Development of an Ishikawa diagram for the occurrence of extremely high sea levels

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Abstract. A little more than 10,000 years ago, the so-called ice age, with the average temperature of the Earth about 10° lower than today. After the ice age, there was an increase in temperature and the melting of glaciers, and in the last 1,000 years the temperature trend has been slightly negative. The exception is the last 100 years, when there is a sudden increase in air temperature due to the increased emission of greenhouse gases of anthropogenic origin. The increase in temperature in the last hundred years was about 1°. Of course, these changes have an impact on the dynamics of the ocean, and a particular problem is the global rise in sea level. In the paper, an Ishikawa diagram was developed that analyzes the impacts of sea level rise. As the main causes of sea level change, both in time and in space, are included: tidal oscillations, meteorologically caused sea level changes, and changes on a seasonal and multi-year time scale. Each of these main causes is explained and sub-causes are found using the laws of physical chemistry and thermodynamics. Sub-causes have been identified that can be influenced most easily and quickly, acting preventively to save densely populated areas.

1. Introduction

The main causes of sea level change, both in time and in space, are [1]:

- tidal oscillations,
- meteorologically caused sea level changes, and
- changes on a seasonal and multi-year time scale.

Tidal oscillations (sea changes) are caused by the gravitational attraction of the Earth's water masses by the Sun and the Moon, and the Earth's centrifugal force. Gravitational action has a periodic character, with pronounced semi-diurnal and diurnal components. Due to the tidal force, the sea level periodically oscillates.

Meteorologically caused changes in sea level include all non-periodic and quasi-periodic changes in sea level that are not caused by tidal forces, but by processes at the atmosphere-sea interface. This group includes a time scale from a few minutes (free oscillations of smaller bays and harbors) to tens of days (influence of planetary atmospheric

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waves). The main causes are air pressure and wind, but other processes (precipitation, evaporation, etc.) can also significantly affect the changes. Meteorological influence on sea level fluctuations has a double effect [2]:

(1) forced oscillations (slowdowns) - they are the result of constant action of force (wind and air pressure) on the surface of the sea. They take place (mostly) on the time scale of synoptic and planetary disturbances, i.e., over a period of more than one day, and

(2) free oscillations (seshi) - represent the response of the sea to rapid changes in meteorological parameters, i.e., they arise due to the inertia of the system that tends to return to the equilibrium position from which it was excited by the action of the force on the sea surface. Free oscillations are time-space characteristics determined by the topographic properties of the basin in which they occurred.

Dynamic processes in the sea can also affect sea level changes. Thus, during the process of sea sinking (downwelling), the sea level rises, while during upwelling, the sea level decreases. These processes occur both in coastal areas and in the open sea, as part of cyclonic and anticyclonic systems and smaller cells. The dynamic influence on the sea level is also manifested in the appearance of various long-period waves in the sea (Rossby waves, gravity-inertial waves) and topographic waves that arise along the coast or other topographical forms on the bottom of the sea. [3]

Sea level changes on a seasonal time scale are the result of the seasonal effect of meteorological parameters (air pressure, wind) on the sea surface, as well as the seasonal course of the water balance (evaporation, precipitation, river inflows) on the sea surface. In areas where the seasonal thermocline (pycnocline) is formed, changes in sea level can occur because of the thermal expansion of the water column (the so-called steric effect), which occurs due to changes in the density of the surface layer caused by temperature changes. On a multi-year scale, sea level changes are the result of changes in the regime at the atmosphere-sea boundary, i.e., the water and heat balance on the sea surface, climate changes in the dynamics and composition of water masses, and geological-tectonic changes, i.e., vertical ground movements. [3]

2. Causes

2.1. Tidal oscillations theory

The tidal force is caused by the gravitational attraction of water masses by the Sun and the Moon, and by the centrifugal force created by the rotation of the Earth and the Moon, that is, the Earth and the Sun around the common centre of mass. Its action is periodic in nature, with the most pronounced half-day and day components.

Due to the action of the tidal force, the sea level and sea currents occasionally oscillate (so-called sea changes). Episodes of sea level rise or fall are called sea ages (or tides). Tidal force is a combination of gravitational and centrifugal force acting on water masses on Earth. Namely, the movement of water masses is affected by the gravitational attraction of the Sun and the Moon, which is variable and depends on their position in relation to the Earth, and the centrifugal force that arises because of the revolution of the Earth. Thus, the tidal force has a changing character in space and time, and it has a dominant effect on the horizontal movement of water masses, thus causing fluctuations in the sea level and sea currents. [1]

Gravitational interaction of two bodies is [4]:

$$F_g = \frac{G \cdot M_1 \cdot M_2}{R^2} \tag{1}$$

where are they:
M_1 and M_2 - mass of body 1 and body 2 (kg),
R - the distance between centres of bodies (m) and
G - universal gravitational constant ($G = 6.672 \cdot 10^{-11}$ Nm^2kg^{-2}).

