MEAN SEA LEVEL AS A FACT AND AS AN ILLUSION

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1. — THE TWO CONCEPTS OF MEAN SEA LEVEL

We should recognize two fundamental aspects of mean sea level, these being :

Concept M : monthly (and annual) mean heights M as calculated from observations at an individual gauge;

Concept N : the physical mean level of the oceans.

The second concept is that of common parlance. It is used by Mr. Everyone as well as by scientists in many disciplines. It is the concept intended in handbooks in verbal descriptions as, for example "the height of the mountains above sea level".

This physical concept N has the intent to deny or ignore every motion of sea level. It intends to say : no waves, no tides, no storm surges, no wind influences, no special summer levels, no special winter levels, no density anomalies, no temperature anomalies. In many cases the real content of the physical concept N of mean sea level is typically this no-no character. "Mean" is — following this concept — the rejection of everything that could be qualified as being "special".

The other concept of mean level is that of M. The symbol M stands here for "mean" or even "monthly means". So M represents facts, whatever the philosophy behind the facts may be.

The records of sea level at an individual gauge are the origin of every quantification. In its original form the record contains a lot of information about sea level at the site of the gauge. The usual process of getting rid of the excess of information is the building of means : means of one month and means of one year.

One can debate the best way to arrive at an ideal mean value : by physically measuring the area of the tidal curve, by calculating means of the heights for 24 hours a day, for 8 hours a day, moon hours, only highwater and low water and adding a constant correction, the best length of one month or any other concept. A choice among these possibilities is, for the object of this paper, of minor importance and we will suppose M to be the best approximation in any situation.

This concept M leads to figures of local importance, needed in coastal engineering, maritime structures, harbour engineering, etc.

It is customary to have in mind the concept N and to accept a figure M as the representation of the physical mean sea level N for the site of the gauge. It is our intention to discuss this habit and to lay stress upon the fundamental difference and divergence between the two concepts.

2. — THE SPATIAL CHARACTER OF N

Mean sea level as a physical object and characterised by N exists primarily in space. It is the way in which the oceans span the globe. If we are interested in the world's mean sea level we declare the intention to look for the "mean"; thus excluding its systematic as well as its arbitrary motions, at least waves, tides, and annual cycles.

We will subdivide this physical concept into three : a global, a regional, and a local mean sea level concept.

If we should aim at the global sea level in an absolute sense, two things would be necessary : first to measure and calculate M at a great number of gauges and second to determine the zero heights of these gauges in mathematic coordinates, independent from the anomalies of the globe. (We may call this "Surface 1"). According to our present knowledge, in principle only satellites will be able to produce adequate information. This mathematical height of mean sea level all over the globe would be of little use unless it could be compared with the mathematic height of the coast. This would lead to the height of sea relative to the coast. This is *identical to the outcome of every gauge without satellites.* But the contribution of the satellites would be to reveal the anomalies of the oceans' levels from the mathematical shape of the globe, being just what we aimed to know. The gauges would not bring us this result, the satellites would.

In our present situation this idea is not realistic. Quite the same as the next : if we were to achieve by levelling one geopotential plane all over the globe (surface 2), direct comparison of the gauge's mean sea level M with that global surface 2 would give us exact information about the real shape of the oceans' anomalies. Relating world's mean sea level to surface 2 would not be identical to relating it to the mathematical surface 1, since the geopotential surface differs from the mathematical surface.

If the oceans were subjected to the same forces as the continents, the ocean's mean sea level would follow the geopotential surface 2. The anomalies from surface 2 describe the physical mean sea level. We are not able to realise a geopotential surface over the oceans' surfaces. It is only partly possible to do this over the continents by levelling. We will not discuss here the fact that a geopotential plane over the continent will not be identical to the presumed geopotential plane over the oceans.

