Sea Level Changes

Below follows a short introduction concerning different factors controlling sea level changes.

Past sea level positions and past sea level changes represent relative sea level and relative sea level changes, i.e. the combined net effects of the deformation with time of the ocean level as well as the land level. This is illustrated in Fig.3-1 .

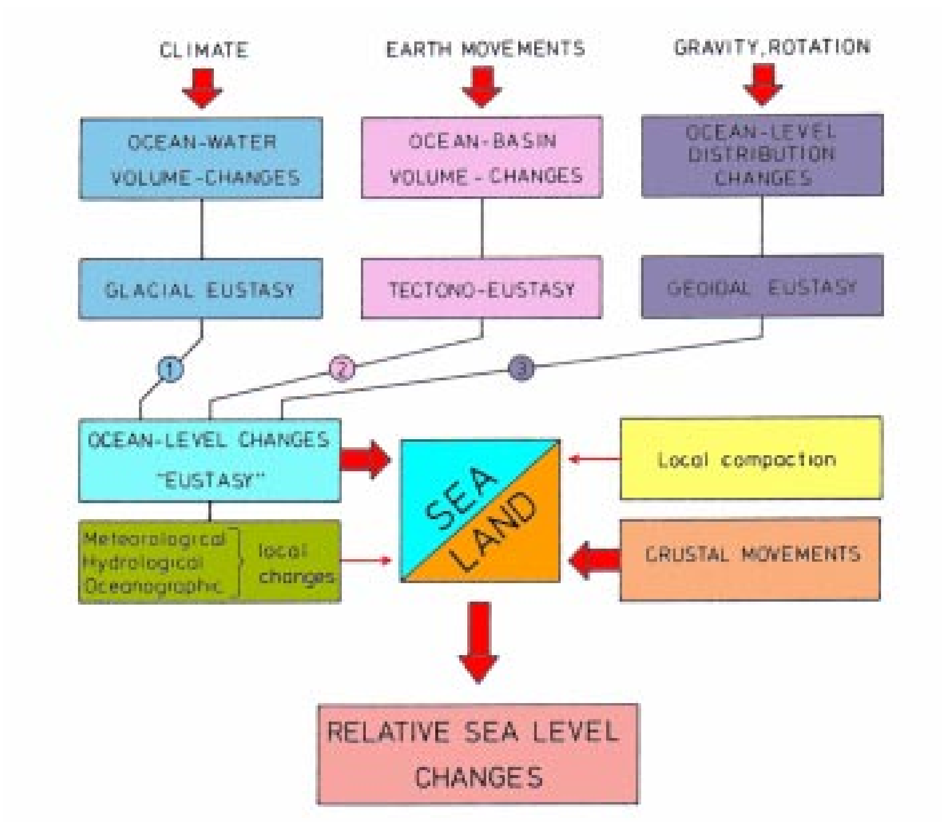


Fig. 3-1. Relative sea level changes are the combined function of all variables affecting the ocean level and land level, respectively (from Mörer, 1980)

The land level is deformen by crustal factors, sediment compaction and geoid changes. The ocean level is deformed by three main groups of factors; viz. those changes

1. the water volume in the oceans,
2. the volume of the ocean basins, and
3. the distribution of the water.

This is illustrated in Fig. 3-2. Below follows a short discussion of the different variables controlling the ocean level changes.

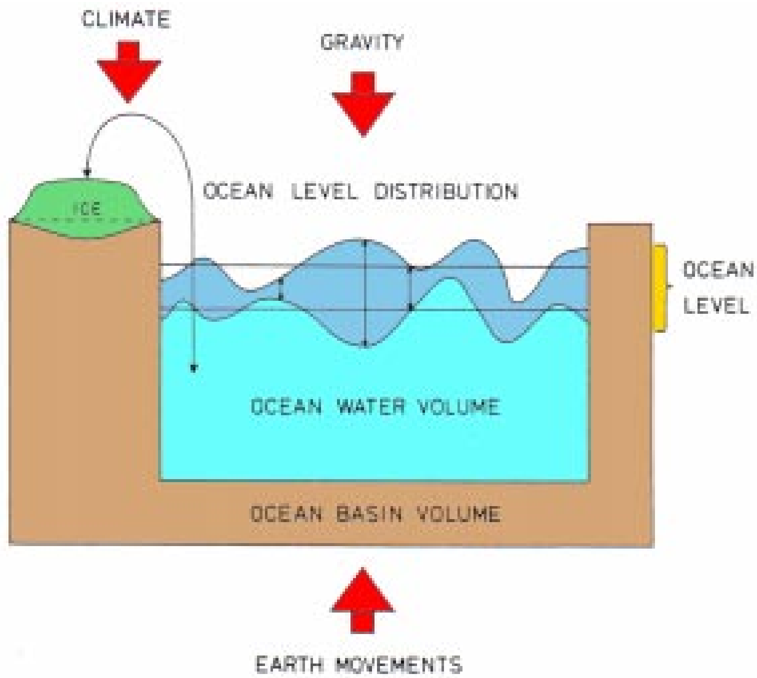


Fig. 3-2. The three main ocean variables and the irregular deformation (pink field) betweet two eustatic ocean level positions (from Mörner, 1976).

