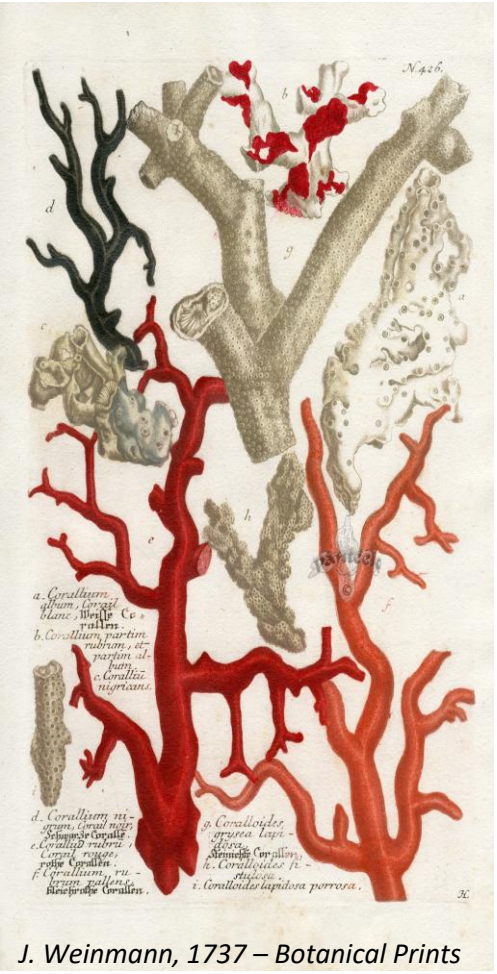
After trees in connection to Dendrochronology, it is useful to speak about the use of another group of organisms that can provide information for the characterization of past climatic conditions, actually for habitats where trees are completely absent: the oceans. We shall speak of **CORALS** and of **CORAL CHRONOLOGY**.





J. Weinmann, 1737 – Botanical Prints

The classification of corals has been discussed for millennia, owing to having similarities to both plants and animals.

Aristotle's pupil **Theophrastus** described the red coral, **korallion**, in his book on stones, implying it was a mineral, but he described it as a deep-sea plant in his Enquiries on Plants, where he also mentions large stony plants that reveal bright flowers when under water in the Gulf of Heroes.

Pliny the Elder stated boldly that several sea creatures including sea nettles and sponges "are **neither animals nor plants**, but are possessed of a third nature (*tertia natura*)". The Babylonian **Talmud** refers to coral **among** a list of types of **trees**, and the 11th-century French commentator **Rashi** describes it as "a type of **tree** that grows underwater that goes by the (French) name «coral»."

The Persian polymath **Al-Biruni** (d. 1048) classified corals as **animals**, arguing that they respond to touch.

People believed corals to be plants until the eighteenth century when **William Herschel** used a microscope to establish that **coral had the characteristic thin cell membranes of an animal**.

Stony corals are members of the class **Anthozoa**, which groups together marine invertebrates such as the sea anemones, soft and stony corals, sea fans and sea pansies. Adult anthozoans are almost all attached to the seabed, while their larvae can disperse as part of the plankton.

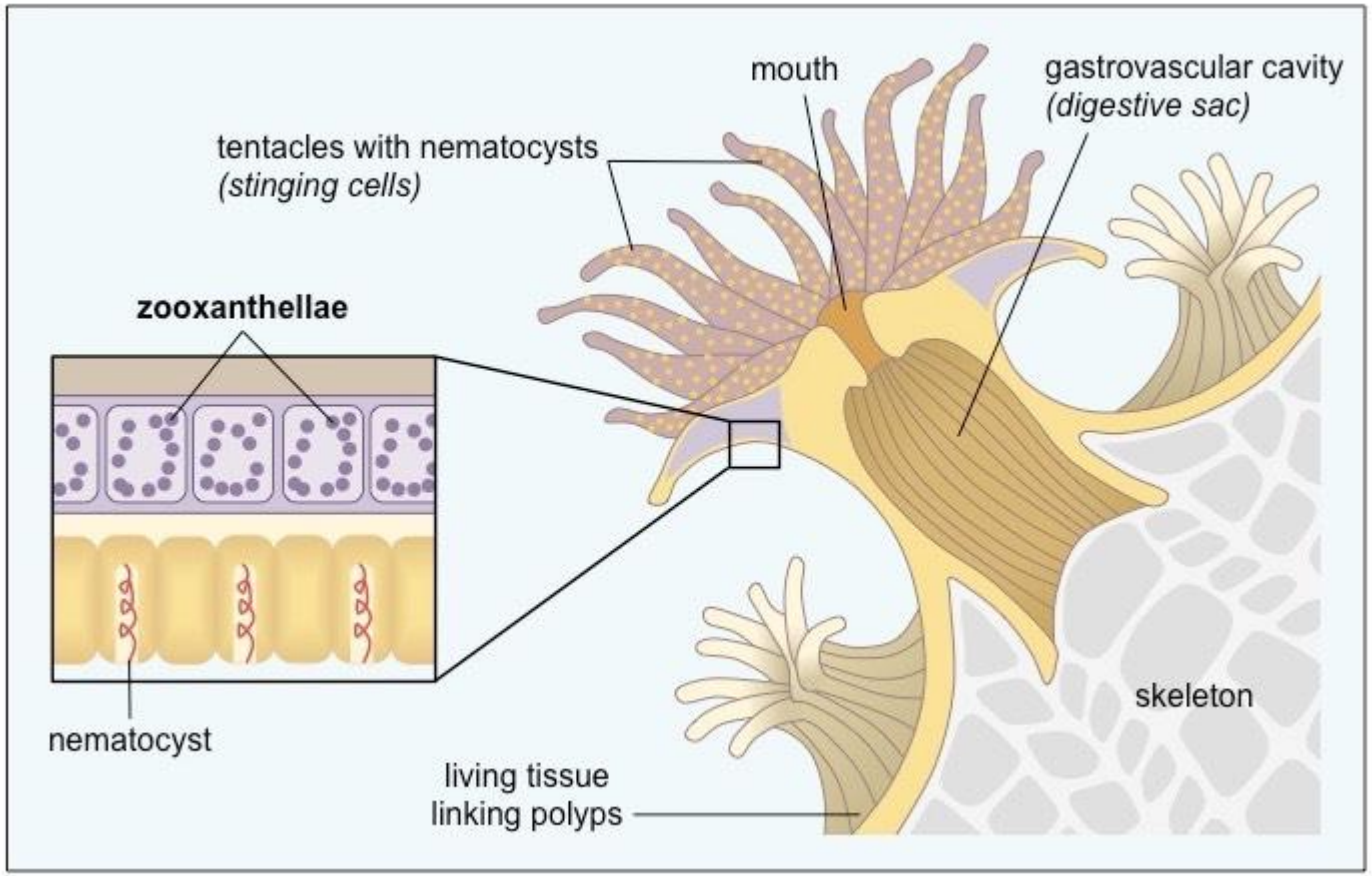
The name "Anthozoa" comes from the Greek words ἄνθος (ánthos; "flower") and ζώα (zóa; "animals"), hence ανθόζωα (anthozoa) = "flower animals", a reference to the floral appearance of their perennial polyp stage.

They range in size from small individuals less than half a centimeter across to large colonies a meter or more in diameter.

The Class Anthozoa is subdivided into three subclasses: **Hexacorallia, Octocorallia**, and **Ceriantharia**, which form monophyletic groups, with different symmetry of polyp structure for each subclass. **the stony corals (Scleractinia)**, together with sea anemones (Actiniaria), **belong to Hexacorallia**.

The basic body form of an anthozoan is the polyp. This consists of a tubular column topped by a flattened area, the oral disc, with a central mouth; a whorl of tentacles surrounds the mouth. In solitary individuals, the base of the polyp is the foot or pedal disc, which adheres to the substrate, while in colonial polyps, the base links to other polyps in the colony.

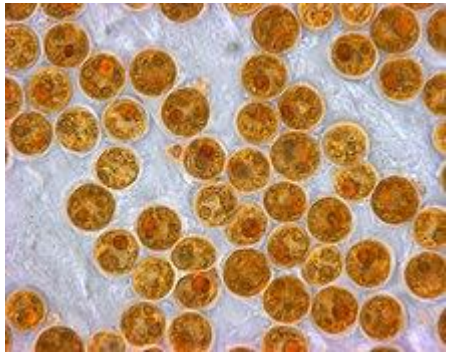
Colonial corals consist of multiple polyps with a common origin joined by living material. Polyps bud off from a sheet of living tissue, the **coenosarc**, i.e. a thin membrane from which the polyps project (in the soft corals the coenosarc consists in a thick fleshy mass in which the polyps are immersed apart from their oral discs).



Most anthozoans supplement their predation by incorporating into their tissues certain unicellular, photosynthetic organisms known as **zooxanthellae** (a generic name); many fulfil the bulk of their nutritional requirements in this way.
In corals, zooxanthellae are dinoflagellate belonging to the genus *Symbiodinium*. They contain chlorophyll a and chlorophyll c, as well as the dinoflagellate pigments peridinin and diadinoxanthin. They are contained in vacuoles of the host's gastrodermal cells. Some stony corals use **chemotaxis**, with infection occurring as a result of the emission by the polyps of a chemical attractant



A giant green anemone, a zooxanthellate species (top), and closer view of the endosymbionts (bottom).



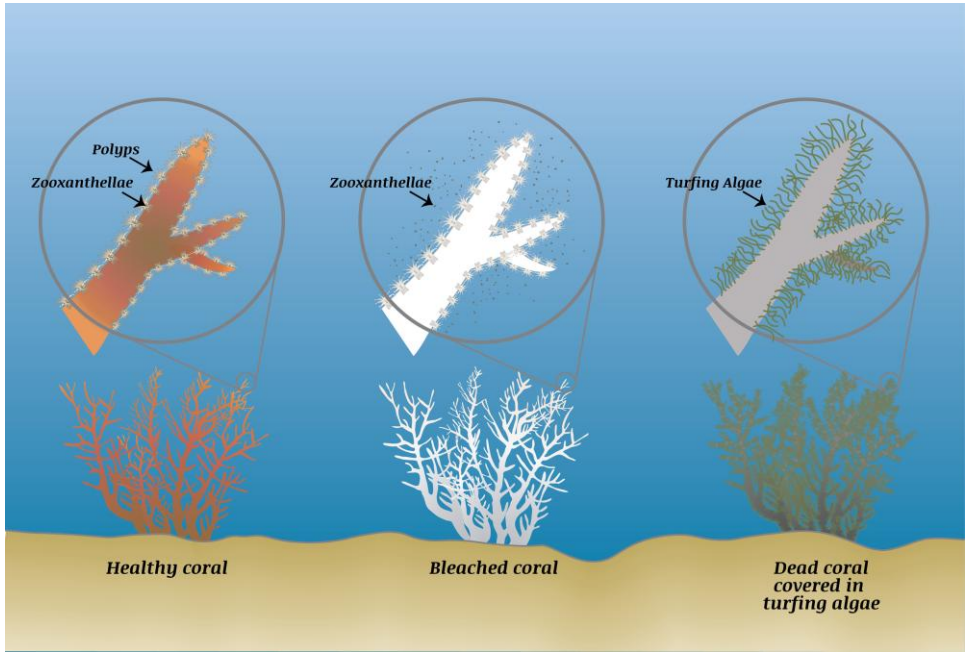
In this symbiotic relationship, the zooxanthellae benefit by using nitrogenous waste and carbon dioxide produced by the host while the cnidarian gains **sugars, glycerols and amino acids** and facilitate the precipitation of calcium carbonate, a substance of great importance to stony corals.

