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MODELIRANJE VODOSTAJA MORJA Z METODO NEVRONSKIH MREŽ NA PRIMERU NEURNEGA VALA V TRŽAŠKEM ZALIVU DECEMBRA 2008

NEURAL NETWORK APPROACH TO SEA-LEVEL MODELING. CASE STUDY OF A STORM SURGE IN THE GULF OF TRIESTE IN EARLY DECEMBER 2008

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Na mnogih območjih so tablice plimovanja priročno orodje za napovedovanje morskega vodostaja. Sektor za hidrološke prognoze Agencije RS za okolje za napovedovanje morskega vodostaja v Tržaškem zalivu pogosto uporablja tablice plimovanja skupaj s harmonično analizo. Meteorološki vplivi, kot so gradient zračnega tlaka, veter in lastno nihanje morja vzdolž glavne osi Jadrana, so se mnogokrat izkazali kot pomembni dejavniki, ki vplivajo na višino vodostaja v Tržaškem zalivu. Ti dejavniki so v harmonične analize vključeni le posredno. Poleg tega za uporabne kratkoročne prognoze s pomočjo harmonične analize potrebujemo veliko število natančno umerjenih modelskih parametrov. Novejše raziskave so pokazale, da lahko uporaba umetnih nevronskih mrež bistveno izboljša napovedovanje vodostajev, če le vnesemo ustrezne vhodne spremenljivke (npr. predhodni vodostaj, zračni tlak, hitrost in smer vetra, tablice plimovanja itd.) Na dogodku neurnega vala (ang. storm surge) in poplavljanja morja na slovenski obali v začetku decembra 2008 smo izdelali analizo s pomočjo umetne nevronske mreže. Rezultati uporabe nevronskih mrež so dobro primerljivi s trenutno uporabljanimi konvencionalnimi metodami napovedovanja višine morskih gladin.

Ključne besede: *nevronske mreže, napovedovanje višine morja, harmonična analiza, Jadransko morje, neurni val*

Tide tables can be a useful tool for sea-level forecasting in many areas. Slovenian operational service for hydrological forecasts at the Environmental Agency of the Republic of Slovenia frequently deploys tide tables alongside least square harmonic analysis to predict maximum sea levels in the Gulf of Trieste. Meteorological influences such as pressure gradient, wind stress and induced basin eigenoscillations (seiches) along the main axis of the Adriatic basin have repeatedly been proven as important factors influencing the sea level in the Gulf of Trieste. They are, however, only indirectly included in the harmonic analysis which in itself requires a large number of carefully tuned model parameters in order to make useful short-range forecasts. A number of recent reports show that an artificial neural network (ANN) can greatly improve sea level forecasts, providing we supply it with suitable input variables (ie. previous water levels, air pressure, wind speed, wind direction, tide charts etc.) We report on an ANN-based analysis of the recent storm surge and flooding events at the Slovenian coast in the beginning of December 2008. The ANN model compares favourably with the currently used conventional forecasting methods.

Key words: *neural networks, sea-level forecasting, harmonic analysis, Adriatic Sea, storm surge*

1. UVOD: PLIMOVANJE IN LASTNO NIHANJE

Osnovo za napovedovanje vodostaja morja predstavljajo podatki, zbrani na mareografskih merilnih postajah. Natančno napovedovanje vodostaja je pomembno za mnoge gospodarske dejavnosti, kot so plovba, načrtovanje priobalne infrastrukture, turizem itd.

Visoki vodostaji so na slovenski obali že velikokrat povzročili materialno škodo. Enega takih dogodkov so zabeležili tudi v zgodnjem decembru leta 2008, ko je morska gladina dosegla najvišjo raven v petdesetih letih. Škodo so ocenili na 1 milijon EUR. Zaradi tega se je Agencija Republike Slovenije za Okolje (ARSO) v sodelovanju z Morsko biološko postajo v Piranu ter s Fakulteto za gradbeništvo in geodezijo (FGG) Univerze v Ljubljani odločila analizirati trenutne prognostične metode vodostaja morja, ter razviti nove, ki bi omogočale večjo natančnost. Satelitske meritve in daljinsko zaznavanje nam danes omogočajo izdelavo usklajene in podrobne slike vzorcev spreminjanja morske gladine, kar v primerjavi s starejšimi in razmeroma nenatančnimi, na priobalni pas vezanimi metodami, predstavlja pomemben mejnik. Razvoj na področjih Fourierove in harmonične analize nam omogoča razklopitev nihajnih načinov različnih harmoničnih komponent v vzorcih dinamike morske gladine ter izdelavo spektralne analize sprememb vodostaja.

V pričujočem delu želimo predstaviti analizo relevantnosti doslej uporabljanih metod za prognoze vodostaja morja na ARSO ter predlagati nove pristope, ki bi izboljšali natančnost napovedi.

V večini primerov (vsaj v Jadranskem morju) so zgolj gravitacijski mehanizmi zaradi prisotnosti Sonca in Lune premalo za ustrezen opis opazovanih vodostajev. Regularne in predvidljive vzorce plimovanja v veliki meri spreminjajo neregularni meteorološki dejavniki, kot sta vetrna napetost na gladini morja ter zračni tlak. Na gladino morja v Tržaškem zalivu še zlasti vplivata JV in JZ veter, ki gladino tipično višata, ter burja, zaradi katere se gladina v Tržaškem zalivu tipično nekoliko zniža.

1. INTRODUCTION: SEA-LEVELS AND SEICHES

Analysis of data collected by sea-level observing stations provides a basis for predicting future sea-levels. Accurate sea-level forecasting is important for a wide variety of maritime activities from shipping and coastal engineering to tourism and other economic sections in coastal regions.

Storm surges have also repeatedly resulted in tremendous aftermaths in Slovene coastal towns, most recently in December 2008 when the sea-level hit a 50-year high, causing an estimated 1 mio EUR of damages. Therefore the Environmental Agency of the Republic of Slovenia (EARS), Marine Biology Station Piran and the Faculty of Civil Engineering have set out to analyse current methods of sea-level forecasting and develop new ones of higher accuracy. Due to remote sensing and satellite sea-level measurements we can today give a consistent and thorough account of sea-level variation patterns around the globe which is a milestone achievement in comparison to relatively inaccurate older observations confined to the coast line. Mathematical developments in the fields of Fourier and harmonic analyses have made it possible to decouple various harmonic constituents in sea-level patterns and thereby making a spectral analysis of the sea-level variations.

In this paper we aim to present a relevance analysis of methods used hitherto for sea-level prediction at the EARS and suggest new approaches to improve the accuracy of forecasts.

In most cases in the Adriatic basin, Solar and Lunar gravitational mechanisms are insufficient for an accurate description of observed sea-levels. The regular and predictable gravitational tide patterns are modified to a large extent by mostly meteorological irregular factors, the principal ones being air pressure variations and wind stresses (in the case of the Gulf of Trieste stresses due to Adriatic SE and SW winds raise the sea level, and NE wind lowers the sea level).

V nasprotju z laičnim razumevanjem plimovanja kot kakršnegakoli spreminjanja gladine morja, strokovno definiramo plimovanje kot periodično premikanje vode, ki je v svoji amplitudi in fazi neposredno povezano s katerokoli periodično geofizikalno silo (Pugh, 1987). Največjo geofizikalno silo predstavlja spreminjanje lokalne težnosti zaradi periodičnih gibanj Zemlje, Sonca in Lune. Gibanje, ki ga povzročajo te sile, imenujemo težnostno ali astronomsko plimovanje. Vsaka sprememba vodostaja morja ima komponento plimovanja in komponento, ki ni povezana s plimovanjem. Zato razlikujemo med astronomskim plimovanjem, ki nastane zaradi težnosti in t.i. residualnimi višinami, ki so posledica vseh drugih fizikalnih vplivov na vodostaj (predvsem veter, zračni tlak itd.).

In distinction to popular understanding of tide as any type of change of sea-level, we define the tide as a periodic movement of water, directly related in amplitude and phase to any periodic geophysical force (Pugh, 1987). The dominant geophysical forcing is the variation of the local gravitational force caused by the regular movements of the Earth, Sun and Moon. Movements due to these forces are called gravitational or astronomic tides. As noted above, any sea-level variation will have a tidal and a non-tidal component, therefore we talk about astronomic tides which are due to gravitational attractions and the so-called residual sea-level heights which are due to all other physical disturbances of the local sea-level (mostly wind stress, air pressure etc.)