1. Changes in water volume in the oceans

The water in the ocean and the volume of glacial ice on land are in balance; when one increases the other decreases. This is known as *glacial eustasy* (first proposed by Maclaren, 1842). At the last glaciation maximum at around 20,000 BP (20 ka), sea level seems to have fallen in the order of 120 m (Fairbanks, 1989). We may try to reconstruct past glacial volume changes by the following three means:

(1) the recording of corresponding sea level positions,
which are affected by numerous other varibales, too
(2) the recoding of corresponding oxygen isotope variations,
which are affected by other factors, too, not least temperature
(3) volumetic estimated of corrsponding ice caps,
which is quite a rought method (presently stored ice in Antarctica,
Greenland and alpine glaciers are estimated in this way).

Though all three methods have their limitations and problems, there is a general agremment that the 20 ka glacial eustatic lowering was in the order of 120 m (in sea level by Fairbanks, 1989, in oxygen isotope values by Shackleton, 1987, and in glacial volume by Flint, 1969).

The ocean volume is also affected – or rather somewhat modulated – by a number of other factors like addition of juvenile water, storage of water in sediments, variations in the main hydrologic cycle changing continental lake volumes, cloudiness, and the evaporation/ /precipitation balance.

A factor of high significance is the *steric expansion/contraction* of the water column. This has been very much debated in the last decade, and advocated as one of the most important factor in future sea level estimates. The steric changes are driven by changes in temperature and, to a lesser degree, in salinity. The expansion of water heated in steps from 0.1 to 5.0 °C is given in Fig. 3-3. The effect from surface water is small. If the intermediate water is heated, too, the effect becomes significant.

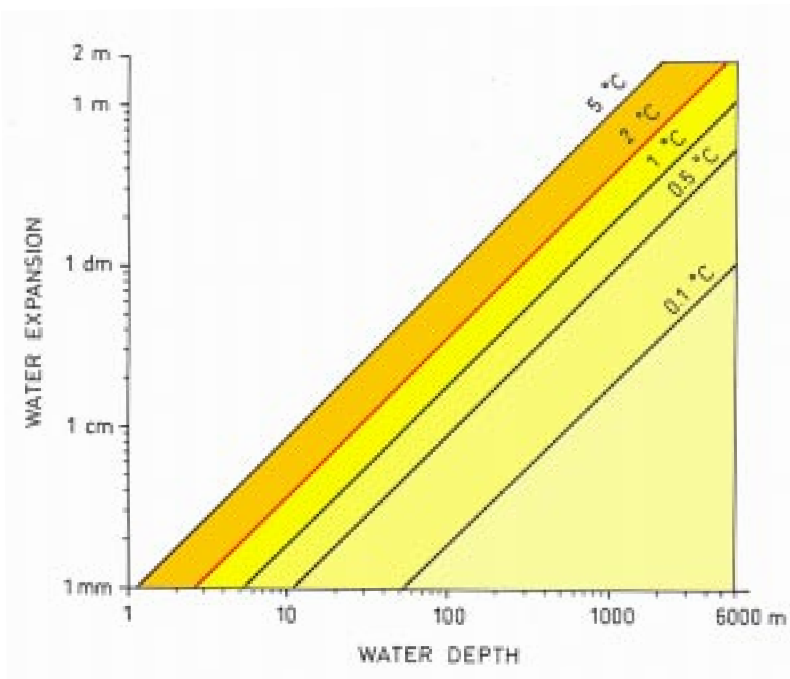


Fig. 3-3. Steric water expansion (vertical logarithmic scale) versus ocean water column heated (horizontal logarithmic scale) in steps of heating (diagonal lines) from 0.1 to 5.0 °C with the 2.0 °C line marked in red.

2. Changes in ocean basin volume

The basins of the oceans may change their for via crustal movenents so that it increases and decreases in total volume. This is known as *tectono-eustasy* (and was first proposed by Suess, 1888). In reality, this is nothing but deformation of the hypsographic curve. This is a slow process, however, not exceding 0.06 mm/yr in sea level changes as illustrated in Fig. 3-12 (Mörner, e.g. 1996b).