The behaviour of the anthozoan can also be affected, with it choosing to settle in a well lit spot, and competing with its neighbours for light to allow photosynthesis to take place.

Where an anthozoan lives in a cave or other dark location, the symbiont may be absent in a species that, in a sunlit location, normally benefits from one.
Anthozoans living at depths greater than c. 50 m are azooxanthellate because there is insufficient light for photosynthesis.

The presence of zooxanthellae is not a permanent relationship. Under some circumstances, the symbionts can be expelled (“bleaching corals”), and other species of algae may later move in to take their place; if the stress is too high, the corals can die, and the coral colonies become the substratum for other marine organisms, macroalgae included.





Bleaching occurs when corals are under stress. A primary cause of coral bleaching on the Great Barrier Reef during summer is heat stress resulting from high sea temperatures and increased UV radiation.

A temperature increase of just one degree Celsius for only four weeks can trigger bleaching. Deprived of their food source, corals begin to starve once they bleach. If these increased temperatures persist for longer periods (eight weeks or more) corals begin to die. High water temperatures can affect reefs at regional and global scales.

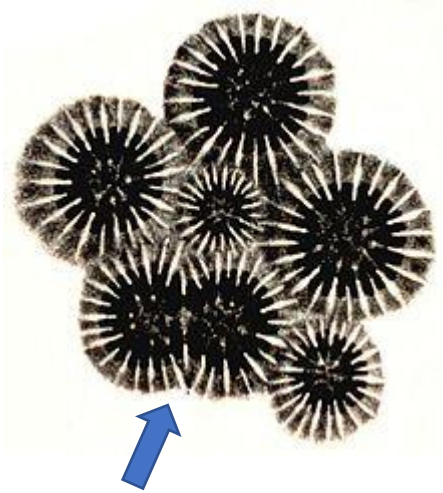
Other stressors that can also cause bleaching include colder temperatures, freshwater inundation (low salinity), and poor water quality from sediment or pollutant run-off.



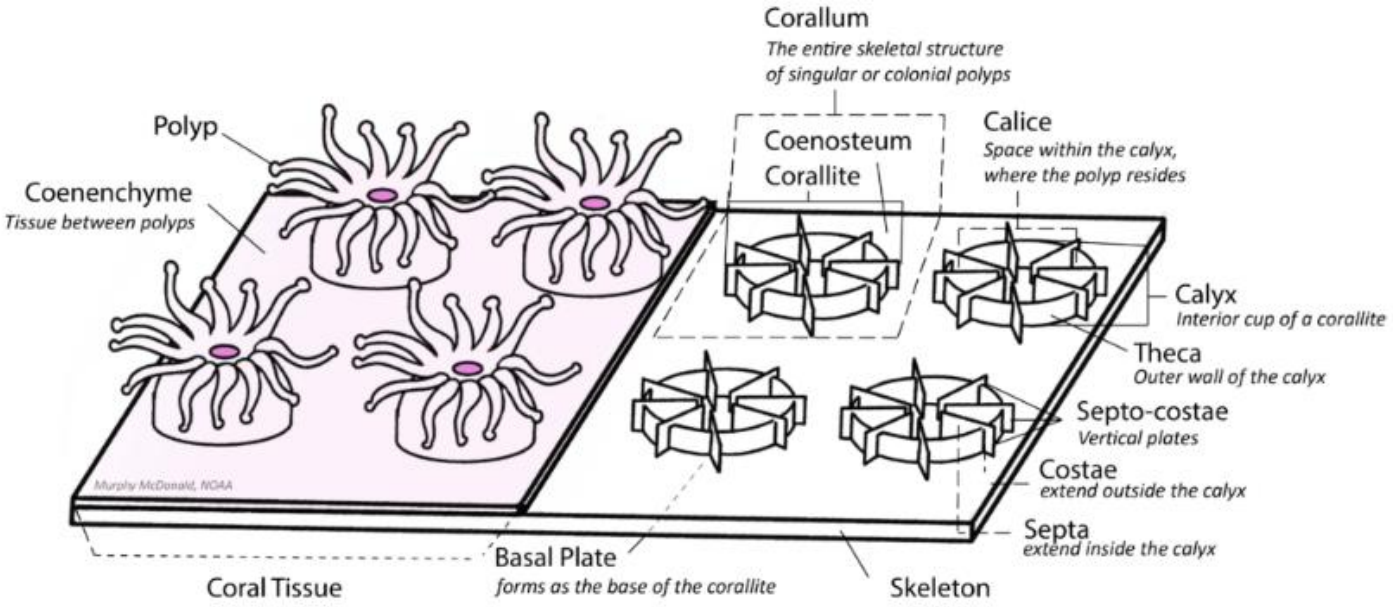
The physiological mechanisms behind endosymbiont expulsion remain under research but are speculated to involve various means of detachment of zooxanthellae or gastrodermal cells from host corals. During a bleaching event, entire gastrodermal cells containing zooxanthellae may leave the host. In other cases, gastrodermal cells will remain in the host tissues, but zooxanthellae contained in vacuoles may separately undergo damage or may physically leave the cells and enter the surrounding environment

A bleached coral is not dead. Corals can recover from bleaching if heat stress lessens, temperatures reduce, and conditions return to normal. Following previous mass bleaching events recorded on the Great Barrier Reef prior to 2016 and 2017, the vast majority of corals survived. In 1998, 50% of the reefs on the Great Barrier Reef suffered bleaching and in 2002 60% were affected, yet only around 5% of the coral reefs experienced coral mortality on both occasions. Not surprisingly, different corals recover at different rates, e.g. the fast-growing branching corals are usually the first to bounce back.

The skeleton of a stony coral in the order Scleractinia is secreted by the epidermis of the lower part of the polyp; this forms a corallite, a cup-shaped hollow made of **calcium carbonate**, in which the polyp sits. The porous skeleton that links polyp corallites within a colony is called the **coenosteum.**



Basal plates (calices) of Orbicella annularis *showing multiplication by budding (small central plate) and division (large double plate, arrow)*

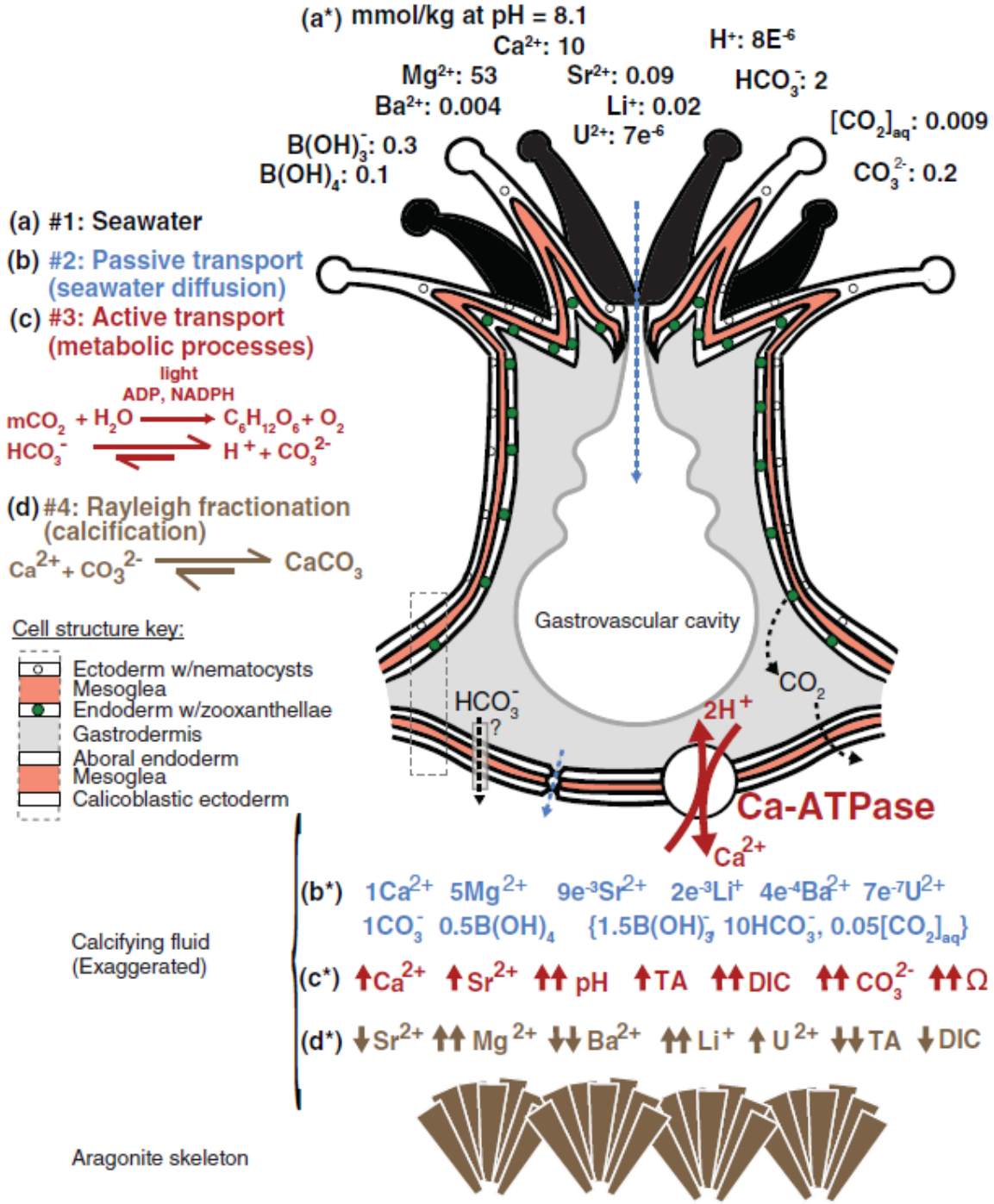


The stony skeleton of hard corals is a biocomposite (mineral + organics) of calcium carbonate, and is made of spicule of aragonite (orthorhombic $CaCO_3$). In scleractinian corals, "centers of calcification" and fibers are clearly distinct structures differing with respect to both morphology and chemical compositions of the crystalline units. The organic matrices extracted from diverse species are acidic, and comprise proteins, sulphated sugars and lipids; they are species specific. The soluble organic matrices of the skeletons allow to differentiate zooxanthellae and non-zooxanthellae specimens.

