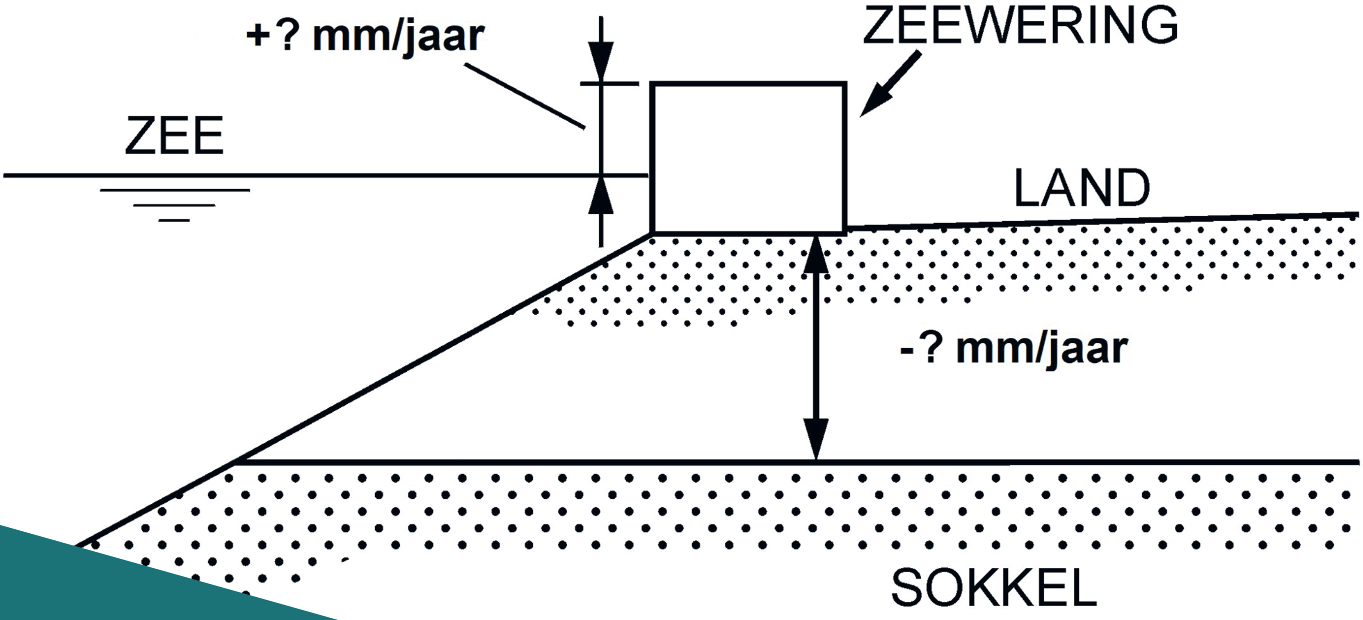

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WL rapporten

Kennisrapport Zeespiegel Vlaanderen – Synthese Vraag 1: prognoses zeespiegelstijging & Vraag 2: belang verticale bodembeweging

DEPARTEMENT
MOBILITEIT & OPENBARE WERKEN

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Kennisrapport Zeespiegel Vlaanderen – Synthese Vraag 1: prognoses zeespiegelstijging & Vraag 2: belang verticale bodembeweging

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Abstract

De werkgroep Zeespiegelstijging met vertegenwoordigers uit beleidsdomeinen Omgeving (OMG) en Mobiliteit en Openbare Werken (MOW) formuleerde 3 vragen vanuit beleid & beheer m.b.t. zeespiegelstijging in Vlaanderen:

1. Hoe kunnen prognoses voor Vlaanderen inzake zeespiegelstijging, wind, golven, evolutie gemiddeld hoog- en laagwater (en bijhorend tijverschil) alsook voor stormevents met een bepaalde terugkeerperiode afgeleid worden?
2. Wat is het belang van bodemdaling in Vlaanderen in relatie tot de verwachte stijging van de (absolute) zeespiegel?
3. Hoe kunnen versnellingen in zeespiegelstijging betrouwbaar gedetecteerd worden?

Om hierop antwoorden te formuleren werd een groep van deskundigen onder de arm genomen:

- Philippe Huybrechts, Jonas van Breedam, Wim Thiery, Margaret Chen, Vrije Universiteit Brussel
- Dries Van den Eynde, Koninklijk Belgisch Instituut voor Natuurwetenschappen
- Aimée Slangen, Koninklijk Nederlands Instituut voor Onderzoek der Zee
- Frank Pattyn, Université Libre de Bruxelles
- Rafiq Hamdi, Koninklijk Meteorologisch Instituut
- Michel Van Camp, Koninklijke Sterrenwacht van België
- Kevin Gobron, Koninklijke Sterrenwacht van België
- Patrick Willems, Katholieke Universiteit Leuven
- Dieter Meire, Waterbouwkundig Laboratorium
- Yves Plancke, Waterbouwkundig Laboratorium

Dit rapport bevat de synthese van de antwoorden op Vraag 1 rond prognoses inzake zeespiegelstijging en op vraag 2 over belang van verticale bodembeweging in Vlaanderen.

Inhoudstafel

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Lijst van de figuren

1 Inleiding

De klimaatwijziging kent voor de Vlaamse kust- en rivierbeheerders vele uitdagingen. Naast de coördinatie van de mitigatie, waarmee we de impact op het klimaat willen reduceren, zijn er ook de noodzakelijke adaptatiemaatregelen. Het voorkomen van overstromingen is hier een belangrijk aspect van. Een cruciale parameter, zowel voor het vermijden van overstromingen vanuit zee als voor het voorkomen van overstromingen langs de waterlopen voor wat betreft hun afvoer, is het waterpeil op zee of zeespiegel.

De zeespiegel wordt al sinds begin 20^{e} eeuw gedetailleerd gemonitord. Op basis hiervan zien we een quasi continue stijging van het niveau, schommelend door de nodale cyclus van de maan. Op basis van de historische meetwaarden kunnen we via extreme-waardenstatistiek de terugkeerperiodes berekenen om een gewenst veiligheidsniveau te bereiken, bijvoorbeeld tegen een 1.000-jarige stormvloed op zee.

Als welvarende regio willen we ons ook in toekomstige situaties beschermen tegen de schadelijke gevolgen van overstromingen. Uit wetenschappelijke rapporten blijkt dat de toekomstige klimaatwijziging, gebaseerd op de uitstoot van broeikasgassen en de eruit volgende opwarming van de aarde, een grote impact zal hebben op de zeespiegel die hierdoor een versnelde stijging in de toekomst zal kennen. Hoe groot deze zeespiegelstijging zal zijn, is een verhaal met vele onzekerheden. Het IPCC rapporteert op regelmatige basis over de klimaatmodellen en de eruit volgende globale scenario's van zeespiegelstijging. Recenter onderzoek leert dat de zeespiegelstijging wereldwijd niet gelijkmatig is, maar afhangt van lokale effecten.

De werkgroep Zeespiegelstijging met vertegenwoordigers uit beleidsdomeinen OMG en MOW formuleerde 3 vragen vanuit beleid & beheer m.b.t. zeespiegelstijging in Vlaanderen en legde deze voor aan een expertengroep (zie boven).

1. Hoe kunnen prognoses voor Vlaanderen inzake zeespiegelstijging, wind, golven, evolutie gemiddeld hoog- en laagwater (en bijhorend tijverschil) alsook voor stormevents met een bepaalde terugkeerperiode afgeleid worden?
2. Wat is het belang van bodemdaling in Vlaanderen in relatie tot de verwachte stijging van de (absolute) zeespiegel?
3. Hoe kunnen versnellingen in zeespiegelstijging betrouwbaar gedetecteerd worden?

Dit rapport bevat de synthese van de antwoorden op Vraag 1 en Vraag 2. De derde vraag zal in een ander rapport worden beantwoord.

2 Enkele begrippen

2.1 Absolute vs. relatieve zeespiegelstijging

Absolute zeespiegelstijging (tov. het zwaartepunt van de aarde) wordt gemeten door satellieten (= wijziging oceaanniveau). Relatieve zeespiegelstijging (tov. een punt dat meebeweegt met het land aan de kust) wordt gemeten door tijmeetposten (= resultante van wijzigingen landniveau en wijzigingen oceaanniveau).

2.2 Globale vs. regionale zeespiegelstijging

IPCC-AR6 verwacht tegen 2100 een (absolute) stijging van de globale zeespiegel (tov. zeeniveau in de periode 1995-2014) van +38 cm (SSP[1]1-RCP[2]1.91, in lijn met +1,5 °C cfr. doelstelling klimaatakkoord van Parijs) tot +77 cm (SSP5-RCP8.5, wat overeenkomt met een verdubbeling van de CO_2 emissies in 2050).

Regionale zeespiegelstijging, de (meestal relatief uitgedrukte) wijziging van het zeeniveau in een bepaalde (kust)regio, kan (sterk) afwijken van globale (gemiddelde) prognoses.

2.3 Componenten die bijdragen tot niet-uniforme zeespiegelwijzigingspatronen

2.3.1 Wijzigingen in oceaanniveau

Barystatische effecten

Veranderingen in de massa van de ijskappen en waterberging op de continenten leiden tot niet-uniforme wijzigingen in de zwaartekracht, vervormingen van de vaste aarde en rotatieveranderingen.

Sterodynamische effecten

Veranderingen in temperatuur en zoutgehalte leiden tot niet-uniforme wijzigingen in de oceaanstromingen en -densiteiten, welke op hun beurt de oceaandynamiek beïnvloeden.

Vb. Een afname van de zgn. Atlantic Meridional Overturning Circulation (AMOC) met 10% kan het oceaanniveau langs de Europese kusten al met 8-10 cm doen stijgen.

[1] Socio-economic Pathways
[2] Radiative Concentration Pathways

Atmosferische effecten

Veranderingen in atmosferische circulatie en luchtvochtgehalte kunnen leiden tot wijzigingen in lokale luchtdruk.

Vb. Een daling van de lokale luchtdruk met 1 hPa doet het oceaanniveau stijgen met 0,01 m. Een verandering van de luchtvochtigheid heeft een minder uitgesproken effect.

Wijzigingen in getijsysteem

Veranderingen in getijvoortplanting tgv. verminderde demping, veranderingen in de resonantieperioden van het getijdensysteem en/of een verhoogde reflectie van water.

Vb. Een toename van de getijamplitude (hoogwaters stijgen sterker, laagwaters trager dan de gemiddelde zeespiegel) langs de Belgische kust, volgens sommige onderzoeken met wel 10%.

2.3.2 Wijzigingen in landniveau

Glacial Isostatic Adjustment (GIA): door afsmelten van ijskappen

In onze regionen ervaren wij het effect van het verdwijnen van de Fennoscandische ijskap tussen 20.000 en 10.000 jaar geleden.
Deze veranderingen worden alsmaar kleiner. De effecten van GIA van huidige veranderingen in Groenland en op Antarctica zijn verwaarloosbaar bij ons, te ver weg en de veranderingen zijn veel te klein. Idem voor de gletsjersmelt in de Alpen.

Tektonische bewegingen

(stopzetting) (diep) grondwaterextractie

Veenoxidatie

Antropogene bodemverdichting

vb. Antwerps havengebied

(ontmanteling) stuwmeren

3 Vraag 1: prognoses voor Vlaanderen

Hoe kunnen prognoses voor Vlaanderen inzake zeespiegelstijging, wind, golven, evolutie gemiddeld hoog- en laagwater (en bijhorend tijverschil) alsook voor stormevents met een bepaalde terugkeerperiode afgeleid worden?

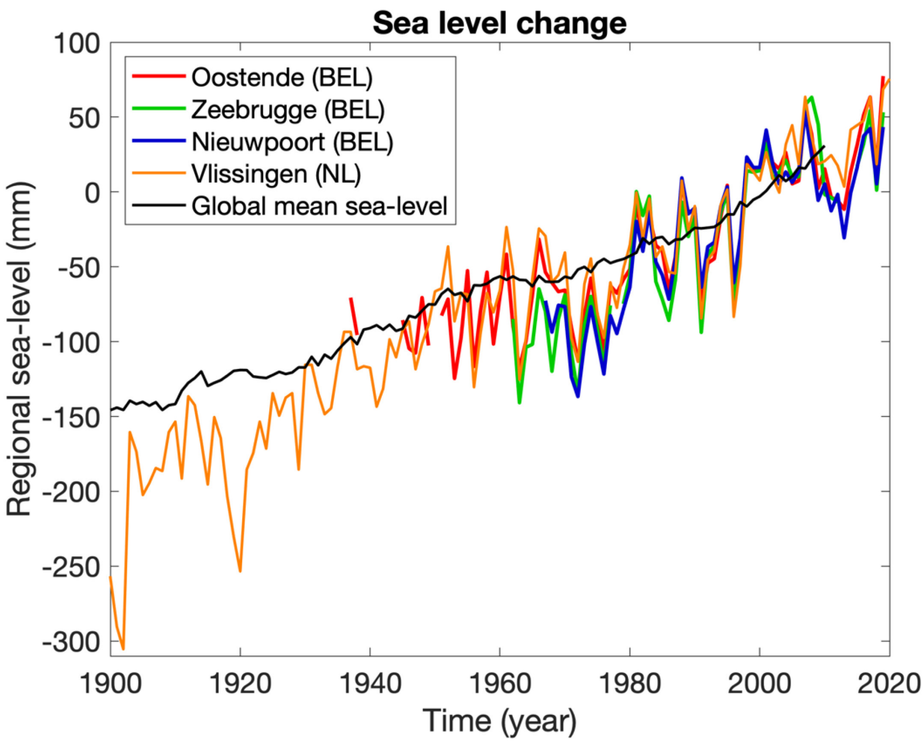
- Wat bestaat er aan cijfers voor zeespiegelprognoses aan de Belgische kust? Hoe betrouwbaar is deze data?

