EU Strategy for the Adriatic and Ionian Region
EUSAIR

EUSALP

EUSBSR
EU STRATEGY FOR THE BALTIC SEA REGION

DANUBE REGION strategy

TEDEN SREDOZEMSKE OBALE IN MAKROREGIONALNIH STRATEGIJ
Izola, Slovenija
15. – 17. september 2025

MEDITERRANEAN COAST AND MACRO-REGIONAL STRATEGIES WEEK
Izola, Slovenia
15 – 17 September 2025

Key Oceanographic Conditions for Coastal Defense Design in Slovenia

Vlado Malačič

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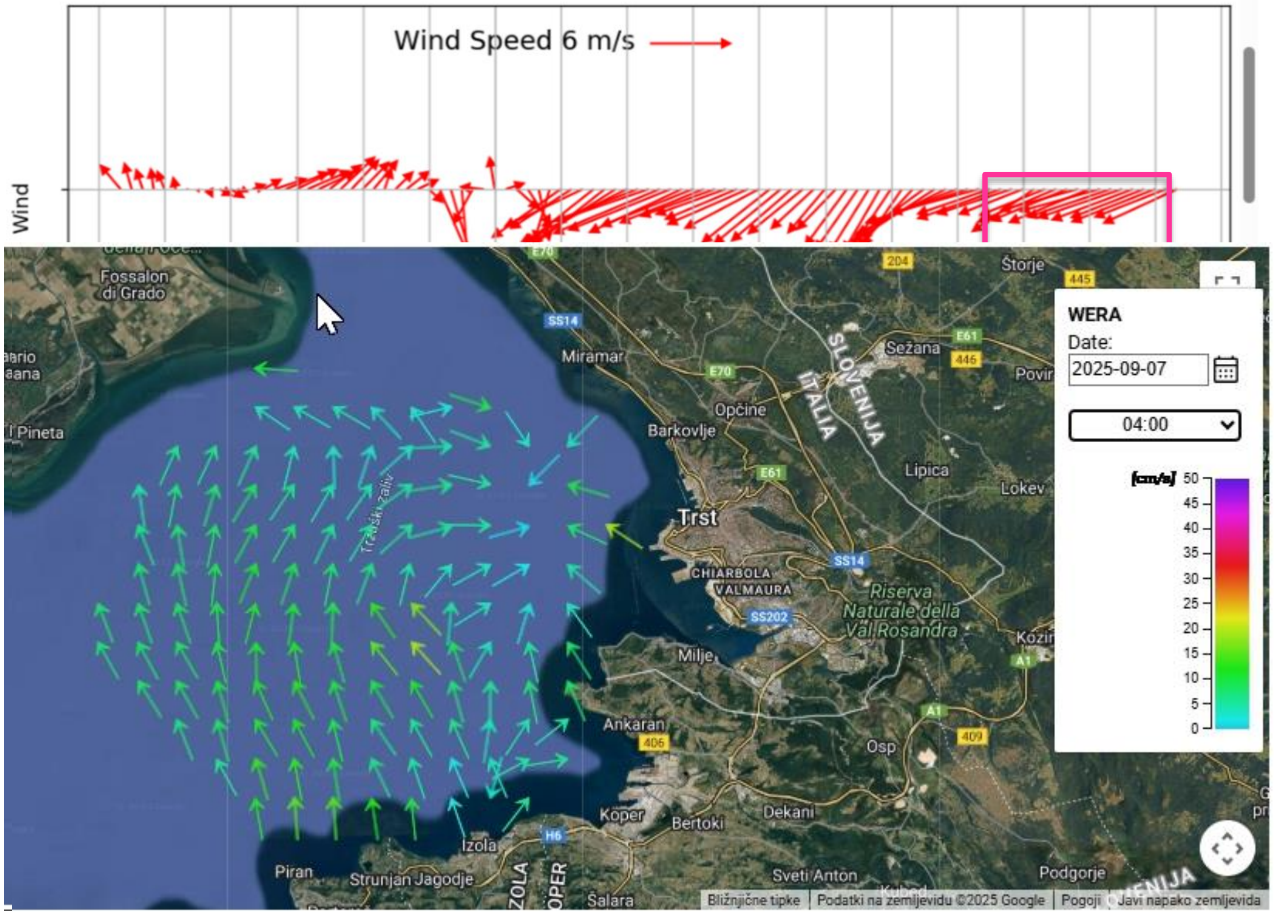
Faculty of Maritime Studies and Transport, Portorož, Slovenia


• Circulation/currents
• (Wind) waves
• Sea-level (SL) rise
Kap. KP, SEA
Vida, MBS-NIB
FMST, UNI-LJ
MBS-NIB

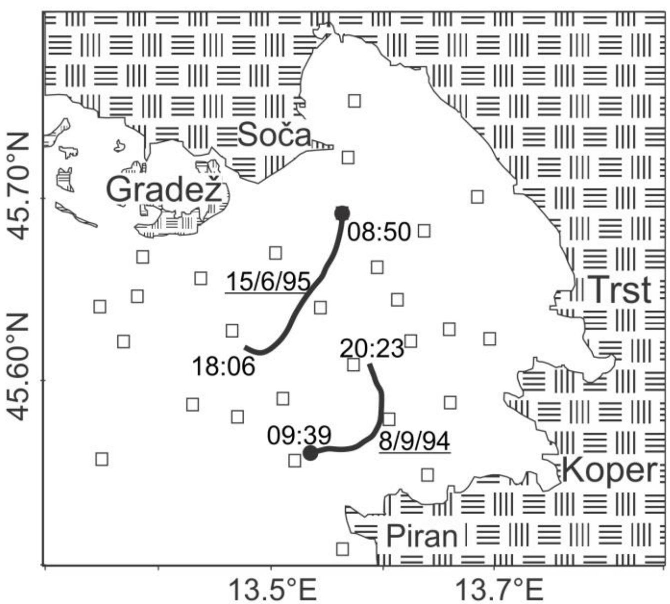
Circulation – measurements



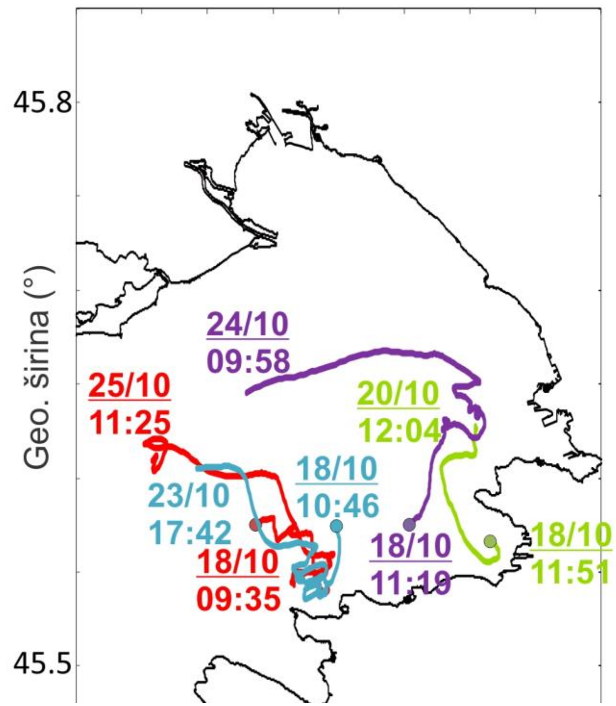
http://www.nib.si/mbp/en/oceanographic-data-and-measurements/buoy-2/new-vector-plots

http://www.nib.si/mbp/en/oceanographic-data-and-measurements/other-oceanographic-data/hf-radar-2

Circulation – measurements

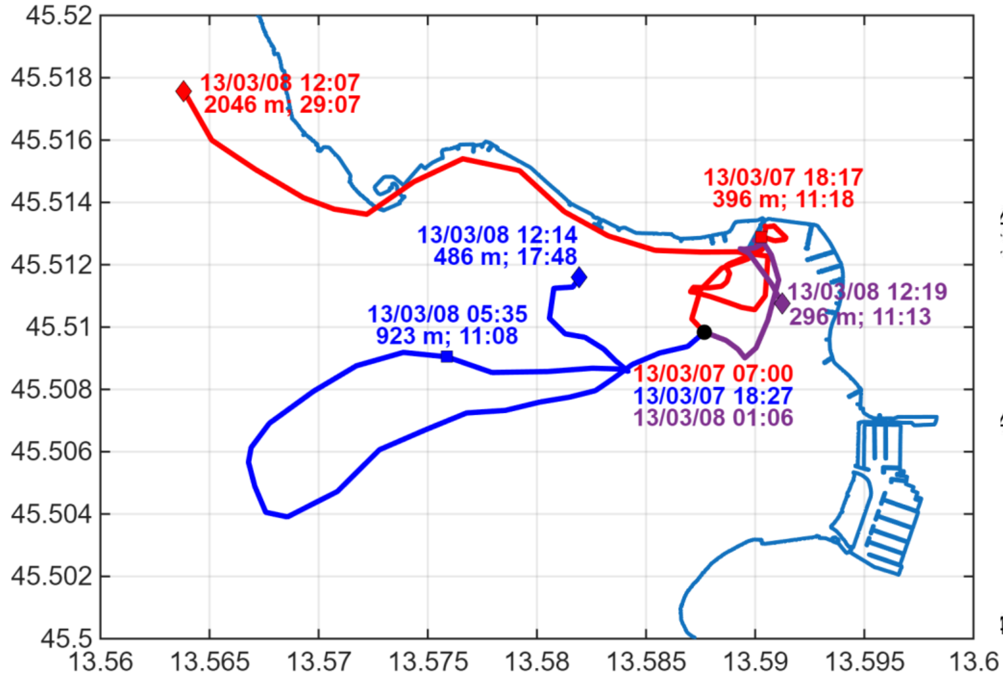


Malačič, Celio, & Naudin, 1999: 'Paloma', Proc. Portonovo.

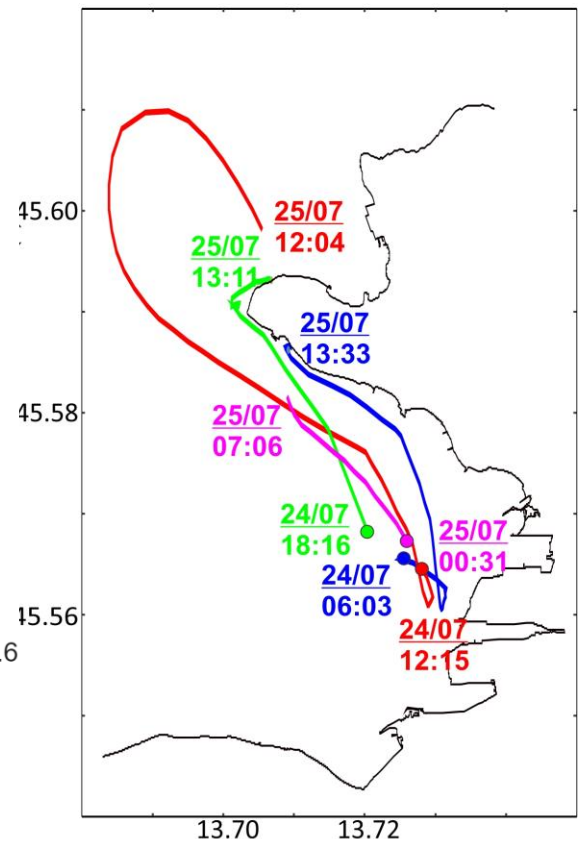


Gerin et al. 2013. ‚Tosca', OGS Rep. Rel. 2013/36 OCE 19 MAOS

Circulation-measurements

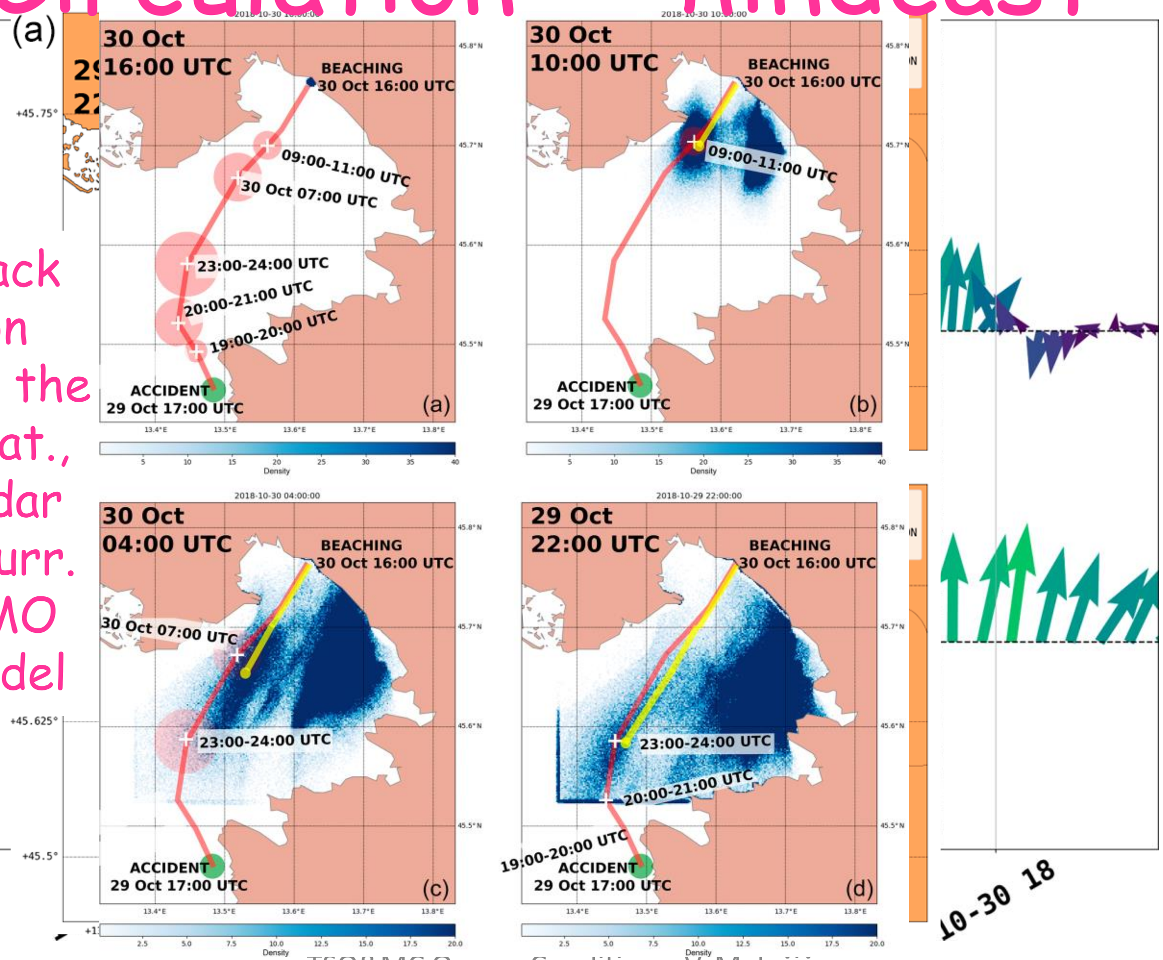


Drifters, Bay of PI, 7-8 March 2013
clement weather



Drifters, Bay of KP, 25-26 July 2013
clement weather. Malačič, 2019, Slov. matica

