# Holocene subpolar gyre dynamic as viewed from geochemical tracer records of cold-water corals

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# HOLOCENE SUBPOLAR GYRE DYNAMIC AS VIEWED FROM GEOCHEMICAL TRACER RECORDS OF COLD-WATER CORALS

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***Abstract***

*To reconstruct time series of oceanic patterns beyond the time covered by instrumental sea water measurements geochemical tracers recorded in cold-water corals provide a unique oceanic archive. Throughout this presentation it will be shown, which corals develop surrounding Iceland, which water masses influence and steer the growth of such corals and how the organisms incorporate information about the oceanic regime in which they develop.*

## Introduction

Deep water corals have come to light in the past decade as a new archive to study modern and past ocean circulation patterns (Adkins et al., 1998; Mangini et al., 1998; Montagna et al., 2006; Robinson et al., 2005; Robinson and van de Flierdt, 2009; Smith et al., 1997). Iceland being situated on the northern edge of the North Atlantic is known to be surrounded by a belt of frame work building and solitary deep water corals bathing in a complex oceanic regime driven by Atlantic and Arctic current systems operating at various depth and influenced by the support of matter and freshwater from Iceland's glaciers and volcanic aerosols. Many coral species construct aragonite skeletons to attach themselves in areas of strong bottom water currents. Through calcification trace elements and trace isotopes are incorporated into the skeletons that can be used to reconstruct oceanic parameters such as water mass origin, state of ventilation, temperature and even productivity. In addition, corals incorporate uranium from sea water and thus using uranium series disequilibrium methods the time of growth can be precisely determined (Cheng et al., 2000; Frank et al., 2004). Consequently time series of geochemical tracers can be established that allow reconstructing ocean dynamics and climate change in the past. The northern North Atlantic south of Iceland represents a part of the world ocean of great importance as warm waters are transported towards the north through the Irminger current that enter the supolar gyre and the Arctic Ocean. At depth intermediate depth waters originating in the Labrador Sea re-circulate along the topographic boundaries and at even deeper depth newly formed deep waters from the Norwegian and Greenland Seas enter the basin and mix with deep waters formed in the Labrador Sea to create the southward flowing North Atlantic Deep Water (NADW). Consequently Iceland is situated close to key areas of deep water production and northward flow of warm water. In addition, atmospheric circulation causes changes in the size and strength of the surface gyres that propagate to depth and that cause basin scale modifications of oceanic salt and temperature thus heat budgets. Through the use of "cold-water corals" as oceanic archive we may be able to reconstruct climate related change of the current systems and thus heat transport through time. Here, it will be briefly shown which coral species develop on the southern slopes of Iceland and how corals can be dated and how they can be used to determine the geochemical composition and physical parameters of sea water. The crucial location of Iceland in a highly dynamic environment between two main atmospheric circulation cells and its location at the interface of the oceanic polar front and the Atlantic gyre dynamic is well known since long, but cold-water corals and geochemical tracers to investigate such dynamic hydrological processes, the later operating on scales of years, decades and centuries, are just being developed. Consequently, this presentation will mainly focus on efforts undertaken during the past decades in various regions of the north Atlantic to demonstrate the potential of this new archive for future oceanic research south of Iceland.

## Cold-water coral ecosystems

"Coral ecosystems evoke images of warm, tropical waters, not the deep, dark depths of the sea. Yet in the cold recesses of the ocean, there are coral ecosystems as biologically complex and diverse as their tropical counterparts. Cold-water corals are found worldwide and vary from reefs made by hard scleractinian corals to vast thickets of softer gorgonian corals. In the North Atlantic Ocean cold-water corals were first recorded in the 18$^{th}$ century but only in the last two decades have improved deep-ocean technologies allowed an exponential increase in scientific research on cold-water coral ecosystems. These studies have shown that cold-water corals support high biodiversity, are long-lived and slow-growing making them susceptible to physical disturbance by human activities (especially bottom trawling). They have also highlighted the importance of cold-water corals as habitat for deep-water fishes, indicators of **past ocean climate regimes** and sources of novel bio-compounds. Finally, recent studies have shown that anthropogenic carbon dioxide is altering the chemistry of the seas and Atlantic corals may be among the most vulnerable marine ecosystems to this ocean 'acidification'" (cited from M. Roberts: TRACES - Prospectus: Trans-Atlantic Corals ecosystem study: www.lophelia.org). As mentioned by Murray Roberts such corals provide new and extraordinary ocean climate archives: as through their relatively slow growth rates (mm to cm/year) and intermediate to abyssal depth habitats (mostly 500 - 2000 depth), these species can record ocean changes in chemistry and circulation on many different time scales. Some species are constructional and form carbonate mounds, or bioherms while other species are ahermatypic occurring more sparsely throughout the world oceans (Figure **1** and **2**). Both constructional and ahermatypic corals mostly build up aragonite skeletons.

