes (Lenton et al., 2008) and determines alterations in the strengthening or weakening of cycles.

Mitchell et al. (2006) went further in pointing out the occurrence of extreme events in the future due to human-induced climate change, resulting in a non-linear evolution of the MOC, ice sheets and methane release at high latitudes.

Conclusions

Marine records of palaeo-events provide insights into the Earth's past climate variability. The results of spectral analyses reveal a probable combination of multiple modes driven by more than one mechanism. Similar mechanisms seem to function and integrate in a complex system, yielding periodical responses and cyclic patterns regardless of their time-scale. As the past is relevant to future predictions, understanding the modes of cyclic changes is critical, as is discerning the real capacity of anthropogenic activities to interfere in these modes. If GI climate cycles are very large, DO abrupt climate events are faster, and multidecadal climate cycles concern human standards of life, in an equally global way.

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