The Sun is about 390 times farther from the Earth than the Moon, but it has a much greater mass. However, the Sun's action on water masses on Earth represents 46% of the Moon's action, so the Moon's tidal components in the tidal signal are more pronounced than the Sun's components. When the Sun, Moon and Earth are approximately in the same plane, i.e., when the Moon is in conjunction (new Moon) or in opposition (full Moon), then the gravitational effects of the Sun and Moon on the water masses are added, and the sea changes are more pronounced. This period is called syzygy. [5]

The opposite is the period of quadrature when the Moon is perpendicular to the direction of the Sun and the Earth (first and last quarters). Then the tidal force is the weakest, and therefore the sea waves are the least pronounced.

Tidal components also depend on the topographic characteristics (coastline, depth) of the sea. Namely, the speed of propagation of long waves depends on the depth of the sea, while the Coriolis force causes the movement of the tidal signal along the coast, in the form of a Kelvin wave. In the case of a semi-closed basin, the combination of incoming and outgoing waves results in the appearance of an amphidromic point where the amplitude is equal to zero, that is, around which the circulation of the tidal oscillation occurs. Each tidal component at a point is characterized by its harmonic constants (amplitude and phase), which are determined by harmonic analysis. Harmonic synthesis, i.e., the summing of all tidal components, synthesizes a time series of sea level oscillations caused by the tidal force, and serves to forecast sea changes in the future.

2.2. Meteorological causes of sea level change

Meteorologically caused sea level fluctuations include all non-periodic and quasi-periodic sea level changes caused by processes at the atmosphere-sea interface. Forced oscillations ("storm surge") are the result of the constant action of force (wind and air pressure), while free oscillations (seshi) represent the sea's response to rapid changes in meteorological parameters, i.e., they arise due to the inertia of the system that tends to return to an equilibrium position.

Storm surge i.e., forced oscillations of the sea level take place without a significant disturbance of the hydrostatic balance in the sea. Their behaviour is non-periodic and is mainly caused by strong and long-lasting winds and unusually high or low air pressure. These changes in the open sea do not cause major sea level fluctuations, up to 1 meter at most, while in coastal areas due to topographical effects they can reach several meters and cause flooding, damage, and destruction of coastal infrastructure.

The slowdown is a consequence of the simultaneous effect of air pressure and wind, which pushes water masses towards coastal areas. The effect of air pressure on changes in sea level, assuming that the situation is stationary, and that currents in the sea are negligible due to the uniform effect of air pressure in space, from the equations of a shallow fluid, integration over space yields the relation [1]:

$$\zeta = -\frac{p_a - \overline{p_a}}{g \cdot \rho} \tag{2}$$

where are:
ζ - the change in the height of the sea level
p_a - $\acute{p}_a$ - the change in the atmospheric pressure (p_a) in relation to the mean pressure (p_a).

g – the gravity (9.81 m/s^2), and
ρ - the density of the sea (about 1025 kg/m^3).

According to equation (2), it follows that an increase in atmospheric pressure of 1 hPa causes a drop in sea level of about 1 cm and vice versa.

The effect of wind on level changes depends on the wind tension t on the sea surface, and is shown by the equation [1]:

$$\zeta = \frac{1}{g \cdot H \cdot \rho} \left(\tau_x x + \tau_y y\right) + C \tag{3}$$

where are they:
$\boldsymbol{\tau}_x$ and $\boldsymbol{\tau}_y$ - wind stress components,
H and ρ - depth and density of the sea, and
C - constant.

Therefore, the sea level rise at the closed end is greater in shallow seas, while this effect is not significant in deep seas. For a one-dimensional homogeneous pool with a depth of 10 m, a length of 100 km and a wind speed of 10 m/s, the sea level rise at the closed end is about 10 cm.

Free oscillations (seshes) appear in lakes, bays, or canals because of sudden changes in meteorological parameters over an area, primarily sudden changes in wind. These oscillations are barotropic, and their characteristics are defined by the topographic characteristics of the area. For a homogeneous, regular pool, the shallow fluid equations apply. With the assumption that some force on the surface (wind) has already caused the movement of the water mass from the state of equilibrium, and that it has ceased to act after that, and with the neglect of bottom friction, which normally stifles oscillations in nature, the equation reads [1]:

$$\frac{\delta U}{\delta t} = -g \frac{\delta \zeta}{\delta x} \tag{4}$$

$$D \frac{\delta U}{\delta x} + \frac{\delta \zeta}{\delta t} = 0 \tag{5}$$

where are:
U - the speed of the current in the direction of the x axis,
ζ - the unevenness of the sea surface,
D - the depth of the basin, and
g - the gravity.

