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Relative Sea Level Rise Along The Belgian Coast: Analyses and Conclusions with Respect to the High Water, the Mean Sea and the Low Water Level

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ABSTRACT

The greenhouse gases, concentrated in the atmosphere of our planet, should cause a global rise of Relative Sea Level (RSL) and a rise of the RSL along the Belgian coast in particular.

Long term records of continuous tidal observations, collected from 3 tide gauges, allowed the Coastal Hydrographic Service in Oostende, Belgium, to use various practical methods in order to study this phenomenon in more detail.

With linear and cyclic best-fit calculations, it was evidenced that the estimates of the rise of RSLs (High Water, Mean Sea Level and Low Water) along the Belgian coast were different, depending on the yearly levels taken into consideration.

1. INTRODUCTION

1.1. Tide gauge stations only measure the local Relative Sea Level (RSL) oscillations. These variations, measured relative to the land, originate through periodic (tidal effects), random (meteorological and hydrological influences), isostatic (redistribution of the mass of the earth, due to geological processes), tectonic (crustal movements) and eustatic (changes of the capacity of the water volumes of the seas and the oceans) agents.[1,2,3,4] The so-called uplifts of Scotland and Scandinavia are isostatic as the result of the glacial melting of the former ice-sheets through which the shape of the geoid gradually changed (a geological process, due to the post glacial rebound). Local earthquakes (crustal movements) are tectonic and can also modify the geoid. Eustacy will produce changes in the capacity of the water-volumes of the seas and the oceans and is due to, the melting of large amounts of glaciers and polar ice-sheets (glacio-eustacy), tectonic movements (tectono-eustacy) and sedimentation, originating from the erosion of the continents in the long term (sedimentation-eustacy). We may consider the periodic and random effects as being short term influences, whilst the isostatic, tectonic and eustatic changes generally have a long-term character.

1.2. The world today is consuming its resources at a relatively high speed and is producing large amounts of waste. Some of these products, the so-called "greenhouse" gases, such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons (CFCs), etc., are concentrated in the atmosphere, mostly generated by industry but also by other human activities. The "Intergovernmental Panel on Climate Change" (IPCC) assumed in 1990 that a doubling of the CO_2 content in the atmosphere would cause an increase in global mean temperature between 1,50 to 4,50°C[5]. This may lead, probably in the second half of the next century, to irreversible global changes in sea level, i.e. this phenomenon may produce the so-called "greenhouse effect". For low-lying areas, such as the Dutch and the Flemish coastal plains, situated at about mean sea level and only being protected from the sea by dikes and dunes, it thus looked very opportune to monitor and to investigate any change.

1.3. This paper is in an updating of two earlier studies [6,7], both being contributions of the Coastal Waterways Division-Hydrographic Service, Oostende, to previous European Community contracts.

2. CHOICE AND QUALITY OF THE DATA

The analyses of the relevant tidal elevation data along the Belgian coast in the past, such as the annual levels of High Water (HW), Mean Sea Level (MSL) and Low Water (LW) for Oostende, Zeebrugge and Nieuwpoort, yielded information about both the short and the long term trends. At the same time we found it interesting to make a comparison with the same levels calculated for Vlissingen (Netherlands). Before attempting to analyse the tidal data we needed to consider their value and usefulness. As the history of the tidal observations for these three locations had already been published in an earlier paper[1] we found it useful to repeat and to update it. The Annexes 1, 2 and 3, give a synopsis of these observations along the Belgian coast (Oostende, Zeebrugge and Nieuwpoort). Here the periods, for which harmonic analyses exist, are also indicated.[8 to 19] We want to stress that tidal observations need to be reliable and should be obtained over extended and uninterrupted periods. As can be seen in the tables, there are significant gaps for some years in these series, mainly for the earlier periods. It is obvious that Oostende has the longest records therefore this location can be considered as the main tide gauge station for the Belgian coast. Reasonably good observations (readings of HW and LW on a tide pole) began in 1820, but unfortunately these data have been lost. All the other earlier records, mainly predating World War 1 and 2, were also carefully examined:

(1) For the period 1835-1852, the monthly values of HW/LW are based on continuous HW/LW records, read from a tide-pole, close to a lock in the harbour of Oostende[3] and near to a reliable benchmark to which the gauge was referred. This benchmark was incorporated in a quay wall.

Because only monthly mean values of HW/LW were available, mean tide levels (i.e. the mean of HW and LW) could be calculated. The difference between this level and MSL along the Belgian coastline is nearly constant; e.g. for the period 1949-1988 the difference is +0,063m. Thus, knowing the mean tide levels, we were able to determine the MSL value for each year of the period concerned.

(2) For a number of reasons the data of period 1878-1914 were not useful for this study: some data have been lost, there are too many gaps and the reference datum is uncertain. If we also compare the yearly values of this period with those of Vlissingen (Netherlands), there are some differences of more than 10cm, whereas differences of only 3 or 4mm are the norm for those years with reliable observations. From 1925 to the present (1998), the records of the years 1925, 1926 and of most part of World War II (1940, 1941, 1942 and 1944) are very discontinuous. We decided not to use them in this study, except when using the technique of moving averages (see 3.3). From the Rijksinstituut voor Kust en Zee (RIKZ) of the Dutch Rijkswaterstaat in The Hague, we kindly received the analogue information for Vlissingen, being a reliable and continuous period of 109 years (1890-1998). For Zeebrugge and Nieuwpoort, the observations started in the early thirties, but the data for 1932-1940 and 1941-1943 were also very discontinuous. Continuous data are only available respectively from 1964 and 1967 onwards, as indicated in the Annexes 2 and 3.

3. LOCAL TRENDS FOR HW, MSL AND LW

For the EC-project EPOC [6], only the tidal elevation data for Oostende and Vlissingen were taken into consideration, i.e. those for High Water (HW), for Mean Sea Level (MSL) and for Low Water (LW).

In a later study [7], besides the data of Oostende and Vlissingen, we also made use of the data of Zeebrugge and of Nieuwpoort. For the determination of the local trends, we previously used the following methods:

- linear (curve fittings) [6,7]
- cyclic curve fittings [6]
- moving averages [6]
- single spectrum analysis [7]

The first three methods were applied again for this work (see 3.1., 3.2. and 3.3.). As the last method, applied in the second work [7] did not give much added value, we did not use it in this present work. Another additional approach in methodology is to make an investigation of the values of the main harmonic components for the main tide gauge station (Oostende), this is reported in 3.4.