3.1 Synthese antwoord expertengroep

Bron: Huybrechts, P.; van Breedam, J.; Thiery, W.; Van den Eynde, D.; Slangen, A.; Pattyn, F.; Hamdi, R. (2023). Zeespiegelstijging voor Vlaanderen – Vraag 1. Versie 4.0. WL Memo's, 21_127_1. Waterbouwkundig Laboratorium: Antwerpen. (zie Bijlage)

- De voorbije decennia liep de zeespiegelstijging aan de Belgische kust quasi gelijk met de globale jaargemiddelden (Figuur 1)

  Thermisch uitzetting van water verklaart 50% van de ZSS in de periode 1971 tot 2018, verlies van ijs van gletsjers en ijskappen resp. 22 en 20% en verandering in waterberging op de continenten 8%.



Figuur 1 – Zeespiegelstijging aan de Belgische kust en globaal uitgedrukt tov. het gemiddeld peil voor periode 1991-2010 (Huybrechts et al.,2023)

- Toekomstige zeespiegelstijging
  - Hoewel de bijdragen van de verschillende componenten voor onze contreien niet helemaal gelijk lopen met deze voor globale prognoses, heffen de verschillen elkaar obv. de huidige proceskennis en -inzichten op.
  - Door mogelijke wijziging in de sturende processen is een periodieke evaluatie van de bijdragende componenten aangewezen (bv. bij een nieuwe IPCC-rapport).

  Conclusie: **De globale IPPC-AR6 prognoses zijn bruikbaar voor de Belgische Kust**.

  De in Tabel 1 vermelde gemiddelde stijgingen van de zeespiegel gelden als prognoses in 2100 en 2150, relatief tov. 1995-2014.

Tabel 1 – Verwachte globale en regionale zeespiegelstijging in 2100 en 2150 relatief tov. 1995-2014, in cm (Huybrechts et al., 2023)

2100 **+ (cm)**	Gobale IPCC-AR6 (absoluut)	Belgische kust IPCC-AR6 (incl. wijziging landniveau, relatief)	Belgische kust *expertengroep* (excl. wijziging landniveau, absoluut)
SSP1-RCP2.6*	44 [32-62]	48 [29-71]	42 [25-68]
SSP2-RCP4.5*	56 [44-76]	61 [42-85]	53 [34-82]
SSP5-RCP8.5*	77 [63-101]	81 [58-112]	73 [50-109]
SSP5-RCP8.5 low confidence**	88 [63-160]	90 [58-137]	81 [46-140]

2150 **+ (cm)**	Globale IPCC-AR6 (absoluut)	Belgische kust IPCC-AR6 (incl. wijziging landniveau, relatief)
SSP1-RCP2.6*	68 [46-99]	68 [36-109]
SSP2-RCP4.5*	92 [66-133]	94 [59-141]
SSP5-RCP8.5*	132 [98-188]	133 [86-196]
SSP5-RCP8.5 low confidence**	198 [97-482]	198 [86-503]

**'Medium confidence' met mediane waarden en betrouwbaarheidsintervallen > 66% waarschijnlijkheid.*

***'SSP5-RCP8.5 low confidence' bevat potentiële effecten van ijskapprocessen met een lage waarschijnlijkheid doch grote impact, die niet kunnen worden uitgesloten:*

  - Het BI = [17de tot 83ste percentiel van de p-box] is hier anders berekend, waarbij de ondergrens goed samenvalt met deze van SSP5-8.5 zonder 'low confidence' processen, maar de bovengrens daar ver boven zit.

- Enkel dit scenario bevat simulatieresultaten met een zeespiegelstijging van +2m in 2100, maar dan moet het [5e tot 95e percentiel van de p-box] beschouwd worden.
- Tot 2100 zijn de mogelijke effecten van ijskapprocessen beperkt. Nadien is dit niet meer het geval met mediane waarden in 2150 en 2200 van resp. +2 m en +3 m, weliswaar met aanzienlijke onzekerheden.

- Stormvloeden en maatgevende golfhoogte
  - Simulaties met klimaatmodellen suggereren een toename in windsnelheden en bijgevolg een toename van golfhoogte in de zuidelijke Noordzee met 25 tot 35 cm.
  - Ook een verhoging van de frequentie van extreme windsnelheden wordt verwacht tegen het einde van de 21e eeuw.
    - Geen duidelijke trend wordt vooralsnog waargenomen aan de Belgische kust.
  - Een hoger oceaanniveau zorgt ook voor verdere golfpropagatie richting kust als gevolg van minder bodemwrijving en zo mogelijks voor hogere golven nabij de kust.
  - Stormpeilen zullen extra toenemen in vergelijking met de gemiddelde stijging van de zeespiegel. Waar in 2100 onder SSP2-RCP4.5 en SSP5-RCP8.5 een gemiddelde stijging van de zeespiegel met resp. +56 en +77 cm wordt verwacht (Tabel 1, kolom 2), betreft dit voor het T100-stormpeil in 2100 resp. +75 en +98 cm (20 à 25% extra toename). Hoeveel deze extra toename bij andere retourperiode bedraagt, wordt nagevraagd.

- Extreme neerslag en *compound events*
  - Extremere neerslag met hogere piekafvoeren richting zuidelijke Noordzee worden verwacht.
  - De kans op gecombineerd voorkomen van stormtijen en extreme neerslag (zgn. compound events) lijkt in de toekomst toe te nemen met hogere overstromingsrisico's tot gevolg.

3.2 Conclusie expertengroep

Het vrij kleine verschil tussen globale prognoses en verwachtingen voor de Belgische kust zal naar verwachting gelijk blijven voor de beschouwde tijdshorizon.

Pas wanneer de bijdrage van de Antarctische ijskap aan de zeespiegelstijging zeer groot wordt, zal de zeespiegelstijging langs de Belgische kust meer divergeren en hoger zijn dan het wereldgemiddelde. Veranderingen in de oceaancirculatie die verband houden met de *Atlantic Meridional Overturning Circulation (AMOC)* hebben het potentieel om de lokale zeespiegel aanzienlijk te verhogen. De gecombineerde sterische en dynamische oceaanbijdrage heeft de hoogste schaalfactor voor de Noordzee dichtbij de Belgische kust.

Andere elementen waarmee rekening moet worden gehouden zijn meer frequente stormen, hogere stormgolven (tot 30 cm) en een verhoogde getijdenamplitude (tot 10% van de zeespiegelstijging). Deze factoren samen zorgen ervoor dat extreme zeespiegels sneller stijgen dan het gemiddelde niveau op lange termijn.

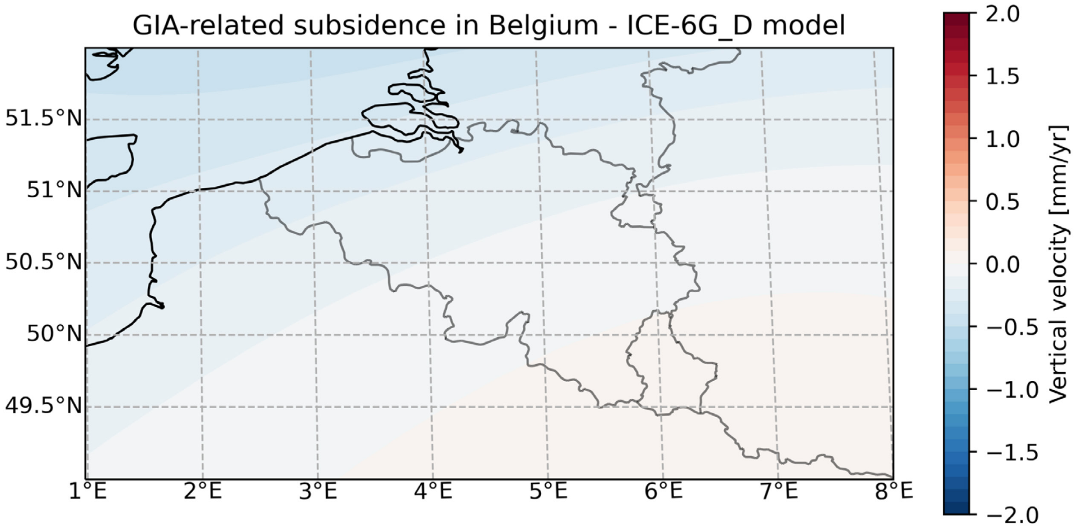
4 Vraag 2: bodemdaling in Vlaanderen

Wat is het belang van bodemdaling in Vlaanderen in relatie tot de verwachte stijging van de (absolute) zeespiegel?

4.1 Synthese antwoord Expertengroep

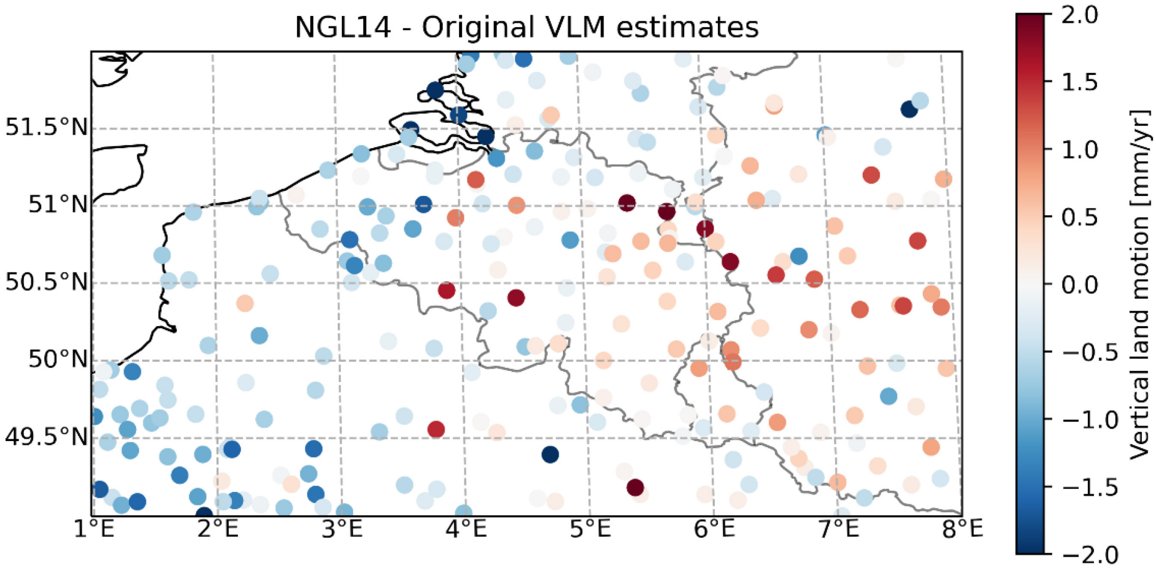
Bron: Van Camp, M.; Gobron, K.; Pattyn, F.; Huybrechts, P.; Chen, M. (2023). Zeespiegelstijging voor Vlaanderen – Vraag 2. Versie 4.0. WL Memo's, 21_127_2. Waterbouwkundig Laboratorium: Antwerpen. (zie Bijlage)

- Modellen voorspellen een Glacial Isostatic Adjustment (GIA) aan de Belgische kust van -0,29 mm/jaar (Figuur 2).



Figuur 2 – Voorspelde verticale landbeweging in België ten gevolge van GIA (Van Camp et al., 2022)

- Tot heden werden geen significante non-linear bewegingen van het landniveau gedetecteerd
- Figuur 3 toont de geschatte verticale landbeweging (*Vertical Land Motion,* VLM) obv. GNSS (*Global Navigation Satellite Systems*) stations in België en omliggende landen in de voorbije 10 à 15 jaren.