Besides tectonic and isostatic factors affecting the basin volume, sedimentation also act in decreasing the volume.

3. Changes in the ocean water distribution

The global distribution of oceanic water should, in theory, follow the rotational ellipsoid (with a distance difference between the polar and equatorial radius of 20,000 meters). Due to the irregular distribution of mass, the equipotential surface or *the geoid level* is heavily irregular, however, as illustrated in Fig. 4. The real sea level often departs a little from the geoid because of various dynamic forces defining actual sea level, the so-called *dynamic sea level*.

The geoid relief does, of course, not remain stable with time; it deforms vertically as well as horizontally (Fig. 3-2). This is known as *geoidal eustasy* (Mörner, 1976, 1980).

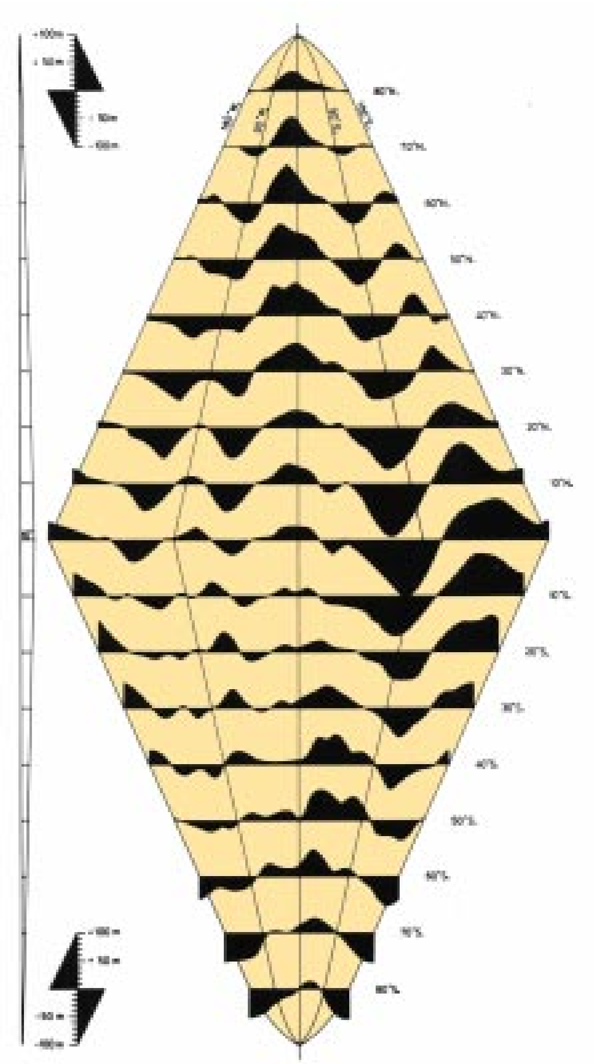


Fig. 3-4. Departure of the geoid from the teorethical hydrospheric ellipsoid drawn in profiles for every 10° latitude with positive geoid values above and negative geoid values below and with the corresponding scale in meters given at the left side (from Mörner, 1976).

If the Earth's rate of rotation changes – accelerate or decelerate – the rotational ellipsoid will deform in accordance with this. We may call this *rotational eustasy*. The largets effecs occur between glacial sea level low stands and interglacial high stands, when the changes in radius inevitably has th affect the Earth's total angular momentum; speeding-up at low stands and slowing-down at high stands. In principles, 1 metre sea level equals 15 milliseconds in the length of the day (LOD). Changes in the tilt axis – the 42,000 year obliquity cycle – will also deform the rotational ellipsoid.

The sea level topography is also affected by several dynamic factors forcing the actual sea level to depart from the geodetic sea level, the geoid. These factors are ocean currents, air pressure, inbalance in evaporation/precipitation balance, coastal run-off, etc. The deviations are in the order of up to 2 m (Mather et al., 1979; Levitus, 1982). The Gulf Stream may depart as much as 5 m from the geoid surface (Fig. 3-5). We may term sea level changes caused by these dynamic factors for *dynamic eustasy*.