2.3. Changes on a seasonal and multi-year time scale

During the process of sea sinking (downwelling), the sea level rises, while during upwelling, the sea level decreases. On a molecular spatial scale, in parts of the ocean, where saltier and warmer water is located above colder and less salty water, the process of double diffusion or the so-called "salt fingering". Since the transfer of thermal energy takes place faster than the transfer of salt, the layer of saltier and warmer water is cooled before its salinity equalizes with the surrounding water. This layer becomes denser, so instabilities and vertical movements occur at the boundary between the two water masses. Eventually, a certain part of both water masses gets mixed, forming a new water mass in that area. This process is significant in certain areas of the ocean, for example in the North Atlantic where the saltier and warmer Mediterranean water is above the colder and less salty North Atlantic deep water.

A special case of vertical movements is the dynamics of deep convection, which occurs in deep sea areas during the formation of deep-water masses. During the winter months, with a pronounced loss of energy from the sea, the surface layer of the sea is cooled so much that the sea column becomes unstable. Because of this, the cooled dense water sinks, and mixes with the deep waters until the density of the newly created water equals the density of the surrounding water.

There is a [3]:

- coastal inundation/sinking, where the wind causes a longshore current, while the mass is pushed away from or towards the coast (the so-called Ekman transport),
- equatorial drifting, which is a consequence of wind shear in that area, and
- sinking/sinking which is a consequence of convergence or divergence of water masses due to wind or horizontal pressure gradient in the sea.

3. Ishikawa diagram

The Ishikawa diagram (cause and effect diagram, "fishbone") is a simple and very useful method for seeing the causes that lead to the effect being analysed. It is often used as a conceptual model for computer model development. The Ishikawa diagram of the occurrence of extremely high sea levels is shown in Figure 1. [6]

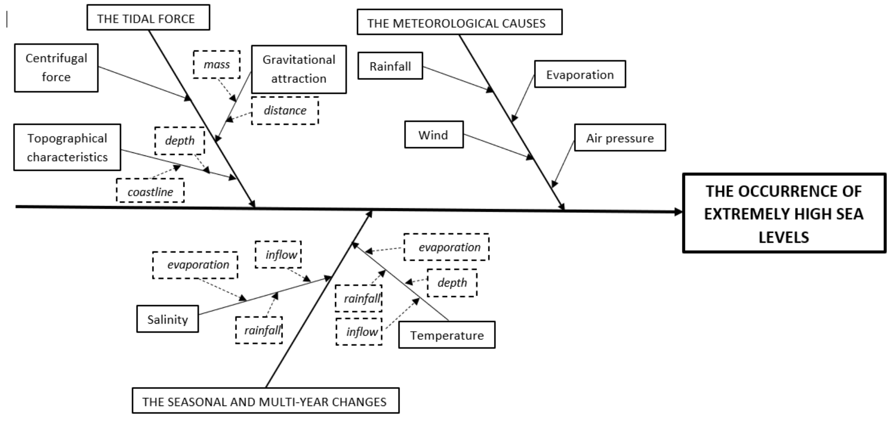

Fig. 1. Ishikawa diagram.

The main causes of the effect *"THE OCCURRENCE OF EXTREMELY HIGH SEA LEVELS"* are: *"THE TIDAL FORCE", "THE METEOROLOGICAL CAUSES"* and *"THE SEASONAL AND MULTI-YEAR CHANGES".*

Cause "THE TIDEL FORCE" has sub-causes: "GRAVITATIONAL ATTRACTION", "CENTRIFUGAL FORCE" and "TOPOGRAPHICAL CHARACTERISTICS". The first two consequences cannot be acted upon because they depend on the Earth (mass, rotation speed, etc.), however, the 3rd can be acted upon. Sub-cause "TOPOGRAPHICAL CHARACTERISTICS" depend on sea/ocean depth ("DEPTH") and indentation and steepness of the coast ("COASTLINE").

Cause "THE METEOROLOGICAL CAUSES" has sub-causes: "EVAPORATION", "RAINFALL", "WIND" and "AIR PRESSURE". These sub-causes can be influenced by reducing climate change.

Cause “THE SEASONAL AND MULTI-YEAR CHANGES” has sub-causes: “SALINITY” and “TEMPERATURE”. Both sub-causes depend on inflow of rivers, evaporation, and rainfall, so the main influence on it is climate change. But, on but sea/ocean temperature also depends on its depth.

4. Conclusion

The main cause of “*THE OCCURRENCE OF EXTREMELY HIGH SEA LEVELS”* is climate change due to anthropogenic influences, and climate change must be acted upon (among other things) for the consequences discussed in this paper. A cause that can be acted on much more quickly and easily, and to save the area by the sea, is the indentation of the coast and the depth or steepness of the coast.

Maritime constitutions, i.e., dam systems that will be raised electromagnetically to prevent flooding of the coast, can be a salvation. Barriers on the beds placed on the seabed will raised as needed. Although it will have a great impact on the views, as well as on the damage to the seabed, we will have to get used to such things in the future, if we do not seriously start reducing the impact of climate change.

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