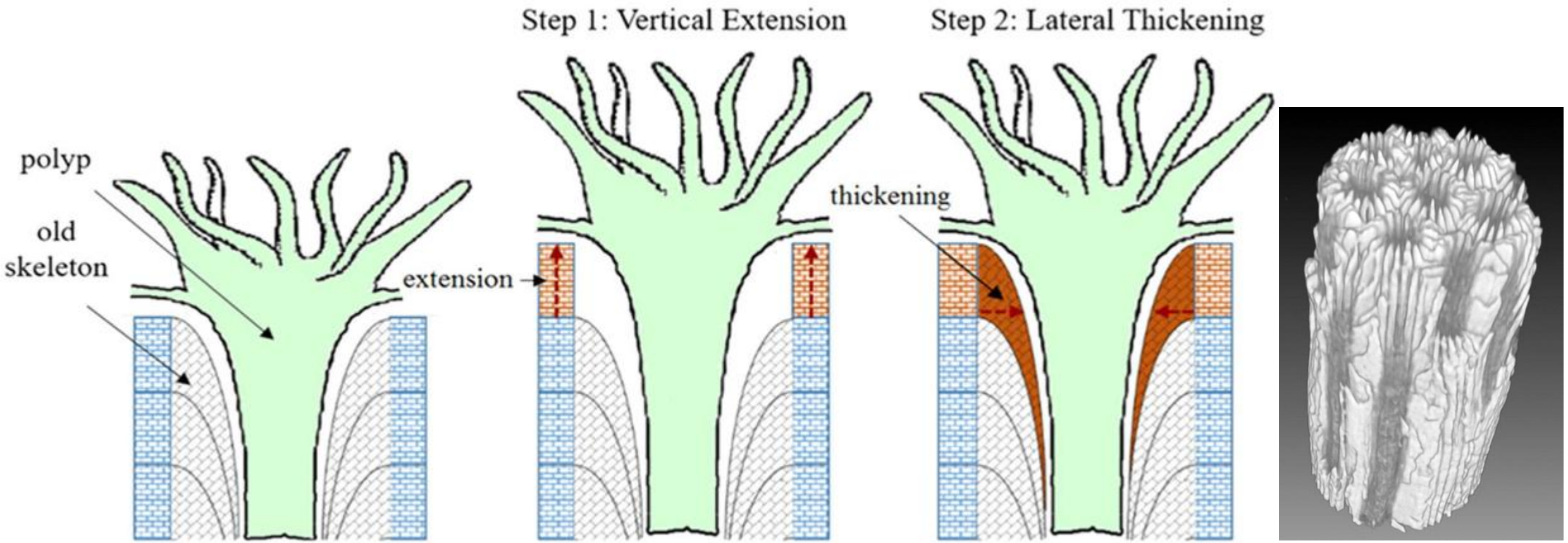
Although aragonite is a metastable polymorph of calcium carbonate, the exoskeleton of scleractinian corals is made entirely of this mineral, whose deposition is mainly controlled by the Mg^{2+}/Ca^{2+} ratio in marine water. Since aragonite is precipitated at a Mg^{2+}/Ca^{2+} ratio greater than two and the actual marine water has Mg^{2+}/Ca^{2+} ratio of 5–12 this could be a good explanation why the exoskeleton of actual corals entirely consists of pure aragonite.

The responsible for deposition of aragonite outside the polyp are the specialized calicoblast cells. The process takes place in a very thin space between calicoblastic epithelium of outer epidermis and the existing coral skeleton. Here, the hydrogen pumps present on the cell walls pump hydrogen ions (H^+) out of this space to produce more carbonate (CO_3^{2-}) ions that bond with (Ca^{2+}) ions existing in the seawater to produce and deposit solid calcium carbonate ($CaCO_3$) for their exo-skeleton.

This mechanism makes coral sensitive to ocean acidification as there are more HCO_3^- ions but fewer CO_3^{2-} ions in acidified seawater which determine corals to spend more energy to pump out H^+ ions from calcifying space to build skeletons

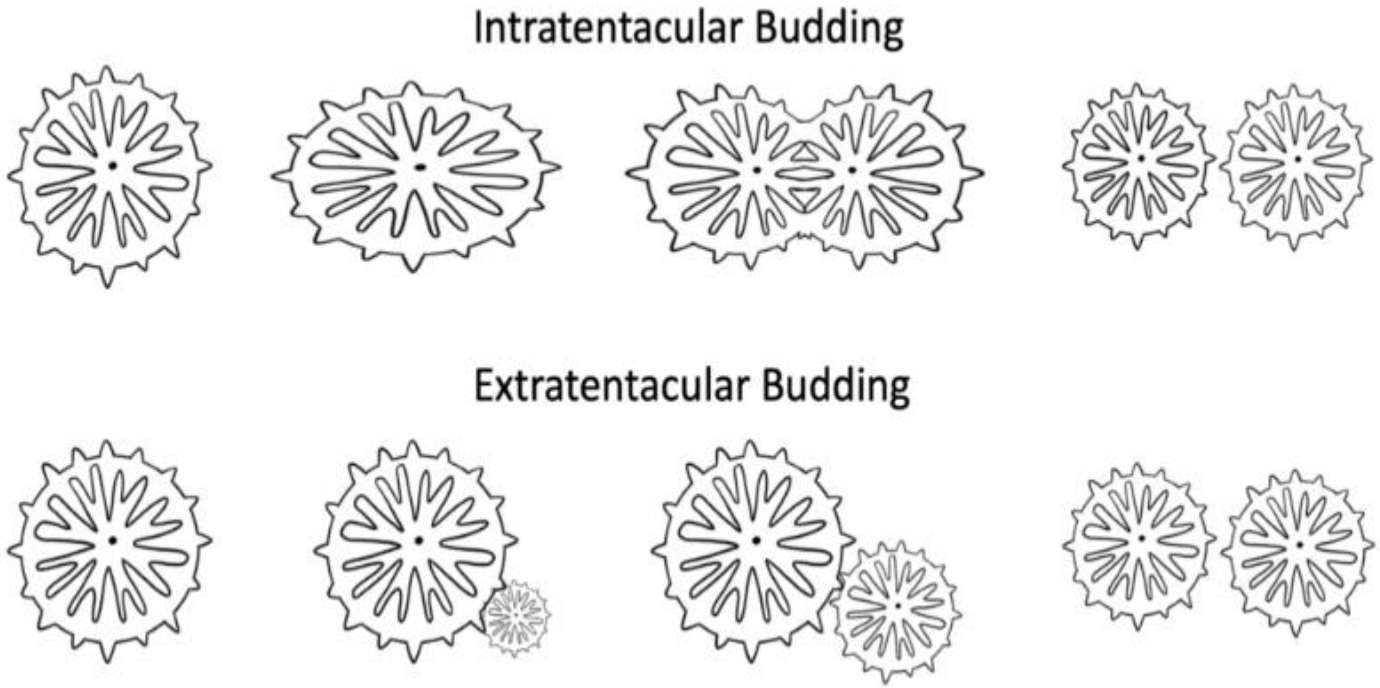


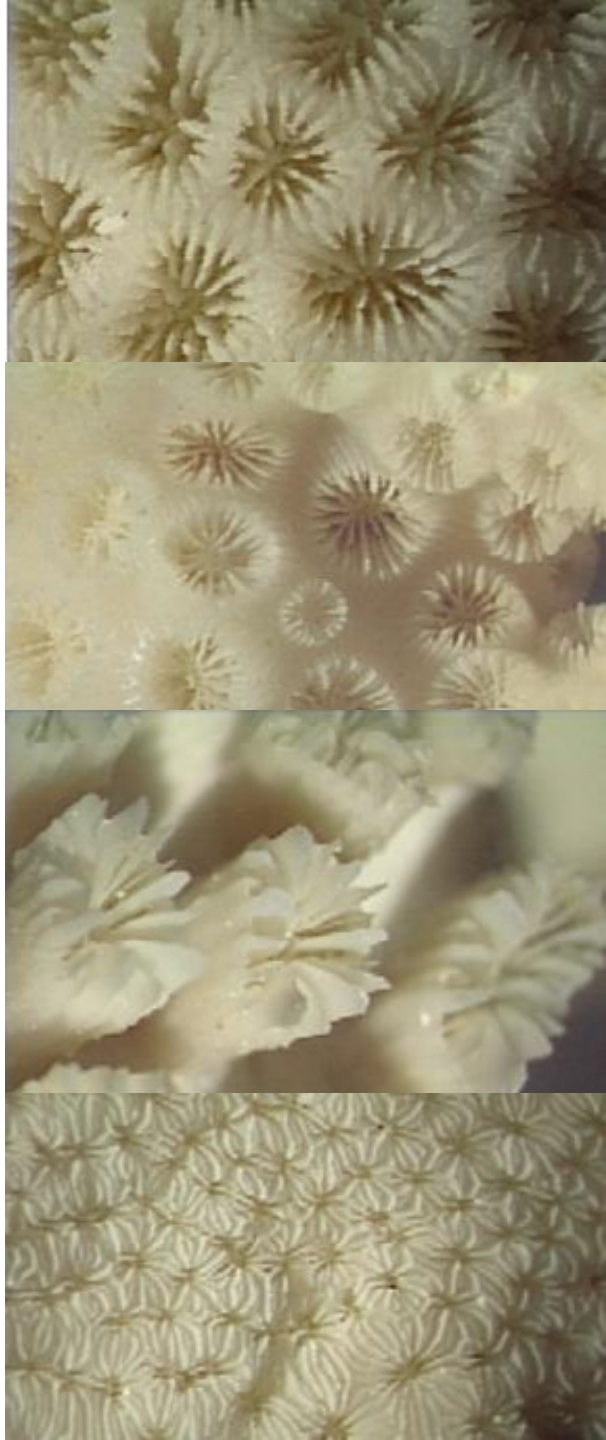
Overview of the four main factors impacting the geochemistry of the coral **calcifying fluid (CF)**: (a) seawater chemistry (black); (b) passive transport of ions via diffusion and invaginated vacuoles (blue); (c) active transport via transcellular pathways such as the Ca-ATPase pump, linked to metabolic DIC (mCO2) and ATP production by respiration and zooxanthellae photosynthesis, respectively (red); and (d) Rayleigh fractionation during calcification (tan). For major cations and anions discussed in the text, the notation is as follows: (a*) concentration in seawater at a pH of 8.1 (in mmol/kg, rounded to one significant figure; values approximate typical open ocean stoichiometry, e.g., Millero, 1974); (b*) as in (a*), due to 1:1 passive transport of ions, but now expressed as stoichiometric ratios with respect to 1 mole of CaCO3 (ions in curly brackets are thought to play a minor role in coral carbonate reactions); (c*) the relative impact of Ca-ATPase pump on the CF geochemistry, where known (Marchitto et al., 2018; McCulloch et al., 2017); (d*) impact of calcification on the concentration of major cations whose substitution for Ca2+ is used for paleo proxy(ies), based on the partitioning of each between the fluid and aragonite phases (DeCarlo, Gaetani, et al., 2015; Gonneea et al., 2017; Hathorne, Felis, et al., 2013; Holcomb et al., 2016; Marchitto et al., 2018; Z. Wang et al., 2013). While the stoichiometry of major ions in seawater varies regionally (see Sections 4.4 and 6.1), the relative change in calcifying fluid geochemistry by active and passive transport should respond proportionally to the processes depicted here. DIC, dissolved inorganic carbon; TA, total alkalinity. Diagram not to scale.