Circulation – hindcast

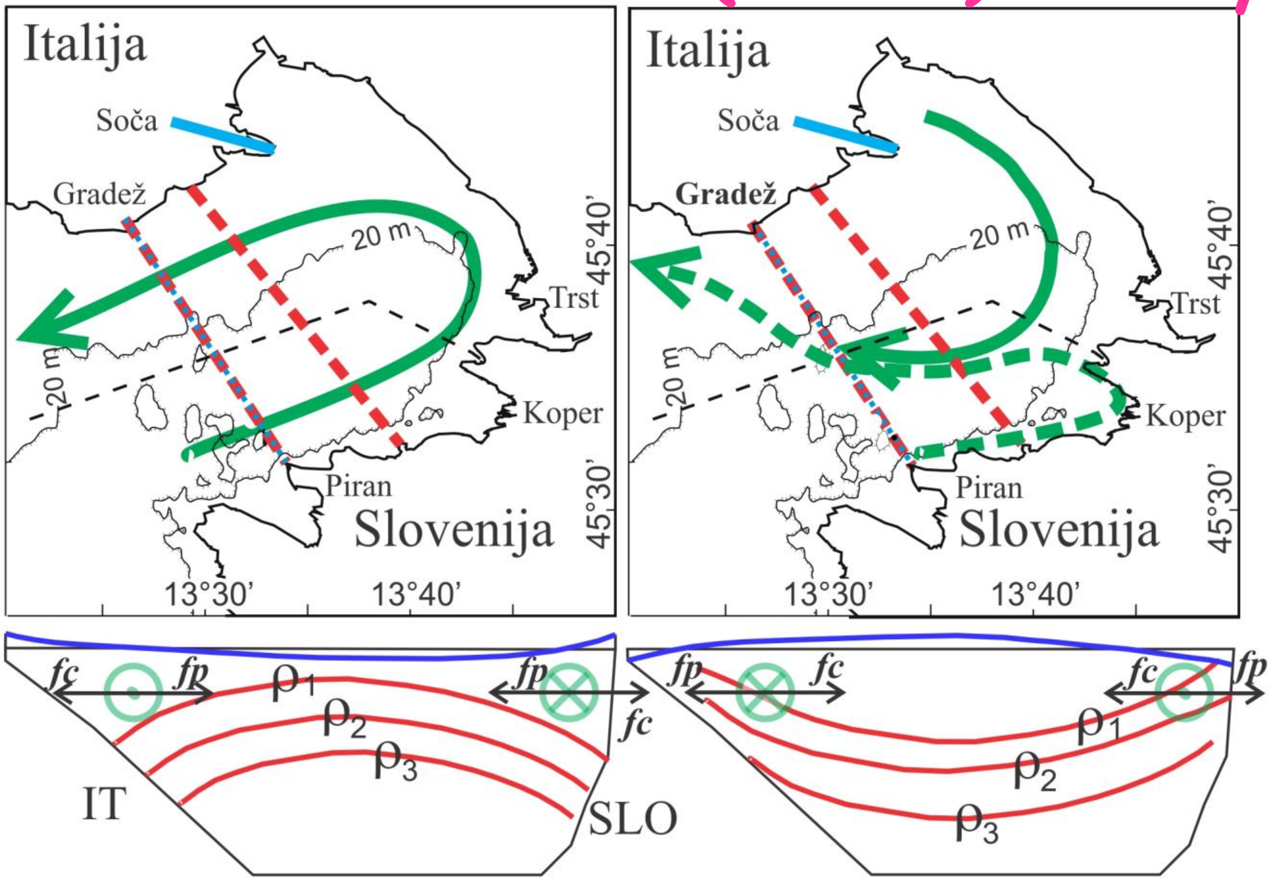


Temporal back propagation (yellow) from the beaching locat., using HF radar measur. of curr. Aladin&NEMO forecast model

$$\frac{d\boldsymbol{r}_p}{dt} = \boldsymbol{u}_c + \boldsymbol{I}_p + \boldsymbol{u}_s$$

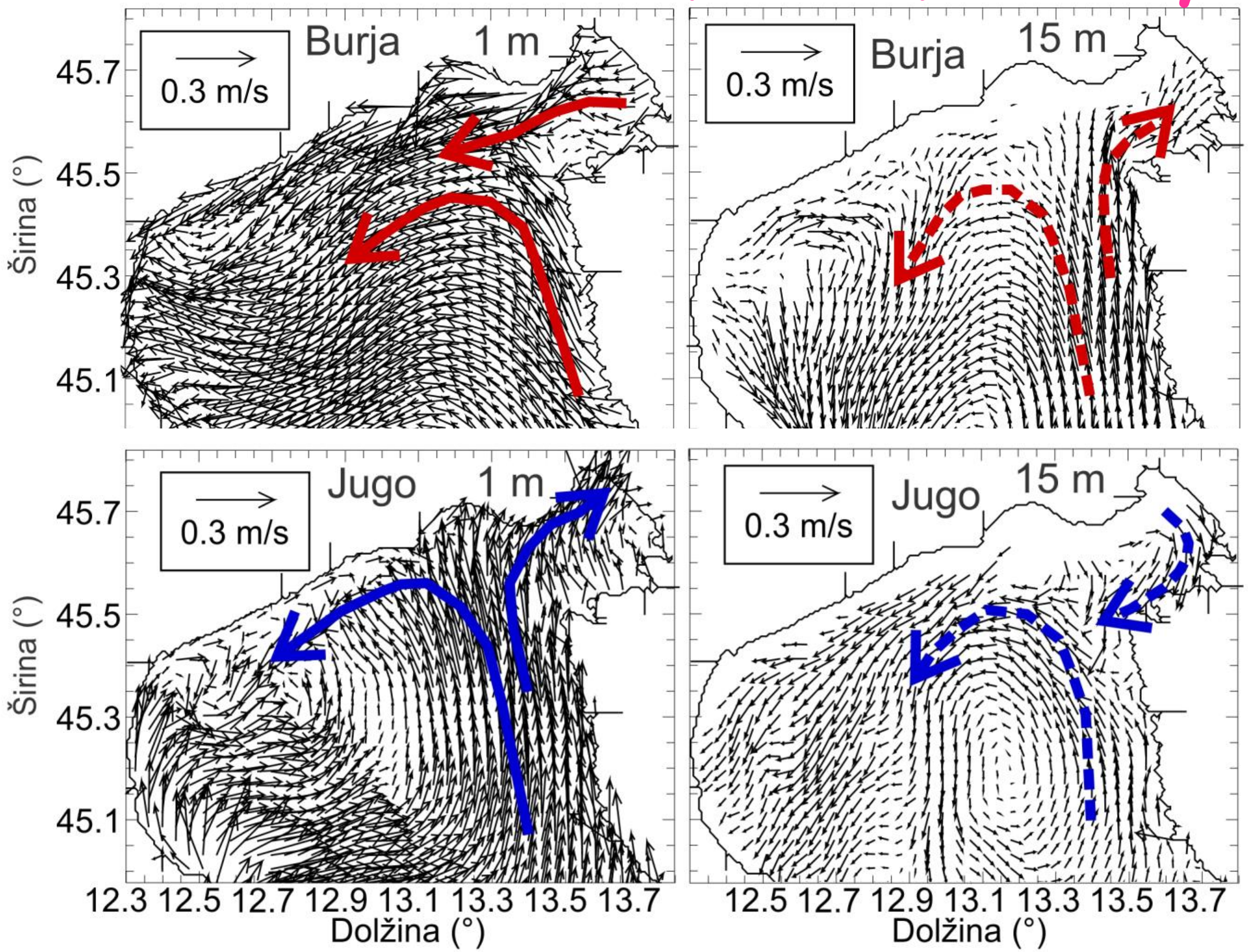
Ličer et al, Nat. Hazards Earth Syst. Sci., 2020.

Circulation – (num.) analysis



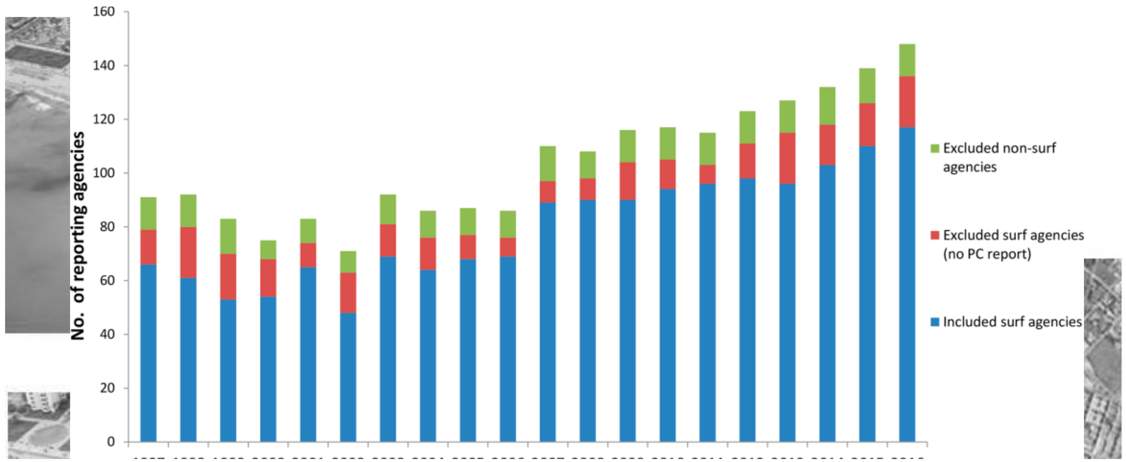
Malačič&Petelin, JGR, 2009.

Circulation – (num.) analysis



Malačič et al, JGR, 2012.

Circulation –rip currents

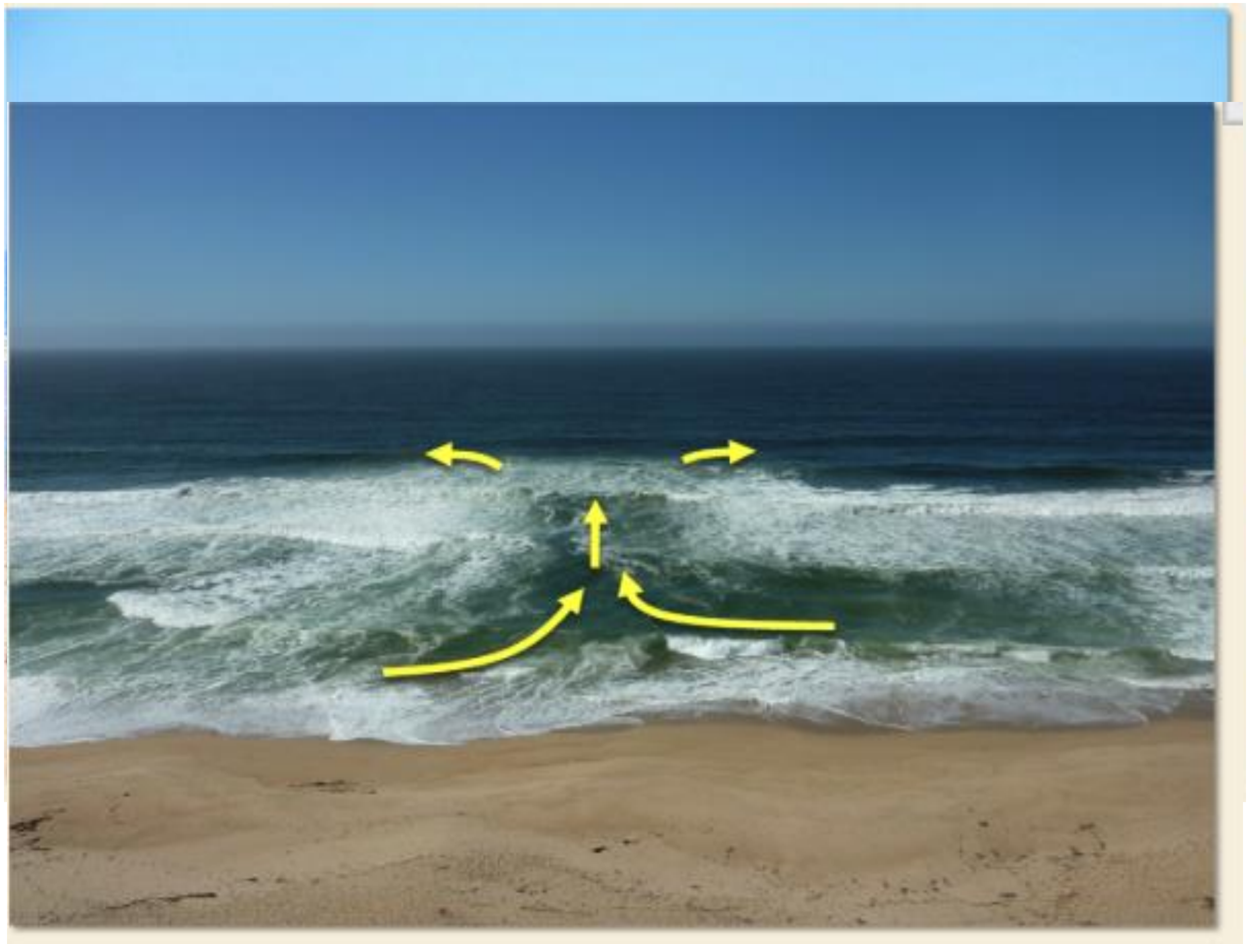


Brewster et al. Nat. Hazards Earth. Sys. Sci., 2019

Rescues by region

Region	All	Rip current	Surf	Scuba	Other
East Coast	233 167	175 572 (75.3)	50 135 (21.5)	227 (0.1)	7 233 (3.1)
West Coast	608 041	514 935 (84.7)	65 349 (10.7)	4288 (0.7)	23 469 (3.9)
Gulf Coast	15 154	11 876 (78.4)	3157 (20.8)	16 (0.1)	105 (0.7)
Hawaiian Islands	47 191	37 632 (79.7)	7262 (15.5)	150 (0.3)	2147 (4.5)
Total	903 553	740 015 (81.9)	125 903 (13.9)	4681 (0.5)	322 954 (3.6)

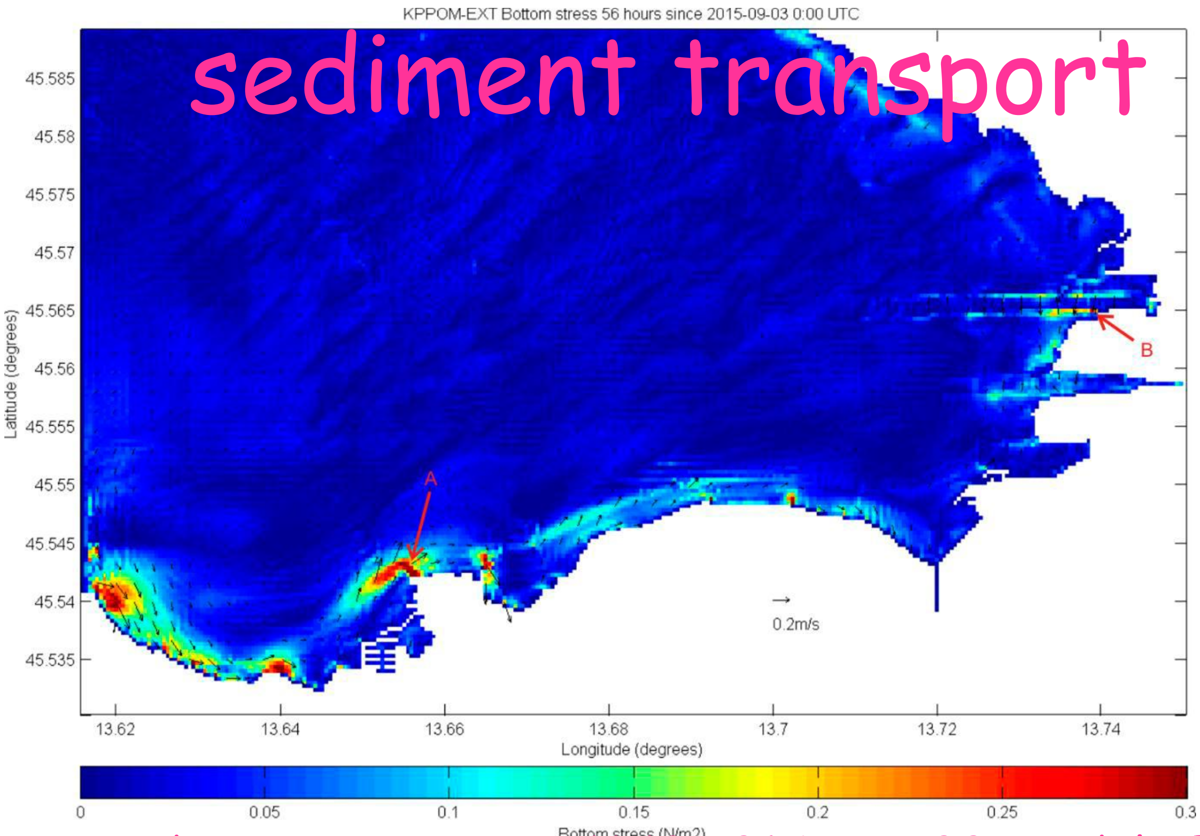
Circulation – rip currents?



https://www.scientificamerican.com/article/why-hurricanes-like-erin-trigger-rip-currents-hundreds-of-miles-away/

NOAA, U.S. rip current risk map for August 18-19, 2025

Circulation – bottom stres => sediment transport



Bottom stress due to currents on 11.10.2015 at 8:00, model KPPOM-EXT (bora, compen. currents). Orlando-Bonaca et al. 2015. NIB Rep. 156 for the MSFD.