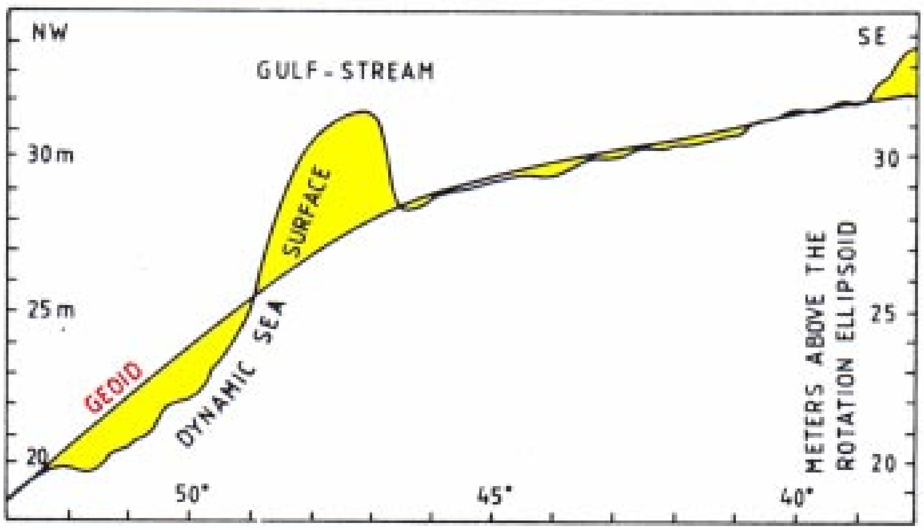


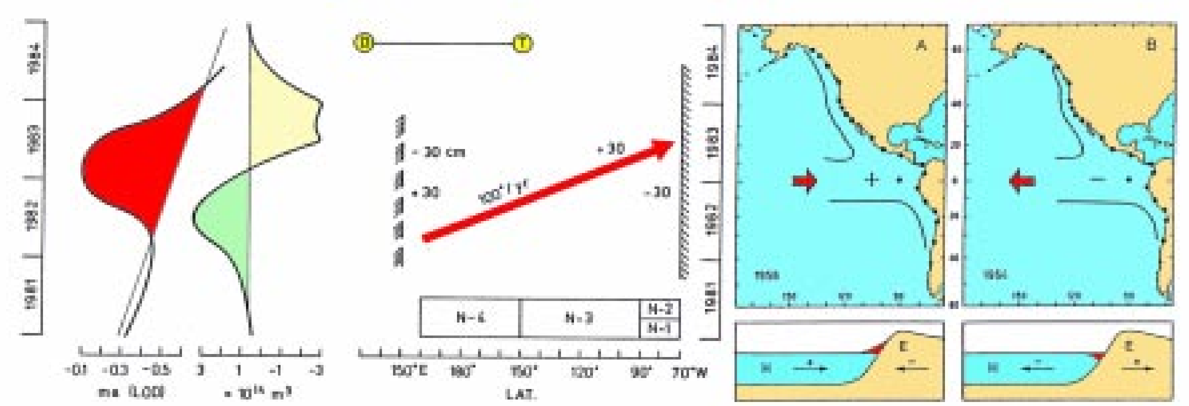
Fig. 3-5. Satellite profile over the NW Atlantic recording the strongly slooping geoid surface and the dynamic sea surface departure due to the strong forces of the Gulf Stream (from Mörner, e.g. 1995).

Because the Earth is a multi-layered body, it may interchange angular momentum between its different layers and sub-layers though the total angular momentum is kept constant (Mörner, e.g. 1988). This is the case on the annual to intra-annual time-scale between the "soild" Earth and the atmosphere. It seems to be the case between the core and the mantle on the decadal basis at periods of so-called geomagnetic jerks. And, its seems to be tha case on the decadal to centennial time-scale between the hydrosphere and the "solid". We may term this *momentum eustasy*.

4. ENSO and Super-ENSO events

El Niño/ENSO events include a part that represent interchange of angular momentum between the hydrosphere and the "solid" Earth (in a feed-back coupling). This is illustrated in Fig. 3-6 where 0.4 ms is transferred from the Earth's LOD to the hydrosphere and then back again to the "solid" Earth (LOD).

The Holocene observational records of changes in climate, ocean current beat and sea level changes seem to records seem to recods ENSO-equivalent events on the decadal to centennial time-scale or what we may call *Super-ENSO events* (Mörner, 1988, 1995). This generates opposed climatic-eustatic signals on the east and west sides of ocean basins (Fig. 3-7) and an irregular beat in the Gulf Stream and the Kuro Sivo Current (Fig. 3-8). The Gulf Stream beat is illustrated in Fig. 3-9.