Figuur 3 – Geschatte verticale landbeweging in België en omliggende landen (Van Camp et al., 2022)

- Aan de Belgische kust kent VLM een snelheid van zo'n -0,85 mm/jaar (+/-0,2 mm). (enkel meetlocaties met significante VLM binnen 95% BI worden getoond Tabel 2)

Tabel 2 – Geschatte verticale landbeweging obv. GNSS aan de Belgische kust (Van Camp et al., 2022)

Land	Stad	Naam meetstation	Verticale landbeweging (mm/jaar)	Standaardafwijking (mm/jaar)
BE	**Zeebrugge**	**ZEEB**	**-0.84**	**0.15**
BE	**Oostende**	**OOST**	**-0.85**	**0.22**
FR	**Dunkerque**	**COUD**	**-0.87**	**0.17**

- VLM in de rest van Vlaanderen (enkel meetlocaties met significante VLM binnen 95% BI worden getoond in Tabel 3)

Tabel 3 – Geschatte verticale landbeweging obv. GNSS in de rest van Vlaanderen (Van Camp et al., 2022)

Land	Stad	Naam meetstation	Verticale landbeweging (mm/jaar)	Standaardafwijking (mm/jaar)
BE	**Ieper**	**IEPE**	**-0.54**	**0.15**
BE	**Pittem**	**PITM**	**-1.01**	**0.19**
BE	**Dentergem**	**DENT**	**-0.64**	**0.15**
BE	**Menen**	**MENE**	**-1.49**	**0.25**
BE	**Erpe-Mere**	**ERPE**	**+1.02**	**0.26**
BE	**Oudenaarde**	**OUDE**	**-1.05**	**0.12**
BE	**Ruiselde**	**RUIS**	**-2.04**	**0.77**
BE	**Hoegaarden**	**HOEG**	**-1.12**	**0.22**
BE	**Maasmechelen**	**MAME**	**+5.25***	**0.49**
BE	**Tongeren**	**TGRN**	**+0.64**	**0.18**
BE	**Houthalen-Helchteren**	**HOUT**	**+6.93**	**0.19**
BE	**Brecht**	**BRCT**	**-0.87**	**0.20**
BE	**Antwerpen**	**BEZA**	**-1.17**	**0.21**
BE	**Gent**	**GENT**	**-1.70**	**0.18**
BE	**Mechelen**	**MECH**	**+0.91**	**0.28**

*Opheffing veroorzaakt door stijging grondwater na stopzetting bemaling bij sluiting koolmijnen

4.2 Conclusie expertengroep

- Er zijn geen indicaties om een versnelling te verwachten in de toekomst.
- 0,8 à 0,9 mm/jaar dient te worden bijgeteld bij absolute prognoses van de zeespiegelstijging voor Vlaanderen.
- Het is aanbevolen een GNSS-ontvanger te installeren op elke tijmeetpost om de verticale beweging te monitoren.

5 Bijlagen 1

5.1 WL2023M21_127_1

Memo

//

Titel: Zeespiegelstijging voor Vlaanderen – Vraag 1

Datum: 29/03/2023

Auteurs: Philippe Huybrechts, Jonas van Breedam, Wim Thiery (Vrije Universiteit Brussel); Dries Van den Eynde (Koninklijk Belgisch Instituut voor Natuurwetenschappen); Aimée Slangen (Koninklijk Nederlands Instituut voor Onderzoek der Zee); Frank Pattyn (Université Libre de Bruxelles); Rafiq Hamdi (Koninklijk Meteorologisch Instituut)

Referentie: Huybrechts, P.;van Breedam, J.;Thiery, W.;Van den Eynde, D.;Slangen, A.;Pattyn, F.;Hamdi, R. (2023). Zeespiegelstijging voor Vlaanderen – Vraag 1. Versie 4.0. WL Memo's, 21_127_1. Waterbouwkundig Laboratorium: Antwerpen.

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Vraag 1 – Question 1: Regional sea-level change for the North Sea/Belgian coast

Hoe moeten/kunnen prognoses voor Vlaanderen inzake zeespiegelstijging, wind (boven Noordzee), golven, evolutie gemiddeld hoog- en laagwater (en bijhorend tijverschil) alsook voor **stormevents** met een bepaalde terugkeerperiodes afgeleid worden obv. mondiale/regionale klimaatmodellen?

Wat bestaat er van cijfers vertrekkende van mondiale/regionale klimaatmodellen voor zeespiegelprognoses aan de Belgische kust? Hoe betrouwbaar is deze data?

INHOUD

1 Introduction

Sea level rise is a serious threat for millions of people living in the vicinity of the coast. In the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), the median estimate of global mean sea level rise by 2100 relative to 1995-2014 is projected to be between 38 cm (SSP1-1.9[1], a very low emissions scenario in line with the 1.5°C target of the Paris agreement) and 77 cm (SSP5-8.5, a very high emissions scenario, with doubling CO_2 emissions by 2050) (Fox-Kemper et al., 2021). Regionally, sea-level can deviate significantly from the global mean estimates. For about 2/3 of the global coastlines, this deviation is within 20% of the global mean. Regional sea-level change (or local sea-level change) is the sea-level change at a specific location along a coast. It is measured by satellite altimetry observations (measuring *absolute* sea-level change relative to the centre of mass of the Earth) and tide gauge observations (measuring *relative* sea-level change with respect to a benchmark on land). Relative sea-level changes are driven by glacial isostatic adjustment (GIA) and tectonic movements such as subsidence or uplift (land-level changes) in addition to barystatic and sterodynamic sea level changes (ocean-level changes). In this question, we focus on the regional effects of barystatic sea-level changes (component of sea-level change due to mass exchange with the land) and sterodynamic sea-level changes (component due to changes in ocean circulation and water density changes). Land-level changes are investigated in Question 2. Sea-level change furthermore differs regionally due to the gravitational effect of mass changes of the ice sheets on the shape of the geoid, while regional steric changes are connected to different warming and salinity patterns in the ocean (Figure 1). Also, the atmosphere and ocean dynamics influence local sea-level mainly by changes in the local air pressure and oceanic circulation patterns.

The Belgian coast is about 65 km long, and is located in the southern part of the North Sea. The North Sea is positioned on the continental shelf and is relatively shallow with an average depth of 74 m (Otto et al., 1990). Between the coast of Belgium, the Netherlands and southeast Great Britain, the depth ranges between 10 and 40 m. The main drivers of natural variability in North Sea levels are the tides (on daily timescales) and meteorological phenomena such as the North Atlantic Oscillation (NAO) (on seasonal time scales), which determines the strength of the wind and the North Atlantic pressure systems (Sündermann and Pohlmann, 2011). The tidal range is large along the Belgian coast with a difference between low and high tide of about 5 m. The tides reach upstream far in the hinterland with tidal ranges noticeable up to the cities of Gent and Mechelen.

[1] Shared Socio-economic Pathways (SSPs) are used to describe the socio-economic trends in five different scenarios (SSP1 to SSP5). These are combined with Radiative Concentration Pathways (RCPs), which describe the increase in the amount of radiative forcing in W/m^2 by the year 2100 (e.g., 1.9, 4.5). In the IPCC AR6, five different combinations of SSPs and RCPs are used as illustrative scenarios: SSP1-1.9; SSP1-2.6; SSP2-4.5; SSP3-7.0; SSP5-8.5.

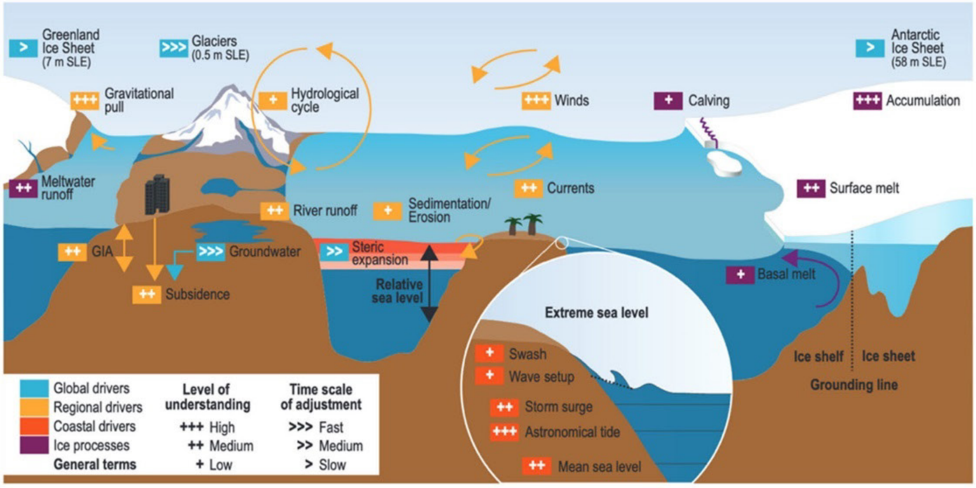


Figure 1 - Sea level rise components and processes governing regional and global mean sea level change (Oppenheimer et al., 2019).

2 Components and processes contributing to regional sea-level changes in the southern North Sea.

In this section, we give an overview of the different processes driving regional changes in sea level and how they affect the North Sea along the Belgian coast.

2.1 Regional influence of mass changes of land ice

All mass on Earth attracts each other. For instance, the Greenland ice sheet (GrIS) and Antarctic ice sheets (AIS) attract the ocean water by gravitational forces. When the mass of the ice sheets is changing, the resulting sea-level change will not be spatially uniform due to gravitational changes, solid Earth deformation, and rotational changes. These non-uniform sea-level patterns are referred to as sea-level fingerprints. The geoid lowers in the vicinity of an ice sheet when its mass is decreasing. Therefore, changes in sea level will be lowest in the vicinity of a melting ice sheet and largest far away from such an ice sheet. Since the GrIS is located relatively close to the Belgian coast and the AIS relatively far away, mass changes from the GrIS will result in local sea-level changes below the global mean and mass changes from the AIS will contribute more than average to sea-level change along the Belgian coast.

Sea-level fingerprints can be used to infer the regional sea-level change along the Belgian coast resulting from ice mass changes. Tamisiea and Mitrovica (2011) determined a scaling factor between 0 and 0.2 for mass loss of the GrIS in the region close to the Belgian coast and between 1.1 and 1.2 for mass changes of the West Antarctic Ice Sheet (WAIS). This range for the AIS contribution close to the Belgian coast was further narrowed by Hay et al. (2014) with a factor of 1.15 to 1.20 for melting of the WAIS and 1.05 to 1.10 for melting of the East Antarctic Ice Sheet (EAIS). Katsman et al. (2011) used a scaling factor of 0.2 for melting of the GrIS and 1.1 for melting of the AIS along the Dutch coast.

Hsu and Velicogna (2017) investigated the sea-level fingerprint trend for the period 2002-2014 from melting of the GrIS, the AIS, and glaciers and ice caps (GIC). For the area of the southern North Sea, they found the AIS contribution to be above the global mean average and the GrIS contribution to be below the global mean average. The contribution from GIC along the Belgian coast was estimated to be between 0.2-0.3 mm year^{-1} for a global mean sea-level contribution of 0.5 mm year^{-1}. This is lower than the time-dependent scaling factor determined by Katsman et al. (2011) of 0.75-0.9 for the Dutch coastline. The sea level fingerprint for glacier melting from Kopp et al. (2014) is about 0.7. The scaling factor for ice sheets and glaciers is not constant in time because of the changes in relative importance of the regions of ice mass loss.

The ice sheets are responsible for a sea-level increase in the North Sea basin during the period 1980-2016 of about 3 cm (thus 0.08 mm year^{-1}) (Frederikse et al., 2016). If a linear trend in the individual processes governing sea level rise in the North Sea is considered since 1958, the glaciers contributed 0.26 mm year^{-1} (0.44 mm year^{-1} global mean), the GrIS contributed 0.00 mm year^{-1} (0.13 mm year^{-1} global mean) and the AIS contributed 0.08 mm year^{-1} (0.07 mm year^{-1} global mean). De Vries et al. (2014) determined a scaling factor of 0.75 for the land ice contribution to global sea-level by 2100 for the Netherlands on account of a contribution of 0.70-0.75 from glaciers, 0.2 from the GrIS and 1.1 to 1.2 from the AIS. Combining the previous information from the literature, a scaling factor of 0.15 for mass loss of the GrIS, 1.1 for mass loss of the AIS and 0.7 for mass loss of GIC can be inferred for the Belgian coast. We will consider these scaling factors for the first set of projections further below in section 4. In the most recent IPCC AR6 projections, the scaling factors for the Belgian coast are 0.20 for GrIS, 1.08 for AIS and 0.62-0.63 for the glaciers (depending on the emissions scenario) (Fox-Kemper et al., 2021). Therefore, we will also consider a second set of projections based on the IPCC AR6 scaling factors. In contrast to constant scaling factors for the first set of projections, the IPCC AR6 scaling factors can change when the location of the mass loss changes: if for instance the ratio of mass loss on East Antarctica versus West Antarctica changes, this will impact the scaling factors. Scaling factors should therefore not be considered constant: they can vary in time and between scenarios.