Slika 1: Neurni val v Piranu decembra 2008. Resonanca med visoko astronomsko plimo in veliko amplitudo lastnega nihanja je povzročila najvišji vodostaj v Piranskem zalivu v zadnjih petdesetih letih. (Fotografija: Mojca Robič, Janez Polajnar)

Figure 1: An extreme storm surge in Piran in early december 2008. A resonant effect of high astronomic tides and high amplitude wind-driven seiche maximum caused a maximum sea-level in the past 50 years on the Piran peninsula. (Photo: Mojca Robič, Janez Polajnar)

Opazovanja kažejo, da pomemben vpliv k gibanju morske gladine v jadranskem bazenu predstavlja lastno nihanje vode v Jadranu. Nekaj dni trajajoči jugovzhodnik s sočasnim

A notable disturbance leading to substantial residual sea-levels in the Adriatic basin has been observed to be a ground state eigenoscillation (a seiche) of water in the Adriatic. A few days of southeastern wind prehodom fronte čez severni Jadran lahko privede do velikih amplitud lastnega nihanja, kar povzroči izjemno visok vodostaj in veliko materialno škodo na slovenski obali (slika 1). Osnovno lastno nihanje ima v jadranskem bazenu frekvenco približno 22 ur, njegova amplituda pa je odvisna od meteoroloških pogojev (hitrost in trajanje vetra, zračni tlak itd.).

coupled with the passage of frontal systems over the North Adriatic shelf can lead to high amplitude seiches causing storm surge events that cause tremendous damages in the Slovenian coastal regions (see Fig. 1). Ground state eigenoscillation of water in the Adriatic basin has an eigenfrequency of roughly 22 hours while its amplitude depends on the meteorological situation (wind speed, wind fetch, wind duration, air pressure etc.)

2. METODE

ARSO se je do sedaj pri napovedovanju vodostaja morja zanašal predvsem na tablice plimovanja, ki se jim je prištelo še efekt inverznega barometra (za statični in dinamični učinek inverznega barometra gl. Pugh, 1897). Če je bil opažen prvi maksimum lastnega nihanja, je bilo možno v napoved vključiti še prispevek dušenega nihanja, ki je bil z metodo najmanjših kvadratov izračunan iz izmerjenih vodostajev. Za analizo vodostajev in za oceno komponent astronomske plime je v uporabi harmonična analiza.

2. METHODS

For sea-level predictions the EARS has been relying mostly on the astronomic tide tables corrected with the inverted barometer effect (for static and dynamic inverted barometer sea-level responses see Pugh, 1987: 196) and, if seiches are observed, with the damped oscillation signal obtained as a least-square fit of the sea-level variations. For sea-level analysis and for the estimation of astronomic tide constituents, harmonic analysis has hitherto frequently been employed.

2.1 HARMONIČNA ANALIZA

Postopek analize vključuje statistiko časovnih vrst morske gladine, s katero pridobimo najpomembnejše fizikalne parametre dinamike vode na opazovanem območju. Harmonična analiza opisuje opazovane vodostaje kot vsoto končnega števila N harmoničnih komponent, katerih faza in amplituda sta določeni prek astronomskih parametrov

2.1 HARMONIC ANALYSIS

The process of analysis involves statistics of sea-level time-series to obtain principal physical parameters of water dynamics in the observed area. Harmonic analysis describes the observed water level as a sum of a finite number N of harmonic constituents whose phase and amplitude are determined from astronomic arguments

$$h(t) \approx \sum_{n=1}^{N} H_n \cos(\omega_n t - g_n). \tag{1}$$

V enačbi (1) je $h(t)$ opazovan vodostaj, H_n je amplituda n - te harmonične komponente, ω_n je krožna frekvenca (v radianih na sekundo) n - te harmonične komponente, g_n pa fazni premik n - te harmonične komponente glede na ravnovesno plimo pri ničelnem poldnevniku (Pugh, 1987). Vzroke za plimovanje lahko pojasnimo s pomočjo razvoja krožne frekvence v vrsto, ki ga je prvi uporabil Arthur T. Doodson (1890-1968) leta

In eq. (1), $h(t)$ stands for the observed water level, H_n is the amplitude of the n - th harmonic constituent, ω_n is the n - th harmonic constituent angular speed (in radians) and g_n is the phase shift of the n - th harmonic constituent to the equilibrium tide at Greenwich (Pugh, 1987). One can significantly improve tide analysis using an angular speed series expansion first employed by Arthur T. Doodson (1890-1968) in 1921

1921 (Doodson, 1921). Pri tem postopku krožne frekvence ω_n razvijemo po šestih[1] skrbno izbranih najpomembnejših harmoničnih komponentah plime

(Doodson, 1921), where he expanded the angular speed ω_n in the Fourier basis of six[2] carefully chosen major harmonic tidal constituents

$$\omega_n = \sum_{k=1}^{6} n_k \omega_k = \sum_{k=1}^{6} \frac{2\pi n_k}{\tau_k}, \tag{2}$$

kjer je n_k k - to Doodsonovo celo število (med -5 in 5). Pri krožnih frekvencah $\omega_k=2\pi/\tau_k$ so periode τ_k naslednje: τ_1 je srednji Lunin dan[3] (1,0351 srednjega Sončevega dneva), τ_2 je Lunin mesec (27,3217 srednjih Sončevih dni), τ_3 je Sončevo (oz. tropsko) leto (365,2422 srednjih Sončevih dni), τ_4 je Lunina perigejska perioda (8,85 julijanskih let), τ_5 je perioda regresije Luninih vozlov (18,61 julijanskih let) in τ_6 je precesija perihelija (20942 julijanskih let).

Slika 2 prikazuje Fourierjev (FFT) spekter astronomskih plim na mareografski postaji Koper za leto 2008. Označeni so najpomembnejše plimne komponente in njihove periode. Poldnevna (semidiurnalna) komponenta na sliki 2 so K2 (lunisolarna poldnevna komponenta, perioda = 11,97 h), S2 (glavna Sončeva poldnevna komponenta, perioda = 12,00 h), M2 (glavna Lunina poldnevna komponenta, perioda = 12,42 h) in N2 (Lunina eliptična poldnevna komponenta, perioda = 12,06 h). Enodnevne (diurnalne) komponente na sliki 2 so ϕ1 (perioda = 23,80 h), K1 (lunisolarna enodnevna komponenta, perioda = 23,93 h), P1 (glavna Sončeva enodnevna komponenta, perioda = 24,07 h) in O1 (glavna Lunina enodnevna komponenta, perioda = 25,82 h).

where n_k is k - th Doodson integer (between -5 and 5). The angular speeds $\omega_k=2\pi/\tau_k$, where the periods τ_k are as follows: τ_1 is a mean lunar day[4] (1.0351 mean solar day), τ_2 is a sidereal month (27.3217 mean solar days), τ_3 is a tropical year (365.2422 mean solar days), τ_4 is Moon's perigee period (8.85 Julian years), τ_5 is the period of regression of moon's nodes (18.61 Julian years) and τ_6 is the Perihelion progression period (20 942 Julian years).

Figure 2 shows the fast Fourier power spectrum of astronomic tides in Koper in 2008. Major tidal constituents are identified and their periods are stated. Semidiurnal (half-day) constituents on Figure 2 are K2 (Lunisolar semidiurnal constituent, period = 11.97 h), S2 (principal solar semidiurnal, period = 12.00 h), M2 (principal lunar semidiurnal, period = 12.42 h) and N2 (lunar elliptic semidiurnal, period = 12.06 h). Diurnal (one day) constituents identified on Figure 2 are ϕ1 (period = 23.80 h), K1 (lunisolar semidiurnal, period = 23.93 h), P1 (principal solar diurnal, period = 24.07 h) and O1 (principal lunar diurnal, period = 25.82 h).

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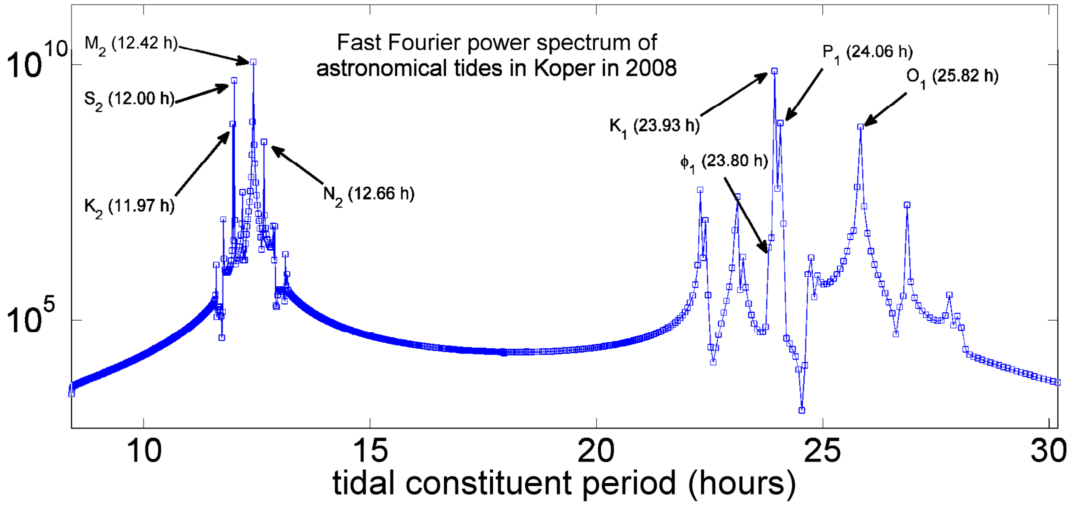
[1] Popolna Doodson-ova ekspanzija pravzaprav vključuje 389 in ne 6 harmoničnih konstituentov (gl. še Janeković, 2006). Zaradi majhnih amplitud so vsi členi višjega reda zanemarjeni.