3-6. Left: The 1982/83 ENSO event and related changes in LOD (red field shows the loss and gain of 0.4 ms in the rate if rotation of the solid Earth), in hot water masses accumulated in the equatorial west Pacific, and a geographic plot illustrating the eastward displacement of hot surface water (with corresponding changes in sea level on the western and eastern sides) up to mid-1983 when it hits the American coasts and 0.4 ms LOD is transferred back from the hydrosphere to the solid Earth. Right: Rises (+) and falls (-) in sea level as recorded by tide gauges (black dots) along the American coasts during ENSO (A) and non-ENSO (B) years with the corresponding interpretation in terms of differential rotation between the ocean (H) and the solid Earth (E) given below (from Mörner, e.g. 1996a).

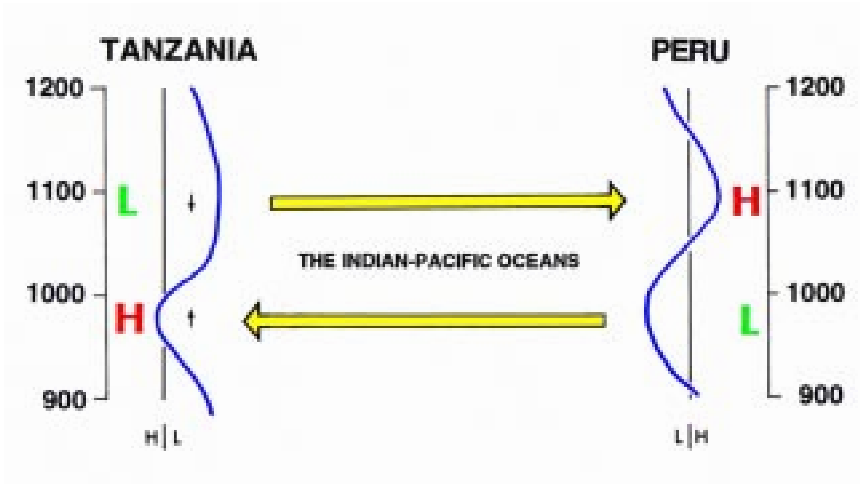


Fig. 3-7. The east-west displacements of oceanic water masses within the Pacific–Indian Ocean basins in the period 900–1200 AD (from Mörner, 2000). At around 950-1000 AD, sea level was high in Tanzania (red H) and low in Peru (green L). A centure later, at around 1050-1150 AD, the situation was reversed. Sea level was low in Tanzania (L) and high in Peru (H). These changes are interpreted as Super-ENSO events as a function of a feedback interchange of angular momentum between the solid Earth and the hydrosphere.