3.1. LINEAR CURVE FITTINGS

Annex 4 contains the yearly values, in the form of scatter diagrams, of HW, MSL and LW data for Oostende. These data are referred to TAW (Tweede Algemeene Waterpassing), the Belgian National Reference Level. Linear best fit calculations on the values of these 3 diagrams have been carried out by means of the method of least squares; the outcome of these curve fittings are recorded in the same Annex; the linear correlation coefficient (Pearson r) and the 95% confidence limits are determined as well. For the 3 annual values we see a linear increase of nearly 0,01m/decade if the two periods, 1835-1852 and 1927-1998 (less 4 years of World War II), are taken into account. On the other hand, if only the last period, without any data for these 4 years is considered, the 3 regression lines for HW, MSL and LW indicate a rise of 0,0217m/decade, 0,0144m/decade and 0,0084m/decade respectively. In all cases, the correlation coefficients are rather high, except for the LW of the period 1927-1998. This is normal because the HW and LW configurations are subject to the same nodal fluctuations (see 3.2.); as a matter of fact, a linear best fit will be better for HW data than LW data. Anyway, all the correlation coefficients are high enough: for a severe one-tailed test of 0,5%, r has to be at least 0,3076 if n or the number of the pairs of observation equals 68. Also for the LW data, the significance of the regression line is not compromised at all.

For the yearly values of HW, MSL and LW for Vlissingen, also referred to TAW, the regression lines for the period 1890 -1998 show increases of 0,0329m/decade, 0,0206m/decade and 0, 0 174m/decade for the 3 main levels. In order to make a comparison with Oostende, we investigated the more recent period 1927-1998. This period indicates nearly the same value for HW (a rise of 0,0339m/decade), but differs for MSL (0,0162m/decade) and even more for LW (0,0099m/decade). In all cases, the correlation coefficients are rather high except at LW for the period 1927-1998, where we obtained the value of r = 0,49648. Nevertheless, as the n pairs of observation equal 72, the test of significance causes no concern (for the same one-tailed test of 0,5%, r is predicted to be 0,2988).

In our former report, we considered the results of the linear trends for Zeebrugge (31 years of data available: 1964-1994) and for Nieuwpoort (with a period of continuous records of 28 years: 1967-1994) as rather disappointing because they did not follow the same trend pattern as found for Oostende and Vlissingen. We re-examined the data of Zeebrugge (1964-1998) and discovered a significant offset for the period 1964-1970. Having made the necessary corrections and after adding data for 4 more years, we noticed for Zeebrugge (1964-1998) an increase of 0,0170m/decade for HW, 0,0150m/decade for MSL and 0,0086m/decade for LW. These values are a little lower than the ones for Oostende, but nevertheless they have almost the same order of magnitude. For the same one-tailed test of 0,5%, r has to be 0,418 (with n = 35).

The correlation coefficient for MSL (0,46138) is thus the only one that is high enough. The other two r-values are too small and the significance of the 2 regression lines for HW and for LW are thus compromised.

At Nieuwpoort, for the period 1967-1998, we found changes of 0,0412m/decade for HW, 0,0277m/decade for MSL and 0,0188m/decade for LW. These higher values are due to a local subsidence of the quay wall on which the tide gauge has been installed. Earlier we corrected for this phenomenon, but probably we did not do it as comprehensively as we should have. For the same one-tailed test of 0,5%, r has to be 0,454 for n = 32. The r-values for HW and MSL (0.77146 and 0.69848) are high enough, but this is not the case for the r-value of LW, being only 0.36152.

We noticed that the periods, for Nieuwpoort and Zeebrugge, represent only 1,72 and 1,88 nodal cycles, whilst the periods used for the curve fitting for Oostende (1927-1998) and Vlissingen (1890-1998), are 3,87 and 5,86 nodal cycles. Thus we have to consider that due to the nodal fluctuations mentioned before, some misinterpretations may occur, if we cannot use multiples of the nodal cycle.

3.2. CYCLIC CURVE FITTINGS

In order to understand why this method of curve fitting is used, it is useful to explain briefly the basic theory behind the nodal cycle. Firstly considering movements of the sun and the moon relative to

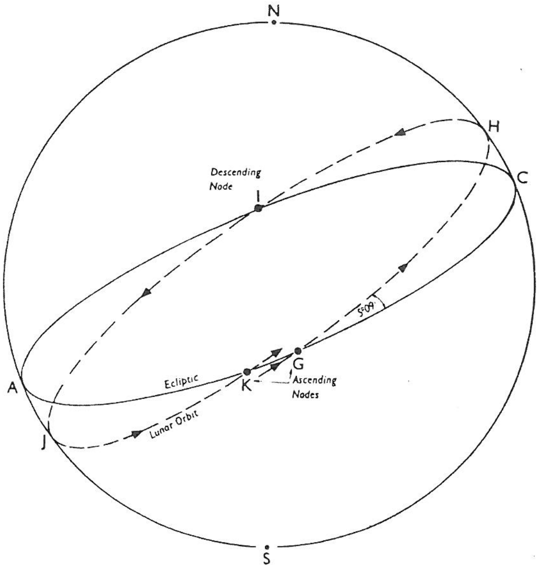

Fig. 1:

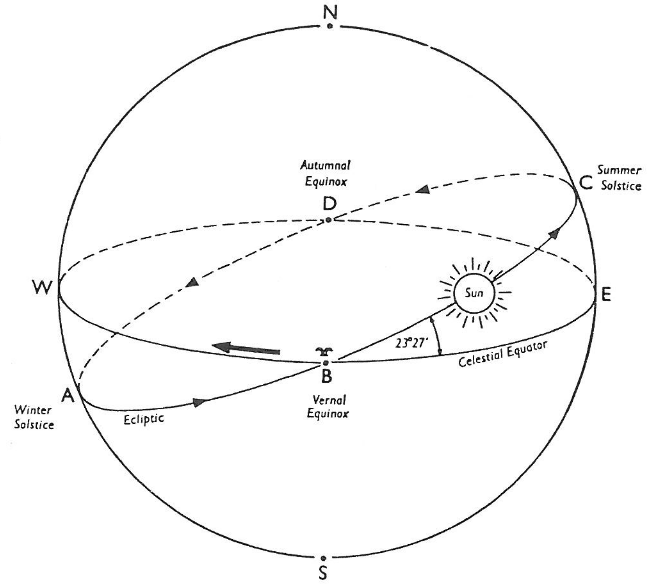

Fig. 2:

the earth; from Newton (1642-1727) we know that the attraction of one mass upon another in general and the gravitational forces of the sun and mainly the moon in particular, are responsible for the tidal movements of the oceans and seas. Relatively we can consider the sun and the moon as moving apparently eastwards around the earth on the celestial ecliptic and on the moon's orbit respectively. Figures 1 and 2 show the movements of the sun and the moon round the earth, at the centre of the celestial sphere.