[2] The complete Doodson expansion actually involves 389 harmonic constituents instead of six (Janeković, 2006). All the higher-order terms are omitted due to their negligible amplitudes.

[3] Srednji Lunin dan je čas, v katerem se Luna zavrti enkrat okrog svoje osi, merjeno glede na fiksne oddaljene zvezde. Srednji Sončev dan je čas med dvema prehodoma 'povprečnega Sonca' čez lokalni meridian. 'Povprečno Sonce' je namišljeno telo, ki z enakomerno kotno hitrostjo opiše celoten letni krog po nebesnem ekvatorju v natanko enakem času kot dejansko Sonce. Srednji Sončev dan znaša 84600 sekund, srednji Lunin dan pa 1.035 srednjega Sončevega dneva. Gl. še AMS meteorološki slovar na naslovu http://amsglossary.allenpress.com/glossary/search?id=mean-solar-day1.

[4] Mean Lunar day is defined as the time required for the moon to revolve once, relative to a fixed star, about its own axis. The interval of time between two successive meridional transits of the "mean sun," an imaginary point moving with such constant angular velocity along the celestial equator as to complete one annual circuit in a time period exactly equal to that of the apparent (true) sun in its annual circuit. See also AMS Glossary at http://amsglossary.allenpress.com/glossary/search?id=mean-solar-day1.



Slika 2: FFT spekter višin morja na mareografski postaji Koper za leto 2008. Označene so periode osnovnih dnevnih in poldnevnih plimnih komponent.
Figure 2: *Fast Fourier power spectrum of astronomic tides in Koper in 2008. Principal tidal consitutents are identified on the spectrum along with their periods.*

Podrobna razlaga pomenov različnih komponent se nahaja na internetni strani http://www.math.sunysb.edu/~tony/tides/harmonic.html). Kot je vidno iz slike 2, ima M2 daleč največji vpliv. Izoliran člen M2 bi podal plimo, če bi lahko izločili vpliv Sonca in če bi Luna krožila v popolnem krogu okoli Zemljine ekvatorialne ravnine. Komponenta S2 opiše sončevo plimo, če bi bilo Sonce vedno v Zemljini ekvatorialni ravnini in bi bila orbita Zemlje popolna krožnica. Ker je Lunina orbita dejansko eliptična, je komponenta N2 korekcijski faktor za eliptično obliko. Diurnalne komponente K1, O1, P1 upoštevajo (med drugim) nagib Zemljine ekvatorialne ravnine glede na ravnino Lunine orbite. V času enega meseca je Luna približno dva tedna nad ekvatorjem in dva tedna pod njim. Do tega pride zaradi nagnjenosti Lunine orbite za 5,145 stopinje glede na Zemljino ekvatorialno ravnino. Ko je Luna nad Zemljino ekvatorialno ravnino, so plime na strani Zemlje, ki gleda proti Luni, višje od plim na nasprotni strani. V naslednjih 12 urah se Zemlja zavrti za 180 stopinj okoli svoje osi in stran, ki je prej gledala proti Luni, je zdaj na nasprotni strani, zato bodo plime tu nižje. Ko je Luna pod Zemljino ekvatorialno ravnino, je ta vzorec obraten. To razliko v višinah

The meanings of various constituents are as follows (see also http://www.math.sunysb.edu/~tony/tides/harmonic.html): as is clear from Figure 2, the M2 constituent has by far the largest coefficient. An isolated M2 term would give the tide if the solar influence could be neglected, and if the Moon orbited in a perfect circle in the Earth's equatorial plane. The constituent S2 accounts for the solar tide if the Sun was always in the Earth's equatorial plane and the Earth's orbit was a perfect circle. Since the Moon's orbit is actually elliptic, the N2 constituent is a correcting factor for this non-circularity. The diurnal constituents K1, O1, P1 take into account (among other things) the inclination of the Earth's equatorial plane with respect to the plane of the moon's orbit. During a month, the Moon spends approximately two weeks above the equator, followed by two weeks below. This is due to the 5.145 degree inclination of the Moon's orbit to the Earth's equatorial plane. When the Moon is above the Earth's equatorial plane, tides on the Earth's Moon-facing side will be higher than tides on the antipode side. In the next twelve hours the Earth will have rotated halfway about its axis, the side previously facing the Moon will rotate away to the opposite side, thus experiencing lower tides. When the Moon is below the izmenjujočih se plim imenujemo dnevna neenakost in je odvisna od Lunine deklinacije. Dvakrat mesečno, ko Luna v svojih vozlih prečka ekvatorialno ravnino, sta obe plimi približno enaki.

Pri naši analizi meritvam prilagodimo funkcijo vodostaja (enačba 1) z uporabo trigonometričnega prilagajanja po metodi najmanjših kvadratov. Parametra H_n in g_n prilagodimo tako, da minimiziramo kvadrat razlike med opazovanimi in izračunanimi plimami. Lastno nihanje vključimo v izračune tako, da dodamo eksponentno dušen harmonični člen (ki lahko vključuje polinomsko ovojnico), da dobimo

Earth's equatorial plane this pattern is reversed. This difference in height of alternate tides is called 'diurnal inequality' and is dependent on the declination of the Moon. Twice a month, when the moon crosses the equatorial plane, the two daily tides are roughly equal.

In the harmonic method of analysis we fit a sea-level function (eq. (1)) using a least-square method, i.e. we adjust the parameters H_n and g_n so that the squared difference between the observed and computed sea-levels is minimum. To include eigenoscillations (seiches) of the Adriatic Sea we add another exponentially decaying harmonic term (with an optional polynomial envelope) to obtain

$$\left[h(t)-\sum_{n=1}^{N}H_n\cos\left(\sum_{k=1}^{6}\frac{2\pi n_k}{\tau_k}\cdot t-g_n\right)-\sum_{k=1}^{\infty}p(t)e^{-t/T_k}\cos(\Omega_k t-G_k)\right]^2=minimum, \qquad (3)$$

kjer je $p(t)=at^2+bt+c$ polinom drugega reda, T_k je karakteristični čas dušenja k - tega lastnega nihanja , Ω_k je krožna frekvenca k - tega lastnega nihanja (k=1 je osnovno lastno nihanje vzdolž glavne osi jadranskega bazena) in G_k je faza k - tega lastnega nihanja. Parametre *a, b, c* ter Ω_k, T_k in G_k določimo z metodo analize najmanjših kvadratov, kot prikazuje enačba (3).

Primer take analize s trigonometričnim prilagajanjem na lastnem nihanju v Jadranu v času med 3. 3. 2008 in 1. 4. 2008 prikazuje slika 3. Zgornji del slike predstavlja opazovane residualne višine (razlike med izmerjenimi vrednostmi in astronomskimi prognozami $h_{res}=h_{meas}-h_{astr}$) skupaj s krivuljo prileganja (po metodi najmanjših kvadratov) eksponentno dušenega vala. Spodnji del slike prikazuje Močnostni spekter opazovanih residualnih višin, pridobljen z metodo FFT jasno izpostavi prevladujoče oscilacije s frekvenco 22,167 ur. FFT analiza je uporabna metoda določanje frekvenc harmoničnih komponent. Na sliki 3 je dominantna komponenta, ki prenaša največ valovne energije, označena z rdečim krogom.

Ena največjih pomanjkljivosti uporabe harmonične analize in trigonometričnega prilagajanja za napovedovanje lastnih nihanj visoke amplitude v Tržaškem zalivu je, da

where $p(t)=at^2+bt+c$ is a 2nd order polynomial, T_k is the typical decay time of the k - th seiche mode, Ω_k is the eigenfrequency of the k - th seiche mode (k=1 being the ground state oscillation along the principal axis of the Adriatic basin) and G_k stands for the k - th seiche mode phase shift. The parameters *a, b, c* along with Ω_k, T_k and G_k are determined using a least square analysis, as indicated in eq. (3).