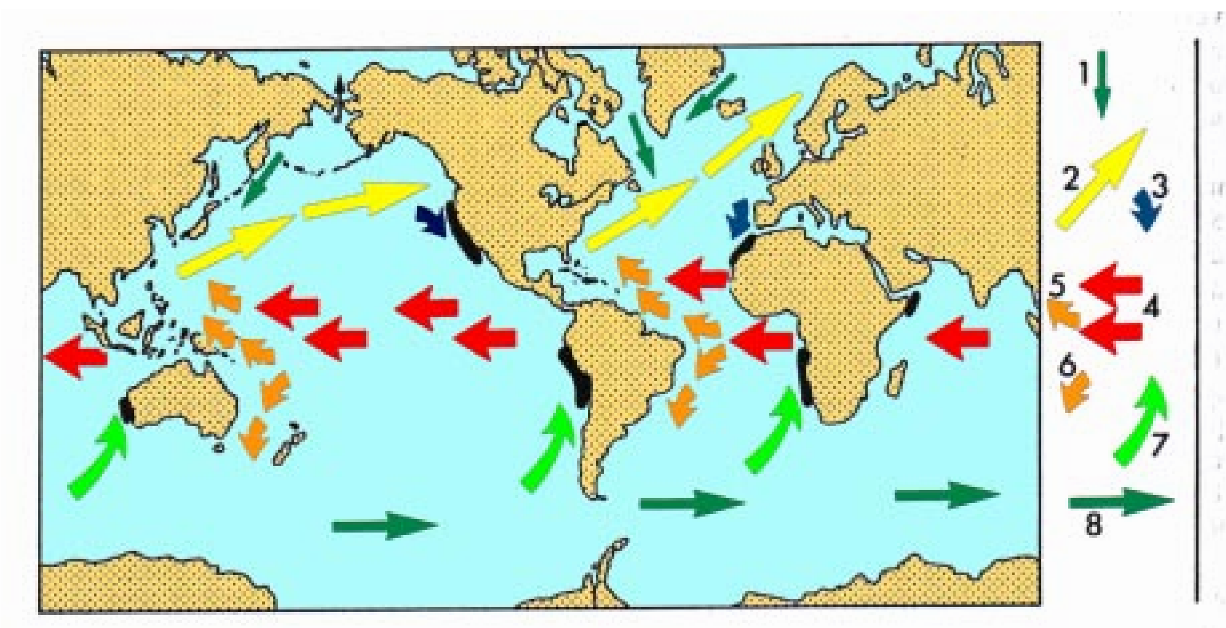


Fig. 3-8. The main global oceanic surface circulation patterns (arrows) and regions of coastal upwelling (black fields). The Gulf Stream and Kuro Sivo Current (yellow arrows) exhibit an irregular beat as a function of feedback coupling in the interchange of angular momentum between the solid Earth and the hydrosphere (from Mörner, 1988).

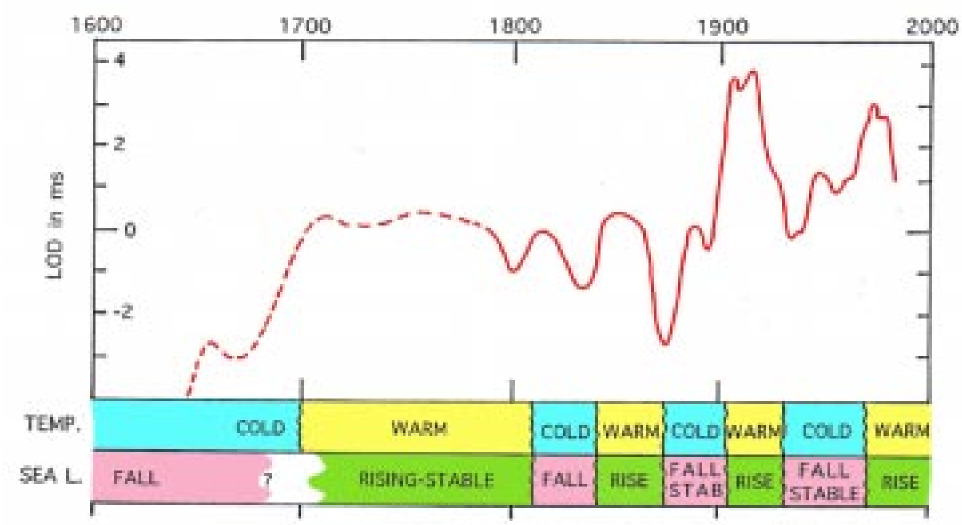


Fig. 3-9. The variations in the Gulf Stream distribution of hot equatorial water controlling European regional eustasy and climate (Mörner, 1988, 1995). Upper left: the main Gulf Stream system. Upper right: the transport is intensified towards the north (recorded by higher sea level and warmer climate in the North Sea region, and the opposite conditions in SW Europe and NW Africa). Lower left: the transport is intensified along the southern branches (giving warmer climate and higher sea level in the Bay of Biscay and in the Gibraltar region. Lower right: the transport isstrongly concentrated on the southern branch and Arctic water is forced far down along the coasts, giving "Little Ice Age" conditions and low sea levels in NW Europe at the same time as the Gibraltar region experiences "Warm Optimum" conditions and high sea levels.

The Gulf Stream is especially interesting as it so effectively controls the climate of northwestern Europe. In the Holocene 16 pulses are recorded in the Gulf Stream, in the continental climate and in the regional northwest European eustasy. Therefore, it is of great significance that the last centuries´ instrumental record in Earth's rate of rotation (LOD), climate and sea level seem to confirm this model (Fig. 3-10).