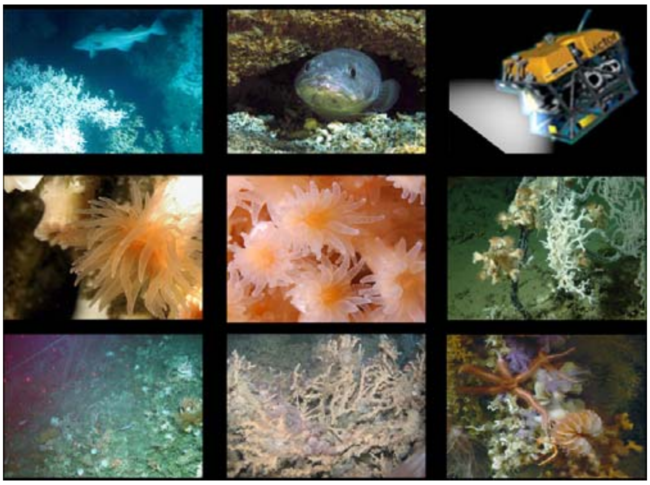

***Figure 1:*** *Photos of living solitary and constructional coral species from Porcupine Seabight including a photo of the French remotely operated vehicle Victor 6000 and fish hiding in the coral frameworks (Images kindly provided by IFREMER - Caracole cruise, Porcupine Seabight). Lower left: destructed coral reef through deep trawling activity.*

Cold-water corals are cnidarians encompassing stony corals (Scleractinia), soft corals (Octocorallia, including ''precious'' corals, gorgonian sea fans, and bamboo corals), black corals (Antipatharia), and hydrocorals (Stylasteridae). They are azooxanthellate (i.e., lacking symbiotic dinoflagellates) and often form colonies supported by a common skeleton, providing structural habitat for other species. Here we focus on scleractinian reef framework– forming species and one specific solitary coral species. Species, habitats, and ecosystems discussed here are distinct from those of tropical coral reefs and are specifically associated with colder and deep offshore waters. Reefs and mounds tend to cluster in ''provinces,'' where specific hydrodynamic and food supply conditions favour coral growth. Some provinces are characterized by small mound features others by giant carbonate mounds where reefs have become repeatedly established since millions of years. Reef distribution, genesis, and development of cold-water corals are largely restricted to oceanic waters and temperatures between 4 and 12 C°. Approximately 800 species of reef-building scleractinians are described in shallow waters, yet fewer than 10 are known to make substantial deep-water reef frameworks. Of these, we have an incomplete view of their global distribution (Figure **2**), which remains skewed by the geographically varied levels of research activity and the bias of deep-water mapping initiatives to the developed world (Roberts et al., 2006). Further important aspects steering corals growth are high bottom water currents, hard substrates to which corals can attach too and important fluxes of labile organic matter and nutrients. Coral reef or mounds are build through the successive growth and decline of coral colonies on top of each other forming complex topographic structures on the seafloor with zones of active coral growth and sediment trapping and zones of dead coral rubbles and erosion (Figure **2b**). Sediment coring performed on such structures therefore provides a pile of fossil coral fragments and sediment representing the often discontinuous vertical development of reef framework forming coral. It is important to note that active coral growth leads to vertical extension rates of cm per year, while mound growth including degradation, compaction and erosion leads to far less vertical growth rates of several mm per year. To investigate solitary corals other than coring technologies need to be implied as corals cover the sea floor without creating significant vertical growth. Thus, either video grabs, dredges or ROV technologies are used to observe and recover such species. The lack of stratigraphic constrains on such complex and unique growth structures require that each individual investigated coral needs to be dated precisely.