To grow up toward sunlight, corals construct a framework of aragonite crystals. At the same time, they buttress this framework with bundles of additional crystals, which thicken and strengthen the skeletons to help them withstand breakage caused by currents, waves, storms, and boring and biting by worms, molluscs, and parrotfish. (Mollica et al., *Proceedings of the National Academy of Sciences,*)

Coral colonies grow by adding new polyps through the process of budding, where a parent polyp is divided into two or more daughter polyps. This division can occur from within the ring of tentacles of the parent polyp, known as **intratentacular budding**, or can occur outside of the tentacle ring where the daughter polyp forms between existing polyps, known as **extratentacular budding.**






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“The Structure and Distribution of Coral Reefs, Being the first part of the geology of the voyage of the Beagle, under the command of Capt. Fitzroy, R.N. during the years 1832 to 1836” was published in 1842 as Charles Darwin's first monograph, and set out his theory of the formation of coral reefs and atolls



Darwin's theory starts with a volcanic island which becomes extinct

As the island and ocean floor subside, coral growth builds a fringing reef, often including a shallow lagoon between the land and the main reef.

As the subsidence continues, the fringing reef becomes a larger barrier reef further from the shore with a bigger and deeper lagoon inside.

Ultimately, the island sinks below the sea, and the barrier reef becomes an atoll enclosing an open lagoon.

Darwin's theory set out a sequence of coral reef formation around an extinct volcanic island, becoming an atoll as the island and ocean floor subsided.

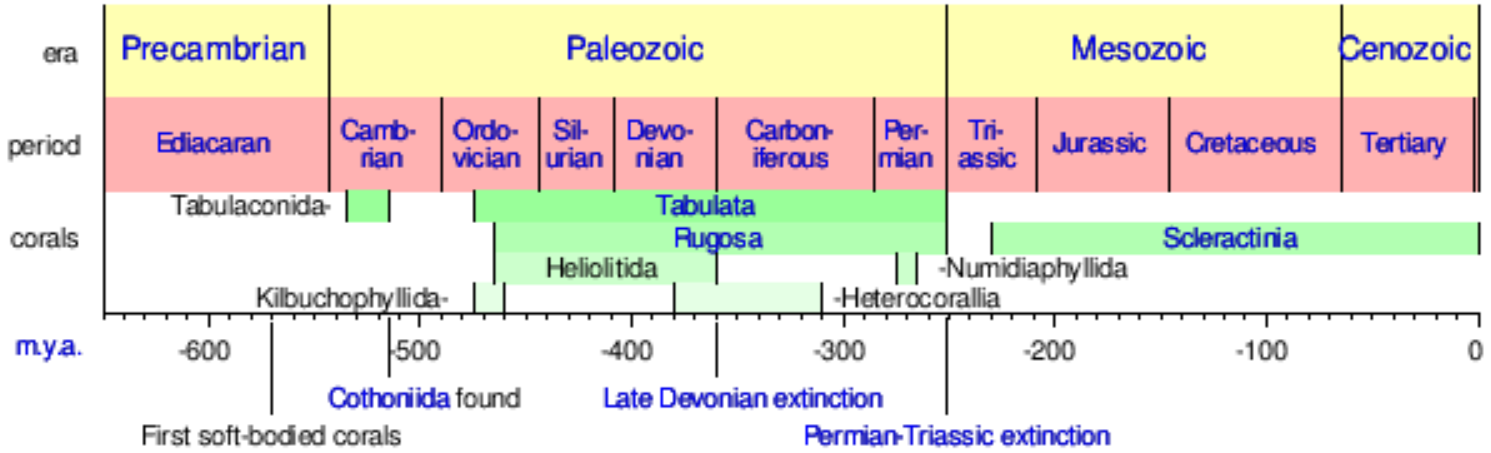




Boundary for 20 °C isotherms. Most corals live within this boundary. Note the cooler waters caused by upwelling on the southwest coast of Africa and off the coast of Peru.

They form coral reefs, some of the most biodiverse habitats on earth, supporting large numbers of species of corals, fish, molluscs, worms, arthropods, starfish, sea urchins, other invertebrates and algae.

Because of the photosynthetic requirements of the corals, they are found in shallow waters, and many of these fringe land masses.



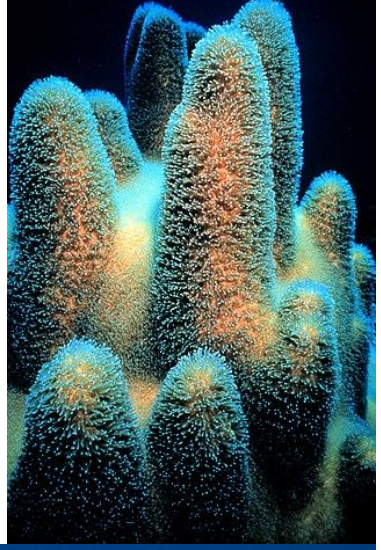
Timeline of the major coral fossil record and developments from 650 m.y.a. to present

The times of maximum reef development were in the Middle Cambrian (513–501 Ma), Devonian (416–359 Ma) and Carboniferous (359–299 Ma), owing to order **Rugosa** extinct corals and Late Cretaceous (100–66 Ma) and all Neogene (23 Ma–present), owing to order Scleractinia corals.



Drilling a massive *Porites* sp. fossil coral colony. Photo credit: Hussein Sayani

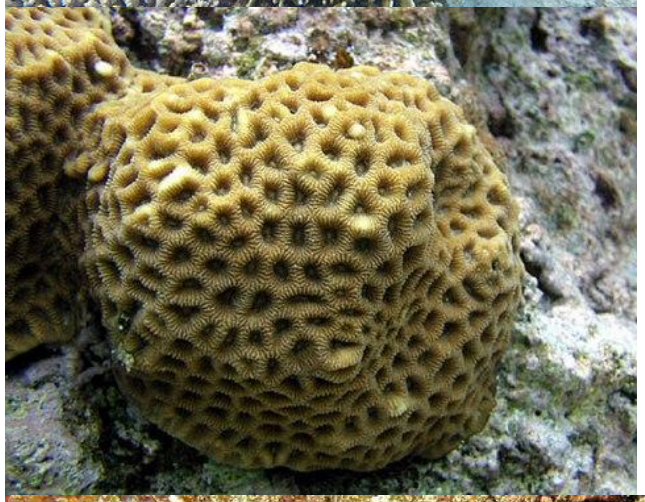




Among the stony corals, there are variuos shaped-forms, conventionally indicated as:

- Blue
- Brain
- Chalice
- Elkhorn
- Pillar
- Staghorn
- Table

All of them are HERMATYPIC, i.e. they are «reef builders»











Coral Reef Records of Past Climatic Change

Coral skeletons serve as excellent natural archives of paleoenvironmental conditions in tropical and subtropical waters. The isotopic, trace, and minor elemental composition of coral skeletons can vary with environmental conditions such as:

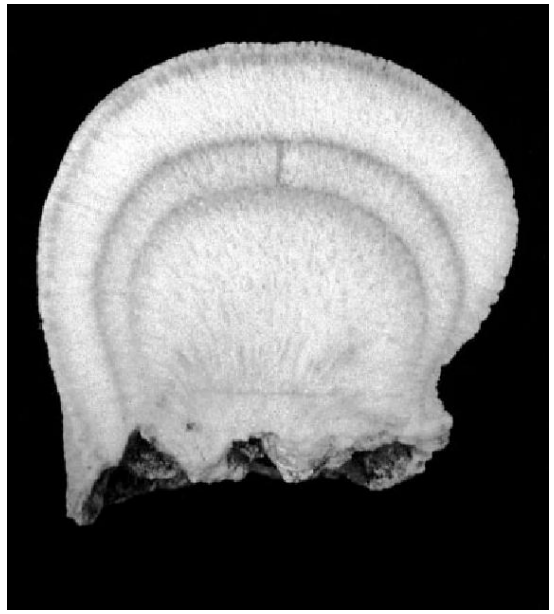
- Temperature;
- Salinity;
- Cloud cover;
- River discharge;
- Upwelling;
- Ocean circulation.



Cores of living corals offer a suite of proxy records with the potential for reconstructing paleoclimatic and paleoceanographic conditions on **interannual-to-centennial timescales**.

Living colonies can provide several centuries of continuous paleo-recordings and have been combined with fossil corals to reveal conditions over recent millennia and earlier periods

A Brief History of Coral Paleoclimatology



The early 1970s, scientists discovered that corals regularly alternated the density of their calcium carbonate skeletons between seasons. With this discovery, sclerochronology (record of coral skeleton growth) was developed as an indicator of environmental conditions.

In one of the first applications of this new tool, Hudson et al. [1976] made the connection to climate, or at least weather, by identifying stress bands recorded in corals during a cold winter in Florida in 1969-70.

Weber and Woodhead [1972] applied geochemical analyses that had been in use in paleoceanographic studies to coral skeletons.