Of course we are first interested in the maximum deviations from surface 2 in space. For these maximum deviations control the whole system in time as well as in space. Where do we find these maximum deviations, what are the physical causes, what are their main fluctuations ? Let us call the system of maximum deviations in space the deviations of first order.

Starting from the regions and belts with maximum deviations one proceeds to every location in, around and above the oceans and downward to places and regions with deviations at a minimum, at zero, or negative. Where do we find those minima ? What are their physical causes and their fluctuations ?

The greater part of the oceans will have a mean sea level somewhere between the maximum and minimum anomaly. So at any arbitrary station the deviations from surface 2 will be an interpolation between the extremes. What we really find there will be called deviations of second order. There will always be a reduction in relation to the extremes.

In fact we do not measure the deviations of second order because we lack a reference height. The gauge supplies only the fluctuations in the deviations of second order. Those fluctuations have to be regarded as deviations of third order.

Between the global concept and the local concept it is necessary to distinguish the regional concept. The world regional may have any meaning in between local and global. If we understand local as the gauge site and its vicinity up to 5 or 10 km on one occasion and 100 or perhaps 500 km on another occasion, regional will be named an area which comprises distances from 6 or 60 km up to 6 000 km or more.

In this connection we will speak about global forces, which influence the global shape of mean sea level in such wide areas as hemispheres and oceans; about regional forces which modulate the global shape to a regional shape; and local forces, which modulate the global as well as the regional forces and cause the definite effect on the gauge records.

3. — THE TIME HISTORY CHARACTER OF M

The records of a gauge do not produce anything to benefit our knowledge of the spatial character of N. The gauge records only produce purely local information and everything of spatial character is missing. To proceed to the spatial character of mean sea level another discipline is needed : namely, levelling. Without connection of the gauge zero heights by levelling, nothing at all is revealed of the world's mean sea level : no shape, no slopes, no deflections from one or another hypothetic geopotential plane. The individual gauges, however, produce another contribution to our knowledge, namely the individual time history of mean sea level.

This existence in time has four fundamental aspects :

1 — A basic height
2 — Trends
3 — Cycles
4 — Stochastics.

The basic height is introduced as an arbitrary beginning point. This basic height reveals nothing : nothing with relation to the spatial character of mean sea level as well as nothing with relation to itself. Moreover it conceals always a part of the unknown trends, of the unknown cycles and in the game of stochastics it is only a sample. Nevertheless this basic height is indispensable to connect the locality to the sea as well as to act as a basis for the trends, cycles, and stochastics.

Trends will be there in a wide variety of time scales and magnitudes. Trends from month to month, from year to year, from any span of time to the other, disclosing a never ending process of adaptation of sea level from one complex of acting forces to the next. In this sense trends are not well separated from cycles or stochastics. For each of those three is the outcome of a statistical process and not a regular straight-line effect of just one, well-defined force. On the contrary, there is a large variety of forces and the highly complicated effects can only in a statistical sense of the world reveal trends and cycles.

As to the cycles, the main one is the annual cycle, this being the statistical result of a large number of acting forces and there is of course no principal difference with the trends and the stochastics. Only the tidal waves Sa and Ssa have a physical amplitude and a sine or cosine character; they belong, the same as the nodal tide of 18.6 years' period, to the game of cause and effect. All the other components are statistical effects. Geological "cycles" as well as glacial "cycles" will be classified here with the trends.

Under stochastics are comprised all of those effects which emphasize the irregularity of the mean sea level values. Though all motion, excepting only the tides, is in principle stochastic, we are inclined to speak of cycles, if the statistical outcome simulates a cycle. And to speak of trends, if the statistical outcome simulates a trend.

4. — CONFRONTING THE CONCEPT N AND THE CONCEPT M BY MEANS OF GAUGES

The gauge is the connection point between the two concepts M and N. It connects the "time history" at the moment "now" with the "spatial mean sea level" at the place "here".

For this work the gauge is not as ideal an instrument as it is sometimes supposed to be. So the system introduces an additional unsound contribution to the basic height, to the trends, to the stochastics.