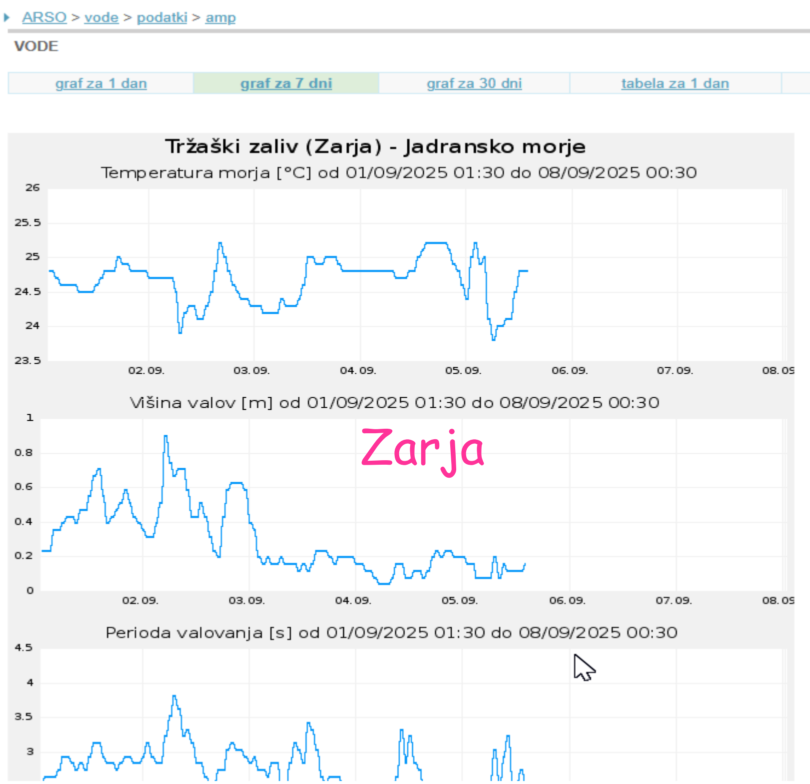
Circulation/currents – conclusions

- The currents are mostly weak (< 0.1 m/s), apart from windy episodes in which they can reach 0.5 m/s. They affect the coastal structures through scour formation and the associated sediment transport.
- The (non-linear) interactions of currents with (wind) waves can be much more dangerous, especially surge waves and rip currents.
- Surge waves (duration of minutes/hours) are known, while rip currents have not been recorded in this area.

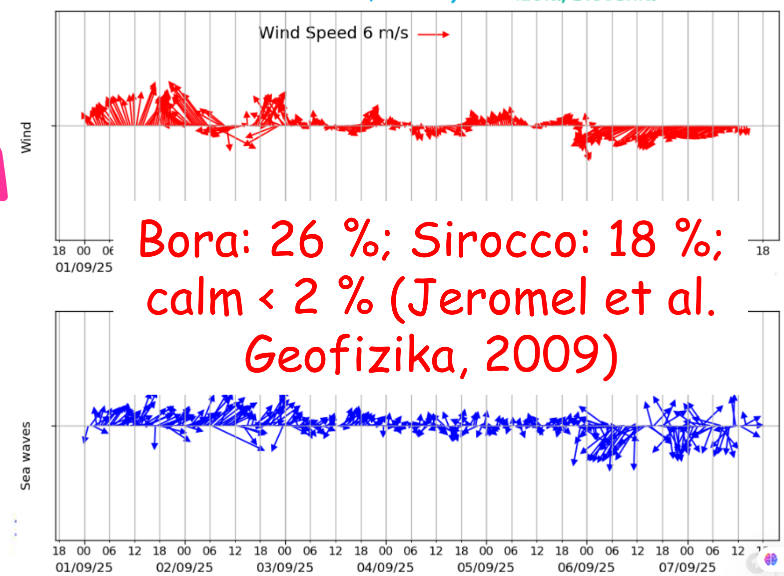
Waves - measurements

Bottom stress due to currents on 11.10.2015 at 8:00, model KPPOM-EXT (bora, compen. currents). Orlando-Bonaca et al. 2015. NIB Rep. 156 for the MSFD.

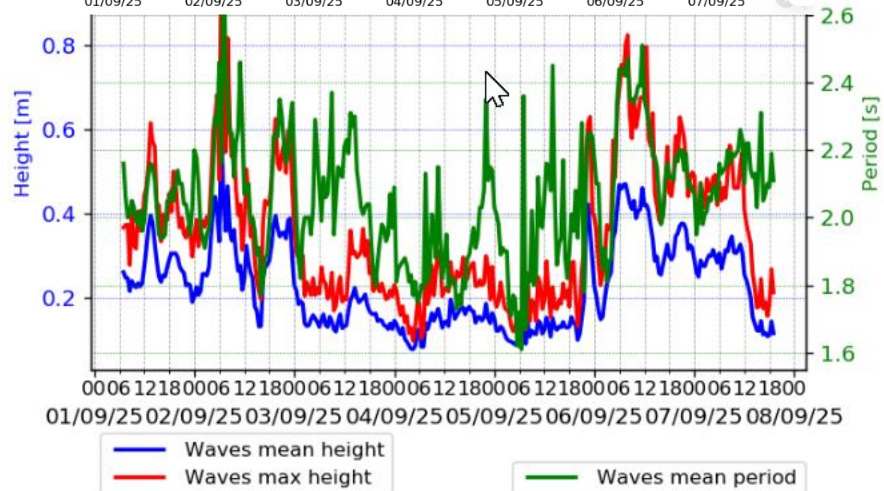
Waves - measurem



https://www.arso.gov.si/vode/podatki/amp/H9420_g_7.html



Bora: 26 %; Sirocco: 18 %; calm < 2 % (Jeromel et al. Geofizika, 2009)



http://www.nib.si/mbp/sl/oceanografski-podatki/buoy-2/novi-skalarni-grafi

Waves - measurements

$\max\langle W \rangle$ = 22.4 m/s;
$\max(W_{max})$ = 32.9 m/s

Here we present the ten strongest wind gusts measured at the oceanographic buoy Vida near Piran from May 2008 onwards and where data quality control was taken into account. The wind is measured in half-hour intervals and the sampling frequency is 10 Hz (measurements every 0.1 s).

date and time end	gust speed [m/s]	gust direction [°]	mean speed [m/s]	mean direction [°]
07.02.2012 20:30	32,9	55,4	22,4	51,8
06.02.2015 06:30	32,2	65,5	21,6	65,5
02.03.2011 08:30	30,8	58,4	21,4	70,0
08.02.2012 03:00	30,7	49,1	20,9	54,4
01.03.2011 21:00	29,9	71,6	20,2	63,2
10.03.2010 09:00	29,9	67,5	22,1	69,9
05.02.2015 23:30	29,8	72,7	22,5	73,5
17.01.2017 22:00	29,3	52,8	20,4	61,6
04.02.2012 03:00	29,0	51,1	20,4	49,2
18.01.2017 07:00	28,9	61,4	20,5	59,7

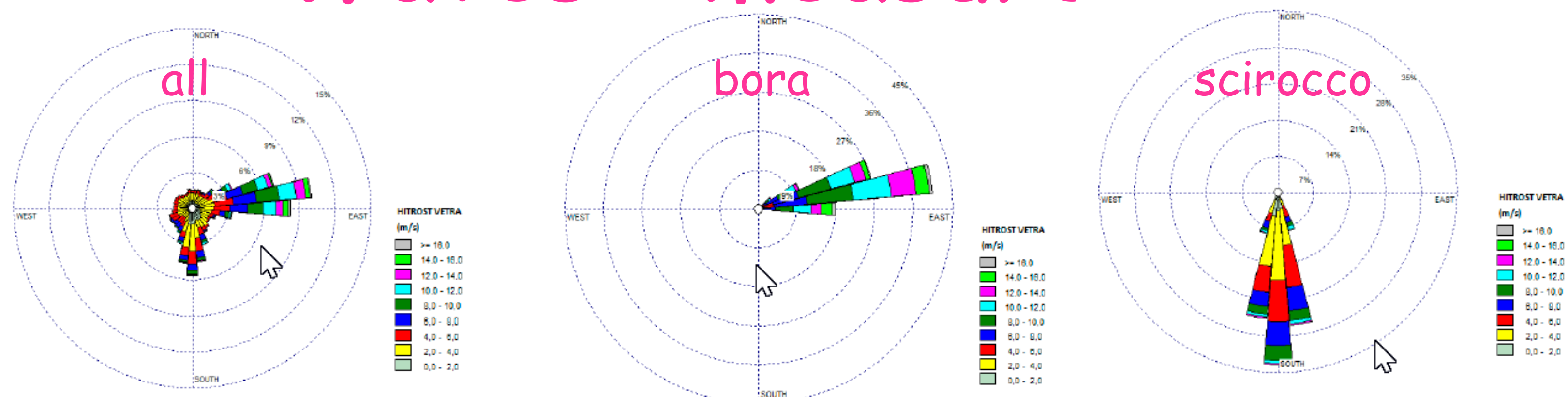
Highest waves (higher than 2 m) from 2008 onwards

Date and time of measurement	wave height [m]	maximum wave height [m]	mean direction [°]	mean period [s]
04.02.2012 05:00	2,4	4,8	40,0	4,4
10.02.2012 23:30	2,4	4,3	39,0	4,7
10.03.2010 07:30	2,4	4,2	46,9	4,7
02.03.2011 10:00	2,4	4,2	37,3	4,6
06.02.2015 04:00	2,2	4,1	51,4	4,5
03.02.2012 15:00	2,2	3,9	39,9	4,4
01.03.2011 19:00	2,4	3,8	44,7	4,7
18.01.2017 05:30	2,2	3,8	38,0	4,4
11.02.2012 01:00	2,3	3,8	34,1	4,4
17.01.2017 13:30	2,1	3,8	41,2	4,3

$\max(H_S)$ = 2.4 m;
$\max(H_{max})$ = 4.8 m
T = 4.4 s

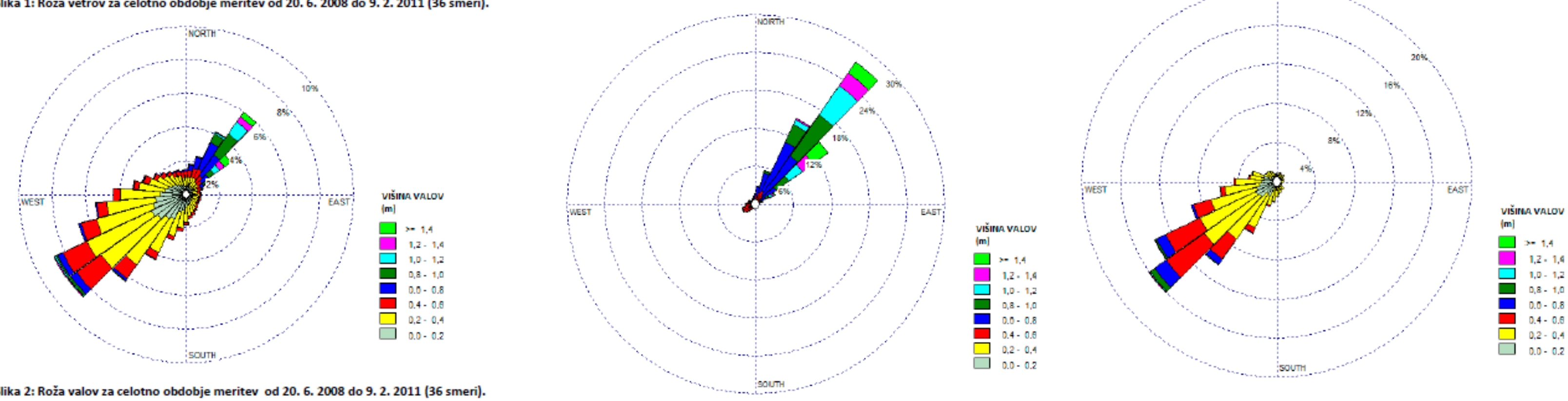
http://www.nib.si/mbp/en/oceanographic-data-and-measurements/buoy-2/extreme-values-2

Waves - measurements



Slika 1: Roža vetrov za celotno obdobje meritev od 20. 6. 2008 do 9. 2. 2011 (36 smeri).

Winds

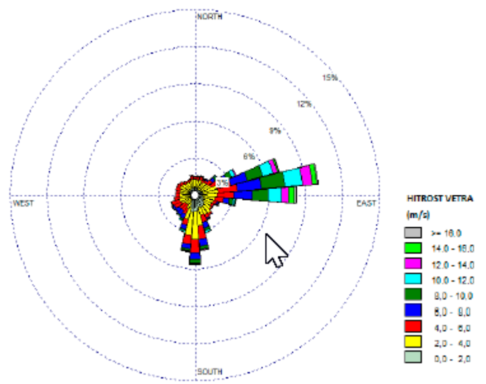


Slika 2: Roža valov za celotno obdobje meritev od 20. 6. 2008 do 9. 2. 2011 (36 smeri).

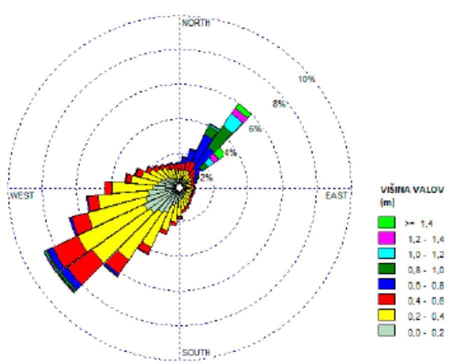
Waves

Hladnik V. & Malačič V. 2011. NIB rep. 129

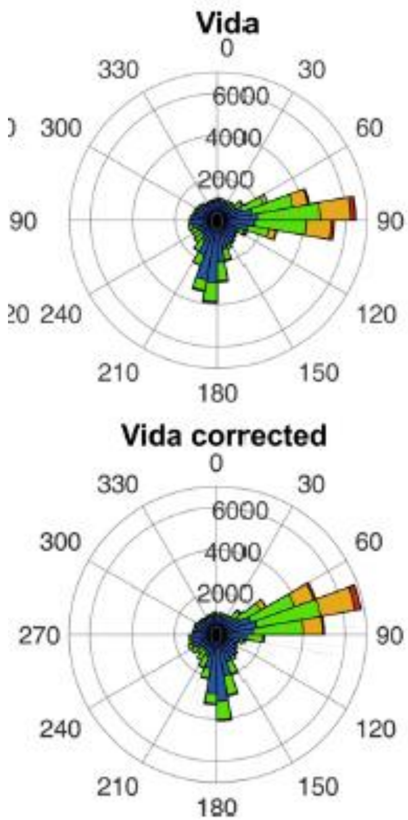
Waves - measurements



Slika 1: Roža vetrov za celotno obdobje meritev od 20. 6. 2008 do 9. 2. 2011 (36 smeri).



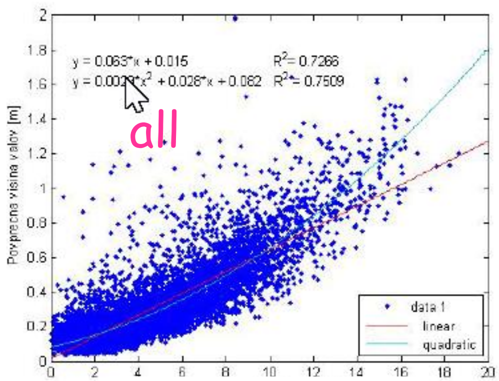
Slika 2: Roža valov za celotno obdobje meritev od 20. 6. 2008 do 9. 2. 2011 (36 smeri).