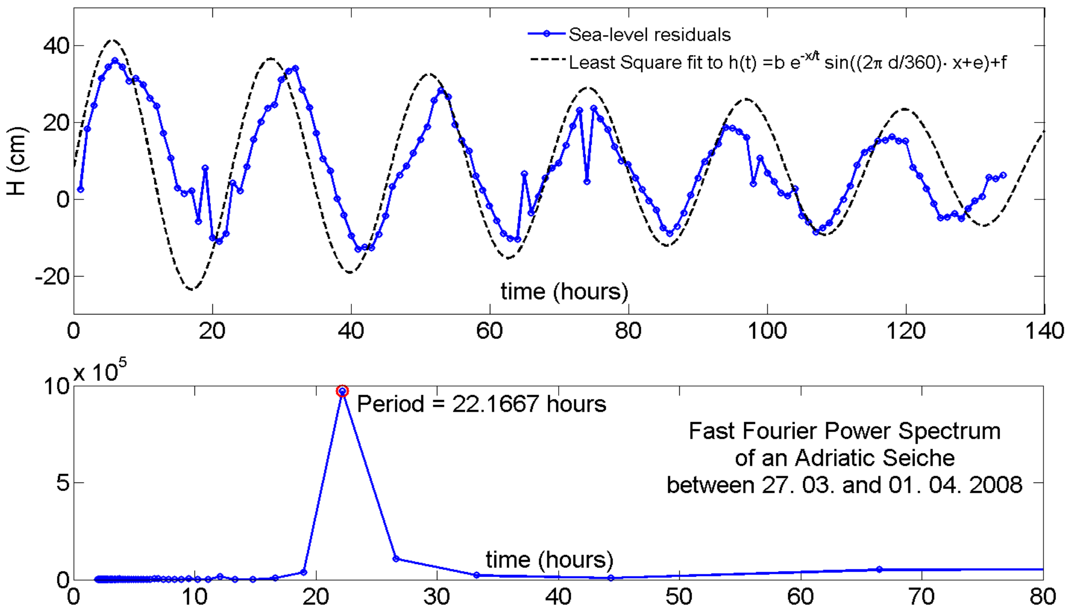
An example of harmonic analysis on an Adriatic seiche between March 3rd and April 1st 2008 is presented in Figure 3. The top panel presents sea-level residuals (differences between measured values and astronomic forecasts $h_{res}=h_{meas}-h_{astr}$) along with a least-square fit of an exponentially damped wave. The bottom panel illustrates fast Fourier transform (FFT) power spectrum of the sea-level residuals with a clearly identifiable ground state basin oscillation with the eigenfrequency of 22.167 hours. Fast Fourier analysis is useful for isolating frequencies of the harmonic constituents, as shown in Figure 3 where the dominant constituent frequency, which transports most of the wave energy, is marked with a red circle.

One of the major drawbacks of employing harmonic analysis to predict the high amplitude seiches in the Gulf of Trieste is that analiza ne more podati faznega premika residualne višine lastnega nihanja, brez katerega ni mogoče prognozirati lokalnih vodostajev morja. Ker so oscilacije Jadranskega morja dušene, nas najbolj zanima ravno čas prvega, najvišjega vrha amplitude stoječega vala. Tega pa z uporabo harmonične analize ne moremo doseči. V primerih, kjer so residualne višine tako velike, kot v Tržaškem zalivu, sta harmonična analiza ali trigonometrično prilagajanje neuporabna za prognozo plime.

Ker so vremenski vplivi in lastna nihanja v harmonično analizo (ki, kot je razvidno iz enačbe (3), že sama po sebi potrebuje številne skrbno umerjene modelske parametre, da so njene napovedi uporabne) vključena le posredno, se je ARSO odločil za izdelavo bolj zanesljivega orodja za napovedovanje vodostaja morja.

the analysis cannot yield the phase shift of the seiche residual height, which is critical to determine the time of the occurrence of the maximum local sea-levels. Since Adriatic Sea eigenoscillations are damped, we are most interested in the time of the first - and highest - seiche amplitude peak. Unfortunately this is something which cannot be obtained by harmonic analysis. It is useless for sea-level forecasting in areas where residuals from astronomically calculated forecasts are high, and the Gulf of Trieste is just such an area.

Since meteorological forcings and basin seiches are only indirectly included in the harmonic analysis (which - as seen from eq. (3) - in itself requires a large number of carefully tuned model parameters in order to make useful forecasts), EARS set out to design a more reliable sea-level forecasting service.



Slika 3: Trigonometrično prilagajanje in harmonična analiza na jasnem primeru stoječega vala v Jadranu med 3.3. in 1.4. 2008. Zgoraj: Opazovani residualni vodostaji skupaj s krivuljo prileganja eksponentno dušenega vala, izračunani po metodi najmanjših kvadratov. Spodaj: FFT spekter opazovanih residualnih vodostajev z jasno izraženo oscilacijo s frekvenco 22,167 ur.
Figure 3: Harmonic analysis on a clear example of a seiche in the Adriatic sea between March 3rd and April 1st 2008. ***Top:*** *Sea-level residuals along with a least-square fit of an exponentially damped wave.* ***Bottom:*** *Fast Fourier transform power spectrum of the sea-level residuals with a clearly identifiable ground state basin oscillation with eigenfrequency of 22.167 hours (marked with a red circle).*

Številne novejše študije (Tsai in Lee, 1999; Lee in Jeng, 2002; Deo in Chaudhari, 1998; Lee 2004; Zampato in sod., 2006; Vijay and Govil, 2006; Bajo in sod., 2008)) so pokazale, da lahko s pomočjo umetnih nevronskih mrež (artificial neural network) pomembno izboljšamo napovedovanje vodostaja, pod pogojem, da vnesemo ustrezne vhodne spremenljivke oz. prediktorje (predhodni vodostaji, zračni tlak, hitrost vetra, smer vetra, tablice plimovanja itd.)

2.2 METODA NEVRONSKIH MREŽ

Nevronska mreža je nestandarden statistični matematični model, ki temelji na bioloških nevronskih mrežah. Primerna je za analizo zelo nelinearnih procesov (gl. Hopfield in Tank, 1986; Tirozzi in sod., 2006). S pomočjo nevronskih mrež lahko v neregularnih in nenatančnih sklopih podatkov iščemo vzorce ter modeliramo kakršenkoli niz podatkov. Ponavadi so sestavljene iz medsebojno povezane skupine umetnih nevronov, ki procesirajo vhodne podatke in podajo izračunan odziv.

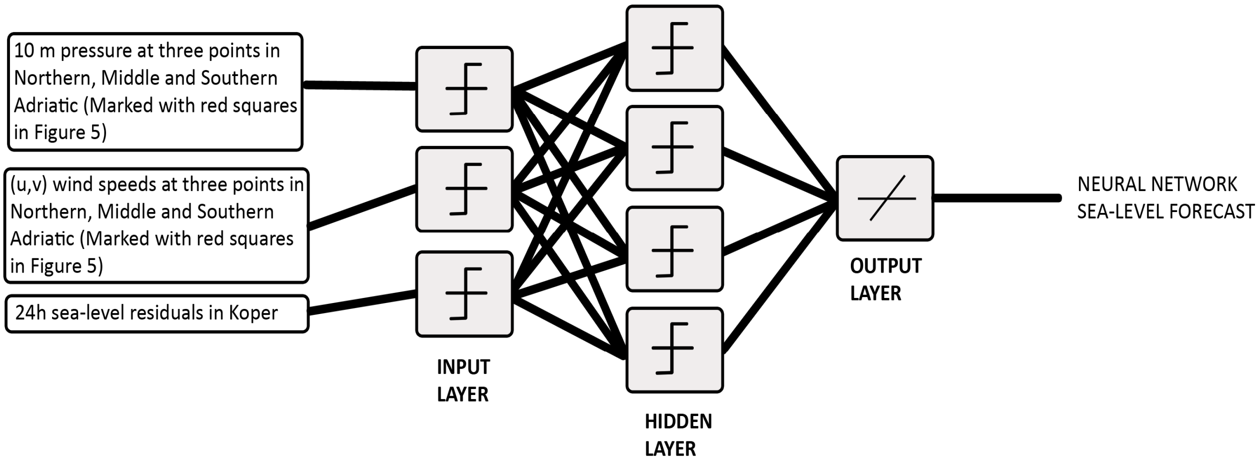
Nevronske mreže k reševanju računskih problemov pristopajo drugače kot konvencionalna harmonična analiza ali večina drugih matematičnih modelov fizikalnih procesov, ki za reševanje uporabljamo algoritmične pristope. Da bi lahko izdelali konceptualno sprejemljiv matematični model fizikalnega sistema, moramo poznati osnovne fizikalne procese, ki ta sistem določajo. Ta zahteva ponavadi omeji zmožnost reševanja na probleme, ki jih fizikalno že razumemo in znamo reševati. To pomeni, da skušamo opazovanja interpretirati na podlagi predhodno izdelanih teorij ter določiti, katere dele stare teorije je potrebno spremeniti, da bodo dobljeni teorijski rezultati bolj ustrezni meritvam.