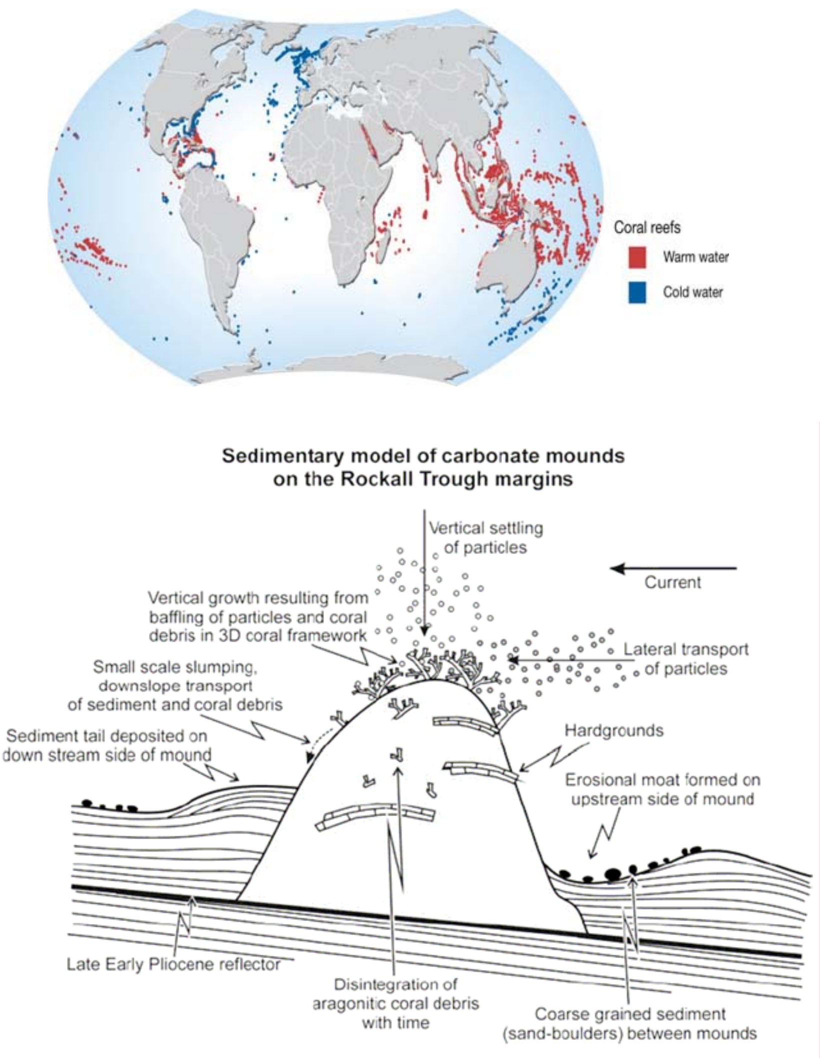


***Figure 2**: a) Present day known global distribution of cold water and tropical corals, largely biased for cold-water environments by the number of research activities. b) Sedimentary model of carbonate mounds at the Rockall Trough margins (extracted from (de Haas et al., 2009)).*

### Coral dating

Corals incorporate into the skeleton uranium from sea water, but the radioactive daughter product $^{230}$Th is not incorporated and thus a radioactive disequilibrium is created at the time of skeleton formation that provides an additional unique radioactive clock (Cheng et al., 2000; Douville et al., 2010). Through the precise and accurate measurement of Uranium-series isotopes ($^{238}$U, $^{234}$U, $^{230}$Th) one can precisely and accurately determine the "chronological" age of a fossil coral through the use of modern mass spectrometric technologies. This provides coral ages ranging from a few years of growth to several hundred thousand years of growth.

An example of coral dating using U-series methodologies is shown in figure **3** that here highlight the discontinuous character of coral reef development and demonstrates that corals provide oceanic archives capable to trace oceanic environmental changes over thousands of years.

### Geochemical tracers and time series

Classically, the physical and chemical properties of water masses are reconstructed on time scales of several thousand years with "proxies" analyzed in carbonates such as foraminifera. Mg/Ca, Sr/Ca, U/Ca ratios are proxies for temperature. To investigate intermediate water properties through benthic foraminifera sequences of slope sediments need to be recovered allowing to reveal the vertical structure of the water column. Despite, those proxies do not reveal changes in air-sea gas exchange and cross thermocline exchange and generally provide no information on strength and direction of flow. Therefore, to better constrain changes in water mass mixing and advection through time other "tracers" are needed. $^{14}C$ is such a tracer derived from cosmogenic nuclide production that enters the largest carbon reservoir through air-sea gas exchange.