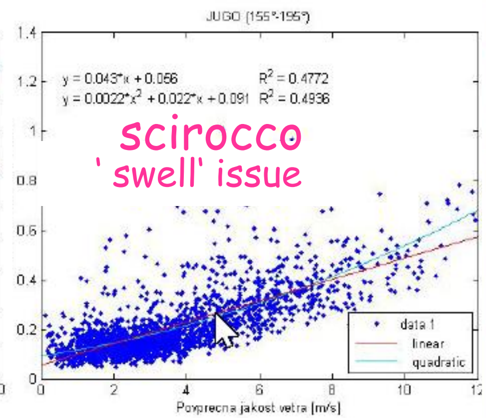


Malačič, 2019 JAOT

Waves - measurements/modeling

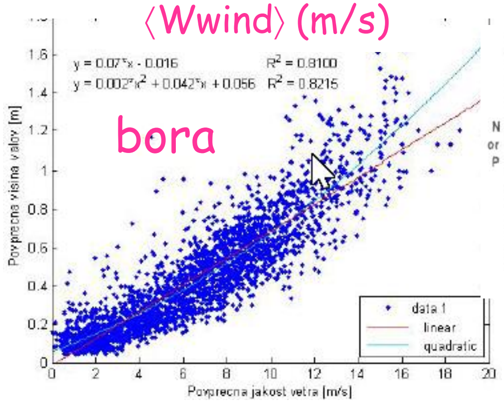
⟨Hwave⟩ (m)

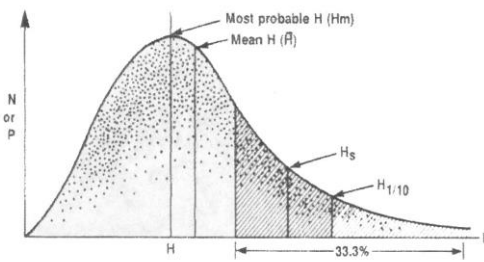




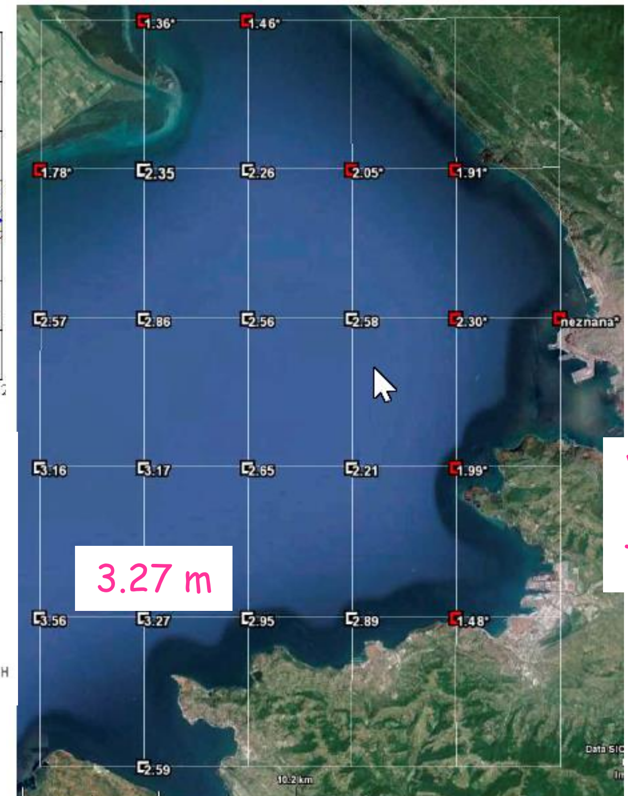
⟨Wwind⟩ (m/s)

⟨Hwave⟩ (m)





https://www.vos.noaa.gov/MWL/apr_06/waves.shtml;
Bretschneider, 1964



Slika 45: Prikaz značilnih višin valov s povratno dobo 100 let v metrih. Točke z * oziroma z rdečimi

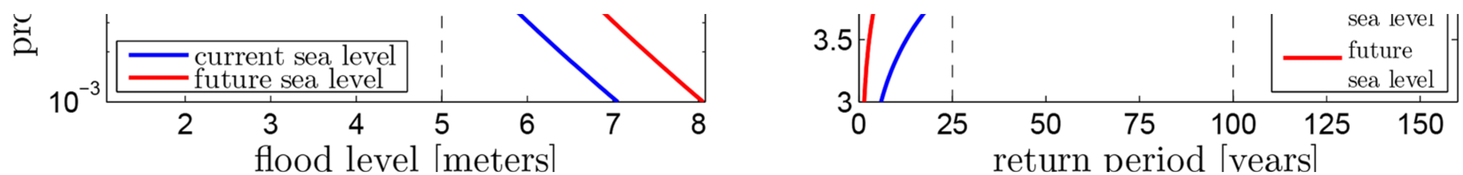
WAM model
H_S (m)
T_{ret} = 100 yr

Kavčič J. & Malačič V., 2008, Rep. NIB 102

Gartner M. B. Sci. Thesis 2014. FCGE, UNI-LJ (superv. Žagar, D., cosuperv. Ličer, M., Jaromel, M.), 120 pp.

Waves & SLR - modeling

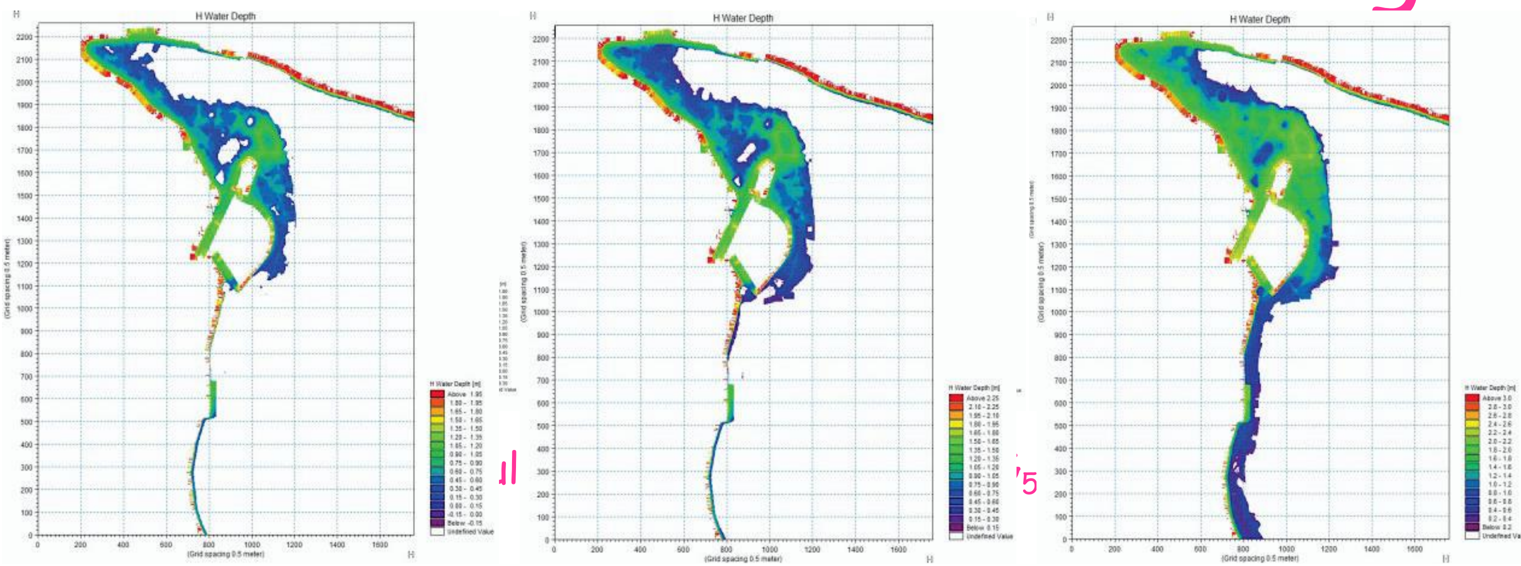
Global sea level is currently rising at ~ 3–4 mm/yr, is expected to accelerate due to ocean warming and land-based ice melt. Global-scale estimates of increased coastal flooding due to sea-level rise have not considered elevated water levels due to waves => underestimate the potential impact. Extreme value theory combines sea-level projections with wave, tide, and storm surge models. Regions with limited water-level variability (Tropics), will experience the largest increases in flooding frequency. The 10 to 20 cm of sea-level rise will more than double the frequency of extreme water-level events in the Tropics.



1 m increase in SL increases the frequency (A) and lowers the return period (B) of the 5m-flood level. The steeper the probability distribution in A, the flatter the return time curve in B, i.e., the greater the increase in frequency and the reduction in return time. Regions with lower variability in flood level will experience larger increases in flooding frequency under SLR.

Vitousek et al- 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. Sci. Rep. (Nature) 7, 1399

Waves/floods – modeling



Model results MIKE 21 (G_{10}, G_{100} in G_{500}) for Piran (later G_{10} -> H_{10})

Centa M., Peček M., Đurović B. Gosar L. Zupančič G. 2014. Izdelava kart poplavne nevarnosti in kart razredov poplavne nevarnosti za dve območji pomembnega vpliva poplav v R. Sloveniji. (Flood hazard maps and flood hazard classification maps for two regions with significant flood impacts in R Slovenia). Report IzVRS (Institute for Water of the R Slovenia), p. 39 + 15 add.

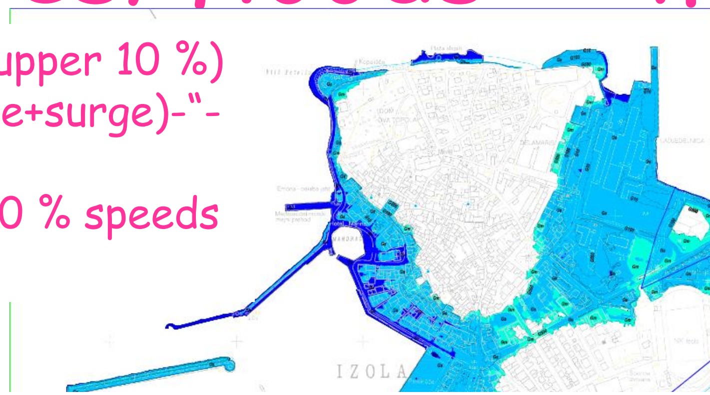
Waves/floods – modeling

Charts of annual (blue) and extreme (yellow) floods (Kolega N., 2005)

Kolega N., 2005. Slovenian coast sea flood risk. Acta geogr. Slov. 46 (2) 143–169. From Centa et al. 2014. Rep. IzVRS.

Waves/floods – modeling

H_{10} = Sea-level height (upper 10 %)
T_{10} = Tidal gauge SL (tide+surge)-"-
W_a = wave range
W_2 = winds with upper 50 % speeds (return period 2 yrs)



$H_{10} = T_{10} + W_a(T_{10},W_2)/2$
$H_{100} = T_{100} + W_a(T_{100},W_2)/2$
$H_{500} = T_{500} + W_a(T_{100},W_{50})/2$

Hidravlična študija visokih vod na območju občine Izola – za OPVP 41-Izola

vir: 3510

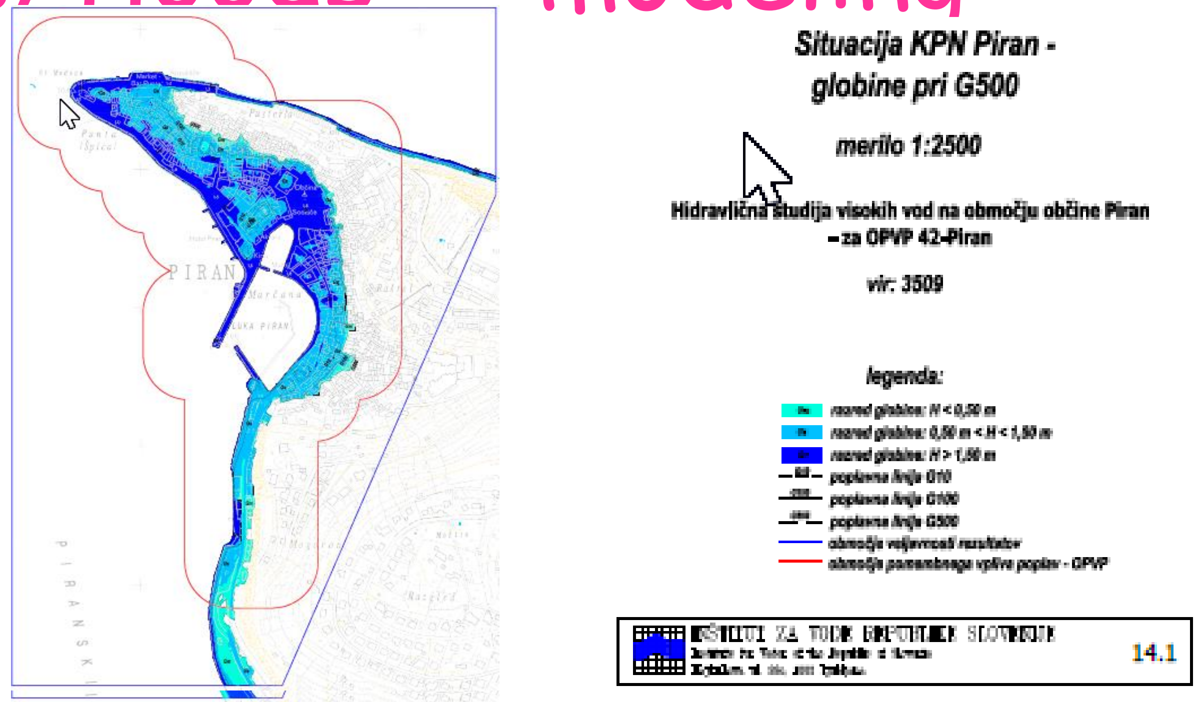
legenda:

URL RS 60/70; 'Pravilnik': gladina G_{10} (H_{10}) je vrednost višine gladine morja, določena … z vsoto vrednosti višine gladine morja zaradi plimovanja P_{10} (T_{10}), ki je v določenem letu dosežena/ presežena z verjetnostjo 10% (višina plime 10 letne povratne dobe), in zaradi morskega vala (Val (W_a)), ki je v določenem letu dosežena/presežena z verjetnostjo 50% (višina vala 2 letne povratne dobe (vetra, W_2)). Fortunately, NOT only tides, but tides with surge (SL, Rep. p. 14)!

Izola: Lines, flooding areas and depths for H_{10}, H_{100}, H_{500}

Centa M., Peček M., Đurović B. Gosar L. Zupančič G. 2014. Report IzVRS (Institute for Water of the R Slovenia).