A number of recent reports (e.g. Tsai and Lee, 1999; Lee and Jeng, 2002; Deo and Chaudhari, 1998; Lee 2004; Zampato et al., 2006; Vijay and Govil, 2006; Bajo et al., 2008) show that an artificial neural network (ANN) can greatly improve sea-level forecasts, providing it is supplied with suitable input variables or so-called predictors (i.e. previous water levels, air pressure, wind speed, wind direction, tide charts etc.)

2.2 NEURAL NETWORK APPROACH

An artificial neural network (ANN) is a non-standard statistical mathematical model based on biological neural networks convenient for fitting and analysis of highly nonlinear processes (Tirozzi et al., 2006). ANNs are immensely useful for extracting patterns from irregular and imprecise data sets and can be thought of as algorithms for modelling any given set of data. ANN typically consists of an interconnected group of artificial neurons which processes the input data to give the computed response.

Neural networks take a different approach to problem solving than that of conventional harmonic analysis or most conventional mathematical modelling of physical systems, where an algorithmic approach is employed to solve a problem. In order to make a conceptually feasible mathematical model of a physical system, we need to know the basic physics that governs the system of choice. This demand usually restricts the problem solving capability of conventional computers to problems that we already physically understand and know how to solve. This basically means that we are stretching the observations to previously formulated theories and then trying to determine which parts of theory are to be rewritten to yield more accurate outputs.



Slika 4: Zgradba nevronske mreže, uporabljene za napovedovanje vodostajev na mareografski postaji v Kopru. Prediktorji so bili naslednji: 1) 24 urna časovna vrsta residualnih višin z 12 urnim zamikom, 2) razlike zračnih tlakov pri tleh Δp_{12}, Δp_{13}, Δp_{23} kjer $\Delta p_{ij}=p_i-p_j$ in $p_{1,2,3}$ so zračni tlaki pri tleh na treh izbranih točkah na Jadranu (rdeči kvadrati na sliki 6), 3) zračni tlak pri tleh v Kopru z 12 urnim zamikom, 4) 24 urne napovedi vetra pri tleh modelov ECMWF in Aladin/SI za Koper z 12 urnim zamikom.

Figure 4: The architecture of an ANN employed to predict the water levels at the tide-gauge in Koper. The set of predictors was as follows: 1) a 24h Koper residual sea level timeseries with a 12h lag, 2) air pressure differences Δp_{12}, Δp_{13}, Δp_{23} *where* $\Delta p_{ij}=p_i-p_j$ *and* $p_{1,2,3}$ *are air pressures at three selected points over the Adriatic sea (red squares in Figure 5)) , 3) air pressure in Koper with a 12h lag, 4) 24h ECMWF and Aladin/SI model wind forecasts for Koper with a 12h lag.*

Opazovanje in prognoziranje plimovanja in lastnih nihanj v severnem Jadranu in v Tržaškem zalivu opisujejo številne znanstvene publikacije. Cerovečki in sod. (1998) na primer opisujejo pojav, razpad in izgubo energije jadranskega lastnega nihanja, Crisciani in sod. (1988) pa podajajo različne faktorje vsiljevanja, ki povzročajo spremembe vodostaja v Tržaškem zalivu. V zadnjem desetletju se je uporaba nevronskih mrež razširila tudi na napovedovanje vodostajev. Vaziri (1997) je uporabil modele nevronskih mrež za napovedovanje povprečnih mesečnih vodostajev Kaspijskega morja. Deo in Chaudhari (1998) sta z uporabo različnih algoritmov nevronskih mrež napovedovala plimna nihanja. Tsai in Lee (1999) ter Mandal (2001) so uporabljali nevronske mreže za napovedovanje urnih sprememb plimovanja, Lee in sod. (2002; Lee, 2004) pa za napovedovanje dolgoročnih plimovanj z uporabo kratkoročnih opazovanj plimovanja. El-Rabbany in El-Diasty (2003) sta zamenjala prej uporabljano harmonično analizo z

Sea-level and seiche observations and forecasts for the Northern Adriatic and in the Gulf of Trieste are described in numerous scientific papers. For example, Cerovečki et al. (1998) describe the occurrence, decay and energy loss of the Adriatic seiche while Crisciani et al. (1988) discuss various forcing factors resulting in the sea-level oscillations of the Gulf of Trieste. During the last decade, the use of the neural network approach found place in predicting sea-levels and is described by several authors. Vaziri (1997) used ANN based models to predict the mean monthly levels of the Caspian Sea. Deo and Chaudhari (1998) predicted tidal oscillations of water level using different ANN algorithms. Tsai and Lee (1999) and Mandal (2001) used back-propagation neural networks to forecast the hourly sea-level variation. Lee (Lee et al., 2002; Lee, 2004) applied ANN based models to predict long-term sea-levels using short-term observations. El-Rabbany and El-Diasty (2003) replaced the former batch harmonic analyses with an ANN based model for modelom nevronskih mrež v namen sekvenčnega prognoziranja višin plimovanja z uporabo natančnih podatkov, pridobljenih na različnih merilnikih.

Neurni valovi so bili opaženi vzdolž celotne obale severnega Jadrana. Do najvišjih vodostajev prihaja v Beneški laguni in iz Benetk in Chioggie prihaja mnogo poročil o ekstremnih vodostajih. V Gradeški laguni in Trstu so taki dogodki redkejši.

Napovedovanje vodostajev v jadranskem morju je težavno predvsem zato, ker še ne razumemo povsem vseh fizikalnih dejavnikov, ki nanje vplivajo. Za dinamične enačbe, ki opisujejo fizikalne procese v morjih in oceanih, še nimamo strogih formalnih izpeljav (Tirozzi in sod., 2006). Najpomembnejša prednost nevronskih mrež je v tem, da nam fizikalnih podrobnosti sistema, ki ga skušamo modelirati, ni potrebno poznati, saj imajo nevronske mreže sposobnost učenja na empiričnih podatkih in lahko podajo »dovolj dobro« rešitev glede na vhodne podatke. To dosežemo tako, da prilagajamo notranjo strukturo mreže v skladu z algoritmi, ki minimizirajo razdaljo med ciljnim vektorjem (meritvijo) in odzivom nevronske mreže. Proces učenja je močno odvisen od izbire prediktorjev – parametrov, za katere verjamemo, da ključno vplivajo na ciljni vektor.

V pričujočem delu smo tri-nivojski model nevronske mreže (slika 4) uporabili za analizo visoke plime iz decembra 2008 ter skušali napovedati vodostaje na mareografski merilni postaji v Kopru. Nevronske mreže tipa feed-forward (slika 4) omogočajo potovanje signalov samo v eno smer, od vhodnih do izhodnih. V sistemu ni povratnih zank. Ponavadi gre za enostavne mreže, ki povezujejo vhodne podatke z izhodnimi preko skritega nivoja, kot prikazuje slika 4. Vsaki povezavi med i-tim in j-tim nevronom pripišemo statistično utež w_{ij}, tako da lahko shematično zapišemo, da je izhodni podatek za vodostaj $h_{ANN}(t)$ povezan z vhodnimi parametri f (kjer je f katerikoli vhodni prediktor – tlak, veter itd.) tako:

sequentially predicting the sea-level heights using sea-level data series collected at various tide gauges with high accuracy.

Storm surges have been observed almost everywhere along the Northern Adriatic coast. The peaks reach their maximum in the Venetian Lagoon and many extreme events are reported in Venice and Chioggia, while such events are less frequent in Grado and Trieste.

One of the basic problems with sea-levels in the Adriatic is that the impacts of all the physical phenomena to the sea-level variations are still not understood with desired theoretical rigor. Dynamic equations that govern the evolution of seas and oceans do not yet have stringent formal derivations (Tirozzi et al., 2006). The main advantage of neural networks lies in the fact that one need not know the physical details of the system one is trying to simulate using an ANN. This is due to its capability to learn how to produce a "good enough" solution from its input data. This is obtained by adjusting the internal structure of the network in accordance with algorithms which minimize the distance between the target (the desired response vector) and the actual ANN response vector. The learning process depends crucially on our choice of a set of predictors – parameters which we believe to have a significant impact on the behaviour of the target vector.