In the next chapter the contributions of the global influences, of the regional influences, the local influences and of the influences of the gauge itself to the basic height, the trends, the cycles and to the stochastics will be summarised. This is done in Table I, giving the influence in space as well as the gauge contribution, numbered 1 through 33 under the heading "Influences working on the physical mean sea level", and the effect assigned to the columns A, B, C and D.

The table in this shape is only meant as an impression. The placing of marks is in many cases a question of appreciation. It is unavoidable to confine each case to the more relevant influences in order not to fill up the whole table with marks.

5. — INVENTORY OF INFLUENCES : TABLE I

The items will be commented upon briefly.

The global influences

No. 1. The ellipticity of the earth is found from :

equatorial radius	6378388 m
polar radius	6356912 m
flattening	21476 m

The surface of the oceans deviates from the true sphere at the poles by being 10 km too low, at the equator by being 10 km too high. Moreover the earth deviates from a hydrostatic equilibrium. The concept of eternal rest of all the earth's forces should result in a deformation of the present earth. The contribution is only marked in column A, though a mark could be placed under B as well because of the instability of the earth's rotation rate on a geological time scale.

No. 2. The contents of the oceans, $1\,450 \cdot 10^{6}$ km^{3}, are submitted to eustatic and tectonic motions, resulting in trends giving tens of meters shift.

No. 3. Daily, fortnightly, and monthly tides do not affect monthly means : no mark.

No. 4. Semi-annual, annual, and nodal tides (18.6 years) give an exact, non-statistical contribution to the cycles.

No. 5. The actual amount of water, being the total amount of H_2O minus vapour and the water stored in lakes, the ground, and in glaciation, is

	Table I	Basic height A	Trends B	Cycles C	Stochas-tics D
	Influences working on the physical sea level	Effect on the monthly mean values M			
	Global influences				
1	ellipticity	x			
2	content of the oceans, eustacy, tectonics		x		
3	daily, fortnightly, monthlv tides				
4	semi annual, annual, and 18.6 year tides			x	
5	the actual amount of water	x	x		
6	glaciation	x	x		
7	sea water temperature and salinity patterns	x			
8	modulation of the effect of item 7 by the ocean currents			x	x
9	force of the drift currents	x		x	x
10	global coriolis ocean currents	x		x	x
11	centrifugal force ocean currents	x		x	x
	Regional influences				
12	monthly resultant of prevailing winds	x		x	x
13	monthly resultant of air pressure	x		x	x
14	groszwetterlage, storm surges				x
15	regional coriolis	x		x	x
16	regional centrifugal forces	x		x	x
17	regional tectonic and eustatic movements		x		
	Local influences				
18	wind waves				
19	local slopes	x		x	x
20	coriolis force local currents	x		x	x
21	density deviat. by temp. and fresh water	x		x	x
22	new maritime works		x		
	Instrumental influences				
23	just that site of the gauge	x			
24	altering the site		x		
25	the accepted zero height	x			
26	unintentional change in zero height		x		
27	readjustment of the recorded height		x		x
28	gauge or benchmark subsidence		x		
29	repeated connection to levelling network		x		
30	pressure head of the adaptor	x			
31	density deviations of the stilling well				x
32	adjusting-, reading-errors				x
33	alteration instr. or working methods		x		
		17	11	12	15

in total 55

highly dependent on the global air temperature. Only A and B have been marked.

No. 6. Though comprised in No. 5, the glaciation must be mentioned separately. During the tertiary era the sea level stood 80 to 100 m higher than at present and 20 000 to 30 000 years ago 60 m below the actual level. So the actual arbitrary state of glaciation produces an important contribution to the basic height A and the trend B.