2.2 Regional influence of ocean circulation changes

The dynamic part of sterodynamic sea-level changes results from changes in ocean circulation patterns (Bilbao et al., 2015). The North Sea is located on the continental shelf and the dynamics of coastal sea level is different from the dynamics in the open ocean (Hughes et al., 2019). However, the North Sea is linked to the Atlantic Ocean and changes in the North Atlantic influence the North Sea region, albeit with a damped signal. The Atlantic meridional overturning circulation (AMOC) is a component of the thermohaline circulation (driven by changes in temperatures and salinity) and transports heat from the tropics to the northern Atlantic Ocean. Cold, salty water sinks to the bottom of the ocean in the northern Atlantic by a process called North Atlantic deep water formation (NADW). NADW formation causes regionally a relatively lower sea level as compared to the northern Pacific (Levermann et al., 2005). Increased warming can lead to increased meltwater from the Greenland Ice Sheet. These meltwater fluxes have the potential to impact the AMOC and NADW formation. Over the last decade, the AMOC has gradually weakened (Boers, 2021). Levermann et al. (2005) showed that a shutdown of the thermohaline circulation could raise sea level along the European coast with up to 40 cm due to a dynamic adjustment of the ocean surface, but even a decrease in the strength of the AMOC by 10% would cause a regional sea level rise along the European coasts of 8-10 cm.

2.3 Steric sea-level changes in the North Sea

Local effects of ocean density changes (the steric part of sterodynamic changes) can be separated into temperature-driven (thermosteric) and salinity-driven (halosteric) components of sea-level change. The North Sea is a shallow sea, mostly less than 100 m deep and less than 10 m close to the Belgian coast. Since the steric effect is integrated over the water column depth, it has a negligible contribution for the North Sea. However, wind-driven coastally trapped waves (alongshore waves) propagate the steric sea-level changes from the North Atlantic into the North Sea basin (Frederikse et al., 2016). Steric changes in the deep ocean have an influence on the regional sea-level in the North Sea and are inferred from the North Atlantic current (Dangendorf et al., 2014). It is thought that a weakened strength of the AMOC also leads to a warming atmosphere and a higher-than-average steric sea level rise (Katsman et al., 2011).

The steric sea-level change in the North Sea shows strong decadal variability with a long-term positive trend (Frederikse et al., 2016). The linear trend since 1958 of the steric and dynamic ocean contribution to sea level is 0.75 mm $year^{-1}$ for the North Sea, slightly higher than the global mean of 0.73 mm $year^{-1}$ (Hsu and Velicogna, 2017). This would correspond to a scaling factor of 1.03 for the North Sea compared to the global mean. The combined contribution of the steric component and dynamical ocean changes (Slangen et al., 2014) results in a higher estimate of the scaling factor of about 1.40.

2.4 Regional influence of land water storage changes

Similar to land ice mass changes, there is also a gravitational effect resulting from land water storage changes, which also leads to a sea-level fingerprint. This contribution includes natural changes (snow, lakes, rivers), but also man-made changes such as groundwater extraction (e.g. Wada et al., 2016) and building of dams and reservoirs (Chao et al., 2008). Compared to ice sheets and glaciers, this is a relatively small contribution. In the IPCC AR6 projections, the contribution of man-made land water storage changes for the Belgian coast is a factor 0.72 of the global mean change.

2.5 Changes in atmospheric pressure

Changes in atmospheric circulation and atmospheric moisture content can result in changes in surface pressure which in turn influences sea level. A decrease in the surface pressure of 1 hPa results in a sea-level increase of 0.01 m (inverse barometer effect). A change in the atmospheric moisture content has an effect on local sea-level, but much less pronounced than changes in the atmospheric circulation. Slangen et al. (2014) investigated the 21^{st} century sea level rise and found that atmospheric loading results in a sea level rise of -0.03 m to 0.05 m at 2100 using RCP8.5. This is much smaller than the total range of the steric and dynamic sea level rise component of -0.03 m to 0.59 m at 2100 for RCP8.5.

There is an important influence of the local atmospheric forcing on the intra- and interannual sea-level variability in the North Sea. Westerly winds in the south-eastern North Sea cause wind-driven coastally trapped waves with a large temporal variability. This variability is especially large in the south-eastern part of the North Sea and goes up to ±60 cm. It is estimated that the influence of the atmospheric forcing on the mean trend for 20^{th} century sea level rise is -0.1 mm $year^{-1}$ for Vlissingen (Dangendorf et al., 2014), close to the Belgian coast.

2.6 Changes in the tidal system

Sea level rise has an influence on the tidal system due to (i) reduced damping, (ii) changes in the resonant periods of the tidal system, and (iii) an increased reflection of water when the hinterland is not flooded. Changes in the amplitude of the tides can threaten the Belgian coast. For a sea level rise of up to 2 m, the tides would increase linearly by up to 10% close to the Belgian coast (Idier et al., 2017). Another study simulating the impact of a +2 m sea level rise yields increasing high tides and low tides near the Belgian coast of respectively +2.02 m and +1.95 m or an increase in tidal difference of 7 cm (Chu et al., 2020).

According to Pickering et al. (2012), the peak spring tide could increase with 14 cm for a sea level rise of 2 m. Pelling et al. (2013) made simulations with sea-level change forcing of 2 to 5 m to detect a change in the tidal system of the North Sea. One experiment allowed for flooding of low-lying land and another used the method of adding a vertical wall of water. Their results show a similar pattern, though flooding of the low lying (Dutch coastal) areas decreases rather than increases the amplitude of the tides. These studies indicate that changes in the tides can pose an additional risk to flooding.

2.7 Changes in storm surges and waves

Storm surge and wave height in the southern North Sea are most susceptible to a storm driven by northerly wind, because of the shallow depths and the funnel effect (Sündermann and Pohlmann, 2011). Global climate model simulations suggest that increased wind speed may increase the wave heights in the southern North Sea with 25 to 35 cm by 2100 (Grabemann and Weisse, 2008). The simulations also show that the frequency of extreme winds increases by the end of the 21st century. Vousdoukas et al. (2017) found a similar increase in the extreme wave height and storm surge of 30 cm by 2100 for both an intermediate and a high-end emission scenario (RCP4.5 and RCP8.5, respectively). These projected changes are not yet manifest in historical observations, as Van den Eynde et al. (2012) did not find any clear trend in the time series of storminess in the Belgian coastal waters. Also the analysis of regional climate projections did not show any increase in storm surges and waves for the Belgian coast (Van den Eynde et al., 2018). Jackson et al. (2015) investigated the effect of a shutdown of the AMOC and found a strengthening of the winter storm track and more frequent storms over northwestern Europe. Note however that transgression of this tipping point is highly uncertain, and that time scales associated with such change are on the order of centuries to millennia. Finally, it is worth mentioning that the sea level rise itself will allow the waves to propagate further towards to coast, due to less bottom friction, and this might also lead to higher waves near the coastline.

2.8 Extreme precipitation and compound events

Extreme precipitation is projected to increase across most mid-latitude regions (Fischer and Knutti, 2015, Seneviratne et al., 2021), which may result in higher peak river discharge into the southern North Sea. A global analysis of gauge data indicated that more than half of the gauging stations show a significant dependency between skew surge and annual maximum richer discharge when including a 5-day lag (Ward et al., 2018). In the Channel, the joint exceedance probability of river discharge and sea-level exceeding design level is substantially higher (by at least factor 5) compared to assuming independence between both variables (Ward et al., 2018). This result highlights a substantial link between the occurrence of extreme sea levels and extreme river discharge, contributing to enhanced flood risk in coastal regions. This dependency of hazards linked to a common atmospheric driver (in this case cyclonic systems) is referred to as a compound event (Zscheischler et al., 2020). Future projections of co-occurring high sea level and heavy precipitation in Europe highlights that compound flood probability will substantially rise along parts of the northern European coast including the southern North Sea (Bevacqua et al., 2019). Therefore, compound flooding in coastal regions along the southern North Sea should be considered as a potential hazard aggravating the risk caused by mean sea level risk.

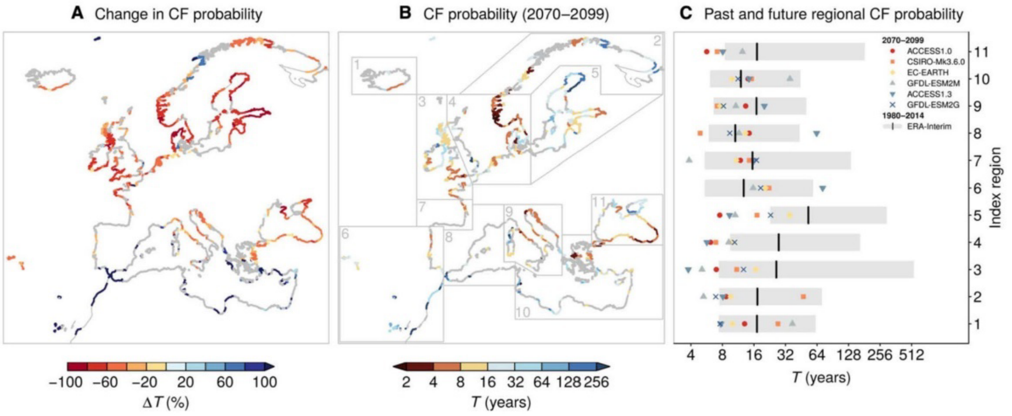


Figure 2 - Future probability of potential compound flooding (CF). (A) Multimodel mean of projected change (%) of CF return periods, between future (2070–2099) and present (1970–2004) climate. (B) Return periods for the future (2070–2099). Gray points indicate locations where only four or fewer of six models agree on the sign of the return period change (three or less of five models in the Black Sea). Areas of gray points in (A) and (B) are slightly different, as the former are computed taking into account the past period (1970–2004) and the latter the period (1980–2004). (C) Median value of CF return periods over regions defined in (B) for past [1980–2014, based on ERA-Interim] and future (2070–2099) climate, separately for individual models. For ERA-Interim, gray shading illustrates the sampling uncertainty 95% range (Bevacqua et al., 2019).

3 Observed past regional sea-level change along the Belgian coast

As shown in Figure 3, the observed relative sea level rise along the Belgian has not deviated much from the global mean sea level rise for the period from 1950 to 2010. The figure suggests a slight east-west gradient along the Belgian coast, with a somewhat higher sea level rise in the east compared to the west, possibly caused by a gradient in vertical land motion. The linear trend of sea level rise measured from tide gauges is 2.34 ± 0.47 mm year^{-1} (1900-2020) for Vlissingen and 1.56 ± 0.30 mm year^{-1} (1960-2020) for Dunkerque (PSMSL, 2022).

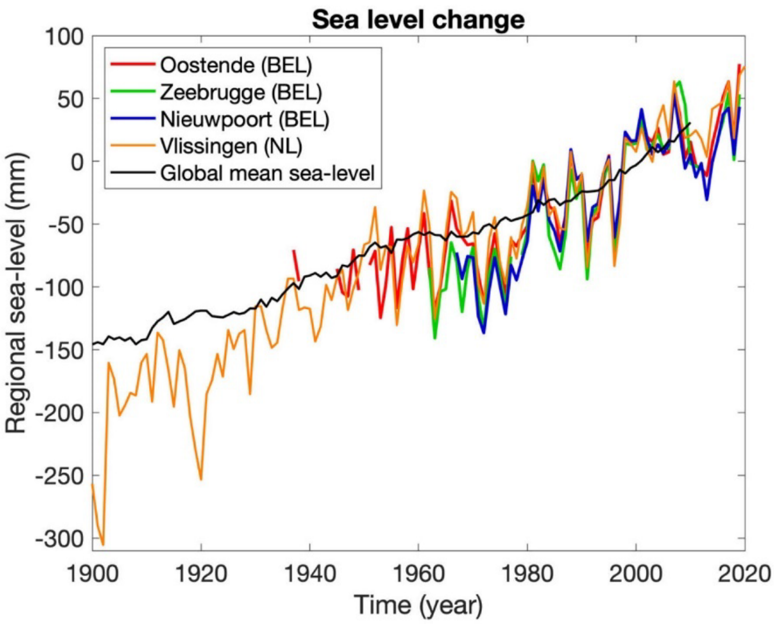


Figure 3 - Global mean sea-level change (black line; Palmer et al., 2021) compared to observed sea-level change in Oostende, Zeebrugge and Nieuwpoort along the Belgian coast and Vlissingen along the southern Dutch coast (Holgate et al., 2013; PSMSL, 2022). The values are annual means relative to the mean sea-level for 1991-2010.