Waves/floods – modeling



Piran: Lines, flooding areas and depths for H_{10}, H_{100}, H_{500}

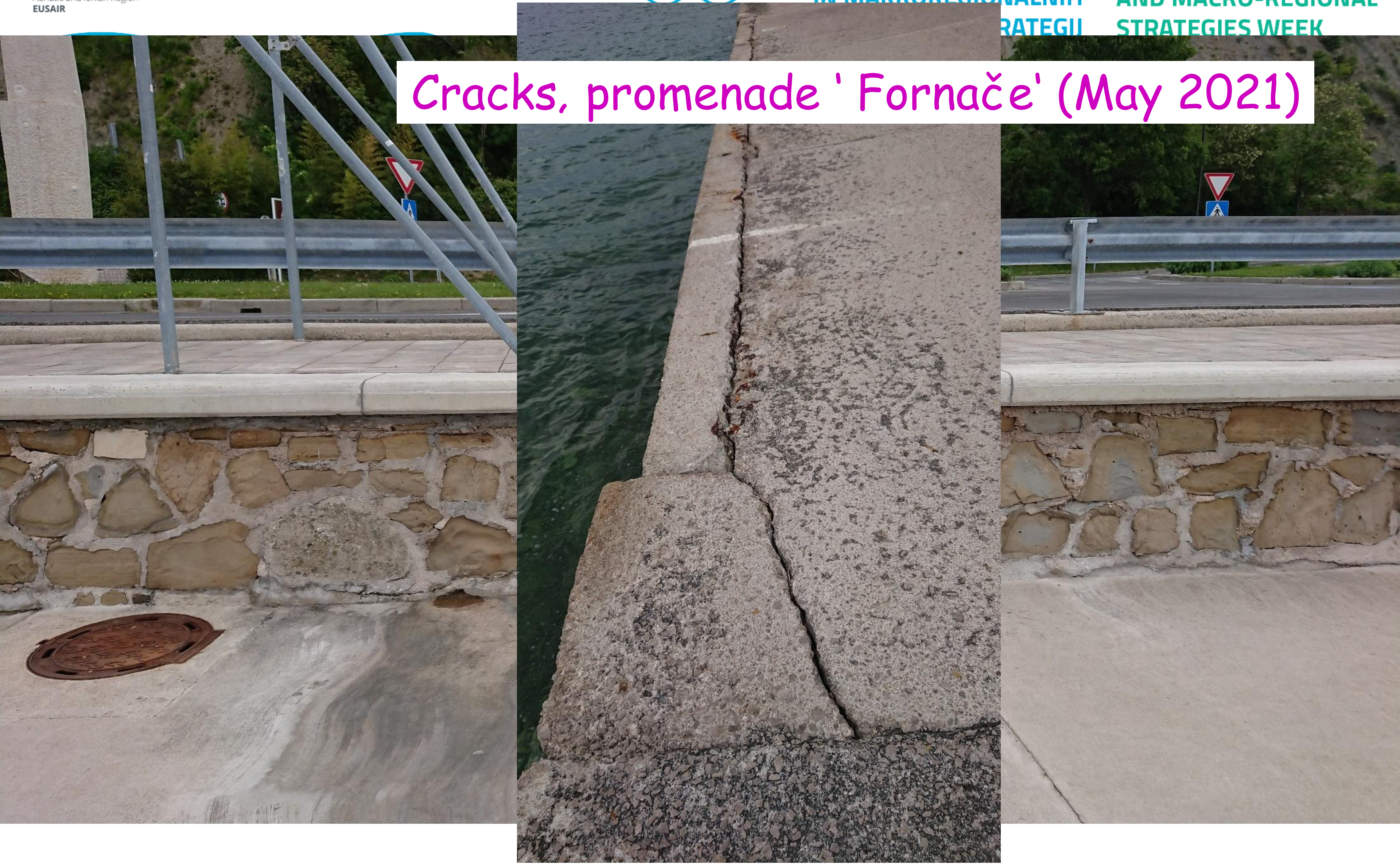
Centa M., Peček M., Đurović B. Gosar L. Zupančič G. 2014. Report IzVRS (Institute for Water of the R Slovenia).

Constr. works 'Piran gate' in front of MBS-NIB feb-maj 2016

Nine years after (Sep. 2025): 'it looks well'

Constr. works: promenade 'Fornače' (Jan 2020)

Cracks, promenade ' Fornače' (May 2021)



Cracks? Promenade 'Fornače' (Sep. 2025)

25

Waves – conclusions

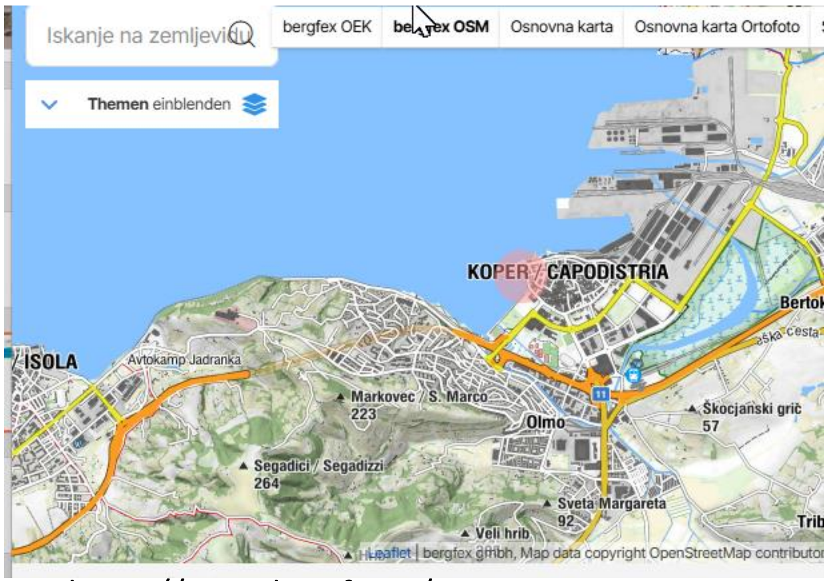
- The Gulf of Trieste (GT) is a shallow (< 25 m) landlocked gulf and the largest waves coming from the northern Adriatic break before reaching the GT.
- From simulations: H_S < 3.3 m (H_{max} < 6.6 m) with T_{ret} = 100 years. Measured $(H_S)_{max}$= 2.4 m; $(H_{max})_{max}$ = 4.8 m.
- While the prevailing winds (Bora/Burja and Scirocco/Jugo) are almost orthogonal, the waves caused by them at the southern entrance of the GT are almost oppositely directed.
- The damaging effects of the waves are felt on the 'exposed' parts of the coast: the tip of the Piran headland, the Piran-Portorož promenade, the coastline around Izola and between Izola and Piran.

Storm surge – definition

- *Storm surge* is the abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide. The surge is caused primarily by a storm's winds pushing water onshore. The amplitude of the storm surge at any given location depends on the orientation of the coast line with the storm track; the intensity, size, and speed of the storm; and the local bathymetry.
- *Storm tide* is the total observed seawater level during a storm, resulting from the combination of storm surge and the astronomical tide. Astronomical tides are caused by the gravitational pull of the sun and the moon and have their greatest effects on seawater level during new and full moons—when the sun, the moon, and the Earth are in alignment. As a result, the highest storm tides are often observed during storms that coincide with a new or full moon.

https://oceanservice.noaa.gov/facts/stormsurge-stormtide.html

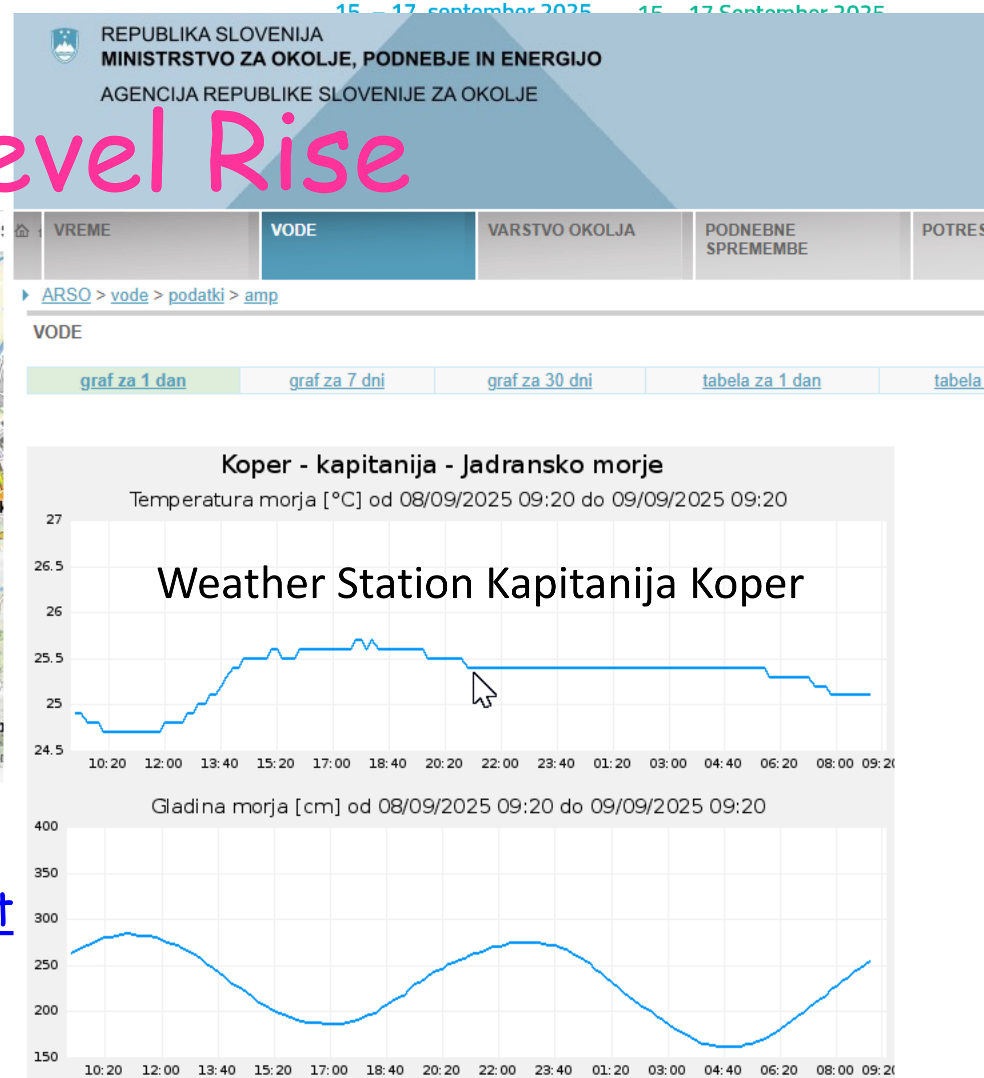
Sea-Level Rise



https://www.bergfex.si/juzna-primorska/wetter/stationen/koper-kapitanija/

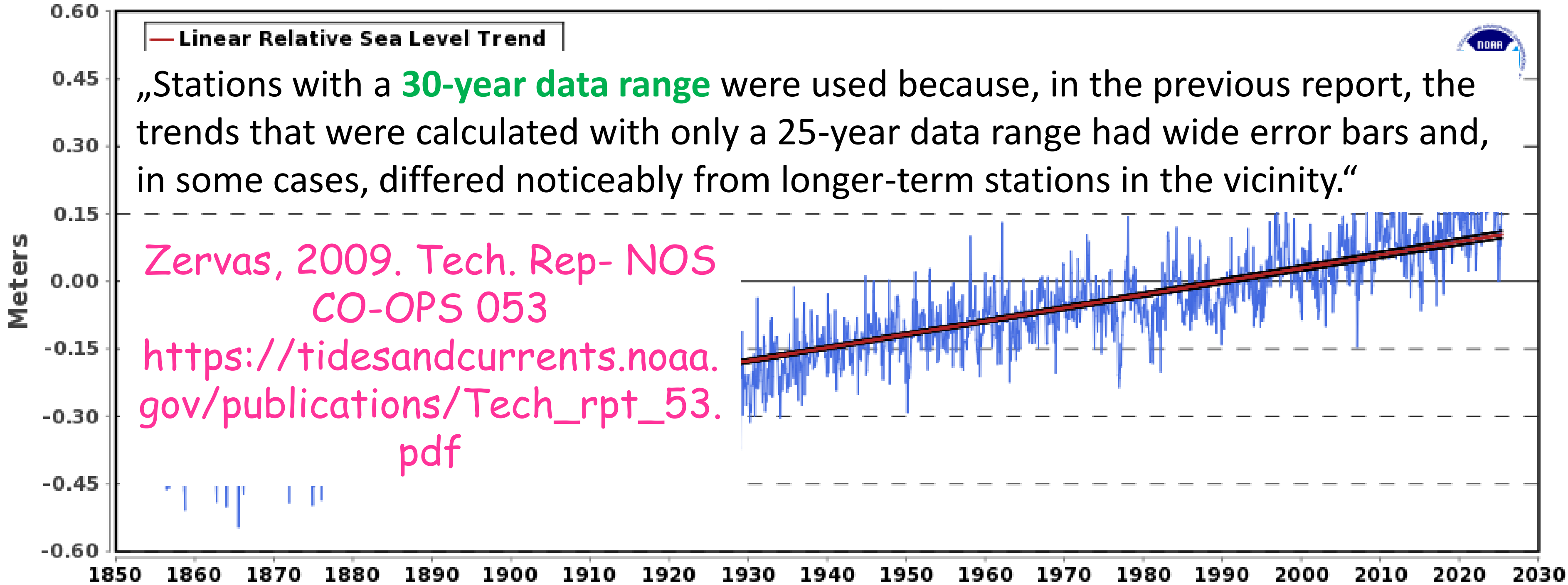
https://www.arso.gov.si/vode/podatki/amp/H9350_g_1.html

Slovenian Environment Agency
Ministry of Environment, Climate & Energy



Sea-Level Rise

8518750 The Battery, New York NOAA 2.94 +/- 0.09 mm/yr



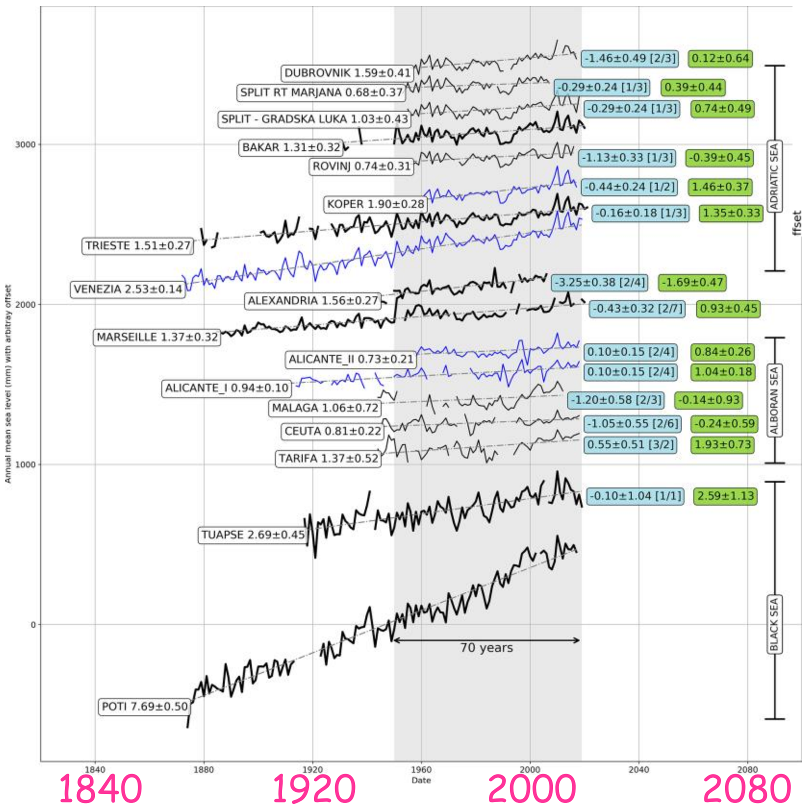
„Stations with a **30-year data range** were used because, in the previous report, the trends that were calculated with only a 25-year data range had wide error bars and, in some cases, differed noticeably from longer-term stations in the vicinity.“

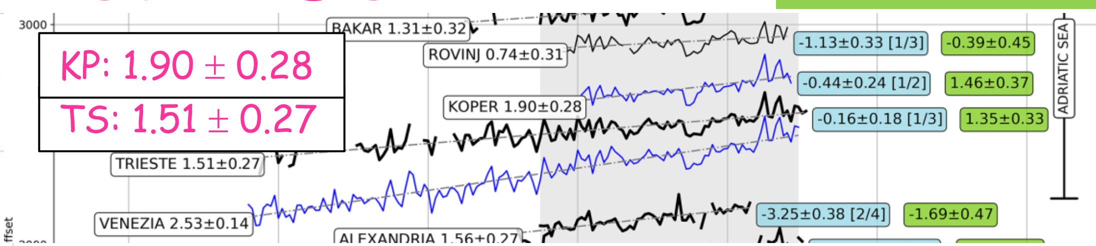
Zervas, 2009. Tech. Rep- NOS CO-OPS 053 https://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750

Sea-Level Rise

KP: 1.46 ± 0.37
TS: 1.35 ± 0.33





70-year-long sea level records (?). Black: PSMSL, bold: 100-year-long records. Blue: updated/new records, not in the PSMSL. White boxes: *relative* sea level trend. Light blue boxes: the rate of VLM, in [] the number of GNSS stations/solutions. The green boxes: the *rate of absolute sea level change* = relative sea level trend + VLM (**mm/yr**).
PSMSL: Permanent Service for Mean Sea Level;
VLM: Vert. Land Motion.