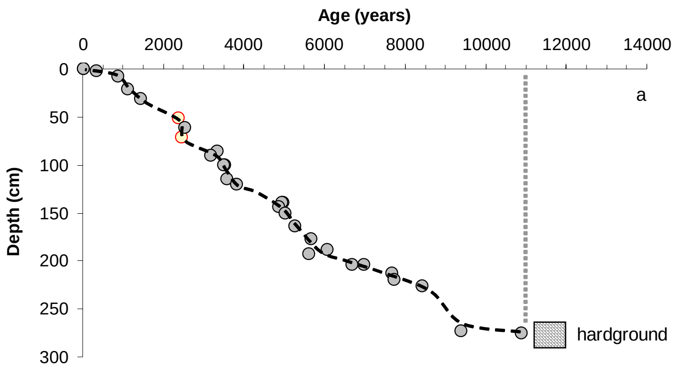


***Figure 3:*** *Coral growth on a carbonate mound determined by means of U-series dating of L. pertusa fragments (Frank et al., 2009). Between 11,000 years and present corals develop prosperously on the investigated site on Rockall Bank (MD01-2454G - 750m water depth). The coral age to sediment depth relationship yields the remaining speed of piling up dead coral fragments and is influenced by other processes such as compaction and erosion.*

It has been widely used to investigate modern ocean circulation as its distribution is strongly related to the state of ventilation in the surface ocean driven by vertical exchange of well and poorly ventilated water masses, sea ice cover and the strength of wind driven gas exchange (Broecker and Peng, 1982; Druffel, 1996; Guilderson et al., 1998; Nydal and Gislefoss, 1996; Östlund et al., 1974). Within the deep ocean $^{14}C$ participates in the advection and mixing of water masses and through radioactive decay the $^{14}C$ concentration is modified along the pathways of water mass (Broecker and Peng, 1982). As a consequence $^{14}C$ can serve to validate advection and gas exchange in coupled ocean circulation and carbon cycle models (Marchal et al., 2001; Rodgers et al., 2004). $^{14}C$ is incorporated in coral skeletons as part of the carbonate matrix and seawater $^{14}C$ contents can be reconstructed through combined U-series dating and $^{14}C$ dating (Adkins et al., 1998; Frank et al., 2004; Mangini et al., 1998). Consequently corals can be used to determine past ocean $^{14}C$ levels and therefore the temporal and vertical structure of ocean circulation and cross thermocline exchange (Robinson et al., 2005). The temporal variability of $^{14}C$ is well known in the atmosphere of the past 11,000 years (Figure **4**) as derived from measurements of $^{14}C$ in tree rings (Stuiver et al., 1998). As a consequence seawater $^{14}C$ can be reconstructed and interpretations of ocean circulation changes are feasible for this time span. For example, figure **4** shows the reconstruction of thermocline water $^{14}C$ on Rockall Bank and in cases for samples from South Iceland (kindly provided by J. Adkins, CALTECH) and the New England Seamounts and temperate Atlantic (Robinson et al., 2005). Without going into the detail of this record it is clear that on first order the early Holocene is marked by strong sub-surface water $^{14}C$ variability while the late Holocene (beyond 7000 years) tend to smoothly follow the atmospheric trend. Consequently, processes affecting the state of ventilation of thermocline water have been different during the early Holocene and seem to be similar to today during the late Holocene indicative of major changes in the water mass balance at upper intermediate depth.

Recently, also Nd-isotope ratios have been shown to be a very promising new tracer of the provenance of water mass and mixing and those have as $^{14}C$ the advantage to be independent of fractionation induced by biological processes in the water column. Nd is mainly in the dissolved form in seawater (90 to 95 %) with a concentration of about $10^{-12}$ g/g. Its residence time, recently re-assessed to about 500 - 1000 yr (Tachikawa et al., 2003), is shorter than the time for inter-ocean mixing. Consequently, through lithogenic inputs, water masses are characterized by different isotopic composition of Nd (continental fingerprint). The $\varepsilon_{Nd}$ values of the North Atlantic Ocean are contrasted with low $\varepsilon_{Nd}$ values in the Labrador Sea intermediate water and with much higher values in the eastern subtropical North Atlantic.