No. 7. Sea water temperature affects the thermal expansion and so the total volume of water. If polar water were constantly 0 °C and equatorial water constantly 25 °C, without compensating currents and without mixing, over 4 000 m of depth and density difference would result in a difference in height of 20 m. In reality there is mixing and there are currents and below 200 m depth seawater is of more or less constant temperature over a greater part of the oceans. These balancing forces reduce the mentioned inequality. Nevertheless a contribution to A of several dm is to be expected.

The same is true for salinity variations in a global pattern. Starting from what may be regarded as an undisturbed layer of minimum motion at a depth of 4 000 m as a reference, LISITZIN calculated differences in the physical sea surface of many dm, up to even more than 3 m.

If those differences interfere with independent coriolis slopes (No. 10), deviations up to 4 or 5 m will be realised.

No. 8. The drift currents and the density currents modulate the static pattern of item 7 with short term cycles and stochastics. They can be estimated to be 1 or 2 dm under C and D.

No. 9. The drift currents cannot exist without acting forces and counter currents, with the necessary counter slopes. They affect, apart from No. 8, A, C, and D. They can be presumed to be on a global scale up to perhaps 1 m.

No. 10. Density currents and drift currents produce their coriolis force. Existing currents of 0.1 m/s (= 3 000 km/year) and 3 000 km width will at 45° latitude cause a fall of 3 m. Such coriolis forces must really exists because the currents exists. From this we can deduce that the shape of mean sea level differs considerably from any static sea level, whatever that may be. On a global scale this highly complicated system of resistance slopes and coriolis slopes will possibly lead to deviations of more than 3 m.

No. 11. The same holds true for the centrifugal forces of the drift-currents, giving a contribution to A, C, and D. In global dimensions this is probably up to some dm.

The global influences 5 and 6 have an equal effect on every station. But the effect of the forces 7, 9, 10, and 11 will not be the same on every location. There is even in relation to the deviations of first order a two-fold reduction, as has been explained in section 2. So it is probable that mean sea level fluctuations at a gauge site disclose the existence of global values which are many times as great.

The regional influences

No. 12. The resultant effect of positive and negative prevailing winds gives in the monthly means a contribution to A, a strong annual cycle C, perhaps irregular cycles, embracing some years, under C, and stochastics D.

No. 13. The resulting barometric pressure will have its own effect on mean sea level in A, C, and D.

No. 14. The *groszwetterlage* and storm surges affect D.

Nos. 15 & 16. Regional effect of coriolis and centrifugal forces have effects on A, C, and D.

No. 17. The regional tectonic and eustatic movements are certainly the most intriguing influences. They affect the trends.

The local influences

No. 18. Wind waves, seiches, and squall oscillations have no effect on mean sea level figures.

No. 19. Local slopes in the vicinity of river mouths may not be neglected in A, in the seasonal cycles in C, and in D.

No. 20. Coriolis effects will locally be important in A, C, and D. The Straits of Dover, for instance, being a small local detail, produces with 6 cm/s drift currents, a coriolis fall of 2 to 3 cm.

No. 21. Gauges are often sited at river mouths. Because of this, density differences and fluctuations must be observed and taken into account. They often have effects of up to 10 cm and even more.

No. 22. Great maritime works, coastal engineering works, the building of harbours or harbour jetties in the (direct) vicinity of a gauge can give a considerable change in mean sea level, due to items 19, 20, and 21. Such an effect simulates the character of a trend.

Influences from the gauge itself

No. 23. The chosen site may be regarded to be as ideal as could be desired, yet the mean sea level, just at that site, will show quite a lot of particularities. Especially the basic height will be affected. It would have been different if another site, even in the immediate neighbourhood, had been chosen.

No. 24. If the gauge in the course of years must be moved, this practically always will result in a shift in the mean sea level height, due to 19, 20, 21, 29, 30, 31, and 33. Even when the gauge is only moved inside a harbour and exactly the same sea level of the harbour's mouth is recorded, yet items 27, 29, 31, and possibly 33 will have a shifting effect.

No. 25. The chosen zero height of the gauge is an arbitrary but inevitable contribution to the basic height.