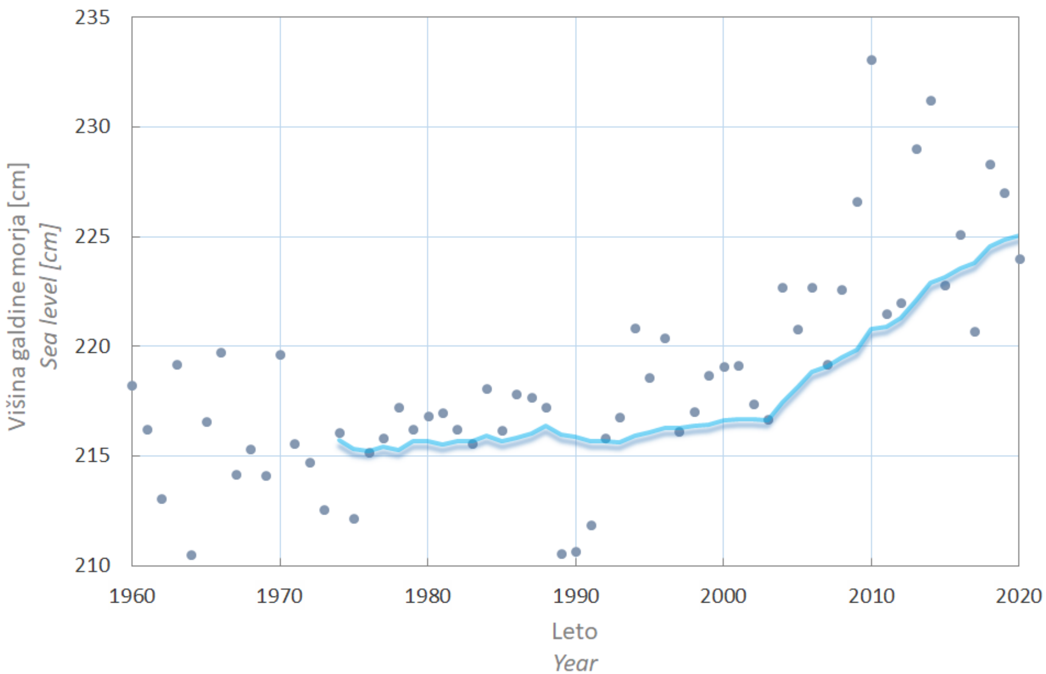
Pérez Gómez, Vilibić, Šepić, Međugorac, Ličer_et al. Ocean Sci, 2022.

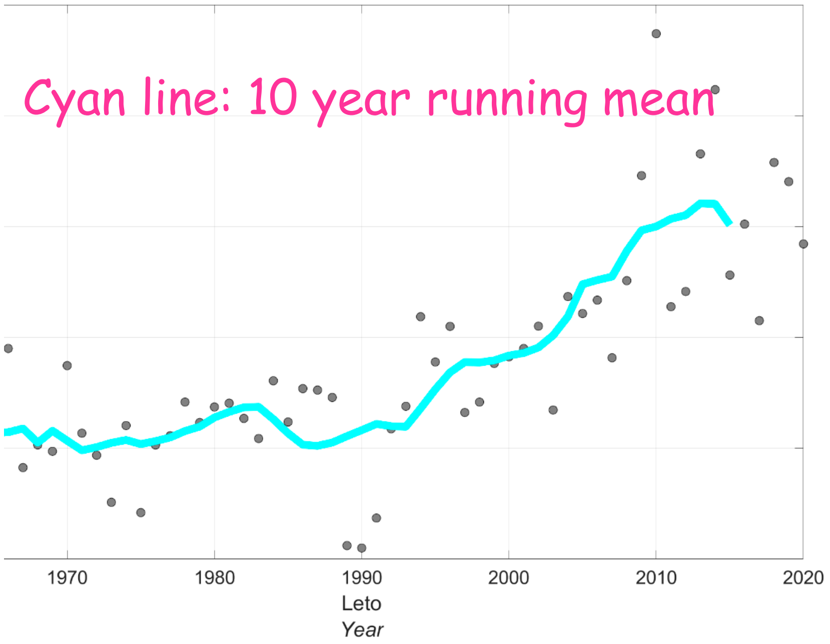
Sea-Level Rise (Kapitanija KP)

- Very ***low*** future emissions of greenhouse gases RCP 2.6 (**R**epresentative **C**oncentration **P**athway; equivalent to 2.6 W/m^2 increase of Radiative Forcing): Slovenian Coastline:
  - SLR: 2046-2065: **0.24 m (0.17-0.32) m** with respect to the mean height in 1986-2005 (=217 cm). To the end of 2100: an increase of **0.43 m (0.29-0.59) m**.
  - 100-year floods: 2045-2065: five times more frequent (returning period reduces to 20 years). To the end of 2100: 20 times more frequent (returning period 5 years)
- Very ***high*** future emissions of greenhouse gases RCP 8.5:
  - SLR: 2046-2065: an increase of **0.32 m (0.23-0.40) m** with respect to 217 cm. To the end of 2100: **0.84 m (0.61-1.10) m**.
  - 100-year floods: 2045-2065: **20 times** more frequent (returning period **5 years**). To the end of 2100: **200 times** more frequent (returning period **< 1 year**)

Terzić, Ličer & Jeromel. SEA (ARSO) Rep. 2021 (in Slov.).

Sea-Level Rise (Kapitanija KP)





Terzić, Ličer & Jeromel. SEA (ARSO) Rep. 2021 (in Slov.). Source ARSO

Tender document (Gosar et al.; in Slov. 2021). Source Malačič 2021

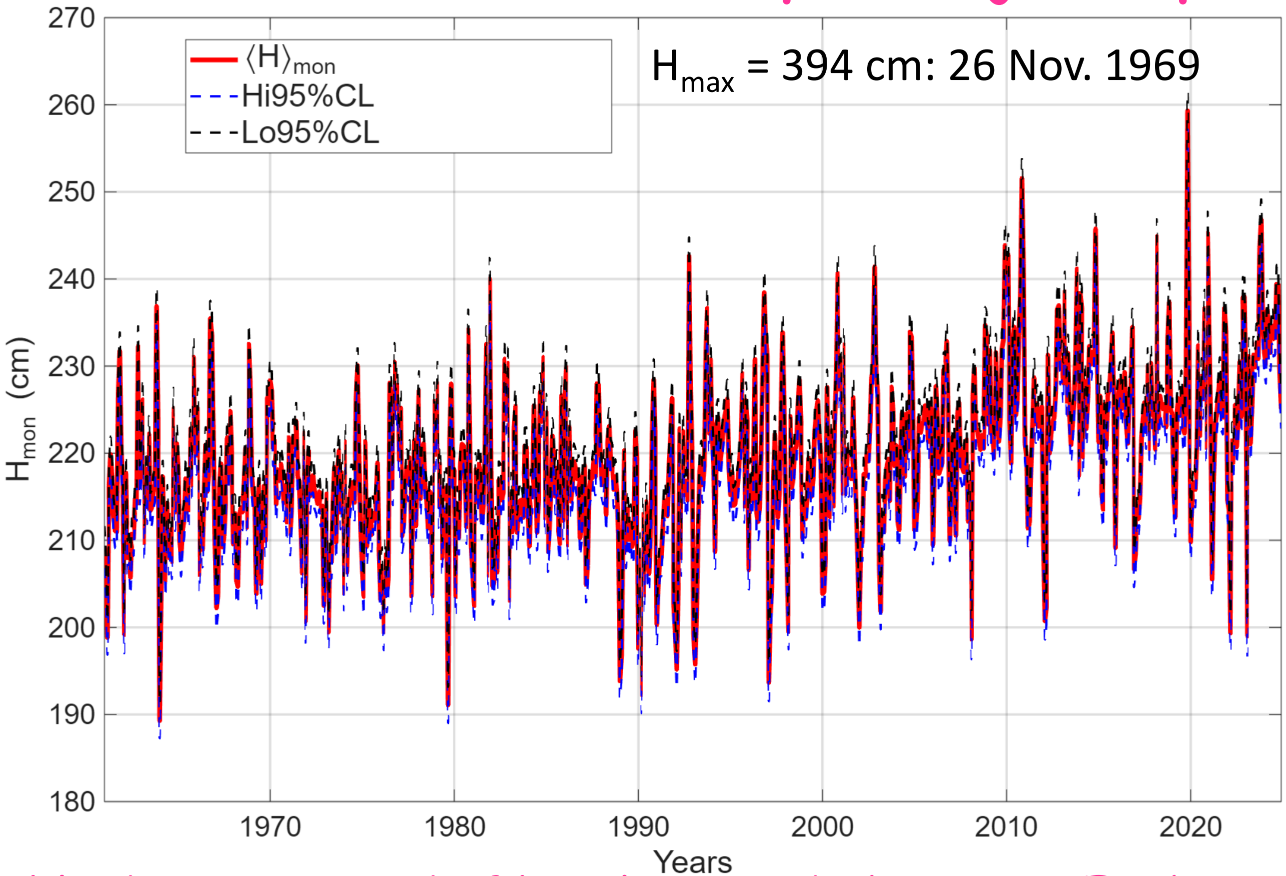
Sea-Level Rise

Zervas, 2009. Tech. Rep- NOS CO-OPS 053 (NOAA).

Executive Summary:

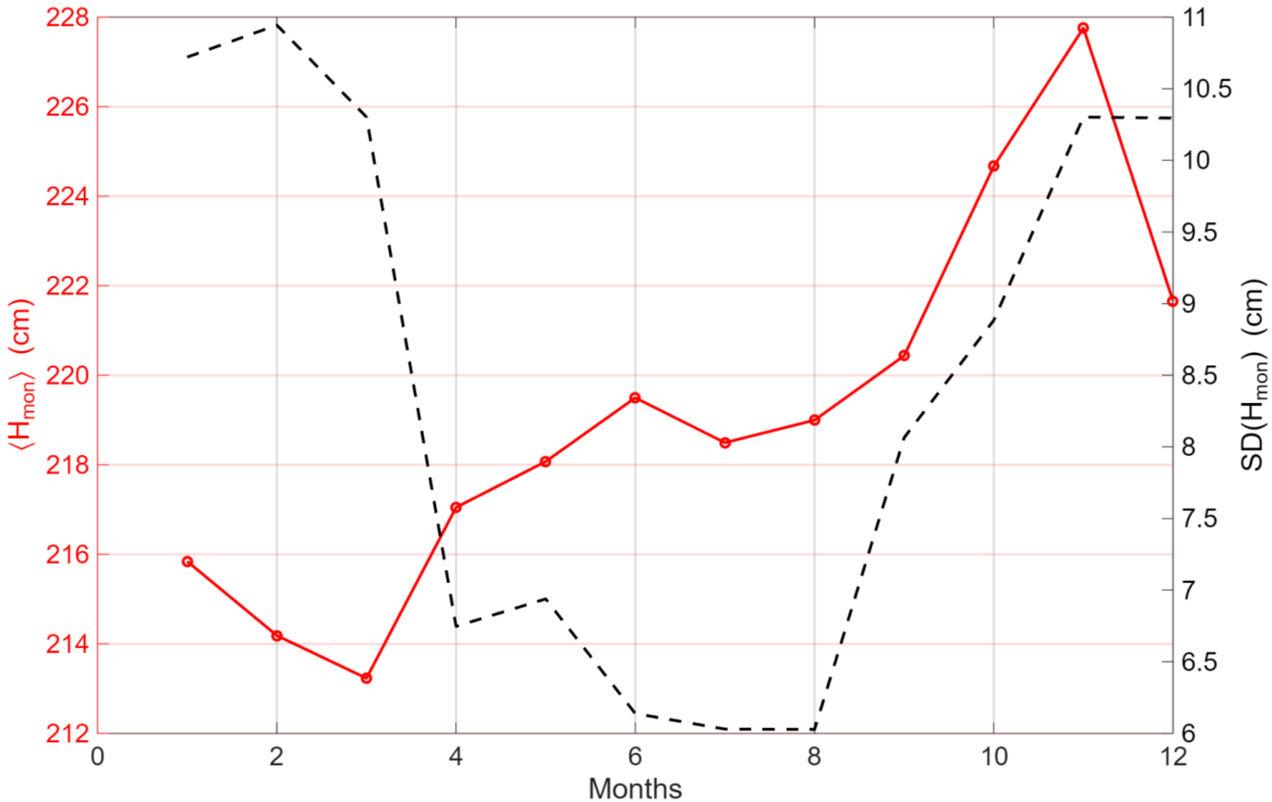
- **Monthly** mean sea level (MSL) data for **128** long-term National Water Level Observation Network (NWLON) **stations** in USA of the Center for Operational Oceanographic Products and Services (CO-OPS).
- The linear trends obtained are relative MSL trends which are a combination of the **absolute global rate of sea level rise** (**1.7 +/- 0.5 mm/yr)** in the 20th century) and the rate of any local vertical land motion.
- The residual time series after the seasonal cycles (12-month average seasonal cycle) and trends are removed represent the regional oceanic interannual variability for each station.
- **50-60 years of data are required to obtain a trend with a 95% confidence interval of +/- 0.5 mm/yr**. This dependence on record length is caused by the interannual variability in the observations.

Sea-Level Rise (Kapitanija Koper)



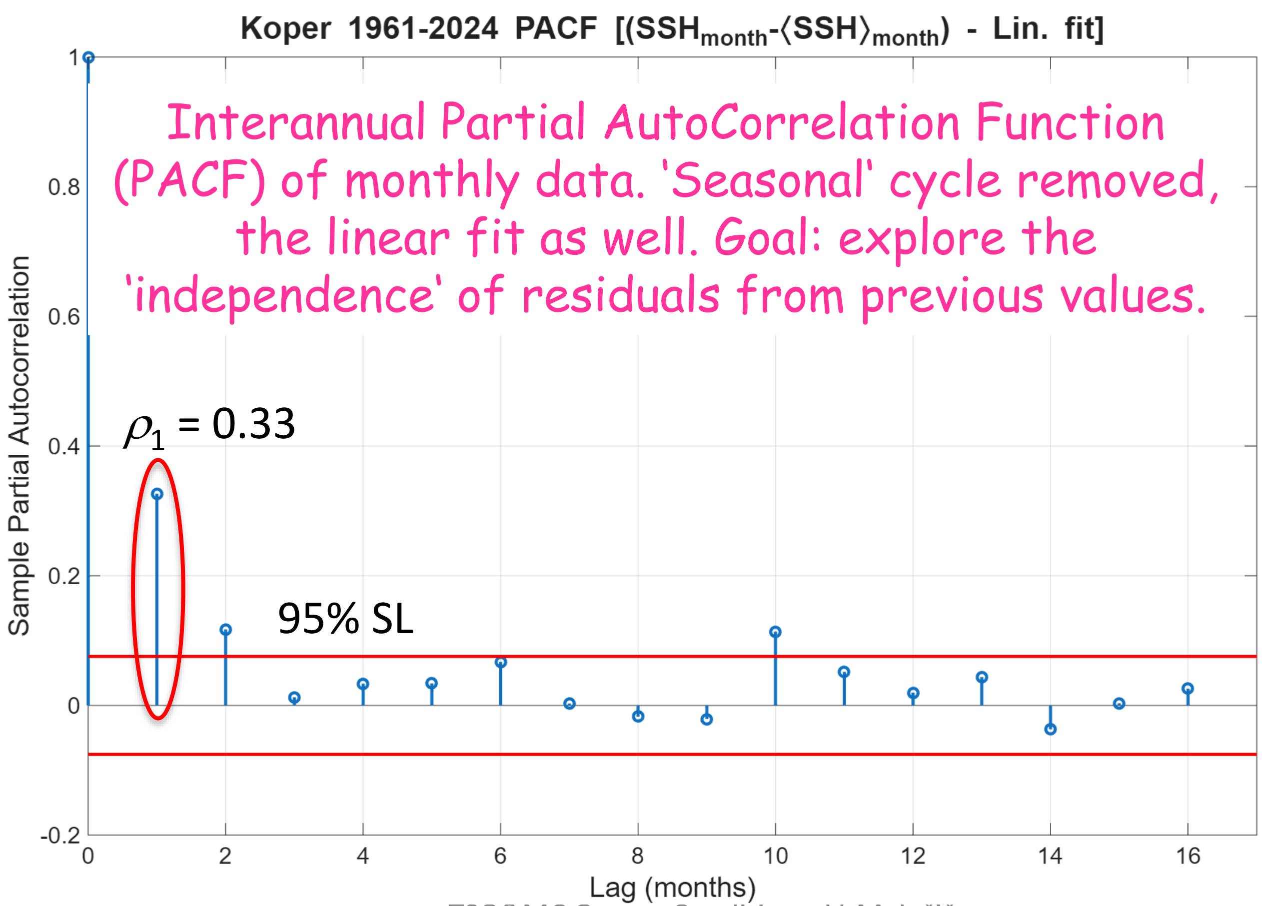
Monthly data composed of hourly records (Source SEA (ARSO), Anja Fettich)