In the present work a three-layer feed-forward ANN (see Figure 4) was employed to analyze a storm surge event in early December 2008 and to forecast sea-levels at the tide gauge in Koper. Feed-forward ANNs (Figure 4) allow signals to travel only one way; from input to output. There is no feedback in the system. Feed-forward ANNs tend to be straightforward networks that associate inputs with outputs via a hidden layer, as shown in Figure 4. Each connection between i-th and j-th neuron is assigned a statistical weight w_{ij} so we can schematically write that the ANN output for sea-level $h_{ANN}(t)$ is related with ANN inputs f (where f stands for any input predictor; pressure, wind etc.) as follows:

$$h_{ANN}(t) = \sum_{i,j} w_{ij} f_i . \tag{4}$$

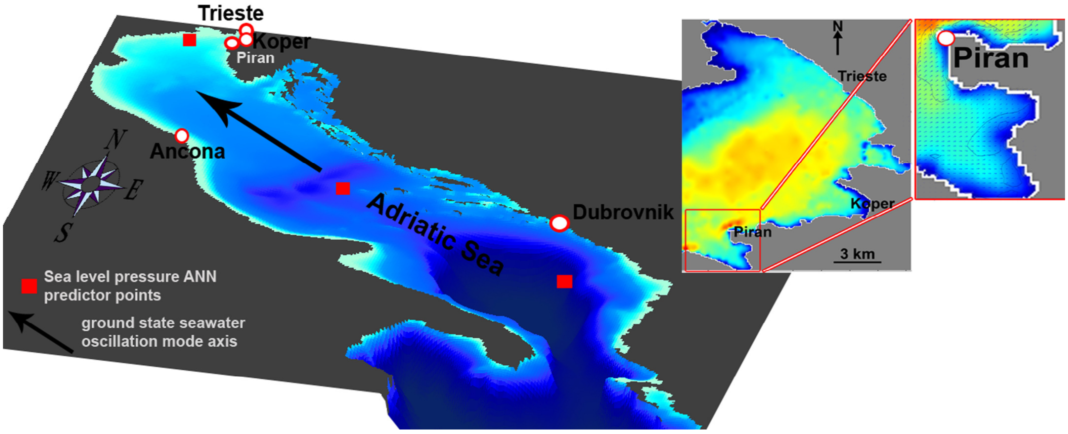
Med procesom učenja v nevronsko mrežo vnesemo naše izbrane prediktorje in opazovane vodostaje $h(t)$ v Kopru. Nato poiščemo takšno matriko statističnih uteži w_{ij}, da velja:

During the training process we supply the ANN with our choice of predictors and with the observed sea-levels $h(t)$ in Koper. The training process then consists of finding such a statistical weight matrix w_{ij} that

$$\text{napaka/error} = \overline{|\,h(t) - h_{ANN}(t)\,|^2} = \frac{1}{N}\sum_{i,j} |\,h(t) - w_{ij} f_i\,|^2 = \text{minimum.} \tag{5}$$

Poznamo številne učinkovite metode najmanjših kvadratov za minimizacijo napake (v tem delu predstavljamo rezultate uporabe minimizacijskega algoritma Levenberg-Marquardt; podrobni opisi metod najmanjših kvadratov se nahajajo v delih Kreyszig (2005) in Tirozzi in sod. (2006)). Ko najdemo minimum, imamo mrežo za naučeno. Takrat jo lahko uporabimo za izračun simuliranega odziva, ki nam služi kot napoved časovne vrste parametra, ki ga mreža simulira. Prognoza z nevronsko mrežo je preprosto odgovor naučene mreže $h_{ANN}(T)$ na prognozirane vhodne podatke (prognoze tlaka in vetra meteoroloških modelov ALADIN ali ECMWF, tablic plimovanja itd). Kakovost napovedi je seveda odvisna od relevantnosti in točnosti vhodnih podatkov.

There are several effective methods of least-square error minimization (in this paper the Levenberg-Marquardt minimization algorithm results are presented; for details on least-square methods see references (Kreyszig, 2005; Tirozzi et al., 2006)) and once the minimum is found the network is considered to be trained. Once the ANN is trained it can be used to provide a simulated response which serves as a time-series forecast of the parameter it was trained to simulate. A neural network forecast is simply trained network's response $h_{ANN}(T)$ to the forecasted input data (pressure and wind forecasts from ALADIN or ECMWF meteorological models, tide tables etc.) The quality of the forecast depends on the relevance and accuracy of the input data.



Slika 5: Jadransko morje z označenim gibanjem stoječega vala (črna puščica) ter podatkovnimi točkami zračnega tlaka in vetra iz modela ECMWF (rdeči kvadrati). Manjša slika prikazuje površinske tokove med stoječim valom v bližini Piranskega polotoka, izračunane z modelom PcFlow3D.

Figure 5: Adriatic sea with marked seiche water movement (black arrow) and air pressure and wind data points from the ECMWF model (red squares). The inset shows surface currents during the seiche in the vicinity of Piran peninsula calculated with the PcFlow3D model.

3. ŠTUDIJA PRIMERA: NEURNI VAL V TRŽAŠKEM ZALIVU DECEMBRA 2008

Model nevronskih mrež, izdelan na ARSO, je bil uporabljen za izračun vodostajev med dogodkom izredno visoke plime na slovenski obali decembra 2008 (slika 1). Naš sklop vhodnih podatkov (prediktorjev) je bil naslednji: 1) 24 urna časovna vrsta residualnih višin v Kopru z 12 urnim zamikom, 2) razlike zračnih tlakov pri tleh Δp_{12}, Δp_{13}, Δp_{23} kjer je $\Delta p_{ij}=p_i-p_j$, $p_{1,2,3}$ pa so zračni tlaki pri tleh na treh izbranih točkah na Jadranu (rdeči kvadrati na sliki 5), 3) zračni tlak pri tleh v Kopru z 12 urnim zamikom, 4) 24 urne napovedi vetra pri tleh modelov ECMWF in Aladin/SI za Koper z 12 urnim zamikom. Nevronsko mrežo smo učili na urnih vodostajih iz mareografske postaje Koper ter na 3-urnih podatkih za vse zgoraj navedene prediktorje v obdobju med 1. januarjem 2005 in 1. septembrom 2008. Neurni val, predstavljen v tej študiji, ni bil vključen v podatke za učenje.

Vsi vhodni podatki imajo ločljivost 1 uro in zamike več kot 12 ur. Zamik podatkov pomeni, da moramo za to, da naučena mreža izračuna napovedi ob času *t*, vnesti prediktorje časovne vrste ob časih t-12h, t-13h,...,t-36h.

Opis vremenskega stanja med 30. 11. in 2. 12. 2008 je sledeč (slika 6): močan Azorski anticiklon je preprečeval zonalni zračni tok v troposferi, nad Francijo pa se je zadrževalo dolgotrajno ciklonsko območje. Severni zračni tokovi nad Biskajskim zalivom so se nad Mediteranom obrnili v zahodnike in nato kot jugovzhodni vetrovi pihali nad Jadranom. Nad Biskajskim zalivom so se pojavljala zaporedna ciklonska območja, ki so se hitro pomikala nad Sredozemlje in naprej nad vzhodno Evropo.

Prišlo je do neobičajne situacije, saj so se nad severnim Jadranom zvrstila tri ciklonska območja z zračnim tlakom pri tleh manj kot 1000 milibarov s frekvenco približno vsakih

3. CASE STUDY: EXTREME STORM SURGE IN THE GULF OF TRIESTE IN EARLY DECEMBER 2008

An ANN model developed at the EARS was employed to hindcast the sea-levels during an extreme storm surge event on the Slovenian coast in early December 2008 (see Figure 1). Our set of input data - or predictors - was as follows: 1) 24h Koper residual sea level time series with a 12h lag, 2) air pressure differences Δp_{12}, Δp_{13}, Δp_{23} where $\Delta p_{ij}=p_i-p_j$ and $p_{1,2,3}$ are pressures at three selected points shown in Figure 5 as red squares over the Adriatic sea, 3) air pressure in Koper with a 12h lag, 4) 24h ECMWF and Aladin/SI model wind forecasts for Koper with a 12h lag. Our ANN was trained on (hourly) sea-level datasets from Koper sea-level gauge and (3-hourly) datasets of the rest of the predictors specified above between January 1st 2005 and September 1st 2008. The storm surge mentioned in this case study was not included in the training set.