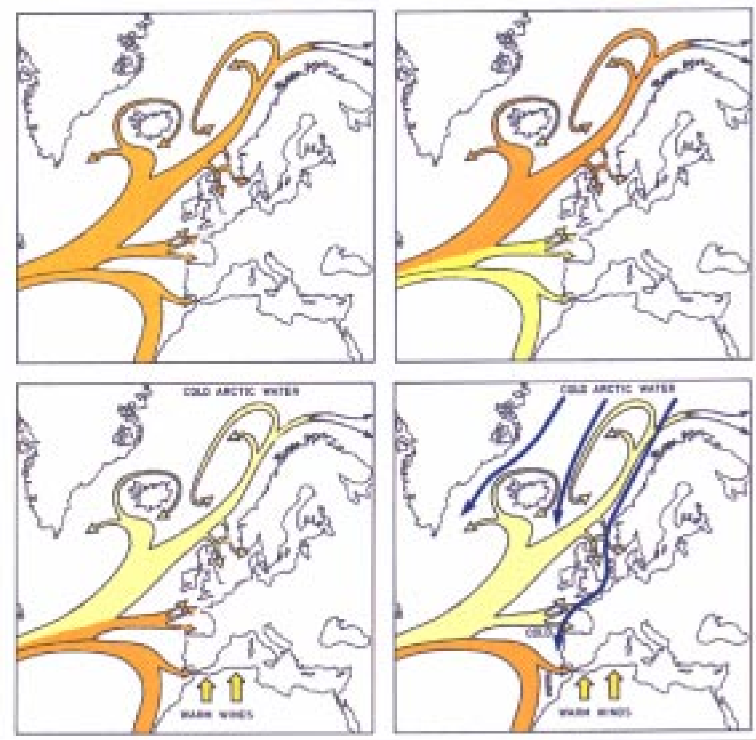


Fig. 3-10. Instrumental LOD changes (accelerations down and ddecelerations up) and corresponding changes in sea level and air temperature in the NW European region (from Mörner, 1996a). The correlations are good and lend strong support to the rotation/circulation theory (Mörner, 1988, 1995, 1996a).

5. The sun spot minima signals

The Spörer, Maunder and Dalton Sun Spot Minima seem all to be roughly correlated with Northwest European cold phases or “Little Ice Ages”. The Maunder Minimum situation is shown in Fig. 3-11. Obviously, it primarily is the oceanic currents that are affected. Whilst NW Europe exprериences a significant cooling, SW Europe and northern Africa experience a strong warming. This is understood in therms of a general speeding-up of the Earth as a function of a decrease in the Solar wind intensity and its interaction with the Earth’s magnetosphere (Mörner, 1996a).

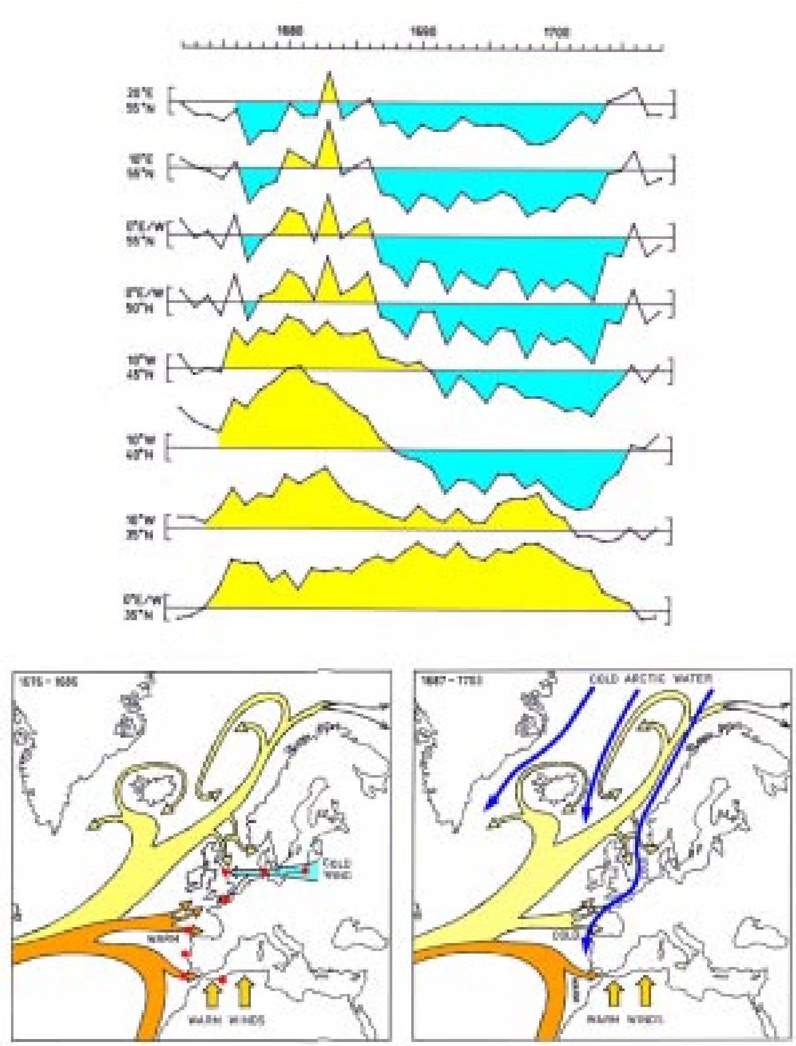


Fig. 3-11. *Above:* eight temperature records covering the period 1672–1708 (blue = cold, yellow = warm) with location of data points given by red dots in the lower left map. *Below:* interpretation in terms of ocean current changes for the period 1676-1686 (left) and 1687-1703 (right) when NW Europe experienced a severe "Little Ice Age" (a 5°C sea surface cooling was regorded between Iceland and the Faerö Islands) and the Gibraltar region experienced a "Warm Optimum" (from Mörner, 1995, 1996a).