Sea-Level Rise (Kapitanija Koper)



Interannual ⟨ ⟩ and STD of monthly data (seasonal variability).
The interannual ⟨ ⟩ **were subtracted from the monthly data.**

Sea-Level Rise (Kapitanija Koper)



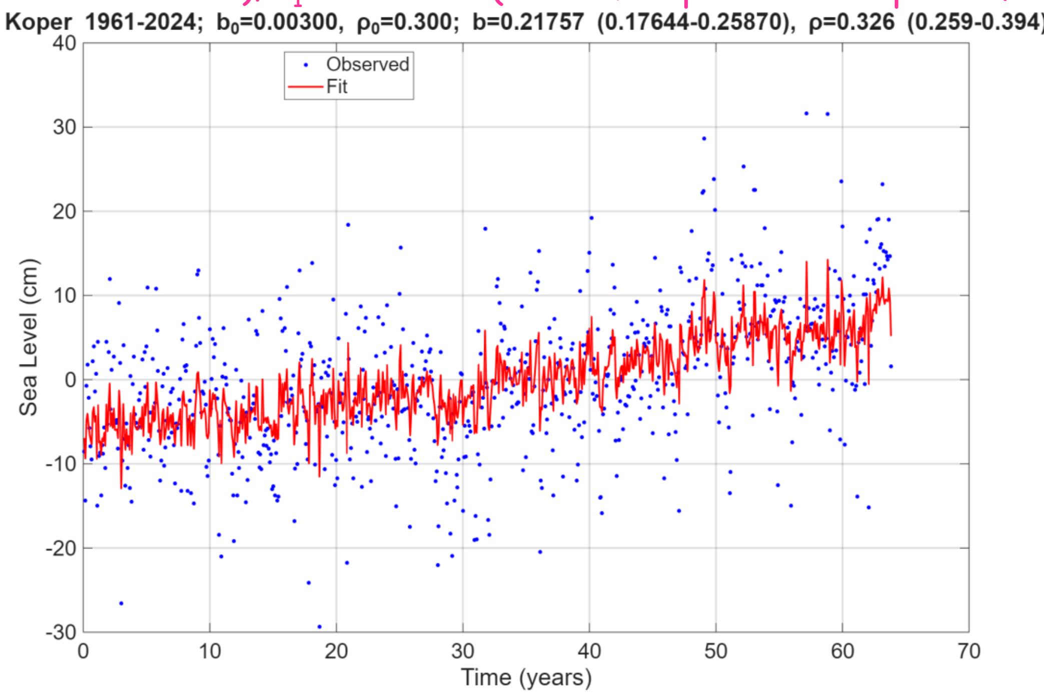
Sea-Level Rise (Kapitanija Koper)

Zervas, 2009. Tech. Rep- NOS CO-OPS 053 (NOAA), eq. (4)

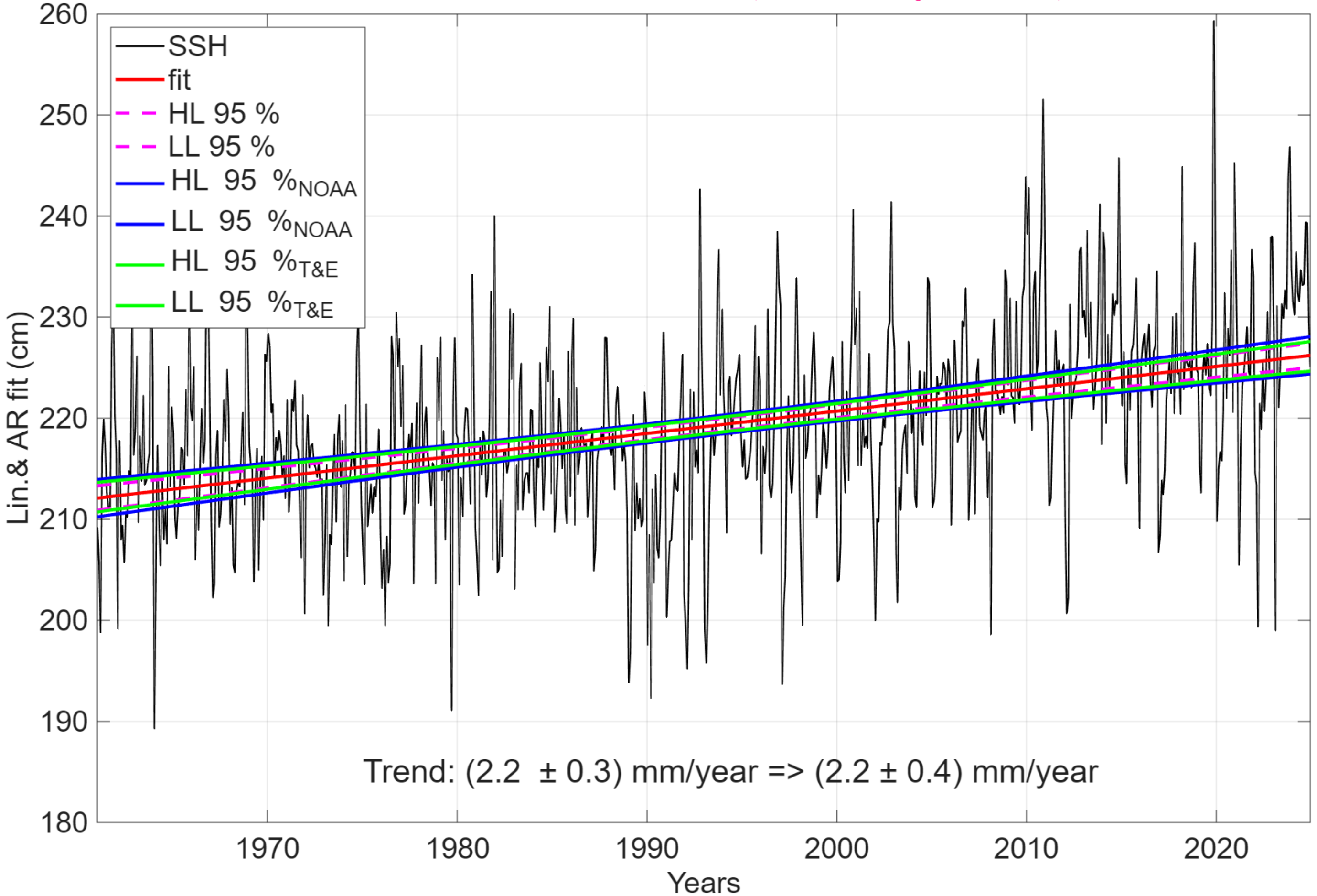
$$H_i = bt_i + \langle H_j \rangle + \rho_1 \left(H_{i-1} - bt_{i-1} - \langle H_{j-1} \rangle \right) + \varepsilon_i$$

The nonlinear, autoregressive (AR) fit

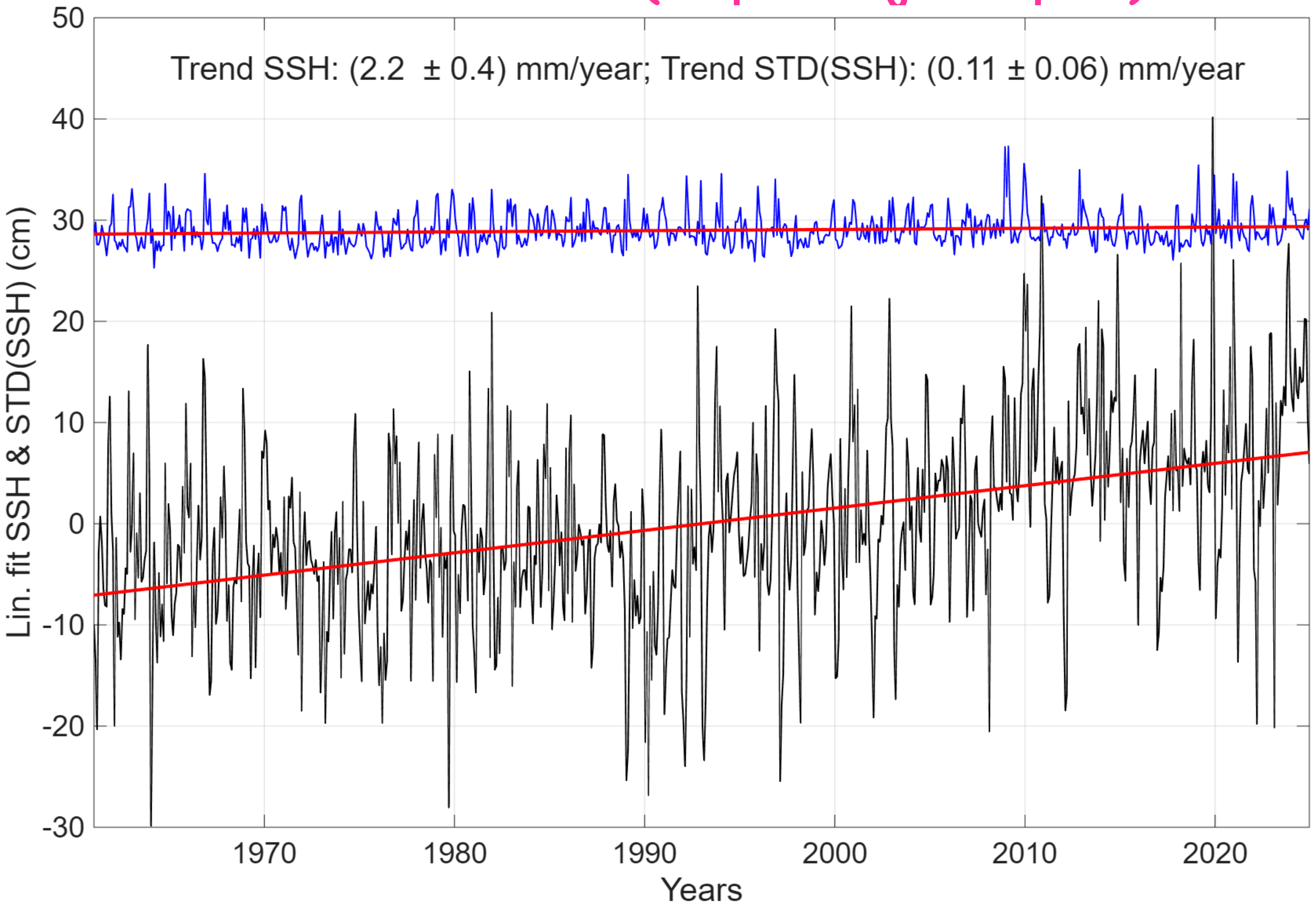
H_i: the i-th monthly H; t_i : the (monthly) time in fractional years; $\langle H_j \rangle$: the interannual average of H_j in a month j; b: the slope of a trend; ρ_1 the lag 1 autoregressive coefficient (the part predictable from the previous month's residual); ε_1 the error (random unpredictable part of the residual)



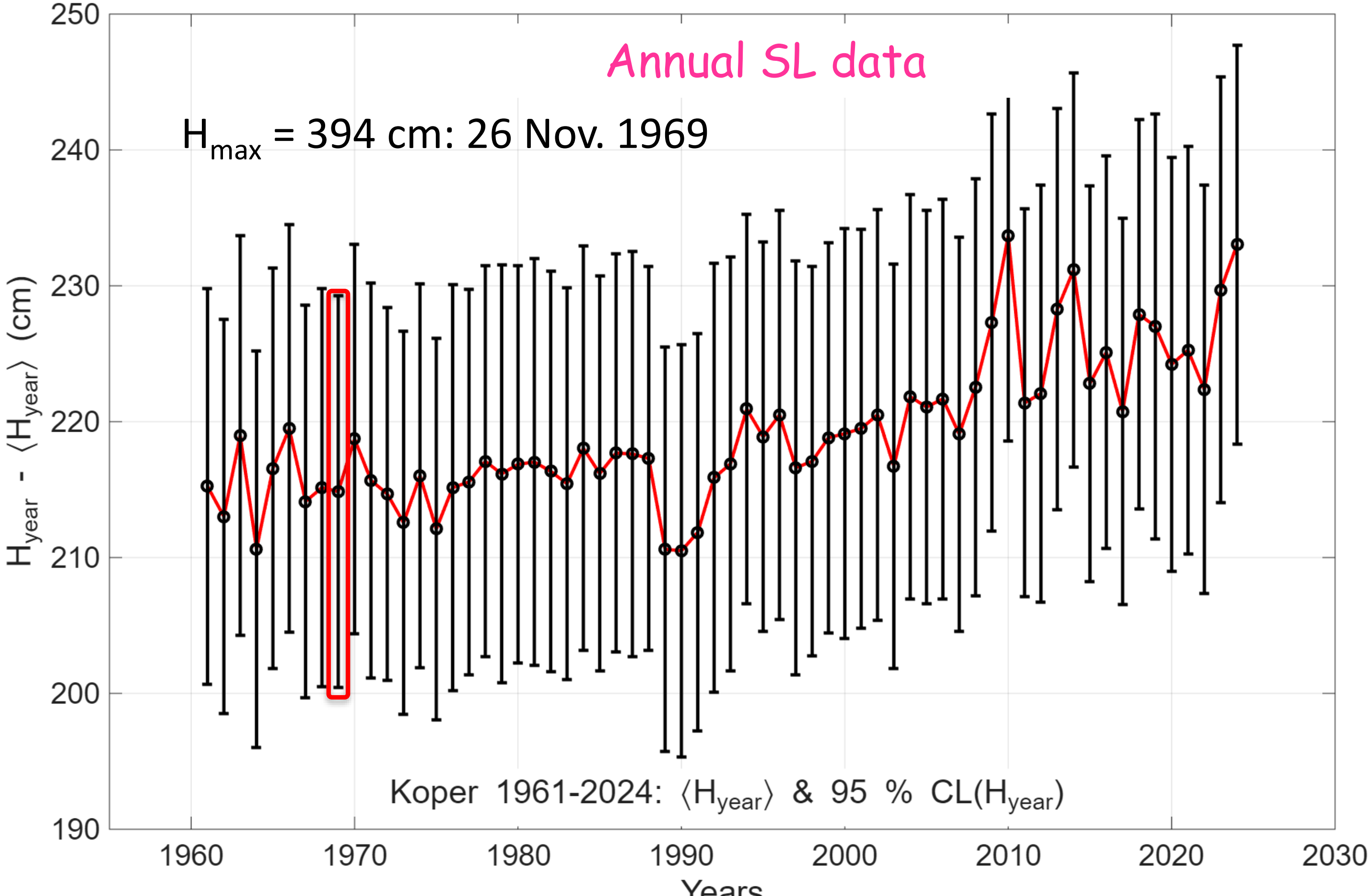
Sea-Level Rise (Kapitanija Koper)