As the moon is much nearer to the earth than the sun, its movement, relative to an observer on the earth, is much faster than the relative movement of the sun around the earth. The sun completes its orbit in one year (365,25 mean solar days). One revolution of the moon takes less time: it amounts, relative to the sun, to 29,5306 mean solar days (i.e.one lunar month or one lunation or 1 synodic period). The plane of the sun is inclined to the celestial equator at an angle of about $23^0\ 27'$, so defining the obliquity of the ecliptic. The moon's path has an inclination of about $05^0\ 9''$, relative to the plane of the ecliptic. The points, where the moon's orbit crosses the ecliptic, are called the nodes. The point where the moon's orbit crosses the ecliptic when it moves from south to north is the ascending node (G and K in Fig.1); the descending node is I in the same figure. The Vernal Equinox (First point of Aries - B in Fig. 2) is the reference point for the Ascending Node whose position is measured by the arc length, L. Point G in Fig. 2 is the ascending node for a lunar orbit, while point K is the ascending node for the next orbit. The regression of the ascending node is its apparent movement westwards along the ecliptic; a complete regression of the nodes on the ecliptic is completed after 18,61 years, this is the nodal cycle. Due to the regression of the nodes, the obliquity of the lunar orbit to the celestial equator (moon's declination) will change gradually with each orbit between a maximum of $23^0 27' + 05^0\ 9' = 28^0\ 36'$ and a minimum value of $23^0\ 27' - 05^0\ 9' = 18^0\ 18'$. As the arc length of the ascending node becomes 90^0 and 270^0, the yearly tidal range has an intermediate value. With values of $0^0/180^0$ the yearly tidal range has a minimum/maximum value. These latter values of L coincide with a maximum/minimum declination of the moon. The Royal Observatory of Belgium (Brussels) kindly provided us with the dates, for more than a century, for the relevant values of L. (Annex 5) The motions of the moon and the sun, relative to the rotating earth, thus produce different tidal patterns of the so-called "equilibrium tide", being the hypothetical tide which would be produced if the earth should be fully covered with a global deep ocean.

The cyclic fluctuations due to the nodal cycle can only be identified from the configuration of the yearly values of HW/LW of a specific tidal station. Annex 6 shows these values for Oostende with the fitting of a cyclic trend. The rather irregular shape of the yearly data is random and originates because of meteorological influences; as a matter of fact, the g-value is very small, but the G-value can be more than 10cm, due to these random influences. In the equations of this cyclic curve fitting we found (with the A-coefficient) an increase of 0,01758m/decade for HW and 0,01149m/decade for LW. The first is slightly less than the similar value in Annex 4 but the latter is greater. Here we also notice the same overall increases of 2 and 1mm/year for HW and LW. For comparative purposes, the similar curves for Vlissingen gave cyclic equations with A-coefficients of 0,03166m/decade and 0,0123m/decade; these values are comparable with those calculated from the data of annual values of HW, MSL and LW for Vlissingen for the period 1890-1998.. The annual increase of nearly 3mm/year for HW and 1mm/year for LW is thus confirmed. We did not carry out the same exercises for Zeebrugge and Nieuwpoort, because we considered the time series there as being too short for this sort of analysis.

3.3. MOVING AVERAGES

We thought that the use of moving averages could be interesting, in order to eliminate the oscillations due to the nodal cycle and to meteorological influences. By applying this sort of filtering, we would be able to detect any acceleration in the increases of the HW, MSL and LW levels of Oostende. The comparable values of Vlissingen are successive groups of observations for 1, 7, 13, and 19 years for the period 1925-1998 (including the 4 years during World War II). In none of these accounts can we find any significant indication of acceleration in the values of the levels.

3.4. HARMONIC ANALYSIS

From the Annexes 1, 2 and 3, we see that Oostende has the longest series of harmonic analyses; the first for the periods 1882-1888 and 1894-1912. However, because there are big gaps in the records, we wondered if the analysed data would form a reliable basis for reference.

Annex 8 is a spreadsheet, where for 2 periods of 19 years (nearly 1 nodal cycle) the vector averages of the 12 main components for

Oostende have been given. These are, in order of magnitude of amplitude, M2, S2, N2, K2, 2MN2, M4, MU2, 01, NU2, 2MS6, MS4 and M6. The first period is 1944-1964 [16] and the second period is1980-1998 [19]. Between the last year of each of the 2 periods, there is a time difference of 34 years. Although we consider a period of 34 years as being not long (nearly 1,83 nodal cycles), we found it worthwhile to compare the Hi and Gi-values of the previous12 components. Concerning the Hi-values, we noticed that the amplitude of M2, being by far the biggest in the series, increases at 15,16mm/34 years or 0,4511mm/ year or 0,84%/34 years. From these figures we calculated that the yearly increase of the range of M2 (being twice the amplitude) amounts to nearly 1mm. This figure partly explains the increase of the rise we found before. Apart from NU2, all the amplitudes of the other 10 harmonic constants were subject to an increase. Looking at the sixth column, we can see that the shallow water components M4, 2MS6, MS4 and M6 underwent the biggest increase; here MS4 (12,75%/34 years), M4 (7,44%/34 years) and 2MS6 (5,17%/34 years) are the largest. No doubt, these increases are due to changes in the configuration of the bathymetry. As a matter of fact, the amplitudes of these constituents are smaller than that of M2; nevertheless these together with the others will contribute to the increase of RSL. The Gi-values also change slightly; M2 and N2 advances with more than 1minute/34 years, but for S2, K2 and 2MN2 a certain retardation occurs. Most often, the smaller ones (from M4 on) also advance; only the diurnal 01 and the shallow water constituent MS4 are delayed. 01 and K2 indicate the biggest delays of 3,33 minutes and 2,41 minutes for 34 years. As expected from the findings, mentioned in 3.1. and 3.2., we can confirm that the amplitudes of the main harmonic constituents increased; also the phases of those constituents were subject to some changes.

4. CONCLUSIONS

After the application of the different techniques on the configuration of the annual values of HW, MSL and LW for Oostende, Vlissingen, Zeebrugge and Nieuwpoort and on the evaluation of the harmonic tidal analysis for Oostende, we came to the following general conclusions.