No. 26. Unintentional alteration of the zero height, of course always small, affects the trends. Example : combatting ice formation in the stilling well by use of oil.

No. 27. In many situations the stylus is readjusted periodically. This results in trends and stochastics.

No. 28. Subsidence of the foundations of the gauge will be eliminated in a good control system. But in some situations a subsidence can remain unperceived for a long time. In that case the subsidence appears in the time series as a trend and the adjustment as a jump. The same holds true if the benchmark subsides.

No. 29. If the gauge zero height is not connected to a local bench mark with a definite height, it must repeatedly be reconnected with the precice levelling network of the country. Reconnection introduces trends.

No. 30. Every adapter (stilling well, air-bubble system, pressure gauge, etc.) is submitted to a pitot-effect or a pressure head. This effect is often asymmetric to ebb and flood current which leads to a resultant effect on mean sea level. If the gauge is sited in a quiet harbour, the rectifying effect will surely be changed for the worse. For the harbour entrance will often give a strong disturbance in the pattern of currents outside the harbour, mostly highly asymmetrical to ebb and flood. For the last 2 or 3 cm one can never be sure.

One must be mindful of the fact that it will not always be the station itself which is guilty of the pressurehead effect. If the instrument is adjusted to the reading of a staff gauge the stream effect on that staff gauge is relevant.

No. 31. If fresh or brackish water and salt water alternately pass the entrance of the gauge, the well will be emptied and refilled with water of ever varying specific weight. Moreover the adjustment of the stylus will depend upon the reading of a staff gauge, likewise affected with varying density influences. This effect, often 3 to 5 cm and more, intensifies the stochastics.

No. 32. The normal periodical instrument handling, the reading of the records, and the calculation introduce a small contribution to the stochastics.

No. 33. Every change in the gauge, in the instrumentation, in the methods of control, in the methods of reading, in the methods of calculation, will produce a small effect on the trends.

These 33 influences are only meant as a rough indication. The same applies for the marks placed in the four columns. More marks might have been entered — or fewer.

6. — WHAT IS MEAN SEA LEVEL ACCORDING TO THE CONCEPT N ?

The table presents a large number of influences. If we exclude 3, 18, and the instrumental items, except 25, the physical mean sea level is the resultant of at least 21 forces. Excluding also 1 and 22, and combining 14 with 12, there are still 18 forces acting on the ocean's mean sea level. So the popular no-no concept of N cannot possibly be adopted. The true character of the world's mean sea level is not an ideal surface of eternal rest, but a dynamic and labile equilibrium between at least the short term factors 7, 9, 10, 11, 12, 13, 15, 16, 19, 20, 21. As shown in section 5 these factors may often add cm or dm or even m to the resultant height of mean sea level at locations where such forces would accumulate.

So if we depart from any hypothetical geopotential surface 2, mean sea level deviates from surface 2 by the forces just mentioned.

What we observe at the coasts of the oceans is, however, not this deviation of first order, for our present means are insufficient for this purpose. We do not even measure the spatial interpolation along the coasts of the global deviations of first order. We will only observe the fluctuations of nature around this labile equilibrium. So what we really observe at the coasts are deviations from deviations from deviations.

These third hand deviations are the trends, the cycles, and the stochastics. They are, as shown in the table, in a complicated way related to a large number of acting forces.

7. — WHAT IS MEAN SEA LEVEL ACCORDING TO THE CONCEPT M ?

The distribution of gauges along the coasts of the oceans suggests the measuring of mean sea level in space. This is, however, only true for some very small regions with gauges with a common reference level. Only in a few cases are these connections present up to distances as much as 1 000 km. In relation to the question of the true shape of the surface of the oceans this may be completely neglected.

Practically every gauge is no more than an individual gauge. As such it reveals nothing about the deviations of first order, or about the deviations of second order. What the individual gauge presents are the just mentioned deviations from deviations from deviations, introduced here as trends, cycles and stochastics. So these three effects bear the character of third hand information.