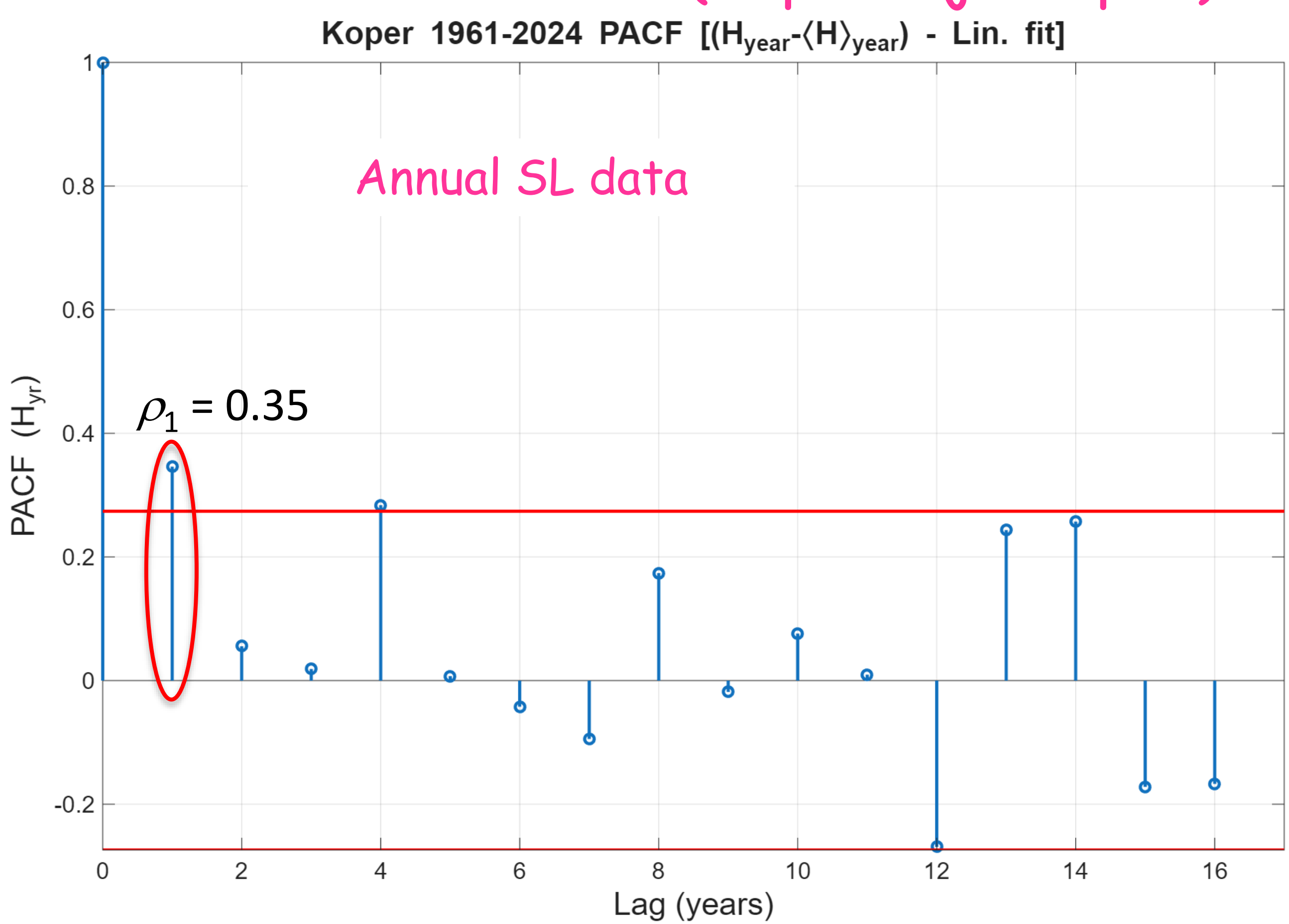
Sea-Level Rise (Kapitanija Koper)



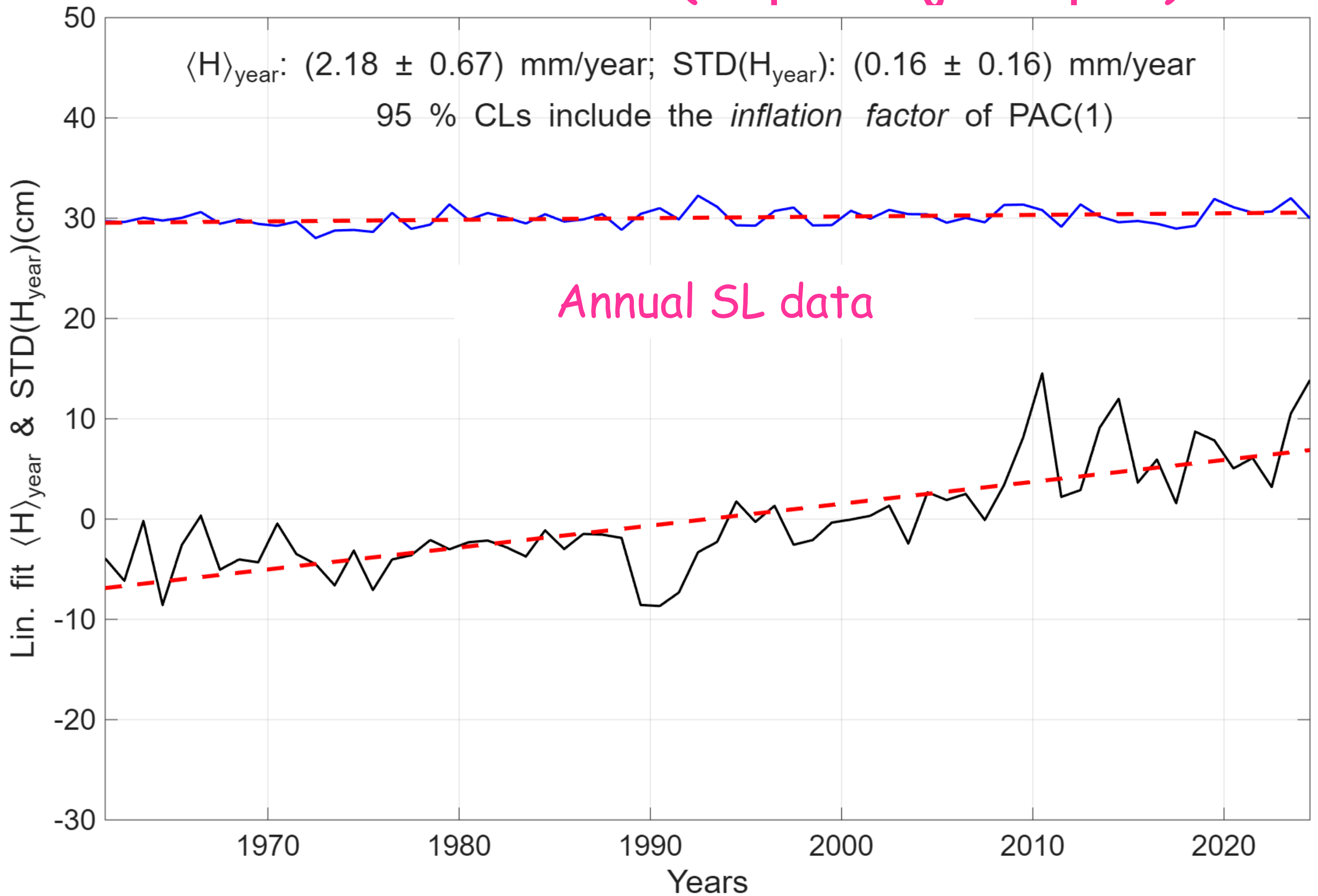
Sea-Level Rise (Kapitanija Koper)



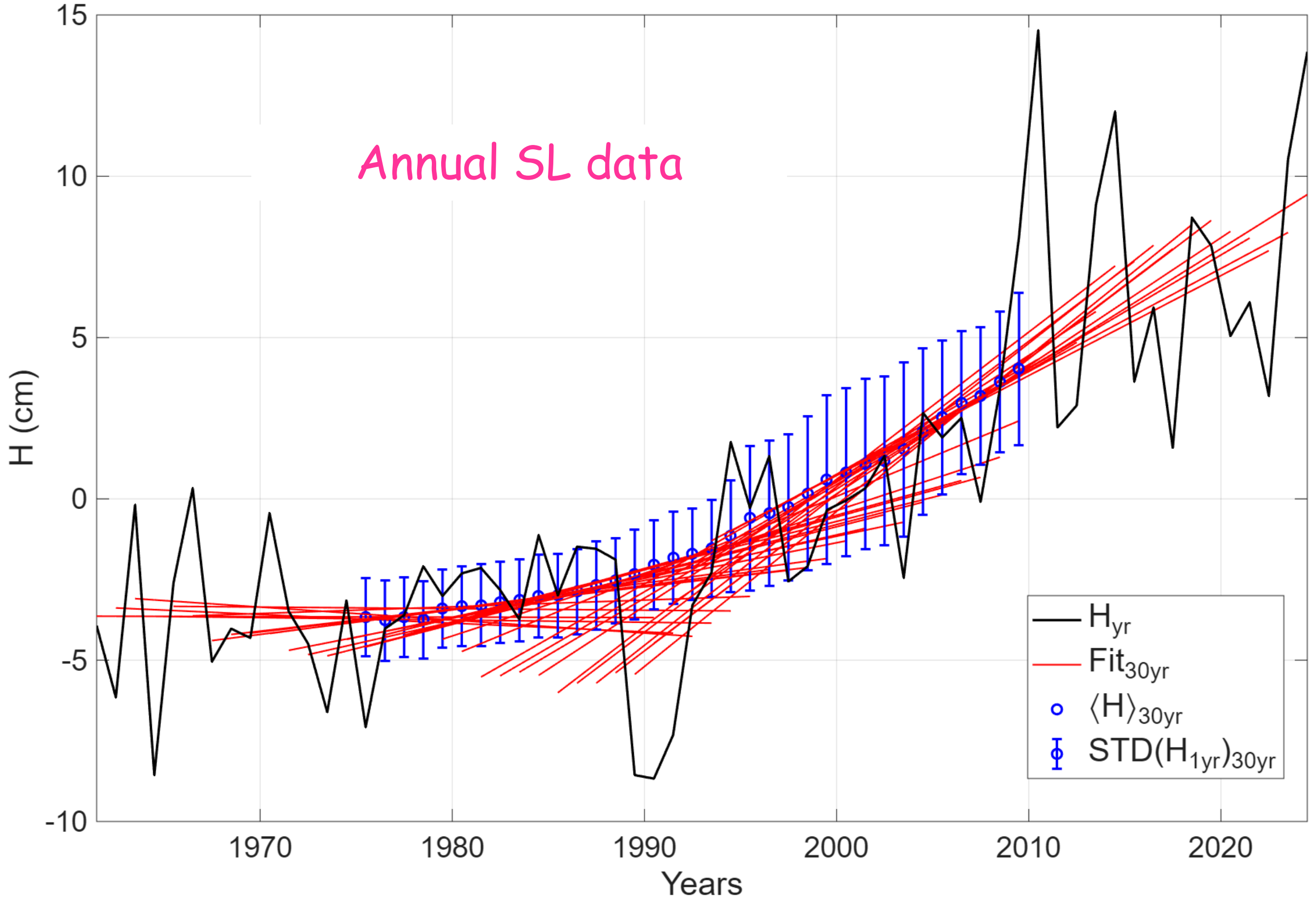
Sea-Level Rise (Kapitanija Koper)



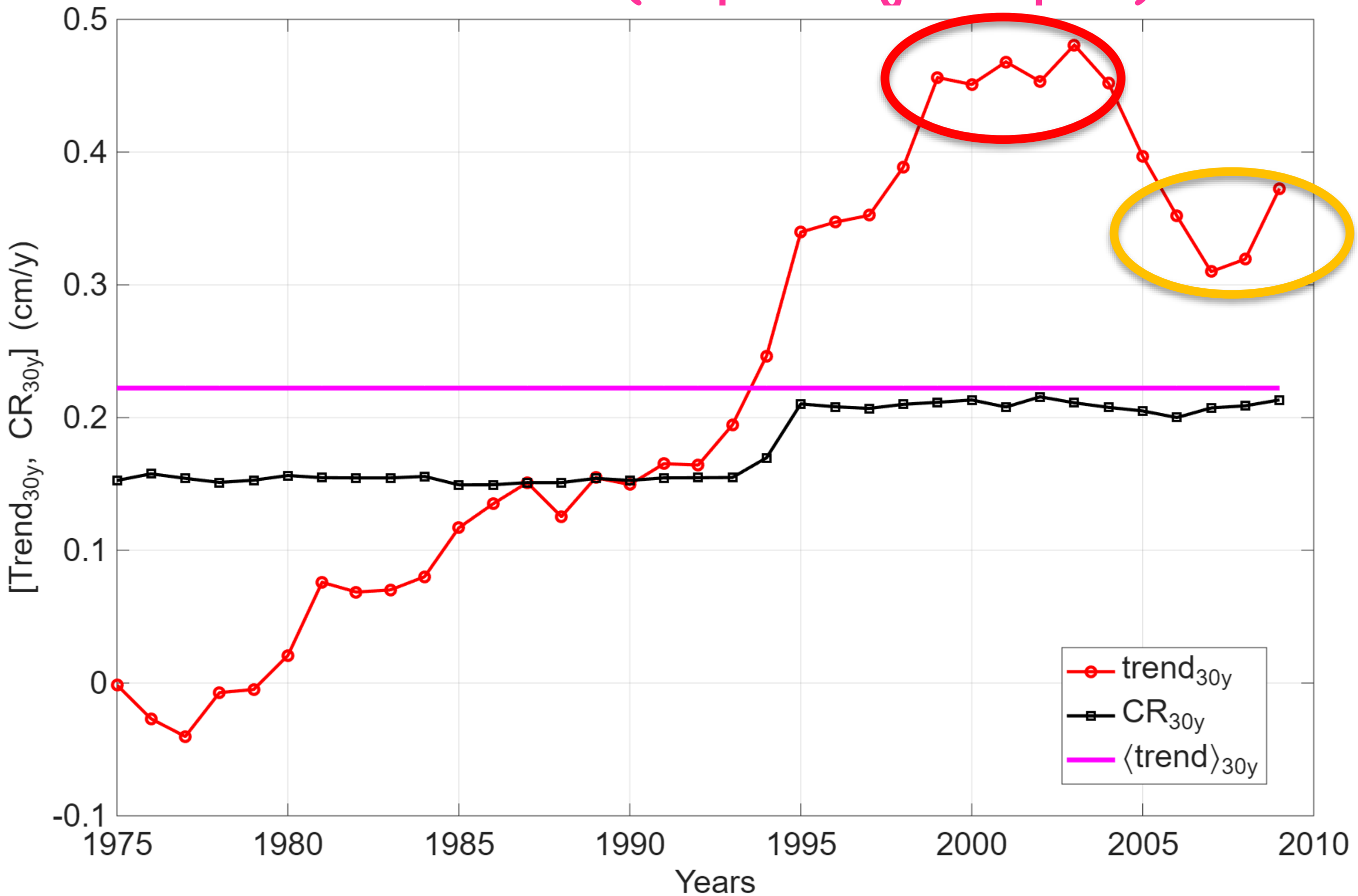
Sea-Level Rise (Kapitanija Koper)



Sea-Level Rise (Kapitanija Koper)



Sea-Level Rise (Kapitanija Koper)



The

Analysing the moving intervals of 30 years gives the highest values of the trend > 4.5 mm/year. However, the first 30-year intervals have a trend < 0 and some 30-year intervals

Sea-Level Rise – conclusions

- The SL trend for the period 1961-2024:
  - Monthly values: Trend = (2.2 ± 0.4) mm/yr
  - Annual values: Trend = (2.2 ± 0.7) mm/yr.
  - The fluctuations (STD) increase by ~ 0.1 × Trend – not negligible.
- The partial autocorrelation (lag 1) increases the variability of the SL trend (the 95 % confidence interval (CR)). However, linear adjustments result in the same value for the SL trend.
- The minimum time span of a time series required to calculate trends is 30 years. 50—60 years 'deliver' the CR of a trend of 0.5 mm/yr.
- Analysing the moving intervals of 30 years gives the highest values of the trend = 4.8 mm/year. However, the first 30-year intervals have a trend < 0 and the last 30-year intervals have trend values in the range of 3.5 mm/yr – 3.7 mm/yr (high SL values between 2010 – 2015).

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