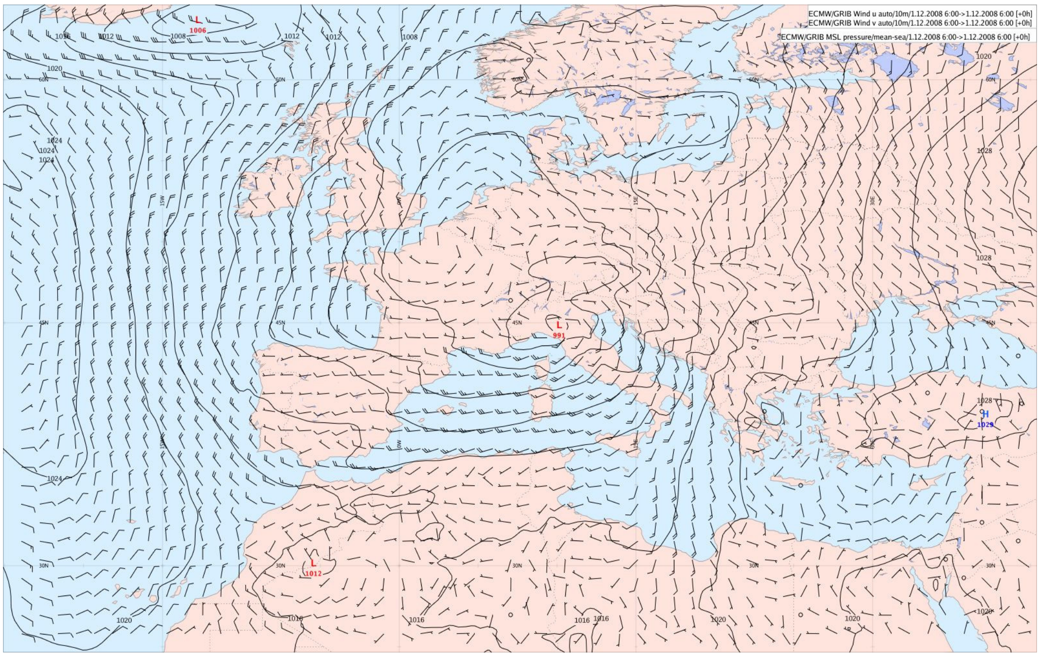
All the predictor data have a 1-hour resolution and a lag of 12 hours. Data lagging means that in order to use the pre-trained ANN to compute the forecast at time *t*, we feed the network with the above mentioned time-series predictor inputs at times t-12h, t-13h,...,t-36h.

Description of the weather situation between 30th November and 2nd December 2008 is as follows (see Figure 6). Strong Azores anticyclone was blocking zonal circulation and there was a persistent low pressure over France causing North flow over Bay of Biscay turning to West flow over West Mediterranean and SE over the Adriatic. There were pressure lows forming in the North flow over Bay of Biscay in a row and passing east into the Mediterranean very quickly and then further to Eastern Europe.

The situation was relatively unusual because there were three cyclones with pressure less than 1000 hectopascals passing the region of Northern Adriatic roughly 25 hours one after the other. This is close enough to the ground state eigenfrequency (≈ 22 hours, Figure 3) of the Adriatic Sea along its principal axis. Due to lows in the Northern Adriatic

25 ur, kar je blizu frekvenci osnovnega lastnega nihanja Jadranskega morja vzdolž glavne osi (približno 22 ur, slika 3). Cikloni so prinašali izmenjujoče se močne JV in JZ vetrove: nizek zračni tlak je v kombinaciji z lastnim nihanjem zaradi jugovzhodnega vetra povzročil 25 urno resonančno modulacijo residualnih višin z veliko amplitudo. To je pokazala tudi FFT analiza, kot je prikazano na sliki 7 (spodaj).

there were exchanging strong SE and SW winds: SE wind in the middle Adriatic and SW winds in the north enhanced the resonance effect: air pressure lows coupled with an existing SE wind-enforced seiche generated a 25 hour high amplitude modulations of sea-level residuals, which is clear from residual fast Fourier analysis depicted in Figure 7 (bottom).

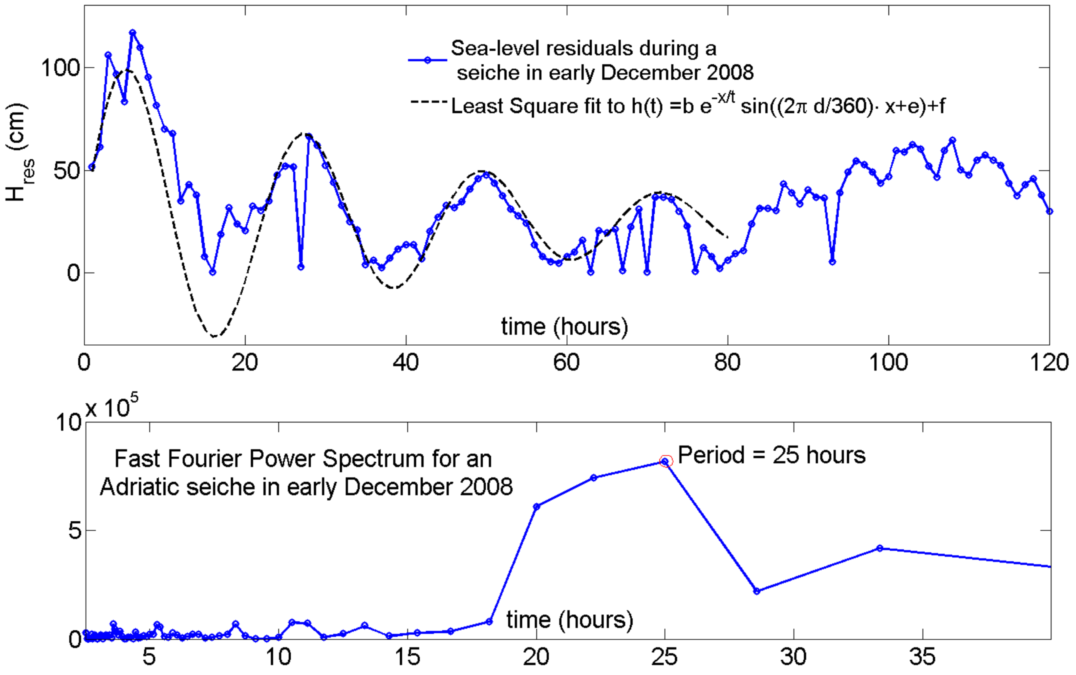


Slika 6: Vremenska analiza iz podatkov modela ECMWF za 1.12.2008 ob 6:00 UTC s povprečnim zračnim tlakom pri tleh in 10m vetrom. Ciklonski jugovzhodni vetrovi, ki so povzročali visoko amplitudo stoječega vala, so jasno vidni nad jadranskim bazenom.
Figure 6: Weather analysis from ECMWF model data for the 1st December 2008 06 UTC with mean sea level pressure and 10m winds. Cyclonic SE winds, responsible for the high amplitude of the seiche are clearly visible over the Adriatic basin.

Zgornji del slike 7 prikazuje rezultate trigonometričnega prilagajanja z metodo najmanjših kvadratov na primeru lastnega nihanja v Jadranskem morju v obdobju med 05h UTC 1. 12. in 13h UTC 3. 12. 2008. Najvišji vodostaj je nastopil ob 10h UTC 1. decembra. Residualne višine smo prilagodili eksponentno dušenemu nihanju. Na spodnjem delu slike 7 je FFT spekter opazovanih residualnih vodostajev z jasno vidno vsiljeno frekvenco prehodnih ciklonov 25.0 ur. Ker je

Top panel of Figure 7 shows harmonic analysis on the case-study seiche in the Adriatic Sea between December 1st (05h UTC) and December 3rd 2008 (13h UTC). The maximum observed sea-level occurred at 10h UTC December 1st. Sea-level residuals were fitted with an exponentially damped wave. The bottom panel of Figure 7 illustrates fast Fourier transform power spectrum of the observed sea-level residuals with a clearly identifiable forcing frequency of the passing ta frekvenca siljenja tako blizu frekvenci osnovnega lastnega nihanja, ki ga povzroča jugovzhodnik (22 ur), je bila posledica teh dogodkov 50-letna plima v Piranu s katastrofalnimi posledicami (slika 1).

frontal systems at 25.0 hours. Since this particular forcing frequency is close to the Adriatic seiche eigenfrequency (22 hours), the result was a 50-year sea-level high in Piran with disastrous consequences (Figure 1).