Fairbanks and Dodge [1979] combined this with sclerochronology and found regular periodicity in geochemical ratios of $^{18}O/^{16}O$ ($\delta^{18}O$) of corals from Jamaica, Barbados, and Bermuda, with warm waters and high-density skeletal bands corresponding to skeletons depleted in ^{18}O.

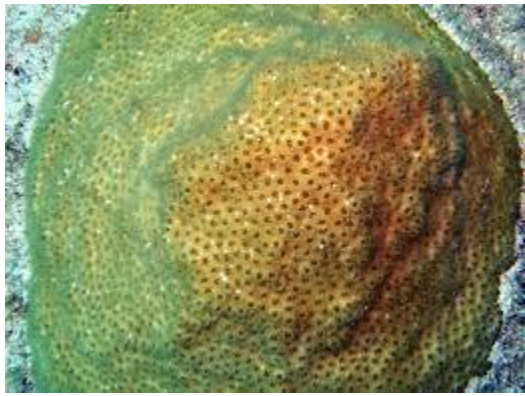
There are several massive coral species which potentially contain chronologically reliable growth records.
To date, the vast majority of paleo- climatic records (see NOAA Paleoclimatic Data Base; http://www.ncdc.noaa.gov/paleo/corals.html), both from modern and fossil corals, are from the Indo-Pacific, and have been obtained from ***Porites***, with a couple of Pacific records obtained from *Pavona* and *Platygyra*.
There are fewer published coral records for the Caribbean and Atlantic region and these come mainly from ***Montastraea*** and ***Solenastrea***.

These species typically have high linear growth rates of 1–2 cm per year.

More slowly growing (0.1–0.5 cm per year) coral species, with the possibility for much longer records, have more recently been examined for their paleoclimatic potential including *Diploastrea* in the Pacific and *Siderastrea* and *Diploria* in the Atlantic.



Montastraea



Solenastrea







Although sclerochronology continues to have direct applications as a temperature proxy [Lough and Barnes, 1997; Slowey and Crowley, 1995], most paleoclimatic data from corals now use geochemical analysis of their skeletons.

To date, approximately 100 coral skeletal and several sclerosponge isotopic and/or elemental records of 20 years of longer have been produced, most of which are available from the World Data Center for Paleoclimatology and other sources.

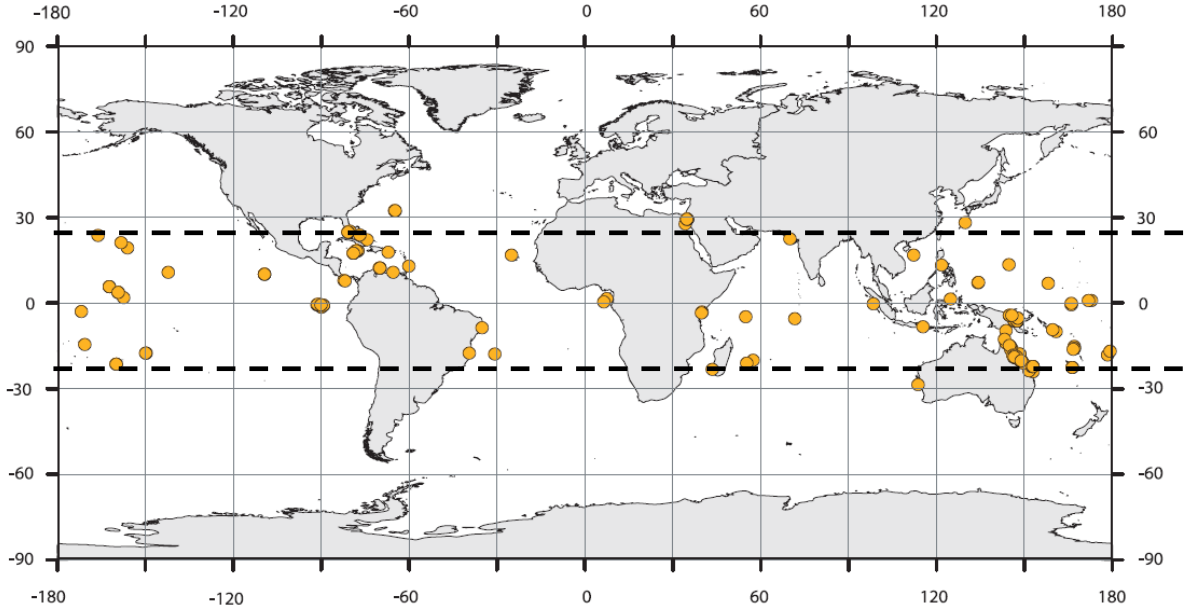


Plate 1a. Locations of coral and sclerosponge records archived in the World Data Center for Paleoclimatology (http://www.ncdc.noaa.gov/paleo/corals.html) as of 1 June 2006.

23°26'11" N e S Cancer tropic

23°26'11" N e S Capricorn tropic

Stony corals are good tropical climate proxy recorders because:

1) they are widely distributed throughout the tropics,
2) their continuous annual skeletal banding pattern offers excellent chronological control,
3) they incorporate a variety of climate tracers from which paleo-ocean temperature, salinity, cloud cover, upwelling, ocean circulation, ocean mixing patterns, and other climatic and oceanic features can be reconstructed,
4) their proxy records can nearly match instrumental records for fidelity,
5) their records can span several centuries
6) their high skeletal growth rate (usually ranging from 5-25 mm /year) permits sub-seasonal sampling resolution.

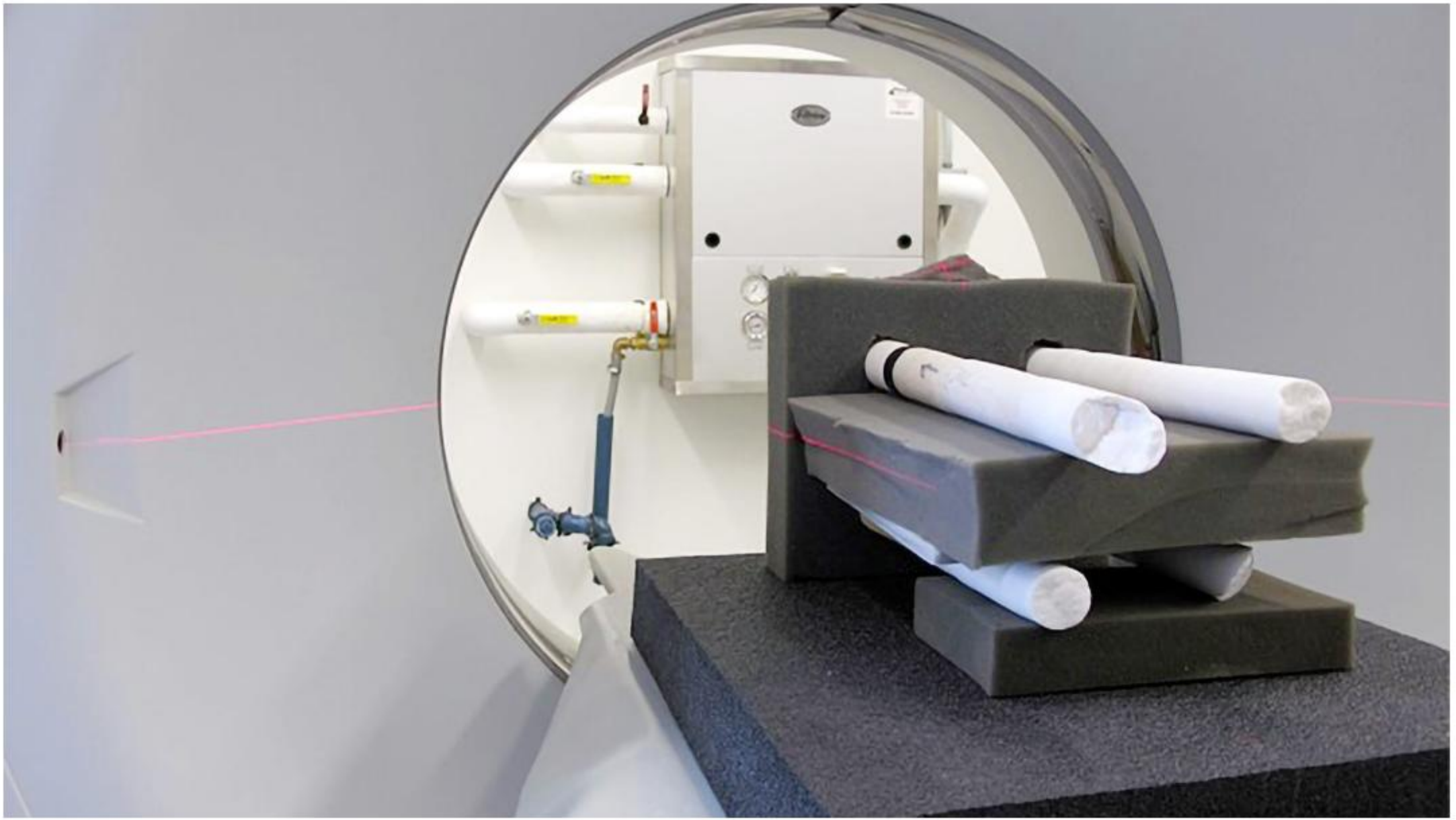
Method



A core from an individual massive coral head along its major axis of growth is extracted.