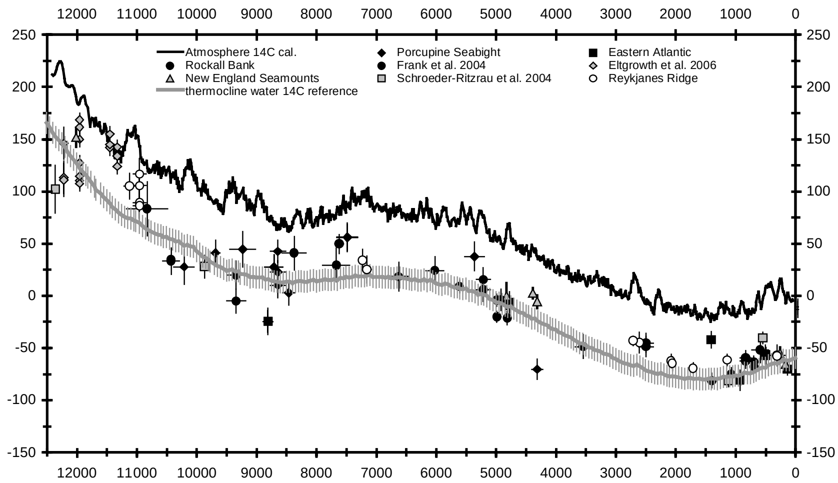


***Figure 4:*** *Seawater radiocarbon in ‰ notation over the past 11000 years as reconstructed from cold-water corals in comparison to atmospheric radiocarbon and estimated intermediate water $^{14}C$ (using a constant reservoir effect of -65‰).*

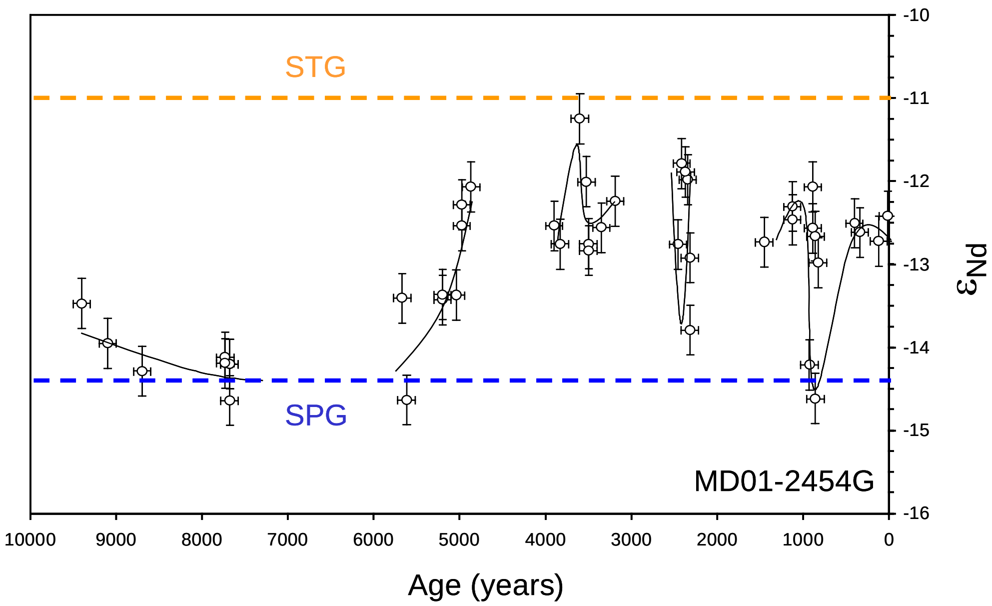


***Figure 5:*** *Nd-isotopic variations ($\varepsilon_{Nd}$) against age [years] recorded over the past 10000 years by deep water corals from Rockall Bank (750m water depth) (Colin et al. accepted QSR ).*

Thus, $\varepsilon_{Nd}$ values of the main surface and intermediate ocean currents which constitute the SPG and STG are highly sensitive to monitor present and past changes of water mass mixing between both. The only way to alter the isotopic composition of seawater despite of water mass mixing is to add Nd with a different isotopic composition through riverine and Aeolian inputs or by mixing with other water masses. But, away from direct riverine input and on short time scales (<500 years) $\varepsilon_{Nd}$ can be considered a conservative tracer in the ocean. Cold-water corals provide excellent archives of seawater $\varepsilon_{Nd}$, allowing reconstruction of time-series of this water mass tracer at equal resolution as for $^{14}C$. First results of this new technique are presented in figure **5** clearly identifying strong changes in water mass composition on Rockall Bank here over the past 10,000 years. In first order, $\varepsilon_{Nd}$ values oscillate between modern SPG ($\varepsilon_{Nd}$~-11) and STG ($\varepsilon_{Nd}$ ~-14) endmember values indicating long-term trends and secular short term oscillations of intermediate water provenance and water mass mixing at Rockall Bank.

Despite tracer used to "colour" oceanic transport and mixing, tracers of the physical and geochemical sea water composition have also been developed that will be briefly described to highlight the potential of corals as unique paleoceanographic archive. Based on the outlined geochronological tools and geochemical tracers it will be shown how those can be applied on cold-water corals from the South of Iceland to understand the temporal variability of the north Atlantic upper intermediate depth circulation from present to the past 10,000 years.

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