4 Projected future regional sea-level change along the Belgian coast

4.1 Projections to 2100

Based on the processes discussed so far, we have calculated the sea level rise for the Belgian coast by 2100 relative to 1995-2014 in comparison to the global mean. First of all, we base ourselves on the scaling factors from the literature discussed above ('own processing') applied to the projected IPCC AR6 global mean values for each contributor for the emission scenarios SSP1-2.6, SSP2-4.5, SSP5-8.5, and SSP5-8.5 low confidence (Fox-Kemper et al., 2021). Secondly, we use the IPCC AR6 Sea Level Projection Tool: https://sealevel.nasa.gov/data_tools/17), which directly provides regional values for any point in the ocean consistent with the IPCC AR6 projections ('IPCC AR6'). The results of applying the two sets of regional projections for the area of the southern North Sea are summarized in Table 1 and Figure 4.

By the year 2100, the relative importance of the different components contributing to sea-level depends on the forcing scenario. For all scenarios and both globally and regionally, and considering the median values, the largest contributor remains the sterodynamic effect, as it is today. For the low-end SSP1-2.6 warming scenario, the AIS would globally contribute more to sea-level change than GIC and the GrIS, while for the high SSP5-8.5 warming scenario, the AIS contribution is similar to the GIC contribution. The median regional sea level rise for the Belgian coast is estimated to be 42/48 cm using scenario SSP1-2.6, 53/61 cm using scenario SSP2-4.5, and 73/81 cm using scenario SSP5-8.5 ('own processing' and 'IPCC AR6', respectively), only slightly different from the global mean values of 44, 56 and 77 cm, respectively. The uncertainty range for regional sea level rise scales with the scaling factor, but the differences between global and regional sea level rise are always less than 20% for these scenarios. The median value of total regional sea-level change at the Belgian coast calculated by any of the two methods deviates by no more than 10% from the global mean for all scenarios considered (Figure 4). The differences between the 'IPCC AR6' regional projections (Figure 5) and the 'own processing' projections (Figure 4) are that (i) the latter do not consider vertical land motion, which is slightly downward along the Belgian coast in the IPCC AR6 Sea Level Projection Tool, and thus exacerbating relative sea level rise, and (ii) that the IPCC AR6 projections take into account that scaling factors can vary over time. Overall, these projections align with the close historical correspondence between global sea-level change and the sea-level change observed along the Belgian coast (Figure 3).

Table 1 - Global and regional (Belgian coast) sea-level change at the year 2100 relative to 1995-2014, in cm. Regional projections are based on IPCC AR6 regional sea-level projections (middle column) and based on literature-derived scaling factors (right column). *Medium confidence* values represent the median and the *likely* range (>66% probability). *Low confidence* projections are in grey shaded cells, where the uncertainty represents the 17th to 83rd percentile of a p-box. Numbers do not always add up exactly because of rounding off.

	GLOBAL MEAN IPCC AR6	BELGIAN COAST ('IPCC AR6') (51°N, 3°E)	BELGIAN COAST (IPCC AR6 scaled) 'own processing'
Sterodynamic			**Scaling factor 1.4**
SSP1-2.6	14 [11-18]	23 [10-37]	19.6 [15.4-25.2]
SSP2-4.5	20 [16-24]	33 [20-46]	28 [22.4-33.6]
SSP5-8.5	30 [24-36]	48 [32-65]	42 [33.6-50.4]
SSP5-8.5 low conf	30 [24-36]	48 [32-65]	42 [33.6-50.4]
Glaciers			**Scaling factor 0.7**
SSP1-2.6	9 [7-11]	6 [4-7]	6.3 [4.9-7.7]
SSP2-4.5	12 [10-15]	8 [6-10]	8.4 [7-10.5]
SSP5-8.5	18 [15-21]	11 [9-13]	12.6 [10.5-14.7]
SSP5-8.5 low conf	17 [11-21]	10 [6-13]	11.9 [7.7-14.7]
Greenland ice sheet			**Scaling factor 0.15**
SSP1-2.6	6 [1-10]	1 [0-2]	0.9 [0.2-1.5]
SSP2-4.5	8 [4-13]	2 [1-3]	1.2 [0.6-2.0]
SSP5-8.5	13 [9-18]	3 [2-4]	2.0 [1.4-2.7]
SSP5-8.5 low conf	18 [9-59]	4 [2-12]	2.7 [1.4-8.9]
Antarctic ice sheet			**Scaling factor 1.10**
SSP1-2.6	11 [3-27]	12 [3-29]	12.1 [3.3-29.7]
SSP2-4.5	11 [3-29]	12 [3-32]	12.1 [3.3-31.9]
SSP5-8.5	12 [3-34]	12 [4-37]	13.2 [3.3-37.4]
SSP5-8.5 low conf	19 [2-56]	21 [2-60]	20.9 [2.2-61.6]

Land water storage			**Scaling factor 1**
SSP1-2.6	3 [1-4]	2 [1-3]	3 [1-4]
SSP2-4.5	3 [1-4]	2 [1-3]	3 [1-4]
SSP5-8.5	3 [1-4]	2 [1-3]	3 [1-4]
SSP5-8.5 low conf	3 [1-4]	2 [1-3]	3 [1-4]
Vertical Land Movement			
All SSPs	n/a	3 [1-5]	n/a
Total	**Total global**	**Total regional**	
SSP1-2.6	44 [32-62]	48 [29-71]	42 [25-68]
SSP2-4.5	56 [44-76]	61 [42-85]	53 [34-82]
SSP5-8.5	77 [63-101]	81 [58-112]	73 [50-109]
SSP5-8.5 low conf	88 [63-160]	90 [58-137]	81 [46-140]

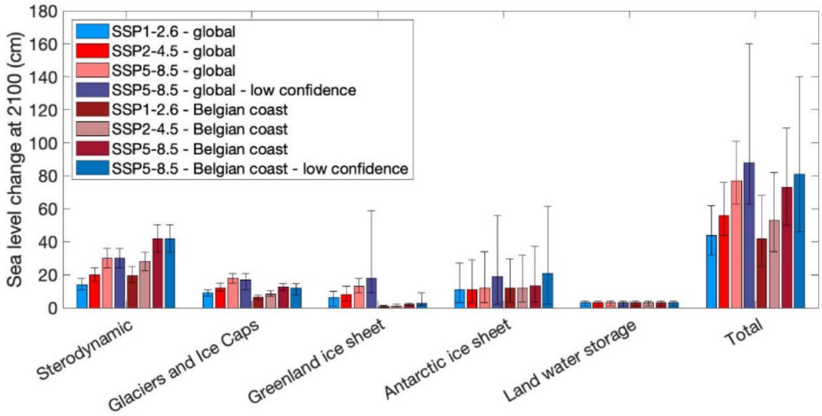


Figure 4 - Comparison between the median values of the different components contributing to global sea-level change and their contribution to regional sea-level change along the Belgian coast for various SSP scenarios. The regional values are calculated according to the 'own processing' method. The whiskers represent the 66% probability interval.

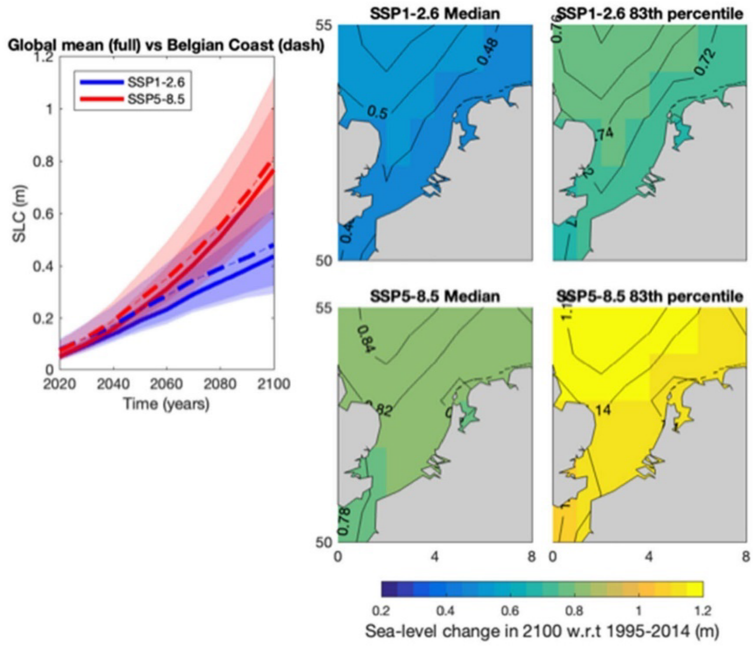


Figure 5 - Regional sea-level changes in the southern North Sea for scenarios SSP1-2.6 and SSP5-8.5 from IPCC AR6 (after the methods described in Fox-Kemper et al., 2021).

4.2 Low confidence projections

The analysis above dealt with the central range of the sea level rise distribution or likely range. However, risk-averse practitioners (e.g., those planning for coastal safety in cities and long-term investment in critical infrastructure) often require information about plausible future conditions that lie in the tails of the sea level rise distribution. These high-end estimates are generally poorly defined, either by the lack of confidence in the processes that lead to such estimates and/or the limited number of models that yield such high-end results and is called deep uncertainty. Deep uncertainty is rooted in the possibility of rapid and/or irreversible ice losses through instability of marine parts of the ice sheet, through the mechanisms of marine ice sheet instability (MISI) and marine ice cliff instability (MICI), both leading to a collapse of the West Antarctic Ice Sheet (WAIS). MISI and MICI both depend on the timing and magnitude of ice shelf disintegration and may lead to multi-meter SLR on century time scales. The SLR contribution of the AIS therefore crucially depends on the behaviour of individual ice shelves and outlet glacier systems and whether they enter MISI (or MICI) for a given level of warming, which remains hard to predict (Pattyn and Morlighem, 2020). The same ice dynamical processes could also occur in some areas of Greenland as long as the ice sheet is in contact with the ocean. In addition, the Greenland ice sheet is susceptible to stronger mass loss from dynamical changes in atmospheric circulation, more frequent extreme melt events, cloud processes, and feedbacks between surface melt and albedo changes (Fox-Kemper et al., 2021).

The IPCC AR6 presented a set of projections under the above assumptions to test the possible effect of additional ice-sheet processes for which there is 'low confidence'. These high-end estimates for global sea level rise are labelled 'SSP5-8.5 low confidence' in Tables 1 and 2 and Figures 4 and 6. For these scenarios, uncertainties are derived from the 17th-83rd percentile range from a p-box including results from a Structured Expert Judgement (Bamber et al., 2019) and MICI (DeConto et., 2021). For this scenario, the 17th-83rd percentile range of global mean sea level rise is 63-160 cm by 2100 but yields up to 50-230 cm when the 5th-95th percentile is considered (Fox-Kemper et al., 2021).

4.3 Projections to 2150

Fox-Kemper et al. (2021) also considered projections up to 2150 relative to 1995-2014. For these longer projections, the individual contributions from the different components are not available and so the regional results are only shown for the 'IPCC AR6' method using the IPCC AR6 Sea Level Projection Tool (Table 2, Figure 6). While ice-sheet processes in whose projection there is low confidence have little influence up to 2100, this is no longer the case up to 2150. The SSP5-8.5 'low confidence' scenario is the only scenario in which a sea level rise of 2.0 m could already be passed by the year 2100 (median is passed around 2150), and 3.0 m before the year 2200 (median ~2190), but this scenario comes with considerable uncertainties resulting from the deep uncertainty of the Antarctic Ice Sheet contribution, and more research is needed to refine these numbers. It is equally noteworthy that the medians of the global mean values for sea level rise hardly differ from their regional values for the southern North Sea, even though the upper bounds (83rd percentile) diverge more (Table 2, Figure 6).

Table 2 - Global and regional (Belgian coast) sea level change at the year 2150 relative to 1995-2014, in cm based on IPCC AR6 sea level projections. *Medium confidence* values represent the median and the *likely* range (>66% probability). *Low confidence* projections are in grey shaded cells, where the uncertainty represents the 17th to 83rd percentile of a p-box.