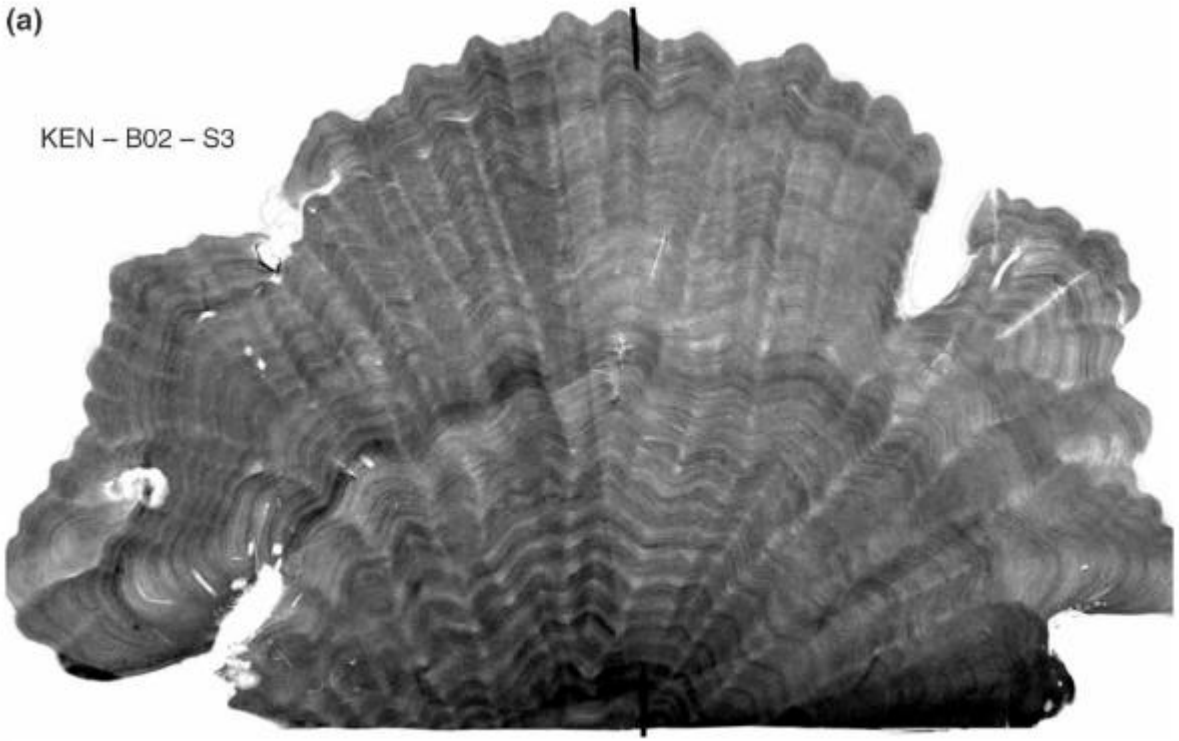


Coring large *Porites* coral, Rowley Shoals, Western Australia (Photo credit: Eric Matson, AIMS).

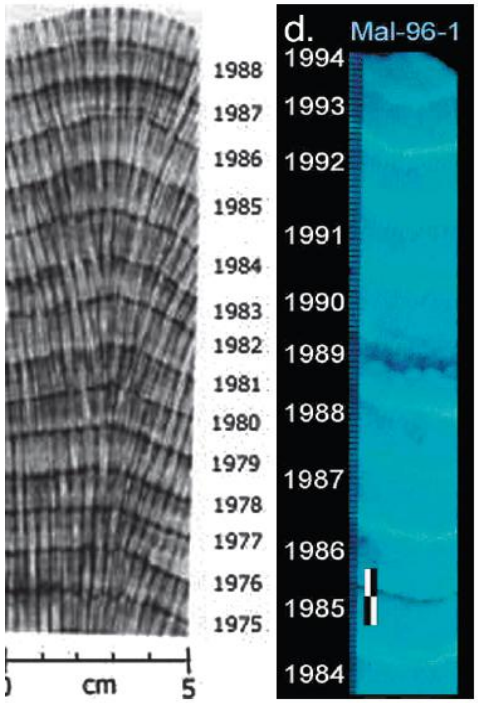


Scientists used a 3-D Computerized Tomography (CT) scanner to image the coral cores. The CT scan images reveal annual growth bands, much like rings on a tree, which showed scientists how corals grew their skeletons upward while also thickening them. (Tom DeCarlo, Woods Hole Oceanographic Institution)

The extracted core is cut longitudinally into slabs ranging in thickness from 0.5-1 cm, cleaned with water and dried, then X-rayed. X-ray positive prints reveal the banding pattern of the slab and are used:
1) as a guide for sample drilling and
2) to establish a chronology for the entire coral record when the banding pattern is clear



(a) Positive print of X-ray of slice from small *Porites* colony from Kent Island, northern Great Barrier Reef, illustrating annual density banding pattern.



In a few cases, composite records have been made by using multiple cores to extend the record length beyond that available from a single core

For geochemical analysis, carbonate powder samples are extracted along the major axis of growth by grinding the skeletal material with a dental drill bit. For high-resolution paleo-reconstructions, samples are extracted every millimeter or less along the entire length of the core. Since corals grow about 5-15 mm per year, this sampling method can yield sub-seasonal resolution. Much higher resolution sampling is possible by microdrilling or using laser ablation techniques that yield samples at approximately weekly temporal resolution [Sinclair et al., 1998], but this is not commonly performed.

The coral carbonate powder is then analyzed for one or more isotopes or elements to build any one of a number of possible paleo-proxy records (Table 1).

TABLE 1. Environmental variable(s) that can be reconstructed from coral skeletal isotopes, trace and minor elements, and growth records.

Proxy	Environmental variable
Isotopes	
$\delta^{18}O$	Sea surface temperature, sea surface salinity
$\delta^{13}C$	Light (e.g., seasonal cloud cover), plankton intake
$\Delta^{14}C$	Ocean ventilation, water mass circulation
$\delta^{11}B$	pH
Trace and Minor Elements	
Sr/Ca	Sea surface temperature
U/Ca	Sea surface temperature
Mg/Ca	Sea surface temperature
Mn/Ca	Wind anomalies, upwelling
Cd/Ca	Upwelling, contamination
Ba/Ca	Upwelling, river outflow
Pb/Ca	Gasoline burning
Skeleton	
Skeletal growth bands	Light (seasonal changes), stress, water motion, sedimentation, sea surface temperature
Luminescence	River outflow, ocean productivity

Coral Paleotemperature and salinity

Since large corals suitable for paleoclimatic reconstructions are typically limited to the top ~20m of the ocean, their proxy records reflect near-surface ocean conditions found on coral reefs.

$\delta^{18}O$ has the longest history as a temperature proxy and, was more common and less expensive than elemental measurements.

Skeletal $\delta^{18}O$ in marine organisms is affected by temperature-induced fractionation and $\delta^{18}O$ of the surrounding water [Epstein et al., 1953]. As temperature increases, the ^{18}O fraction of the coral skeleton decreases [Kim and O'Neil, 1997]. Based on empirical studies, a 1°C increase in water temperature corresponds to an average decrease of about 0.22% in coral $\delta^{18}O$ though that slope can vary significantly from 0.15 to 0.24% among species and locations.

Unfortunately, coral skeletal $\delta^{18}O$ is influenced by both temperature and salinity, and is therefore not a pure indicator of temperature. This confounding influence is minimized when the relative contribution from either salinity or temperature variability is low or the two variables combine to increase the change in coral $\delta^{18}O$.

The interpretation of the skeletal $\delta^{18}O$ record depends on the hydrological regime of the collection site.

Coral Paleotemperature and salinity: an alternative to $\delta^{18}O$

Strontium (Sr) and uranium (U) have long residence times in seawater. Because this provides relatively constant concentrations in surface seawater, the observed fluctuation in coral Sr/Ca has been attributed to changes in SST [Weber, 1973].

Sr and U replace Ca in the skeletal aragonite through thermodynamic processes, with less replacement of Ca by the heavier elements at higher temperatures [Beck et al., 1992; Weber, 1973].

Although it is a well-established geothermometer, **SST-Sr/Ca calibration curves often vary dramatically among species and/or locations**, and may be influenced by growth rate. Thus **Sr/Ca needs to be calibrated to local or regional temperature records for each genus or species and at every location**.

Cloud cover and feeding - $\delta^{13}C$ analysis

While less commonly reported than $\delta^{18}O$, most researchers collect data on $\delta^{13}C$ at the same time as $\delta^{18}O$. Photosynthesis (light) and feeding (which directly affects the respired $\delta^{13}C$) are the primary influences on coral skeletal $\delta^{13}C$.

For corals collected from shallow, non-upwelling sites where coral feeding is relatively constant, changes in $\delta^{13}C$ are predominantly driven by changes in photosynthesis, providing a record of seasonal changes in cloud cover or turbidity (i.e., rainy season vs. dry season).

In upwelling regions where feeding opportunities can vary dramatically, changes in $\delta^{13}C$ have been used as an indicator of vertical mixing through change in coral food source [Felis et al., 1998] and in dissolved inorganic $\delta^{13}C$.

Ocean Circulation: Radiocarbon Analyses ($\Delta^{14}C$)

Corals can be excellent recorders of upwelling and of changes in upwelling regimes of deep water transported to the surface results in a decrease in the $\Delta^{14}C$ of the skeleton.

^{14}C is produced naturally in the stratosphere and was also produced as a result of thermonuclear weapons explosions in the atmosphere in the 1950s and early 1960s. **The base of the $\Delta^{14}C$ -bomb is clearly identifiable as ~1955 in coral carbonate records**.

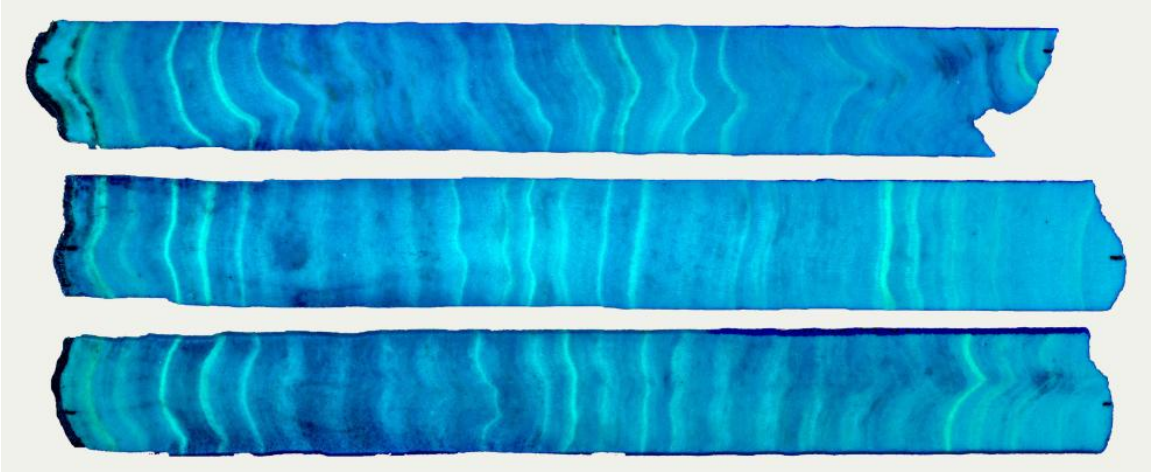
During the pre-bomb period, coral $\Delta^{14}C$ records reflect a declining trend in the 20th century termed the **Suess Effect**: the decrease in ^{14}C in the atmosphere due to dilution of natural 14C by the addition of ^{14}C-free fossil fuel CO_2.



Post-1955, **the bomb-curve signal can be used to help confirm/establish coral and sclerosponge chronologies**. As a new proxy, $\Delta^{14}C$ is an excellent tracer for detecting upwelling and changes in seawater circulation since deep water has a lower $\Delta^{14}C$ value than surface water.