4.1. During the last 70 years, a relative sea level rise has occurred at the main Belgian coastal tide gauge at Oostende This is 2mm/ year for HW, 1,5mm/ year for MSL and 1mm/ year for LW. As the rise is higher at HW than at LW, an increase of the range of the tide is also occurring. These findings are evidenced by linear and by cyclic trends. On the one hand, Belgian geologists have good reasons to believe that Oostende has had a rather high degree of stability of the substratum since the quaternary period. On the other hand we still consider this sea level rise as "relative", because we do not know for sure how stable the benchmarks near the tide gauge are and how stable the land surrounding the tidal stations is with the passage of time. If we also take the data of 1835-1853 into consideration, we only come to an overall increase of 1mm/year for all three levels; however here we are less confident about the vertical references.

4.2. The stability of the area neighbouring the tide gauge in Vlissingen is probably not as high as for Oostende.[20] The phenomenon of subsidence of the substratum in Zeeland (the Netherlands) may cause the bigger increases of the RSL's for HW (3,3mm/ year), for MSL (2,1mm/ year) and for LW (1,7mm/ year), as evidenced in the data of the period 1890-1998. On the other hand, if we just consider the period 1927-1998 in the same dataset, this higher increase is valid just for HW (3,3/ year), but not for MSL (1,6mm/ year) or for LW (1,0mm/ year). The last two figures are thus very similar to those for Oostende.

4.3. Although the continuous time series for Nieuwpoort and Zeebrugge are not very long, we come to similar conclusions as for Oostende as far as the linear trend calculations are concerned.

4.4. To date, the method of moving averages (see 3.3.) does not depict any acceleration in the relative sea level rises of Oostende and Vlissingen.

4.5. As we expected, the comparison of two vector averaging results of tidal harmonic analysis also shows increases for the amplitudes of 11 of the 12 most important harmonic components. The impact of the amplitude of M2 on the RSL rise already amounts to nearly 1mm/ year; expressed in percentages the amplitudes of the most important shallow water constants mostly increased. The phases of these components were subject to both advances and to retardations.

4.6. Similar amounts of RSL rise for comparable areas in the UK and the Netherlands can also be found in some recent papers [21,22,23,24].

4.7. Will the Relative Sea Level rise carry on in the next century in the same way? Is there a chance that, from a given moment, an acceleration of RSL will occur? A prognosis of coming developments in this field is extremely difficult to set up and should be based on a wide range of international climatic research, leading to the establishment of reliable climatic models. So far, the models of the Intergovernmental Panel on Climate Change (IPCC) only provide information, relating to different possible scenarios, ranging from a lower increase to a higher increase of the RSL.

4.8 As time passes, it will be essential to pay great attention to the measurements of the sea levels all over the world in general and of our coastal areas in particular. A thorough quality control on the tidal records in the field must never be overlooked; once again I want to repeat that for this sort of study continuous data are indispensable. A better monitoring of the benchmarks of nearby gauges, with modern techniques such as Differential Global Positioning System (DGPS) "On-the-Fly", will allow the hydrographer to be even more confident about absolute referencing for the future. For this type of work, international co-operation between specialists is also needed. For many years the Coastal Waterways Division, Hydrographic Service, Oostende, has provided information (hourly values on a yearly basis) to the Permanent Service for Mean Sea Level (PSMSL) at the Proudman Oceanographic Laboratory (POL), Bidston Observatory, Birkenhead (UK), which is a source of wordwide oceanographical data. The Global Sea Level Observing System (GLOSS) is an Intergovernmental Oceanographic Commission (IOC) project, which is aimed to improve the quality and quantity of data supplied to the PSMSL. This is a program for the establishment of nearly 300 scientific, quality controlled tide gauges for global climate change and oceanographic sea level monitoring. In this context, Euro-GLOSS is a local densified network of GLOSS. Finally, I mention a recent European program for the observation of sea level called "European sea level Observing System (EOSS) - COST Action 40. The Memorandum of Understanding for EOSS states that "the most important outcome of it is expected to be an organiser that guarantees and co-ordinates the long-term monitoring activities and data exchange along the European coastline". Since the very start of this project (November 1996), the Coastal Waterways Division-Hydrographic Service, Oostende, has participated in this program.