	GLOBAL MEAN (IPCC AR6)	**BELGIAN COAST (IPCC AR6) (51N;3E)**
Total 2150	**Global**	**Regional**
SSP1-2.6	68 [46-99]	68 [36-109]
SSP2-4.5	92 [66-133]	94 [59-141]
SSP5-8.5	132 [98-188]	133 [86-196]
SSP5-8.5 low conf	198 [97-482]	198 [86-503]

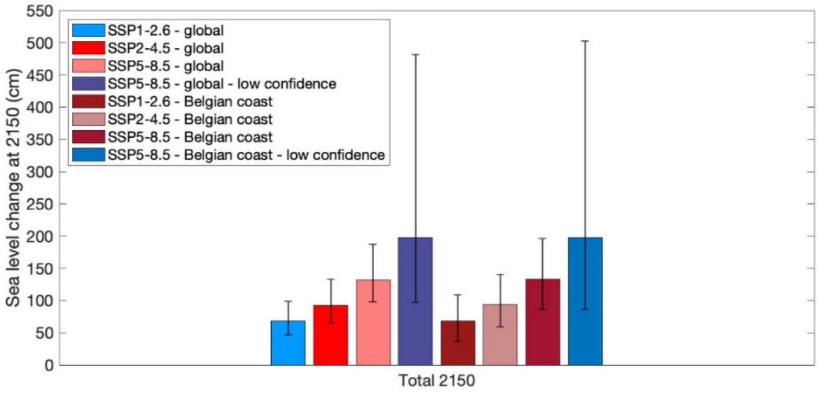
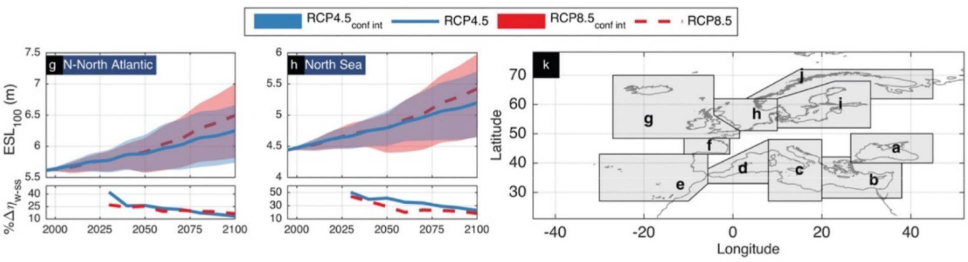


Figure 6 - Median values of the total sea level rise projected for 2150 for various SSP scenarios, both globally and for the Belgian coast, according to the IPCC AR6 method. The whiskers represent the 17th-83rd percentile range.

4.4 Extreme sea levels

Apart from the trend in long-term mean sea level presented above, the scientific literature also provides projections of extreme sea levels for the North Sea. Notably, Vousdoukas et al. (2017) project future changes in 1-in-100 years sea levels (hereafter referred to as Extreme Sea Level, ESL) using a model that incorporates the effects of changes in mean sea level, tides, waves, and storm surges. Their results project the ESL in the North Sea will increase by 35 cm by 2050 under both RCP4.5 and RCP8.5. By 2100, ESL is projected to increase by 75 cm and 98 cm under RCP4.5 and RCP8.5, respectively. The ESL thereby rises considerably faster compared to the long-term mean level of respectively 55 and 78 cm in their study (Figure 7).

Table 3 - Time evolution of the 100-year event extreme sea levels (ESL) (mean sea level [MSL]+tide+waves+storm surges) under Representative Concentration Pathway (RCP)4.5 and RCP8.5. Lines express the ensemble mean and colored patches the inter-model range (best-worst case). The lower plot shows how much of the projected change in ESL100 is attributed to changes in extreme waves and storm surges %Δηw–ss. Europe is divided in 10 geographical regions (see panel k) in order to better reflect the spatial variations of relative sea level rise, here only values for regions g and h are shown as averages over each region (modified from Vousdoukas et al., 2017).



5 Conclusion

Historical sea level rise along the Belgian coast is close to the global mean trend. This is due to a combination of a slightly reduced contribution from the land ice component compared to the global mean with an above-average sterodynamic contribution as well as a small land subsidence owing to ongoing glacial isostatic adjustment, subsidence and groundwater depletion along the coast (which is investigated in Question 2).

Using the IPCC AR6 projections and scaling factors for individual contributions derived from the literature as well as from the IPCC AR6 Sea Level Tool, we find that the likely range of the 21st century regional sea level change along the Belgian coast remains within 20% of the global mean. For the median value this difference is even less than 10% in each scenario.

The barystatic sea level contribution from mass loss of land ice projected for the Belgian Coast is generally found to be slightly below the global mean because of the reduced contribution from the Greenland ice sheet. The ocean sterodynamic contribution in the North Sea, on the other hand, is found to be higher than the global mean. Regional sea level change along the Belgian coast in absence of vertical land motion is projected to remain very close to the global mean value. This quite small difference between global and regional values is expected to remain similar for further time horizons. Only when the Antarctic ice sheet contribution to sea level rise becomes very large, sea level rise along the Belgian coast will diverge more, and be higher, than the global mean.

Changes in the ocean circulation connected to variations in the strength of the meridional overturning circulation contribute significantly to the variability of regional sea level rise. It has the potential to raise local sea level. The combined steric and dynamical ocean contribution has the highest scaling factor for the North Sea close to the Belgian coast. Other risk factors to consider are more frequent storms, higher storm waves (up to 30 cm) and an increased tidal amplitude of up to 10% of the sea level rise magnitude. These factors together cause extreme sea levels to rise faster than the long term mean level.

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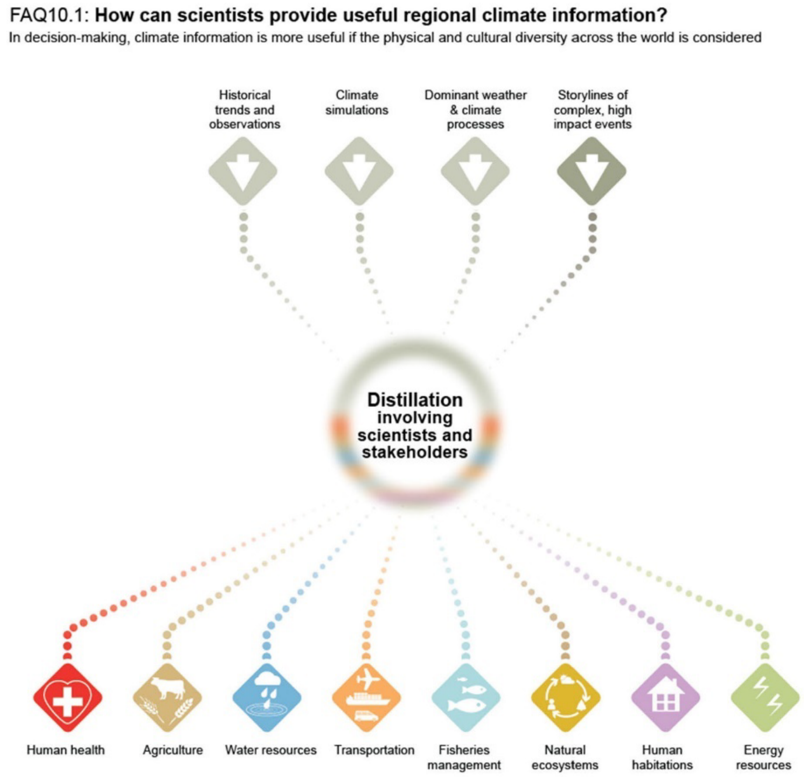
7 Appendix: How can we provide useful climate information at the regional scale?

Constructing useful climate information requires considering all available sources in order to capture the fullest possible representation of projected changes and distill the information in a way that meets the needs of the stakeholders and communities impacted by the changes. For example, climate scientists can provide information on future changes by using simulations of global and/or regional climate and inferring changes in the weather behavior influencing a region. An effective distillation process engages with the intended recipients of the information, especially stakeholders whose work involves non-climatic factors, such as human health, agriculture or water resources. The distillation evaluates the accuracy of all information sources (observations, simulations, expert judgment), weighs the credibility of possible conflicting information, and arrives at climate information that includes estimating the confidence a user should have in it. Producers of climate data should further recognize that the geographic regions and time periods governing stakeholders' interest may not align well with the time and space resolution of available climate data; thus additional model development or data processing may be required to extract useful climate information.



Source: IPCC AR6 (2021), Chapter 10.

Bijlagen 2

5.2 WL2023M21_127_2

Waterbouwkundig Laboratorium Vlaanderen is wetenschap

Memo

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Titel: Zeespiegelstijging voor Vlaanderen – Vraag 2

Datum: 18/05/2022

Auteurs: Michel Van Camp, Kevin Gobron (Koninklijke Sterrenwacht van België); Frank Pattyn (Université Libre de Bruxelles); Philippe Huybrechts, Margaret Chen (Vrije Universiteit Brussel)

Referentie: Van Camp, M.;Gobron, K.;Pattyn, F.;Huybrechts, P.;Chen, M. (2023). Zeespiegelstijging voor Vlaanderen – Vraag 2. Versie 4.0. WL Memo's, 21_127_2. Waterbouwkundig Laboratorium: Antwerpen.

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VRAAG 2 – Question 2: Vertical land motions:

Wat is het belang van bodemdaling in Vlaanderen in relatie tot de verwachte stijging van de zeespiegel?

Wat is nodig om zowel bodemdaling als zeespiegelstijging langs kust en rivieren voldoende nauwkeurig op te volgen?

Wat is effect op overstromingsrisico door bodemdaling terrain?
(*How does land subsidence affect flood hazard?*)

Wat is betrouwbaarheid van de meetreeksen, gegeven een in beweging zijnde omgeving?
(*What is reliability of the measurement series, given a changing environment?)*

INHOUD

1 What is it?

The sea level is rising, and it is a global issue. But the equation governing exactly where the ocean meets the land depends on the land itself (Wöppelmann and Marcos 2016; Hammond et al. 2021). The average long-term trend in the sea level is of 1.7 mm/year along the coast (Ozer et al. 2019). The sea level rise along our coast is partly the result of thermal expansion (steric effect: increase in volume with increasing temperature) and partly the result of the exchange of melting ice on land with the sea (non-steric effect). The melting of the glaciers and land ice in Greenland and Antarctica are especially important for our coast. Until now, it has mainly been the expansion of the seawater that has determined the sea level rise, but in the future the influence of the melting of the ice caps will become increasingly important. Subsidence from aquifer withdrawal, tectonic activity, past and present glacial isostatic adjustment, sediment compaction or surface mass loading cause vertical land motion (VLM) that either amplifies or reduces the threat of sea-level rise. Moreover, correcting tide gauge data for VLM is paramount for both detecting and attributing climate change signals in sea-level records (Wöppelmann and Marcos 2016). Human activity can exacerbate the VLM. This is the case of aquifer or hydrocarbon reservoir depletion or sediment compaction caused by large infrastructures.

Belgium lies on the peripheral bulge of the glacial isostatic adjustment (GIA) and should undergo subsidence of no more than 1 mm/yr. However, this elusive signal remains close to or below the accuracy of current geodetic techniques (Lidberg et al. 2009; Simon et al. 2018; Vestøl et al. 2019). These techniques comprise Global Navigation Satellite Systems (GNSS, of which GPS and Galileo), PSInSAR (Persistent Scatterer Interferometric Synthetic Aperture Radar) and terrestrial absolute gravity measurements. Other expected causes of VLM in Flanders consists in compaction and groundwater depletion, affecting the harbour of Antwerp, the Doel nuclear power plant, or the Flanders plain, for example (Figure 1) (Lebbe 1995; Declercq et al. 2021).

Hence, along the coastline and hinterland, it is important to measure the vertical movements. Let us mention the low-lying Charente basin and Somme valley in France, the Flanders plain in Belgium, or the Netherlands.

1.1 State of current measurements

Given the possible land motion, the tide gauges and the low-lying countries elevation datum must be referenced to an accurate reference frame. Since the 1990s, we have benefited from state-of-the-art geodetic techniques such as first GNSS, later complemented by PSInSAR observations and some repeated absolute gravity measurements. Altogether, these observations provide ever-increasing accuracy and spatial resolution of surface deformation, which allows measuring the vertical movements of coastal regions with respect to the Earth's centre of mass.

Analyses of noise and variability in GNSS data indicate that stations with ca. 10 years or more of measurements provide estimations of horizontal (resp. vertical) velocities with a precision ca. 0.2 mm yr^{-1} (resp. 0.5 mm yr^{-1}) at the 95% confidence level (Wöppelmann and Marcos 2016; Gobron et al. 2021). For 10 years of PSInSAR recordings, a precision of 0.5 mm/yr along the line of sight is expected (Fuhrmann et al. 2015). To some extent, repeated levelling may complement the picture. Those measurements are sparse, both temporally and spatially, and the precision is not better than a few mm/yr (Pissart and Lambot 1989; Camelbeeck et al. 2002; Craig and Calais 2014). However, it may inform on short-scale vertical land movements, providing some information back to the early 20th century.

In Belgium, GNSS stations are typically distant at about 25 km from one another. Such a network density has provided invaluable information on ongoing tectonic processes, from long plate boundaries to the scale of microplates. However, this density is not always sufficient to evidence local man-induced subsidence or, for example, to separate the motion expected in the Eifel volcanic field from the possible rebound caused by intense mining activities in the Lower Rhine Embayment (Harnischmacher 2010; Van Camp et al. 2011; Kreemer et al. 2020; Piña-Valdés et al. 2022).