River Runoff: detection through luminescent banding

Banding is reflected as recurrent variations in density (shown using X-radiographs) and/or luminescence intensity (visible under long-wavelength ultraviolet (UV) light) which appear as alternating bands in slices of coral skeleton cut parallel to the colony growth axis.

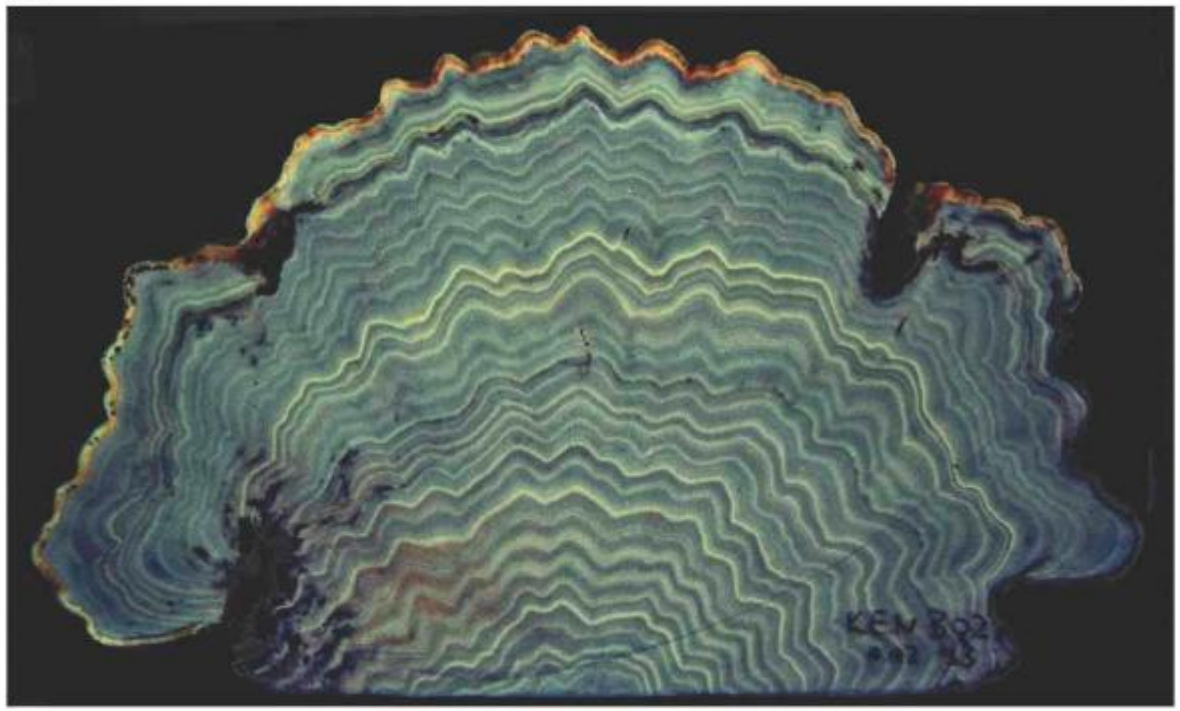


A clear and robust relationship between increased skeletal luminescence and high riverine discharges has repeatedly been shown. The principal cause of the luminescence proposed in this case is the incorporation in the coral skeleton of humic/fulvic acids leached from the terrestrial environment into river water.

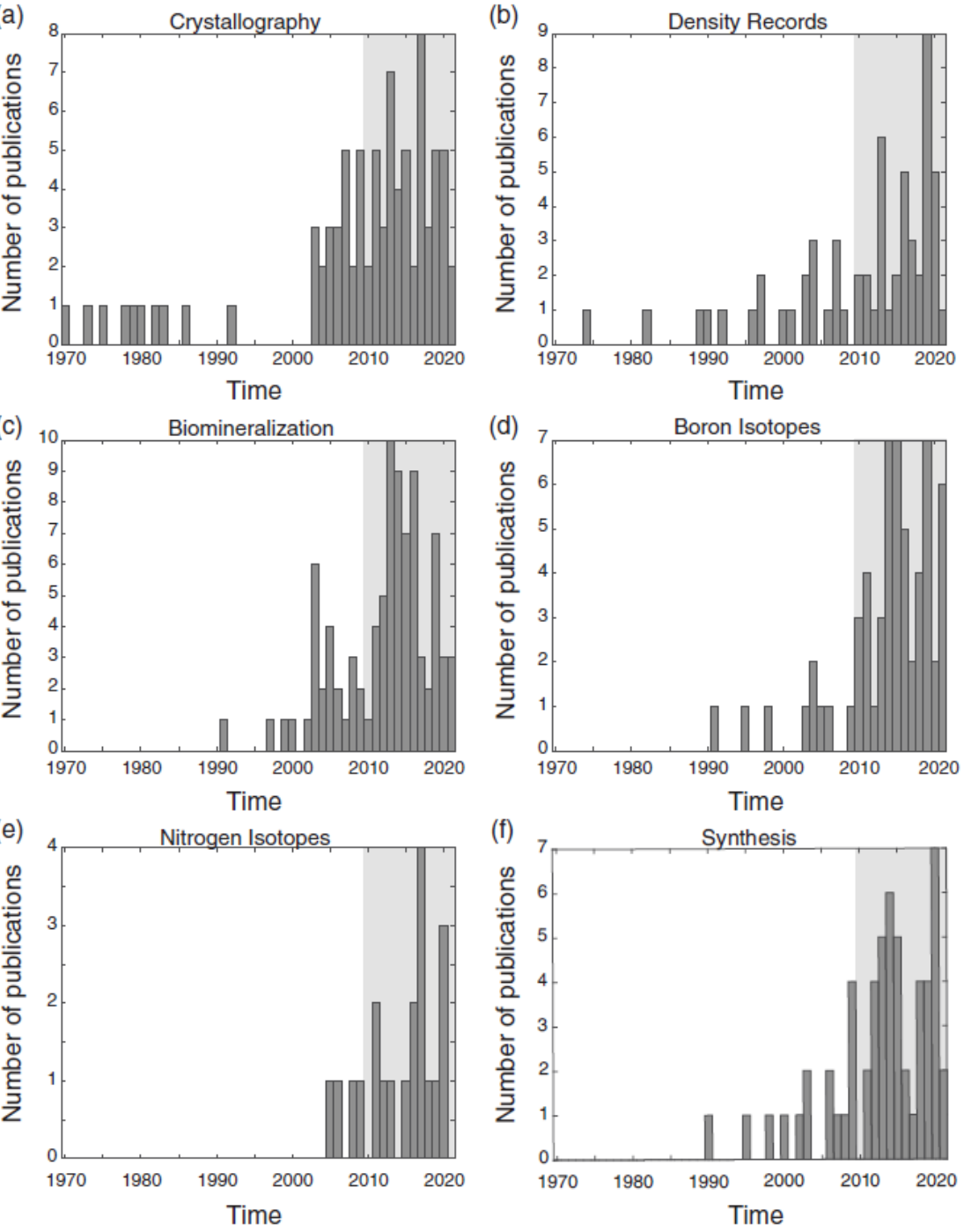
However, anomalous luminescence peaks in the absence of any major river flow event have been observed as well as annually recurring luminescent bands occurring in offshore corals thought to be far removed from terrestrial influences.

Such observations have led to the proposition that luminescence may also be related to and/or caused by variations in skeletal architecture other than chemical composition.

(b)



Slice shown in the previous figure illuminated by UV-light, illustrating bright luminescent lines purportedly documenting freshwater flood events.



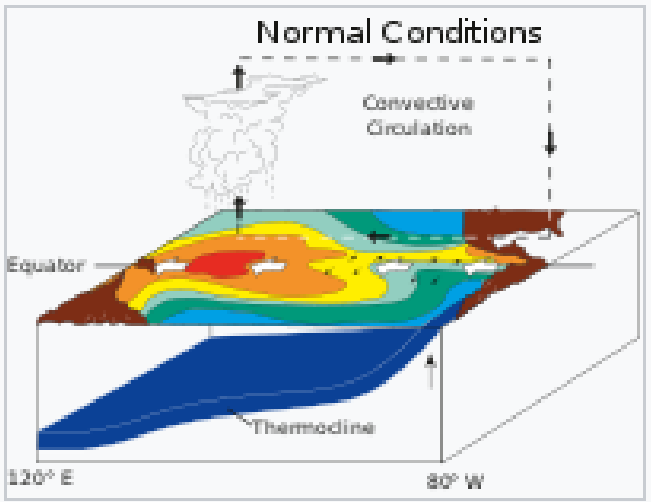
Frequency distribution of the number of publications per year since 1970 for a subset of the methodologies reviewed here: (a) crystallography (e.g., raman, aragonite unit cell structure), (b) skeletal density records (e.g., X-ray or CT densitometry), (c) biomineralization (e.g., histology, ion transport, organic matter, biochemistry, genomics, proteomics, or microstructure), (d) boron isotopes (e.g., pH, acidification, and/or calcifying fluid), (e) nitrogen isotope records (skeletal bound organic δ15N), and (f) coral paleoclimate synthesis (e.g., PAGES 2k, multisite networks, etc.). All subpanels were obtained by searching the Elsevier Scopus database with keywords for each subfield; each list was carefully curated to remove non-pertaining publications (e.g., studies on azooxanthellate or non-Scleractinian coral species).

What’s new…

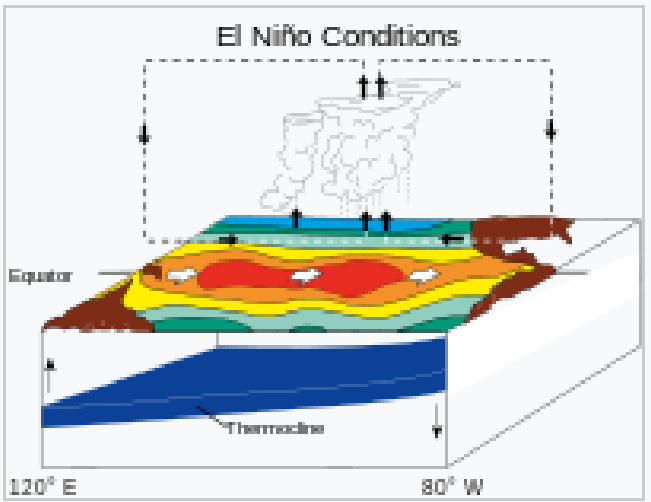
The growing network of fossil coral cores from across the tropical–subtropical Pacific has provided additional constraints on the timing and magnitude of the early- to mid-Holocene (~10-5 thousand years ago, hereafter ka) reduction in El Niño–Southern Oscillation (ENSO) variance in response to orbital forcing.
ENSO is an irregular periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, affecting the climate of much of the tropics and subtropics, and is considered of great importance for the modification of the climate of the whole planet.
Developing countries dependent upon agriculture and fishing, particularly those bordering the Pacific Ocean, are the most affected by ENSO, because ENSO can dramatically affect precipitation.