6. Global glacial isostasy modelling

Farell & Clark (1976) proposed that the glacial isostatic deformation in association with the Ice Age ice caps over North America and Fennoscandia were not compensated regionally but, in fact, affected the entire globe. Peltier (e.g. 1998) and Lambeck (e.g. 1993) have extended this into a detailed modelling. Unfortunately, the model predictions are sometimes used in priority even of the true observational records. The model is what it says "a model", nothing more.

The models assume spherical symethry of the Earth – and this is surely not the case. When it concerns the Fennoscandian uplift, the model input data strongly differ from the observational data base. The models only rarely give an acceptable fit with field data. A Holocene sea level high stand in the central Pacific lasting for several millennia is, for example, not substantiated, and this is cruzial for some of the main interpretations. The model – if improved and tested in a free and constructive way – will, one day, become a very useful tool in sea level research, no doubt about that.

At present, the model predications are rather misused than taken for what they are; model outputs that must always be inferior to good observational data.

7. Rates and amplitudes

The changes in ocean level as well as in land level are bound by certain maximum rates and amplitudes. Fig. 3-12 expresses maximum rates as amplitude/time vector lines for different oceanic and crustal factors from 1 million years down to 1 second (Mörner, 1996b).

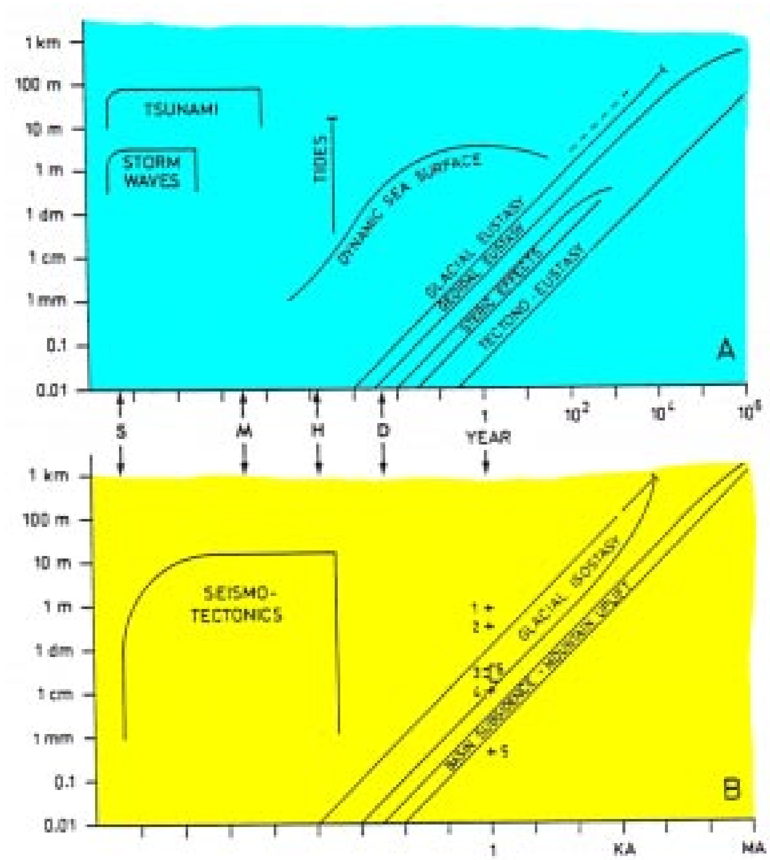


Fig. 3-12. Maximum rates of sea level changes (above in blue) and crustal changes (below in yellow) with amplitudes vertically and time horizontally and with D = day, H = hour, M = minute and S = second (from Mörner, 1996b).

8. Sea level curves

A sea level curve is a graph of past sea level positions plotted in a time/depth-elevation diagram. Its significance depends upon the number of data points, the correct interpretation of its relation to the corresponding mean sea level, and the quality of age determinations. These criteria are hardly ever met. The quality drastically improves if the data are related to morphologically idetifiable shore-marks or shorelines.

In his "*Metamorphoses*" (XV: 261-272), Ovidius (43 BC to 17 AD) wrote:

vidi ego, quod fuerat quondam solidissima tellus, esse fretum,

I have myself seen what once was most solid ground disapear into the sea

vidi factas exaequore terras

and I have heard of land risen out of the ground

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