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REFERENCES

1. Cuchlaine A.M. King. *Oceanography for Geographers.* Edward Arnold Publishers Ltd. London, 1962.
2. D.T. Pugh. *Tides, Surges and Mean Sea level. A Handbookfor Engineers and Scientists.* John Wiley & Sons Ltd. New York. 1987.
3. P. A. Pirazolli. *Secular trends qf Relative Sea-Level (RSL) Changes by Tide-Gauge Records.* Journal of Coastal Research, SI, No. 1, 1986.
4. P. A. Pirazolli. *Recent Sea-Level Changes in the North Atlantic. Late Quaternary Sea-Level Correlation and Applications.* Pp.153-167. Kluwer Academic Publishers. 1989.
5. United Nations Environment Programme - Government of The Netherlands. *Impact of Sea Level Rise on Society. A case study for The Netherlands.* Delft Hydraulics, Rijkswaterstaat and Resource Analysis. Final Report. March 1991.
6. C. Van Cauwenberghe. *Synopsis of the tidal observations along the Belgian coast - Conclusions with respect to the high water, the mean sea and the low water levels.* Final report of the EC-contract EPOC-CP90-0015 -Volume 4. March 1993.
7. C. Van Cauwenberghe. *Relative sea level rise: further analyses and conclusions with respect to the high water, the mean sea and the low water levels along the Belgian coast.* Final report of the EC-contract EVSV CT 93 0266. August 1995.
8. J. Lauwers. *Les marees du port d'Ostende.* Annales des Travaux Publics de Beigique. Aout 1930.
9. L. Jones et R. Heiderscheidt. *Surfaces de niveau zero belges et zero hydrographique* . Annales des Travaux Publics de Belgique. Juin 1952.
10. J. Henrionet. *Notice sur les travaux topographiques executes au Depot de la Guerre de Belgique.* Archives de l'Institut Geographique Militaire. Bruxelles. 1876.
11. A. Stessels. *Discussion des observations de la maree et ses effects dans l'Escaut.* Annales des Travaux Publics de Belgique. Tome XXX, Deuxieme Cahier. 1872.
12. M. Bovie. *Etude sur la regime de la maree au port d'Ostende.* Annales des Travaux Publics de Belgique. Tome XLIV. 1887.
13. P. Melchior et P. Paquet. *Les constantes des marees oceaniques au port d'Ostende de 1882 a 1964* . Koninklijke Academie van Belgie. Mededelingen van de Klasse der Wetenschappen-5e. Reeks-Bock LIV-1968, 10.
14. J. Lauwers. *Les marees des ports d'Ostende, de Zeebrugge et de Nieuwpoort.* Annales des Travaux Publics de Belgique. Avril - Juin 1949.
15. C. Van Cauwenberghe. *Overzicht van de tijwaarnemingen langs de Belgische kust. Periode: 1941-1970 voor Oostende, 1959-1970 voor Zeebrugge en Nieuwpoort.* Tijdschrift der Openbare Werken van Belgie. Nr.4, 1977.
16. P. Melchior, P. Paquet et C. Van Cauwenberghe. *Analyse harmonique de vingt annees oceaniques a Ostende.* Koninklijke Academie van Belgie. Mededelingen van de Klasse der Wetenschappen-5e Reeks-Boek LIII- 1967,2.
17. C. Van Cauwenberghe. *Overzicht van de tijwaarnemingen langs de Belgische kust. Periode: 1971-1980 voor Nieuwpoort, Oostende en Zeebrugge.* Tijdschrift der Openbare Werken van Belgie. Nr.5, 1985.
18. C. Van Cauwenberghe. *Overzicht van de tijwaarnemingen langs de Belgische kust. Periode: 1981-1990 voor Nieuwpoort, Oostende en Zeebrugge.* Infrastructuur in het Leefmilieu - 6/93.
19. C. Van Cauwenberghe. *Harmonic Tidal Predictions along the Belgian coast - History and present situation.* Infrastructuur in het Leefinilieu - 1/99.
20. D. Dillinghen and P.F. Heinen. *Zeespiegelrijzing, getijveranderingen en deltaveiligheid.* Rapport RIKZ - RWS - 94.026 - Juni 1994.
21. P. L. Woodworth, S.M. Shaw and D.L.Blackman. *Secular trends in mean tidal range around the British Isles and along the adjacent European coastline.* Geophys. Journal Int. (1991) 104, pp593-609.
22. I. Shennan and P.L. Woodworth. *A comparison of late Holocene and twentieth century sea-level trends from the UIK and North Sea region.* Geophys. Journal Int. (1992) 109, pp96-105,
23. Commission of the European Communities - Directorate for Science, Research and Development, Clinmatology and Natural Hazards. *Climate Change, Sea Level Rise and associated Impacts in Europe.* Final Reports of the EC-contract EPOC-CP90-0015 - Volumes 1-4. March 1993.
24. P.L. Woodworth, N.M. Tsimplis, R.A. Flather and I. Shennan. *A review of the trends observed in British Isles mean sea level data measured by tide gauges.* Geophys. Journal Int. (1999) 136, pp651-670.

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SYNOPSIS OF THE TIDAL OBSERVATIONS FOR OOSTENDE (Belgium)			
Periods	**Tide pole (a) or automatic tide gauge (b)**	**Harmonic Tidal Analysis**	**References Remarks**
1820-1834	(a)	No	Ref. 8 & 9 Data are lost
1835-1853	(a)	No	Ref. 10 Only monthly mean values available
1866-1871	(a)	No	Ref. 11 Data are lost
1878-1914	(b)	Yes for 1882-1888 and for 1894-1912	Ref. 12& 13. Big gaps in the records Reference level not well known
1925-1940	(b)	No	Ref. 8 & 14. Big gaps in the records for 1925, 1926 & 1940
1941-1970	(b)	Yes for 1943-1968	Ref. 14, 15 & 16. Big gaps in the records for 1941, 1942 & 1944
1971-1980	(b)	Yes for 1976-1980	Ref. 17. Continuous records
1981-1990	(b)	Yes for 1981-1990	Ref. 18. Continuous records
1991-1998	(b)	Yes for 1991-1998	Continuous records

Annex 1

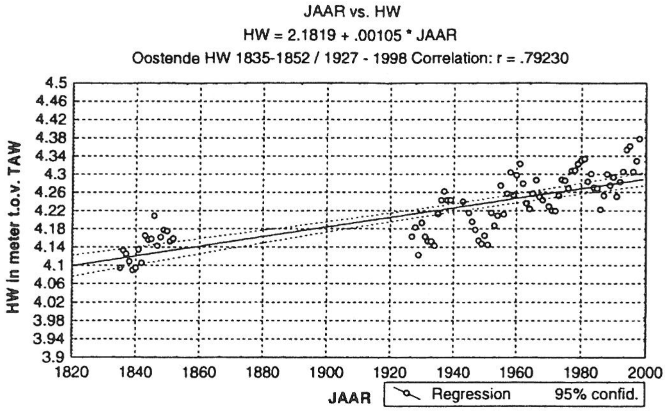
SYNOPSIS OF THE TIDAL OBSERVATIONS FOR ZEEBRUGGE (Belgium)			
Periods	**Tide pole (a) or automatic tide gauge (b)**	**Harmonic Tidal Analysis**	**References Remarks**
1932-1940	(b)	No	Ref. 14. Big gaps in the records for 1932 and 1940
1941-1943	(b)	Yes for 1943	Ref. 14. Big gaps in the records from 1941 to 1943
1959-1970	(b)	Yes for 1943	Ref. 15. Big gaps in the records from 1959 to 1961
1971-1980	(b)	No	Ref. 17. Continuous records
1981-1990	(b)	Yes for 1981-1990	Ref. 18. Continuous records
1991-1998	(b)	Yes for 1991-1998	Continuous records