Mechanisms that cause the oscillation remain under study.

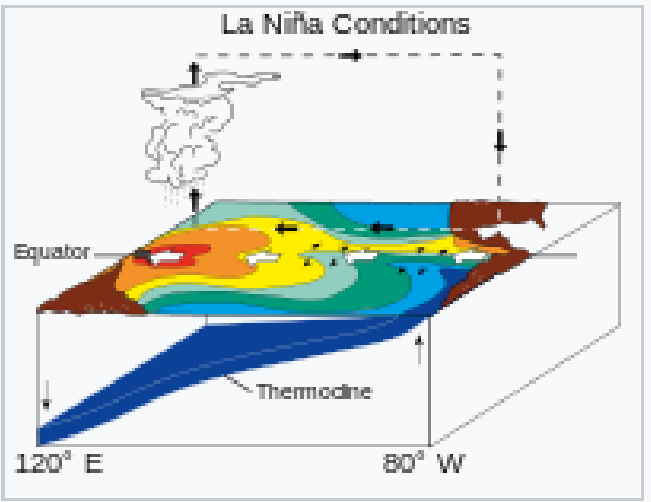
The warming phase of the sea temperature is known as El Niño and the cooling phase as La Niña. The Southern Oscillation is the accompanying atmospheric component, coupled with the sea temperature change: El Niño is accompanied by high air surface pressure in the tropical western Pacific and La Niña with low air surface pressure there. The two periods last several months each and typically occur every few years with varying intensity per period.



Normal Pacific pattern: Equatorial winds gather warm water pool toward the west. Cold water upwells along South American coast. (NOAA / PMEL / TAO)

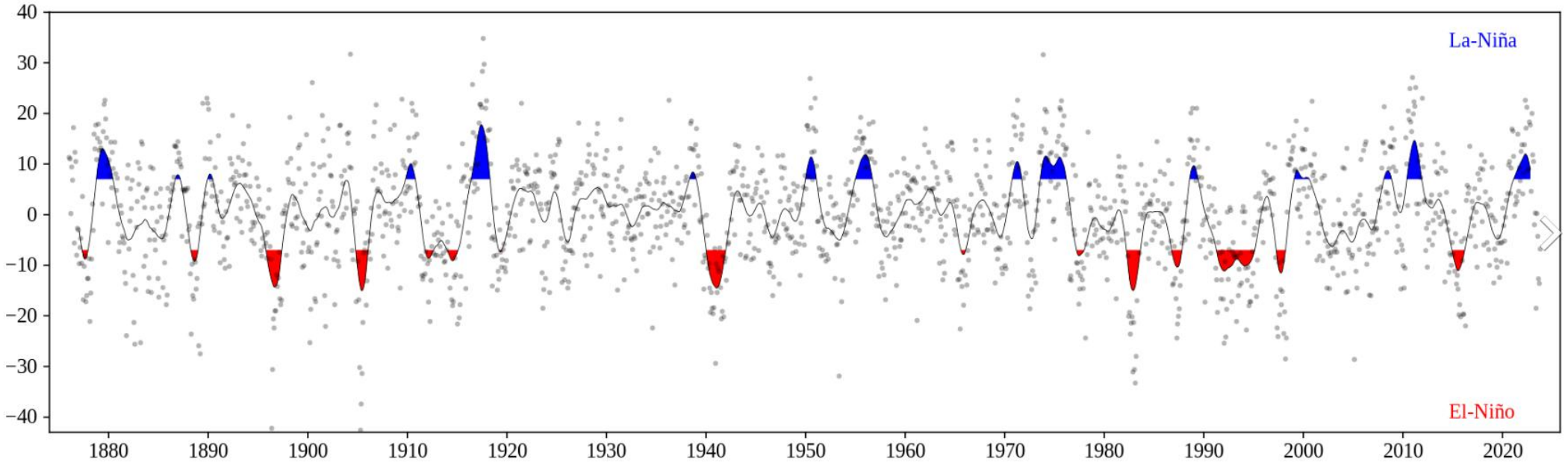


El Niño conditions: Warm water pool approaches the South American coast. The absence of cold upwelling increases warming.



La Niña conditions: Warm water is farther west than usual.

All the models developed so far to describe the fluctuations of ENSO need calibration based on past instrumental data, largely missing before 1880.

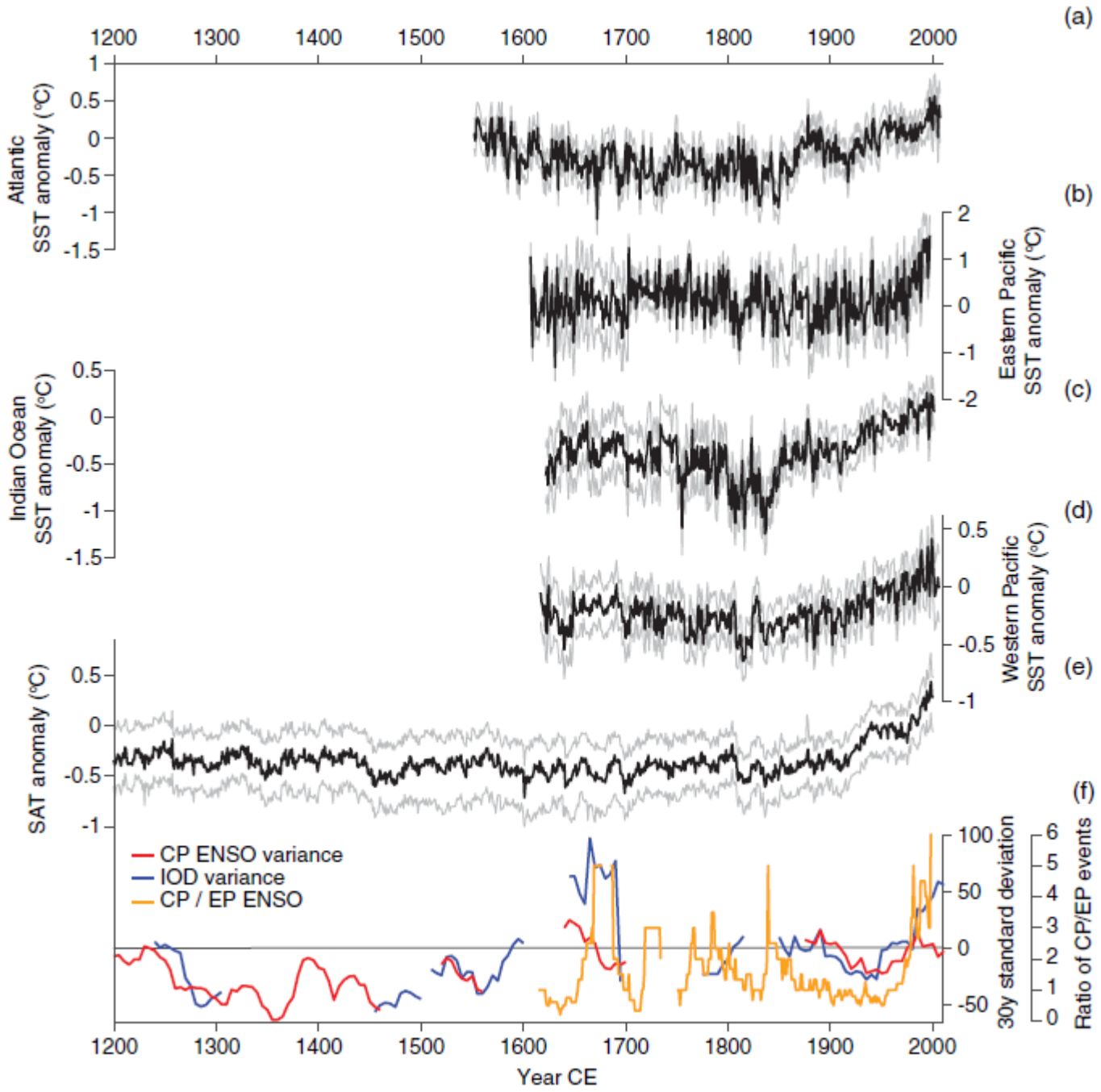


High-resolution coral records from the western Pacific and the eastern Pacific suggest an early-mid Holocene reduction in ENSO variance, in terms of frequency and/or intensity, followed by intensification of ENSO after 4 ka (Carré et al., 2005, 2014).
However, coral records from the Central Pacific and a multiproxy network of coral (and mollusk) records suggest a mid-Holocene reduction in ENSO frequency centered around 3–5 ka, out of phase with orbital insolation changes.

With new coral reconstructions and syntheses of existing records, a compilation of available $\delta^{18}O$ (temperature and seawater $\delta^{18}O$—hereafter $\delta^{18}Osw$) and Sr/Ca (temperature) records with coverage over the Common Era have identified coherent signals of temperature and hydroclimate change in response to volcanic and anthropogenic aerosol and greenhouse gas forcing.

These coherent trends emerge despite noise within individual proxies, regional differences in the timing and/or magnitude of change as a result of regional climate dynamics.

However, despite the community focus on the Medieval Climate Anomaly (~800–1200 CE) and Little Ice Age (~1300–1850 CE) for understanding the climate system response to natural (solar and volcanic) forcing, reconstructions display little regional coherence. Ongoing record development and innovative syntheses will certainly bring additional constraints on the climate-system sensitivity to internal and external forcing in the coming years.



Reconstructions of sea surface temperature anomalies (relative to the 1961–1990 reference period) from annual and sub-annually resolved coral records, where black denotes the best reconstruction and gray indicates the root mean square error (RMSE) in the:
(a) western Atlantic Ocean,
(b) eastern Pacific Ocean,
(c) Indian Ocean,
(d) western Pacific Ocean.
(e) Reconstructed surface air temperature anomalies from the PAGES 2k temperature network (PAGES2k Consortium, 2017).
(f) The running 30-year standard deviations of coral-based ENSO (red) and Indian Ocean Dipole (blue) reconstructions (axis 1) and the ratio of central Pacific-type to eastern Pacific-type El Niño events (yellow,) (axis 2).

The most recent compilations emphasize the unprecedented nature of 20th-century warming and its global coherence, relative to the pre-industrial CE.