In 2016, the launch of the European Space Agency's (ESA) Sentinel-1 constellation made global coverage of the Earth with short time baselines possible. These satellites allow monitoring ground motions at unprecedented spatial resolution: since 2016, they sample the whole European continent every 6 days, with a targeted precision of one mm (Torres et al. 2012; Raspini et al. 2018). In an urban environment, one may expect about 100-1000 permanent scatterers per km², down to 1/km² elsewhere (Hansen 2003; Wang et al. 2011; Biswas et al. 2019). Ongoing initiatives, at regional and national levels (e.g., FLATSIM (Form@Ter 2020), Norwegian NGU, BGR Ground Motion Service Germany, Dutch Ground Motion Service), or the European Ground Motion Service (EU-GMS) aim to provide consistent, regular, standardized, harmonized and reliable information regarding natural and anthropogenic ground motion phenomena over Europe and across national borders, with millimetre per year accuracy. However, these providers focus on specific regions or phenomena such as active faults, landslides, magmatic systems, or man-induced subsidence. The user must rely on given processing, which includes spatial filtering. If the plan is mapping at the sub-mm level deformation in northwest Europe, this requires appropriate processing of all available geodetic data. Reconstructing high-resolution, accurate vertical land motion requires adjusting PSInSAR information to reliable GNSS stations.

The accuracy of the vertical land movements inferred from GNSS is currently limited by various instrumental and environmental factors, including the accuracy of the International Terrestrial Reference Frame (ITRF) itself, which is used to express station's positions and velocities. Since 1988, thirteen ITRF versions have been published, starting with the ITRF88 and ending with ITRF2014, that is currently used in operational geodesy and Earth science applications (Métivier et al. 2020). The resulting uncertainty in absolute vertical velocity is at the 1 mm/yr level because of the reference frame realization (Wöppelmann and Marcos 2016). In addition to the uncertainty of ITRF, the uncertainty on the vertical velocities derived from GNSS is also typically about 3–5 times larger than that of the horizontal velocities because of intrinsic instrumental limitations. The sum of these uncertainties hinders the assessment of absolute vertical land movements at the sub-mm/yr level. Yet, assessing these vertical displacements is very important to determine the relative mean sea level variations, which is paramount for coastal hazard assessment.

Because an uplift (subsidence) can cause a decrease (increase) in gravity, monitoring time-variable gravity can also help studying vertical movements. If the gravity rate of change is very small, it shows that neither vertical movement nor any kind of mass change occurs, unless mass changes are exactly compensated for by vertical motion, which is quite unlikely. Using an absolute gravimeter is especially valuable to estimate these gravity changes as there is no instrumental drift and because its measurements are independent of a terrestrial reference frame. Metrologically speaking, it is also advisable to rely on measurements from independent techniques. Within this scope, the Royal Observatory of Belgium undertook yearly repeated absolute gravity measurements in Oostende in 1997 (Van Camp et al. 2011). This station is 950 m away from the tide gauge and 1500 m away from the FLEPOS GNSS receiver. Along the Belgian coastline, there are two other permanent GNSS stations, in Dunkerque and Zeebrugge (Table 1). A few km in the hinterland, we have the stations of Brugge, Veurne and Oostburg. In Oostburg, the stations OOS1 and OOSB are 200 m apart. OOS1 measured from 2003 to 2014, while OOSB has measured since 2015. Probably, Dutch colleagues had to move the station.

Table 1 - Name and coordinates of the gravity and GNSS stations along, or close to, the Belgian coastline. For more details, see the website of the Nevada Geodetic Laboratory http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap.html

Station	**Latitude (N)**	**Longitude (E)**	**Observation period**
Along coastline			
Zeebrugge GNSS (ZEEB)	**51.335**	3.208	2003.3 – 2021.0
Oostende – Gravimeter	51.225	2.922	1996.5 – 2021.8
Oostende GNSS (OOST)	51.233	2.939	2003.3 – 2020.0
Dunkerque GNSS (DUNQ)	51.048	2.367	2015.0 – 2021.0
Dunkerque GNSS (COUD)	51.023	2.374	2007.6 – 2021.0
Stations hinterland			
Oostburg GNSS (OOS1)	51.332	3.495	2003.0 – 2014.8
Oostburg GNSS (OOSB)	51.334	3.499	2014.8 – 2021.0
Brugge GNSS (BRGG)	51.191	3.200	2013.5 – 2021.0
Veurne GNSS (VEUR)	51.070	2.667	2013.5 – 2021.0

1.2 Situation in Belgium

The coastal and alluvial low-lying plains are vulnerable to flooding, sea level rise and other hazards, and yet, these areas are particularly under the pressures from such as urbanization, tourism, agriculture, dredging, waste disposal, engineering works, and increases in greenhouse gas emissions with subsequent effects on sea level rise.

Along the Rivers Scheldt, Rupel and Durme are the lowest lying areas of Belgium. The main issue there is the discharge of superfluous water. In periods of heavy rain and high tides, discharge of surface water is limited, potentially causing severe flooding of the alluvial plains. A better understanding on the possible subsidence mechanisms, that may worsen the problem, will help to improve drainage system with a precise water level control and maintenance of defense structures.

The Belgian coast is a typical coastal plain type, characterized by the alternation of peat and clay deposits, which makes these areas vulnerable. The peat layers represent the onset of the typical cyclic formation of coastal deposits where peat repeatedly occurred into being alternating with the deposition of tidal sediments. The cyclic formation combined with the intercalated peat layers suggested temporary regressive tendencies in the past. The seaward extension of the coastal plain could not be established and most of the evidence is situated offshore. In addition, the beach and possible dune deposits have been reworked continuously since the beginning of the Holocene.

Thus, the potential for preservation of these sedimentary environments is very low in the case of a transgressive coast related to sea level rise and storminess. This observation is even alarming for some parts of the coastal plains without beaches (de Moor 1979; Montreuil et al. 2020). In addition, the altitude of the coastal plains corresponds to the average sea level and the water table almost reaches the surface, which compromises natural drainage and poses a significant problem (Baeteman et al. 1992). In rainy seasons, some areas, and in particular, river Yser, are regularly flooded. Remember also in 2001 the dramatic flood of the Somme river in France (Habets et al. 2010).

The pedology enhances this critical situation: the clay and peat sediments are very sensitive to compaction and therefore coastal plain suffers considerable land subsidence. Although artificial drainage based on pumping lowers the water table, it simultaneously lowers the soil surface and thus increases the risk of flooding. Besides this, pumping also brings the risk of intruding brackish or salt water into the upper part of the phreatic ground water. Better drainage management is crucial in the near future to avoid complete flooding of the area.

In Belgium, most of the polders have supposedly suffered subsidence since Roman times. This induced brook scour and ground water alteration. The mechanisation of agriculture has necessitated the lowering of groundwater tables, which is achieved through drainage and pumping. In addition, overexploitation of groundwater also contributes to the lowering of the water table (Tavenier et al. 1970; Baeteman et al. 1992; Baeteman 2018). The most superficial layers of large parts of the coastal plain consist of clay and peat. Clay, and especially peat, loses considerable volume when dried out. This results in a continuous subsidence of the soil surface, especially in times of drought. The subsidence can reach a few cm/yr (Declercq et al. 2021).

The Uitkerkse Polder nature reserve in Blankenberge is an example of good practice, where wet meadows have been restored for about ten years. At least in this area, further subsidence is probably stopped, while reversal is almost impossible. We can consider this site as a reference to be compared to the exploited polders. In Vlissingen, the subsidence is approximately 0.24 mm/year (Baart et al. 2019). In the De Moeren plain, drainage through ditches about 2.5 m deep and a 7 m deep channel, as well as pumping of groundwater, caused sediment settlement and soil subsidence of at least 1 m (Baeteman 2018). If the subsidence trend can be halted, absolute sea level rise may continue or accelerate, causing severe and permanent damage to low-lying areas. For all these reasons, low-lying areas are vulnerable and prone to a range of disasters, foremost of which is widespread flash flooding.

2 Estimated amplitudes

To quantify vertical land motions using GNSS, we used the position time series processed by the Nevada Geodetic Laboratory (Blewitt et al. 2018) for about 250 stations in and around Belgium. Figure 1 shows GNSS-based vertical land motion estimates for those stations. The epochs of the positions used for the computation of the mean vertical velocities range between 1996.0 and 2021.0. The actual span of each position series varies between 3.0 and 25.0 years, with an average of 11.5 years. The average observation period of all stations is 2008.0 – 2019.5. Table 2 specifies the vertical velocity estimates for 6 stations along, or near, the Belgian coastline. Table 2 also present the vertical land motion rate estimated from the absolute gravimeter in Oostende, which agrees with the GNSS measurements, within the error bars. For both GNSS and absolute gravimetry, velocity estimates are average rates over the observation period.

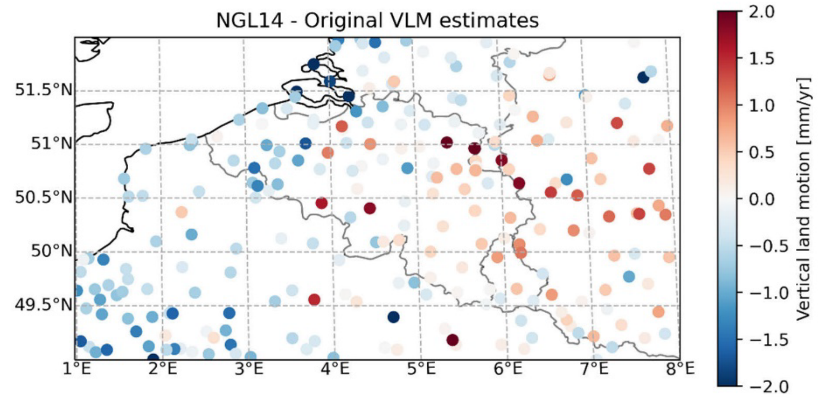

Figure 1 - Vertical velocities estimates for GNSS stations in Belgium and neighbouring countries.

Table 2 - Vertical velocities estimated from GNSS stations along, or close to, the Belgian coastline. Subsidence significant at the 95% confidence level appear in bold font. The gravity rate of change is converted into vertical land movement by using the ratio -2.0 nm/s²/mm. For technical details on the uncertainties, see appendix.

Country	City	Station name	Vertical velocity (mm/year)	Standard deviation (mm/year)
Coastline				
BE	**Zeebrugge**	**ZEEB**	**-0.84**	**0.15**
BE	**Oostende**	**OOST**	**-0.85**	**0.22**
BE	Oostende	Gravimeter	-1.36	1.34
FR	Dunkerque	DUNQ	-0.44	0.56
FR	**Dunkerque**	**COUD**	**-0.87**	**0.17**
Hinterland				
NL	Oostburg	OOS1	-0.39	0.23
NL	Oostburg	OOSB	-0.19	0.30
BE	Brugge	BRGG	0.01	0.23
BE	Veurne	VEUR	+0.09	0.57

Velocity estimates at the coastline report subsidence trends below the level 1 mm/year level. Because of instrumental errors and local processes, the velocity at one GNSS station may not reflect regional vertical land motions. To obtain a regional trend from such pointwise measurements, one must rely on spatial filtering. Figure 2 presents the regional vertical land motion pattern in Belgium obtained by an adaptation of the Robust Network Imaging (RNI) method presented by (Kreemer et al. 2020). We observe a general, but moderate, subsidence pattern in Flanders and uplift trends in Wallonia. Given its wavelength of a few hundreds of km, these phenomena have most probably geological and geodynamical causes (compaction, flexure of the lithosphere due to sediment loading or mantle plum in the Eifel) and are secular phenomena. In West Flanders, the subsidence is at least partly due to groundwater withdrawal and natural compaction of peats (Lebbe 1995). A buoyant Eifel mantle plume possibly causes the uplift in Wallonia (Kreemer et al., 2020).

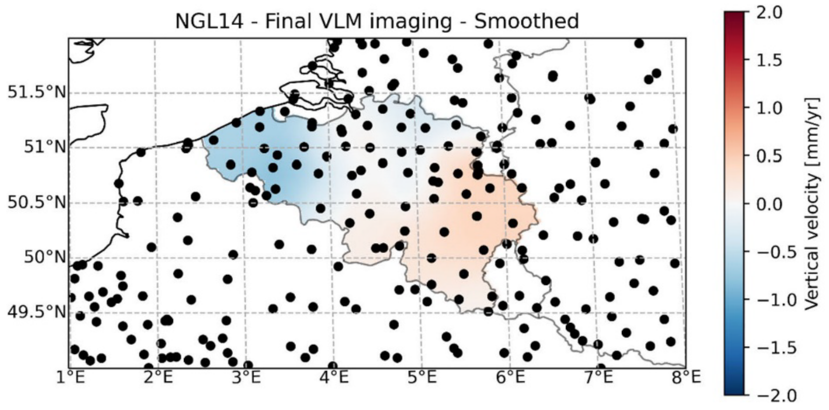

Figure 2 - Regional vertical land motion pattern estimated from the station velocities using the Robust Network Imaging method proposed by Kreemer et al., (2020).