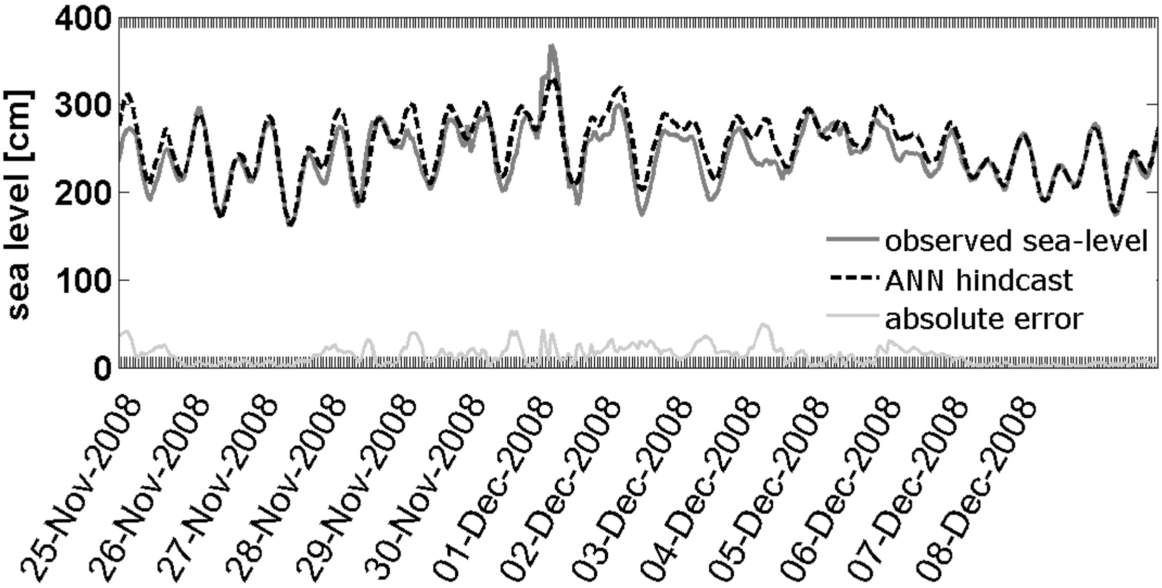


Slika 7: Trigonometrično prilagajanje in harmonična analiza na jasnem primeru lastnega nihanja v Jadranskem morju med 1.12. 2008 (05h UTC) in 3.12.2008 (13h UTC). **Zgoraj:** Opazovane residualne višine skupaj s krivuljo prileganja eksponentno dušenega vala po metodi najmanjših kvadratov. **Spodaj:** FFT spekter z dominantnim vrhom v času 25 ur kaže, kako je prehod frontnih sistemom vplival na residualne višine.so jasno vidni nad jadranskim bazenom.
Figure 7: Harmonic analysis on a clear example of a seiche in the Adriatic sea between December 1st (05h UTC) and December 3rd 2008 (13h UTC). Maximum observed sea-level occurred at 10h UTC December 1st. ***Top:*** *Sea-level residuals along with a least-square fit of an exponentially damped wave. The values of the fitted parameters are stated in the text.* ***Bottom:*** *Fast Fourier transform power spectrum with a dominant peak at a 25 hour period indicates how sea-level residuals were influenced by the passing frontal systems.*

25-urni vrh na FFT spektru na sliki 7 potrjuje, da je prišlo do resonančne sklopitve dveh mehanizmov: 1) lastnega nihanja (zaradi JV in JZ vetrov) s frekvenco približno 22 ur in 2) prehodov ciklonov z nizkim zračnim tlakom s frekvenco približno 25 ur. To je pripeljalo do najvišjega vodostaja (slika 1), ki se je zgodila 1. 12. 2008 zjutraj ob 10h UTC, ko je drugi zaporedni ciklon potoval preko severnega Jadrana. Napoved nevronske mreže na podlagi

The 25-hour peak on the power spectrum of Figure 7 confirms the resonant coupling of two mechanisms: 1) southern (SE and SW) wind-generated seiche with a peak frequency at roughly 22 hours and 2) a peak frequency of roughly 25 hours due to the consecutive passing of three frontal lows. This led to the highest sea-levels (see Figure 1) which occurred at 10h UTC on December 1st when the second of the lows was passing Northern Adriatic. Neural Network forecast based on the 12-hour lagged data from the ECMWF podatkov iz meteorološkega modela ECMWF z 12-urnim zamikom je prikazana na sliki 8. Temno siva črta predstavlja izmerjene vrednosti vodostajev, črtkana črna črta kaže rezultate nevronske mreže in svetlo siva črta kaže absolutno napako napovedi (abs. napaka = |napoved nevronske mreže – merjeni vodostaj|) v centimetrih.

meteorological model is presented in Figure 8. The dark gray curve shows the measured sea-level values, the dashed black line presents the trained ANN response to the ECMWF data predictors, while the light gray line at the bottom presents the absolute error of prediction (abs. error = |ANN hindcast – observed values|) in centimeters.



Slika 8: Prognoze nevronske mreže na podlagi podatkov meteorološkega modela ECMWF z 12-urnim zamikom. Temno siva črta predstavlja izmerjene vrednosti vodostajev, črtkana črna črta kaže rezultate nevronske mreže in svetlo siva črta kaže absolutno napako napovedi.
Figure 8: Neural Network forecast based on the 12-hour lagged data from the ECMWF meteorological model. The grey curve shows the measured values, the dashed black line represents the trained network response to the ECMWF data, while the light grey line at the bottom depicts the absolute error of prediction in centimetres.

4. ZAKLJUČKI IN NADALJNJE DELO

Nevronska mreža daje obetavne rezultate, vendar smo pri simulacijah ozkih vrhov v časovni vrsti vodostajev opazili nekatera neskladja. Tudi v svoji sedanji, preprosti obliki lahko model nevronske mreže daje boljše napovedi kot metode harmonične analize ali linearne regresije, ki so bile doslej v uporabi na ARSO. Nevronska mreža namreč služi kot prognostični model za višine morja v Tržaškem zalivu, česar za harmonično analizo

4. CONCLUSIONS AND FURTHER WORK

The artificial neural network yields promising results although the simulations of the narrow peaks in the sea-level time-series show certain disagreements. The model can - rudimentary as it is - yield better results than harmonic and linear regression methods used at the EARS thus far. For one, ANN can serve as a true forecasting model which is hardly the case with the former approaches. It is clear from the results shown in Figure 8 that in in linearno regresijo ne moremo trditi. Iz rezultatov na sliki 8 je jasno razvidno, da lahko v določenih časovnih intervalih nevronska mreža napoveduje vodostaj z napako, ki je manjša od 10 cm. Tak primer je obdobje med 25. 11. in 28. 11. ter obdobje po 5. 12. To je verjetno posledica nizkih residualnih vodostajev v teh časovnih intervalih in potrjuje, da je model nevronske mreže sposoben zanesljivih simulacij astronomskega plimovanja. V času večjih residualnih višin pa so rezultati veliko manj točni in absolutna napaka ponekod dosega več kot 40 cm. To ni presenetljivo, saj je nevronska mreža statistična metoda, ki bolj uteži povprečna dogajanja in pri kateri se ekstremni primeri manj upoštevajo. To sicer predstavlja problem, že zdaj pa je jasno, da odziv nevronske mreže kljub manjši natančnosti ob ekstremnih dogodkih dovolj jasno nakazuje možnost neurnega vala – prav to pa je tisto, kar ARSO potrebuje od svojih prognostičnih orodij, da lahko v primeru ekstremnih dogodkov ustrezno organizira odziv in komunikacijo z javnostmi. Pričakujemo, da bo model nevronske mreže pridobil na zanesljivosti napovedi, če bo učen na veliko večjem številu primernih podatkov. Potrebno količino učnih podatkov in posledično izboljšanje napovedi je seveda težko oceniti. V učni proces bomo vključili prihodnje podobne dogodke. Bolj točne napovedi pričakujemo v nekaj letih, kar je odvisno predvsem od števila izrednih dogodkov na območju Tržaškega zaliva.

Trenutno je čas, potreben za izračun napovedi za naslednjih 24 ur, približno dve uri. Tudi brez nadaljnje optimizacije je to razmerje uporabno. V razvojni fazi pa je tudi izdelava ansambla nevronskih mrež, ki nam bo omogočil izračun ansambelskega povprečja odzivov posameznih mrež in bo, če bo operativen, Agenciji za okolje omogočal zanesljivejše napovedi in hitrejši prenos informacij vsem zainteresiranim.

certain time intervals the ANN is able to yield a sea-level forecast with errors below 10 cm. Periods between November 25th and November 28th and the one following December 5th can serve as an example. This is probably due to small residual heights at those times and is a demonstration that ANN is able to reliably mimic astronomic tides. During higher residual periods however, the results are much less accurate, with the absolute error at times ascending over 40 cm. This is not surprising since ANN is a statistical method which tends to cancel out extreme cases during ANN training and is therefore less suitable for simulations of situations where meteorological forcings are considerable. This is a problem which demands further attention but it is already clear that neural networks are a useful tool nevertheless: while they do not (yet) provide an accurate quantitative forecast, their forecasts do qualitatively indicate a possibility of a storm surge – and this is a step in the right direction in terms of what EARS needs in order to organize its emergency response and its communications to the affected public. An ANN model is expected to behave much more accurately after having been trained on a substantially larger set of appropriate data. However, the necessary amount of data and the resulting increase in accuracy are difficult to predict. Future storm-surge events will be included into the learning process. We expect to significantly increase the reliability of the model in a few years, depending on the number of such events in the Gulf of Trieste.

Currently the computing time needed to calculate the forecast for the coming 24 hours is roughly 2 hours. Even without further optimization this is a useful ratio. We are, however, working on an assembly of neural networks which will enable us to compute an ensemble average of the network responses and will, once operational, enable EARS to produce more reliable and accurate forecasts and rapidly disseminate the information to all concerned.

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