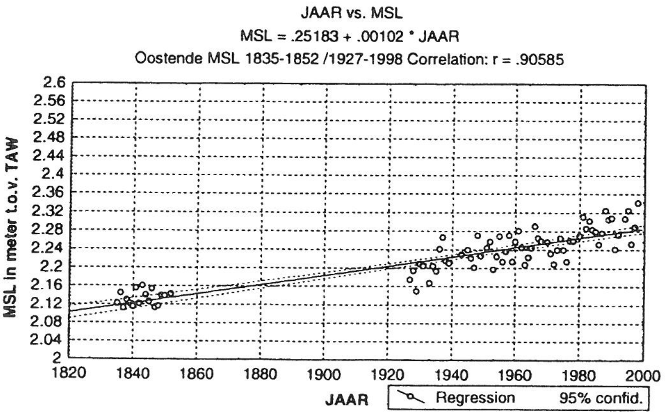
Annex 2

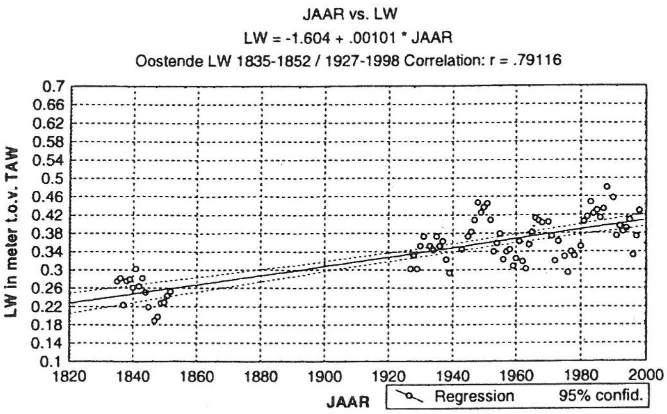
SYNOPSIS OF THE TIDAL OBSERVATIONS FOR NIEUWPOORT (Belgium)			
Periods	**Tide pole (a) or automatic tide gauge (b)**	**Harmonic Tidal Analysis**	**References Remarks**
1933-1938	(b)	No	Ref. 14. Big gaps in the records for 1933, 1937 & 1938
1941-1943	(b)	Yes for 1943	Ref. 14. Big gaps in the records from 1942 & 1943
1959-1970	(b)	Yes for 1967-1969	Ref. 15. Big gaps in the records from 1959 to 1961 & from1964 to1965
1971-1980	(b)	Yes for 1980	Ref. 17. Continuous records
1981-1990	(b)	Yes for 1981-1990	Ref. 18. Continuous records
1991-1998	(b)	Yes for 1991-1998	Continuous records

Annex 3

Period: 1835-1852
1927-1998
(-1940, 1941, 1942, 1944)