Moreover this information is of a highly mixed up nature. If we state a trend at any station then no less than 12 possible influences have to be considered. Six of them are of instrumental origin and have to be avoided to the utmost. But even if the details of every gauge could be published, incertainty would remain. The instrumental influences affect every kind of trend. For instance a single discontinuity of 5 cm over 30 years of observation spoils the whole series. The same is valid in discriminating the important item 17 from, for example, item 22, or to discriminate items 5 and 6 (partly the same influence) from 17 and 22.

It is quite different with the cycles. The table shows that there does not need to be any contribution to the cycles from the instrumentation or the gauge itself. So cycles come from nature; that means from the oceans and from the weather. Table I marks 12 such effects in column C. In these cycles may be discerned 3 groups :

1 — The astronomical group of 1 year and 18.6 years;

2 — Irregular fluctuations from the weather over an irregular span of years;

3 — The annual cycle.

The most important is the annual cycle. It is usual to speak about the "annual cycle" while regarding this as a coherent phenomenon, as the outcome in a cause-and-effect process. For one or two of its components (Ssa and Sa) this is true. But for all the other components a highly different process rules. The twelve monthly mean sea level values are fully independent values. The resultant is not a question of an acting force, but a statistical result. So the annual cycle is the outcome of a process ruled not by the law of cause and effect, but by statistics. Identical values may be brought about as a result of quite different components. High values at spring can be fully independent from low values in autumn. So the spring values can have in the course of years a positive trend and simultaneously the autumn values a negative trend. Thus the resulting "annual cycle" surely may not be regarded as a coherent story.

Moreover, as has been emphasised, the cycles give us only third hand information as to what is happening on a global scale. One of the larger amplitudes of the "annual cycle" shows Maizuru in Japan with 36 cm. Does this mean that we may expect somewhere in the oceans amplitudes up to 40 or 50 cm ? If such an amplitude is only a fluctuation in a semi-static or labile equilibrium on a global scale, we are apt to suppose that the deviation of first order will surpass 1 m.

The stochastics represent the irregularities and seem unimportant for the knowledge of mean sea level. But the opposite is true. First the stochastics are essentially not different from the cycles, they only differ statistically. Second: for the correlations with near as well as distant stations the full monthly values, thus inclusive of the deviations or, more precisely, the stochastics, are relevant. The stochastics, even more than trends and cycles, reveal the coherence of a locality with regional or global influences.

8. — SUMMARY

1. The physical concept N of mean sea level and the concept M based on the observations belong to different worlds.
   The physical concept N is a phenomenon in space with global, regional, and local specification;
   The observations concept M tells a story in time with trends, cycles, and stochastics.
2. A multitude of influences affect the mean sea level data. It is difficult to discriminate.
3. The data of the individual gauge give only third hand information about the global processes.
4. The global processes are governed by physical laws, but the mean sea level data are governed by statistical laws.
5. Items 1, 3, and 4 imply that we meet the physical phenomenon N by inadequate means M.

9. — RECOMMENDATIONS

1. To build many more mean sea level stations.
2. Never to move a station; and, if unavoidable, then to provide simultaneous recordings on the old and new site during 2 annual cycles.
3. Not to change anything whatever in the site, in the entrance to the stilling well, the position of the staff gauge, in the instrumentation, or in the system of calculation.
4. It is a basic requirement that once chosen the zero height be maintained for all times.
5. To promote the connection of gauges by levelling as is already in progress by REUN (Réseau Européen Unifié de Nivellement).
6. Introduction of the possibility of levelling on a global scale by satellites.
7. To relate the M values, as well as trends, annual cycle and other periods, to near stations, distant stations, weather data, current data, density data and temperature data.
8. To continue the publication of mean sea level data in the recently developed form, Publication Scientifique No. 26 of the IAPSO.

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