Models predict a subsidence reaching the mm/yr level on the peripheral bulge of the postglacial isostatic adjustment. Figure 3 shows the vertical land motion predicted by the ICE-6G_D model in Belgium (Peltier et al. 2018), which reaches -0.29 mm/yr at the coast.

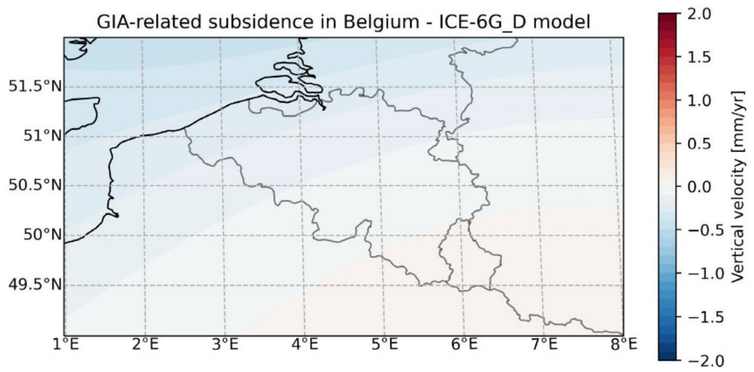

Figure 3 - Vertical velocities in Belgium due to Global Isostatic Adjustment (GIA), as predicted by the ICE-6G_D model (Peltier et al. 2018).

3 Are other analyses required?

The processing of geodetic time series is an ongoing task, the geodetic community aims at mapping 3D motion. With the extension of the time series, the improvement of hardware and computational techniques, and a better knowledge of the instrumental and environmental effects that disturb the observations of land movements, the accuracy of the measurements and the error bars are continuously improved. Moreover, one cannot exclude changes in trends, possibly caused by modifications of human activities or by climate variations. For example, long-term variation in temperature and rainfall could modify the hydrological loading and hence, modify crustal deformation. Last, but not least, the continuous improvement of the international ITRF will further increase the accuracy of the vertical land movements. Of course, all GNSS and ITRF related issues are the responsibility of the international scientific community and fall well beyond the field of a regional or national government. It is rather their responsibility to update regularly, say, every 5 years, the estimates of vertical land motion.

In Belgium, we can combine PSInSAR and GNSS measurements (Declercq et al. 2017, 2021). While PSInSAR allows for a high spatial resolution, it does not ensure accuracy for long-wavelength phenomena and does not provide the full 3D pattern. On the other hand, GNSS stations are much sparer, but they measure continuously the vertical, north-south and east-west positions. This allows much detailed analysis of the noise affecting the geodetic measurements and refers the measurements into the global reference frame ITRF. Combining GNSS and PSInSAR along the coastline, and pursuing the work done by (Declercq et al. 2021) with PSInSAR in Antwerp, one could get insights on local effects that might alias the GNSS series. For example, local subsidence due to water withdrawal, unstable GNSS receivers, or settlement of large infrastructures such as the harbour facilities in Antwerp, as evidenced by Declercq et al. (2021) or possibly, Zeebrugge. Permanent PSInSAR reflectors could be installed in selected locations, to refine the signal. Concurrently, it might be worth installing other GNSS stations, if relevant. This would allow confirming the apparent stability of the low hinterland, as observed at the Veurne, Brugge and Oostburg stations.

Furthermore, some major impacts of a future sea-level rise in coastal and alluvial low-lying areas are permanent inundation, loss of protective zones, increased flooding and saltwater intrusion (Ntegeka et al. 2012; Stark et al. 2017; Baart et al. 2019). A holistic approach of monitoring must be carried out to assess subsidence in Flanders to gain a better understanding on its importance and the relationship with sea level. Monitoring Flanders land elevation over the last 20 years relating to the measured sea level rise and human interventions (water extraction and pumping) would help to gain knowledge on land subsidence mechanisms as well as determining the associated effect of flood risk. Thus, we suggest identifying how the spatial variations of land subsidence of the Flemish coastal and alluvial low-lying plains relate to soil type and shallow subsurface, drainage, water pumping and drilled well exploitation.

When detecting ground deformation, the pending question is attribution: what could be the causes of the detected movements? In the Netherlands, (Kooi et al. 1998) modelled the possible influence of tectonic deformation and flexure of the lithosphere caused by sediment loading. In both cases, it should be at the 0.1 mm/yr level, that is, one order of magnitude lower than the observed movements. The glacial isostatic adjustment effect might be part of the explanation, but the patterns shown here or by (Kreemer et al. 2020; Piña-Valdés et al. 2022) are hardly compatible with the predictions of the GIA models. There are also studies investigating Holocene mean sea level using geological marks (e.g., (Vink et al. 2007)), but this only inform on the relative sea-level, not the absolute vertical land motions.

It remains difficult to attribute a cause to the vertical land motions, apart from well-identified zones where compaction of clay and peats, and anthropogenic activities are clearly identified. Actually, confident, high-resolution geodetic data have only recently provided results that allow raising novel investigation to understand the causes of the observed land motions. The high-spatial resolution PSInSAR data should highly contribute to a better separation of the different sources of deformation.

4 Appendix

4.1 Uncertainties of the GNSS measurements

The velocity estimates and their uncertainties have been obtained by adjusting a functional and a stochastic model to each of the GNSS position time series. To limit biases in the parameter estimation step, non-tidal atmospheric loading displacements were subtracted from the position time series prior to this adjustment using the products provided by the Earth System Modelling team of the German Research Centre for Geosciences at Potsdam (Dill and Dobslaw 2013). To obtain realistic uncertainties, the stochastic model accounts for a linear combination of white noise and power law process, whose parameters were estimated using the Restricted Maximum Likelihood Estimation method (Gobron et al. 2021). The functional model includes long-term linear trends, position offset discontinuities and periodic signals (annual, semi-annual, and terannual signals and draconitic signal of 1.04 year up to the 8th harmonics). The parameters of this functional model and their uncertainties were estimated using the weighted least squares estimator and taking the inverse of the estimated observation covariance matrix as weight matrix. Since the estimated uncertainties account for the presence of time-correlated noise, they reflect the level of non-linearities observed in the position time series.

4.2 Vertical land motions in Flanders

Table 3 - Name and coordinates GNSS stations in the rest of Flanders. For more details, see the website of the Nevada Geodetic Laboratory http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap.html

Station	Latitude (N)	Longitude (E)	Observation period
Other stations in Flanders			
Ieper GNSS (IEPE)	50.849	2.859	2009.6 – 2021.0
Pittem GNSS (PITM)	50.993	3.251	2013.5 – 2021.0
Dentergem GNSS (DENT)	50.934	3.400	1996.0 – 2021.0
Menen GNSS (MENE)	50.781	3.101	2011.1 – 2021.0
Geraardsbergen GNSS (GBGN)	50.769	3.870	2010.0 – 2021.0
Erpe-Mere GNSS (ERPE)	50.923	3.969	2013.5 – 2021.0
Oudenaarde GNSS (OUDE)	50.850	3.619	2013.5 – 2021.0
Zwevegem GNSS (ZWEV)	50.823	3.346	2013.5 – 2021.0
Ruiselde GNSS (RUIS)	51.089	3.341	2013.5 – 2021.0

Sint-Pieters-Leeuw GNSS (LEEU)	50.754	4.254	2011.8 – 2021.0
Hoegaarden GNSS (HOEG)	50.779	4.900	2009.6 – 2021.0
Sint-Truiden GNSS (TRUI)	50.822	5.210	2009.6 – 2015.7
Maasmechelen GNSS (MAME)	50.963	5.696	2004.5 – 2014.5
Tongeren GNSS (TGRN)	50.771	5.478	2003.3 – 2021.0
Houthalen-Helchteren GNSS (HOUT)	51.078	5.374	2003.3 – 2021.0
Diest GNSS (DIES)	50.981	5.049	2004.2 – 2021.0
Aarschot GNSS (AARS)	50.963	4.836	2009.6 – 2021.0
Pelt GNSS (NEER)	51.211	5.473	2009.6 – 2015.7
Mol GNSS (MOL0)	51.183	5.117	2009.6 – 2021.0
Herentals GNSS (HERE)	51.186	4.840	2009.6 – 2021.0
Brecht GNSS (BRCT)	51.353	4.628	2009.6 – 2021.0
Antwerp GNSS (BEZA)	51.307	4.316	2013.0 – 2021.0
Sint-Niklaas GNSS (NIKL)	51.141	4.151	2010.8 – 2021.0
Zelzate GNSS (ZELZ)	51.192	3.805	2013.5 – 2021.0
Gent GNSS (GENT)	51.009	3.709	2013.5 – 2021.0
Buggenhout GNSS (BUGG)	51.013	4.191	2004.2 – 2021.0
Mechelen GNSS (MECH)	51.003	4.470	2013.5 – 2021.0
Bertem GNSS (BER4)	50.862	4.612	2011.8 – 2021.0
Turnhout GNSS (TUR1)	51.313	4.949	2007.8 – 2021.0

Table 4 - Vertical velocities estimated from GNSS stations in the rest of Flanders. Subsidence/uplift significant at the 95% confidence level appear in blue/red bold font.

Country	City (closeby)	Station name	Vertical velocity (mm/year)	Standard deviation (mm/year)
Rest of Flanders				
BE	**Ieper**	**IEPE**	**-0.54**	**0.15**
BE	**Pittem**	**PITM**	**-1.01**	**0.19**
BE	**Dentergem**	**DENT**	**-0.64**	**0.15**
BE	**Menen**	**MENE**	**-1.49**	**0.25**
BE	Geraardsbergen	GBGN	-0.32	0.19
BE	**Erpe-Mere**	**ERPE**	**+1.02**	**0.26**
BE	**Oudenaarde**	**OUDE**	**-1.05**	**0.12**
BE	Zwevegem	ZWEV	-0.54	0.22
BE	**Ruiselde**	**RUIS**	**-2.04**	**0.77**
BE	Sint-Pieters-Leeuw	LEEU	-0.33	0.22
BE	**Hoegaarden**	**HOEG**	**-1.12**	**0.22**
BE	Sint-Truiden	TRUI	-0.06	0.54
BE	**Maasmechelen**	**MAME**	**+5.25**	**0.49**
BE	**Tongeren**	**TGRN**	**+0.64**	**0.18**
BE	**Houthalen-Helchteren**	**HOUT**	**+6.93**	**0.19**
BE	Diest	DIES	+0.08	0.26
BE	Aarschot	AARS	+0.10	0.20
BE	Pelt	NEER	-0.11	0.34
BE	Mol	MOL0	-0.37	0.17
BE	Herentals	HERE	-0.11	0.21
BE	**Brecht**	**BRCT**	**-0.87**	**0.20**
BE	**Antwerp**	**BEZA**	**-1.17**	**0.21**

BE	Sint-Niklaas	NIKL	+0.07	0.11
BE	Zelzate	ZELZ	-0.17	0.27
BE	**Gent**	**GENT**	**-1.70**	**0.18**
BE	Buggenhout	BUGG	-0.39	0.37
BE	**Mechelen**	**MECH**	**+0.91**	**0.28**
BE	Bertem	BER4	-0.12	0.23
BE	Turnhout	TUR1	-0.28	0.23

4.3 Questions sent by MOW-Vlaanderen on June 10, 2022

1) How can it be checked (retroactively and/or from now on) whether the measuring stations of e.g. Vlaamse Banken (tide gauges) are subject to downward or upward movements?

The first possibility would be to interpolate the GNSS series, as shown on Figure 2, but of course, this does not allow to evidence local motions, for example, caused by local subsidence or motion of the monument. If we can find satisfactory reflectors at or close by the tide gauge, it becomes possible to use PSInSAR, but motions of the monument could not be evidenced if there is no reflectors directly connected. Two other reliable methods consist in installing a GNSS receiver or a PSInSAR reflector directly on the tide gauge monument, or to perform repeated levelling to connect tide gauge datum to a well-known benchmark (Wöppelmann et al. 2008).

Retroactively, one may look at PSInSAR data back to the 1990ies. In the future, it is advisable to either install a GNSS receiver at each tide gauge, or to ensure regular connection between geodetic benchmarks and tide gauge datum by performing high-precision levelling.

2) Are there non-linearities in annual vertical velocities for some measuring locations in Flanders?

No, this was checked for each station when adjusting the stochastic and deterministic models. So far, no significant non-linear motion has been detected. Some slow variations may appear, but this is part of the power-law processes belonging to the stochastic model.

3) Can you provide the slides shown during the last meeting in Brussels?

This is sent together with this report.

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