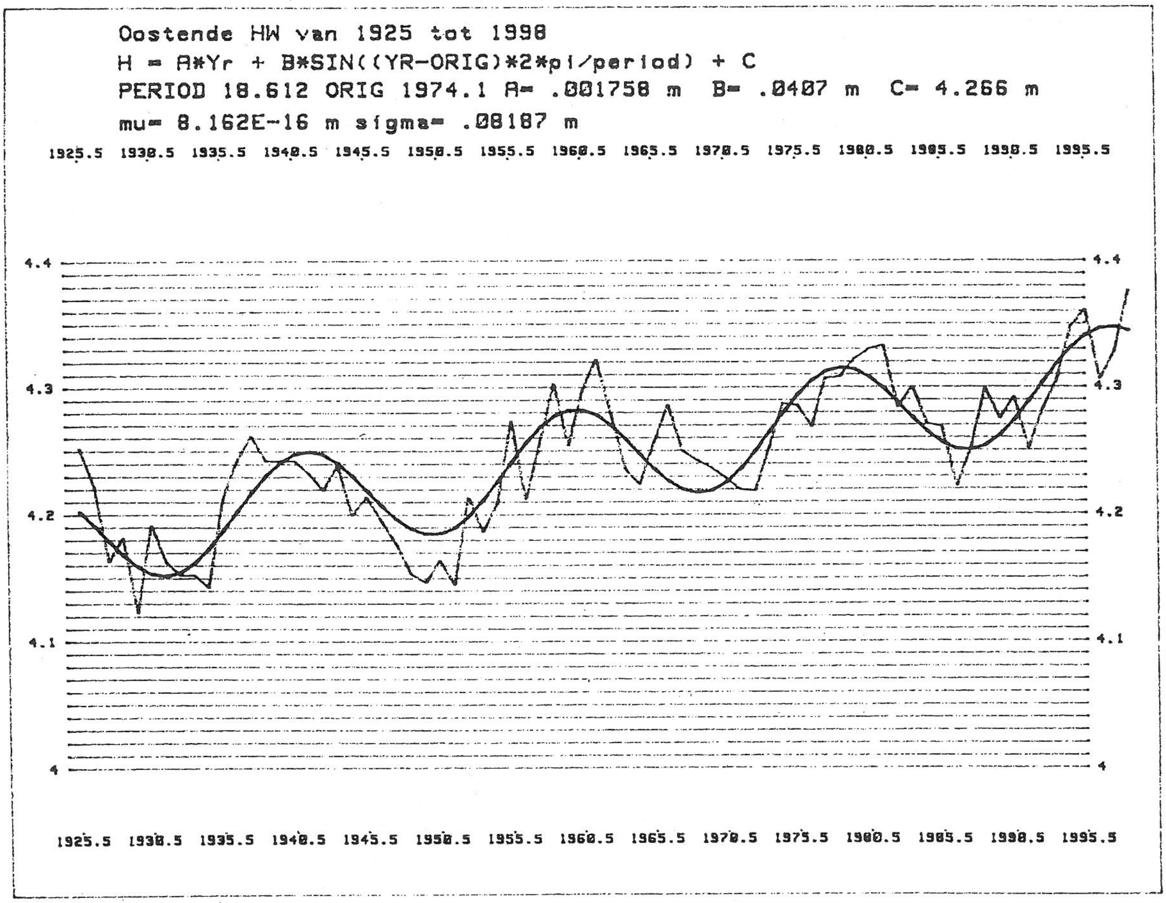


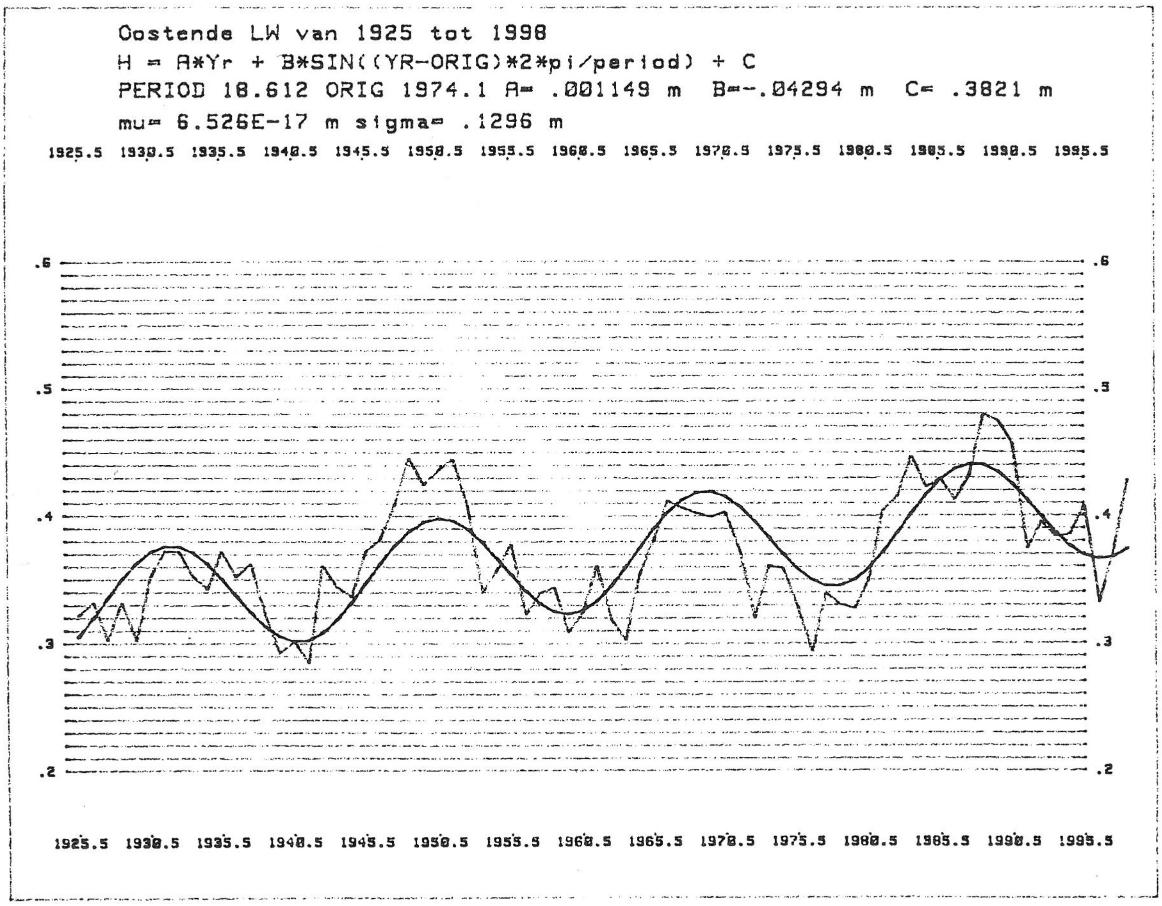


Annex 4: Linear Trends calculated on the Annual Values of HW, MSL and LW for Oostende (Belgium).

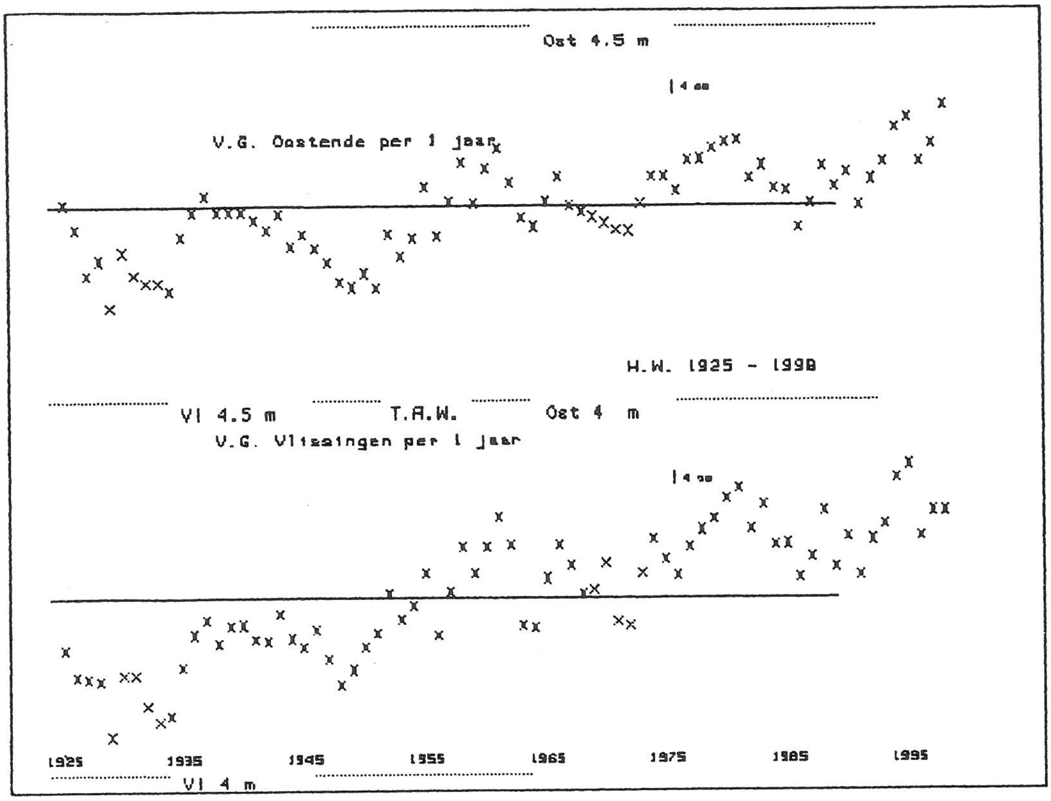
NODAL CYCLES FROM 1913 TO 2025			
L, arc length of ascending node	Date / GMT	Time difference in days	Range of the Tide
0° = 360°	27/05/1913 0:09:14		Minimum
270°	20/01/1918 14:20:51	1699,59140	Mean
180°	16/09/1922 4:32:42	1699,59156	Maximum
90°	12/05/1927 18:44:48	1699,59174	Mean
0° = 360°	6/01/1932 8:57:08	1699,59190	Minimum
270°	31/08/1936 23:09:43	1699,59207	Mean
180°	27/04/1941 13:22:33	1699,59225	Maximum
90°	22/12/1945 3:35:38	1699,59242	Mean
0° = 360°	17/08/1950 17:48:57	1699,59258	Minimum
270°	13/04/1955 8:02:31	1699,59275	Mean
180°	7/12/1959 22:16:19	1699,59292	Maximum
90°	2/08/1964 12:30:23	1699,59310	Mean
0° = 360°	29/03/1969 2:44:41	1699,59326	Minimum
270°	22/11/1973 16:59:13	1699,59343	Mean
180°	19/07/1978 7:14:01	1699,59361	Maximum
90°	14/03/1983 21:29:03	1699,59377	Mean
0° = 360°	8/11/1987 11:44:20	1699,59395	Minimum
270°	4/07/1992 1:59:52	1699,59412	Mean
180°	27/02/1997 16:15:38	1699,59428	Maximum
90°	24/10/2001 6:31:39	1699,59446	Mean
0° = 360°	19/06/2006 20:47:55	1699,59463	Minimum
270°	13/02/2011 11:04:26	1699,59480	Mean
180°	10/10/2015 1:12:11	1699,59497	Maximum
90°	4/06/2020 15:38:11	1699,59514	Mean
0° = 360°	29/01/2025 5:55:26	1699,59531	Minimum

Annex 5: *Origin: Royal Observatory of Belgium, Brussels*


Oostende HW van 1925 tot 1998
H = A*Yr + B*SIN((YR-ORIG)*2*pi/period) + C
PERIOD 18.612 ORIG 1974.1 A= .001758 m B= .0407 m C= 4.266 m
mu= 8.162E-16 m sigma= .08187 m
1925.5 1930.5 1935.5 1940.5 1945.5 1950.5 1955.5 1960.5 1965.5 1970.5 1975.5 1980.5 1985.5 1990.5 1995.5
4.4
4.3
4.2
4.1
4


Oostende LW van 1925 tot 1998
H = A*Yr + B*SIN((YR-ORIG)*2*pi/period) + C
PERIOD 18.612 ORIG 1974.1 A= .001149 m B=-.04294 m C= .3821 m
mu= 6.526E-17 m sigma= .1296 m
1925.5 1930.5 1935.5 1940.5 1945.5 1950.5 1955.5 1960.5 1965.5 1970.5 1975.5 1980.5 1985.5 1990.5 1995.5
.6
.5
.4
.3
.2

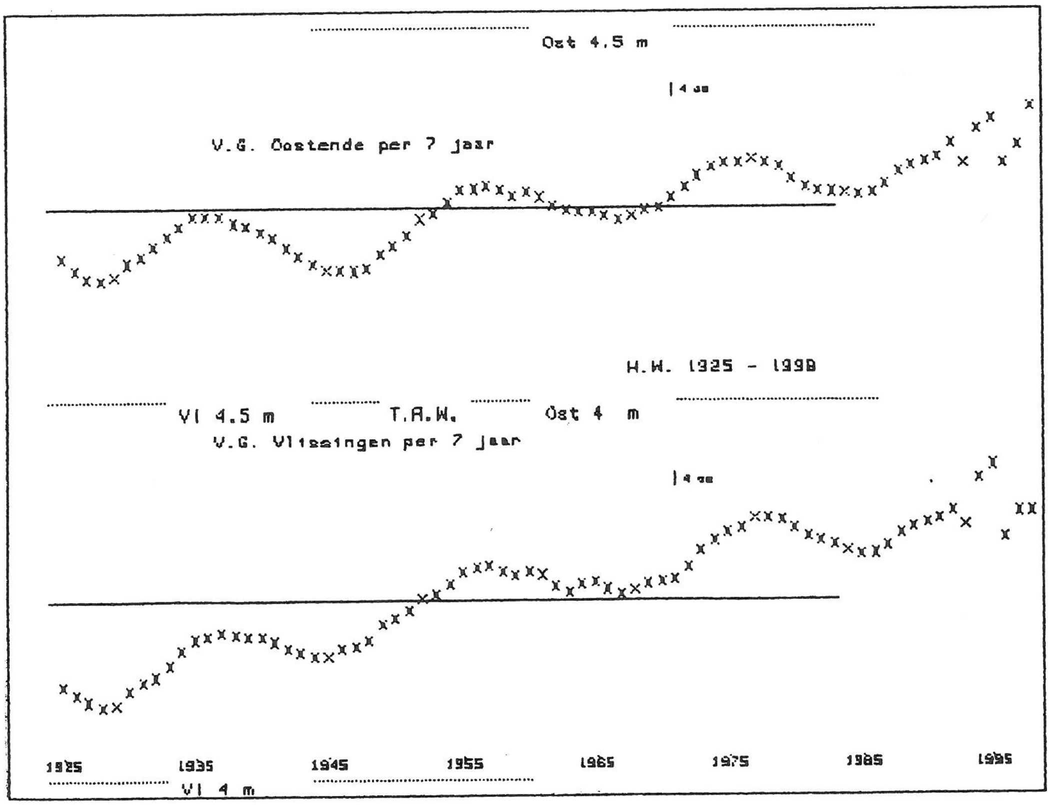
Annex 6:



Moving averages, calculated on the annual values of HW for Oostende

ONE YEAR

Moving averages, calculated on the annual values of HW for Vlissingen



Moving averages, calculated on the annual values of HW for Oostende

SEVEN YEARS

Moving averages, calculated on the annual values of HW for Vlissingen

Annex 7: Moving Averages, calculated on the Annual Values of HW for Oostende (Belgium) and for Vlissingen (The Netherlands)

Period: 1925-1998

EVOLUTION OF THE MAIN HARMONIC COMPONENTS FOR OOSTENDE

	1944-1964		**1980-1998**						
HARMONIC COMPONENT OOSTENDE	Hi in cm (1)	Gi (GMT) in ° (2)	Hi in cm (3)	Gi (GMT) in ° (4)	Δ Hi in cm (34 years) (5) =(3)-(1)	Δ Hi in % (34 years) (6)=((3)-(1))*100/(1)	Δ Hi in cm (yearly) (7)=(5)/34	Δ Gi in ° (34 years) (8)=(4)-(2)	Δ Gi in minutes (34 years) (9)
M2	179,56	5,26	181,08	4,68	1,52	0,84	0,045	-0,57	-1,18
S2	52,42	57,68	52,62	57,95	0,20	0,38	0,006	0,27	0,54
N2	30,55	341,19	30,80	340,44	0,25	0,83	0,007	-0,75	-1,58
K2	15,22	56,90	15,34	58,10	0,12	0,79	0,004	1,21	2,41
2MN2	12,18	200,41	12,38	200,58	0,20	1,66	0,006	0,16	0,34
M4	10,48	335,32	11,26	332,55	0,78	7,44	0,023	-2,77	-2,87
MU2	9,94	113,64	10,05	111,26	0,11	1,11	0,003	-2,38	-5,11
O1	9,48	167,54	9,69	168,31	0,21	2,22	0,006	0,77	3,33
NU2	9,07	335,58	8,97	334,02	-0,10	-1,10	-0,003	-1,56	-3,27
2MS6	6,96	345,44	7,32	343,76	0,36	5,17	0,011	-1,68	-1,15
MS4	6,43	37,35	7,25	38,22	0,82	12,75	0,024	0,87	0,88
M6	6,79	298,68	7,01	295,25	0,22	3,24	0,006	-3,43	-2,36

Annex 8: