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Correction to "North Adriatic tides: observations, variational data assimilation modeling, and linear tide dynamics"

Jeffrey W. Book[1], *Henry Perkins*[2] *and Mark Wimbush*[3]

[1] Naval Research Laboratory, Stennis Space Center, U.S.A.

[2] University of Maine, Darling Marine Center, Walpole, U.S.A.

[3] University of Rhode Island, Graduate School of Oceanography, Narragansett, U.S.A

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A precision/round-off error has been discovered in the tidal analysis routines used in the paper "North Adriatic tides: observations, variational data assimilation modeling, and linear tide dynamics" by J. W. Book, H. Perkins, and M. Wimbush (2009, *Geofizika*, **26**, 115–143). Tidal elevation phases for 12 of the 15 stations are, on average, too low by 3.9° for the diurnal constituents and 7.9° for the semidiurnal constituents in Tabs. 4 and 5. These tables have been corrected and are republished here.

The error also had an effect on the input data used for the linear variational data assimilation model, and combined with a nearest neighbor interpolation scheme produced an approximate 15 minute forward shift in time for 6 of the 43 synthesized tidal records. The error produced final model solutions that had tidal elevation phases 3.5° too high for M_2, 1.6° too high for K_1, and similar matching phase shifts for other semidiurnal and diurnal constituents. The errors in the input data have been corrected, the interpolation scheme has been changed to a piecewise cubic spline method, and the model runs have all been redone.

The new model results suggest a minor change in optimal friction parameter, which in turn alters model Q factors and dissipation. However, the original finding that these values are not well determined by this methodology remains true. Model and observational results originally shown in Figs. 5–7 and Figs. 13–14 have slightly changed and are republished here. The main conclusions from the original work regarding Kelvin waves and TRW dynamics for the North Adriatic basin remain unaltered by these corrections.

1. Measurements

In a recent effort to compare altimeter-based tide models to observations of tides from bottom pressure measurements around the globe, Richard Ray discovered some discrepancies in Tabs. 4–5 published in the paper “North Adriatic tides: observations, variational data assimilation modeling, and linear tide dynamics” by J. W. Book, H. Perkins, and M. Wimbush (2009, *Geofizika*, **26**, 115–143) compared to the model results shown in Figs. 5–8. Upon further investigation by the authors, a precision/round-off error was found in the input/output (i/o) MATLAB® interface code used to initiate the FORTRAN code that performed the Response Method tidal analyses used in this paper. The i/o code used only four decimal places for the time series time step in hours, and thus there was a corresponding loss of time precision if the time step for the data was a repeating decimal, irrational number, or otherwise not accurately expressed when rounded to a precision of 0.0001 hours.

For a majority of the data used in Book et al. (2009a), the time step was 1/4th of an hour and this flaw did not have any effect. Unfortunately, 12 of the 15 bottom pressure fluctuation time series had time steps of 20 minutes and the rounding off of 1/3rd of an hour did have an effect. The i/o error caused a gradual loss of time in the analyzed time series which accumulated to a total loss of 32 minutes over the typical 7.5 month time series length. The result was phase compression that varied between zero at the start of the record to 32 minutes lag at the end of the record. Therefore the Response Method analysis code produced tidal phases that were lagged by approximately 16 minutes from the true phases. This

Table 4. Calculated tidal amplitudes (amp.) and phases (pha.) in cm and degrees respectively, for the JRP moorings on the SS line (Fig. 1). The phases are the Greenwich phase lags according to the convention given by Foreman (1977). Numbers given in red have been corrected.

	SS2	SS4	SS5	SS6	SS8	SS9	SS10
O_1 amp.	4.22	4.17	4.16	4.14	4.09	4.10	4.10
O_1 pha.	52.6	53.7	50.8	49.3	42.8	38.0	35.3
P_1 amp.	4.27	4.20	4.23	4.23	4.20	4.21	4.17
P_1 pha.	67.5	67.3	65.0	63.3	55.8	51.1	49.2
K_1 amp.	13.46	13.32	13.33	13.32	13.25	13.27	13.17
K_1 pha.	70.7	70.1	68.1	66.4	58.8	54.1	52.0
N_2 amp.	1.48	1.41	1.37	1.34	1.32	1.44	1.54
N_2 pha.	284.7	280.6	277.1	271.3	244.2	228.5	222.2
M_2 amp.	8.07	7.78	7.55	7.37	7.21	7.82	8.22
M_2 pha.	285.2	281.6	277.4	271.5	243.1	226.3	220.4
S_2 amp.	4.73	4.51	4.39	4.26	4.08	4.38	4.53
S_2 pha.	292.6	289.1	284.8	278.8	249.1	231.5	224.5
K_2 amp.	1.32	1.25	1.22	1.18	1.13	1.21	1.25
K_2 pha.	293.3	289.7	285.5	279.5	249.8	232.2	225.1

Table 5. As in Tab. 4, but for the JRP moorings on the CP, KB, and VR lines (Fig. 1).

	CP2	CP3	KB1	VR1	VR2	VR4	VR5	VR6
O_1 amp.	4.67	4.62	4.28	5.16	5.10	5.01	4.97	4.89
O_1 pha.	48.9	47.0	36.8	43.4	45.5	43.9	42.1	39.8
P_1 amp.	4.81	4.76	4.46	5.90	5.35	5.20	5.12	5.03
P_1 pha.	63.1	60.5	49.9	58.9	59.7	57.8	56.0	53.5
K_1 amp.	15.17	14.99	14.05	18.30	16.82	16.34	16.08	15.81
K_1 pha.	66.2	63.6	53.0	61.7	63.1	60.9	59.0	56.5
N_2 amp.	2.55	2.45	2.03	3.93	3.93	3.71	3.52	3.28
N_2 pha.	265.4	259.7	227.9	258.1	257.3	253.3	249.1	243.6
M_2 amp.	14.60	13.93	11.29	23.50	22.73	21.24	20.10	18.74
M_2 pha.	265.8	259.2	226.7	259.5	257.8	253.4	249.1	243.3
S_2 amp.	8.78	8.33	6.52	14.49	13.87	12.89	12.14	11.25
S_2 pha.	272.0	265.3	231.8	265.2	263.7	259.3	255.0	249.2
K_2 amp.	2.44	2.31	1.81	4.02	3.85	3.58	3.37	3.13
K_2 pha.	272.6	266.0	232.4	265.7	264.2	259.9	255.6	249.8

error in analysis has now been corrected by re-analyzing all time series using eight decimal places for the time step in hours instead of four. Tables 4–5 are reprinted here with corrections for the 12 affected sites highlighted in red. Phase increases from the original published values are on average 3.9° for the diurnal constituents and 7.9° for the semidiurnal constituents. Amplitude changes are small for all constituents, increasing on averaging only 0.03 cm.

The 15 velocity time series and remaining 3 bottom pressure time series with 15 minute sampling were all also re-analyzed. As expected, no significant changes from the original published values were found. The only value that changed with regard to the published table precision was the N_2 tidal-current phase for site S4, which went from a value of 173.147 to a value of 173.162 due to a 5 second drift in time over the record length. This change is not significant, so Tabs. 2–3 are not reprinted in this correction.

2. Linear, variational data-assimilation model

The data-assimilation modeling in Book et al. (2009a) relied on the tidal solutions from the Response Method analysis and is therefore also affected by this error. In the synthesis of tidal time series, the former i/o code assigned the output from the Response Method to the original time values. Therefore time series with phases that were too low were gradually stretched by this assignment, and the resulting tidal time series lagged the true tide at the beginning of the record, had near zero phase lag in the middle of the record, and led the true tide at the end of the record. The model used only a two month subset of the tide records taken from the second half of the records, and therefore the data input had phases that were too high rather than too low. The error was further complicated by use of a nearest neighbor interpolation of the time series in order to align the bottom pressure fluctuations to a single time basis chosen to match closely the time basis of the current measurements. This nearest neighbor interpolation creates the potential for an additional maximum ±10 minute random

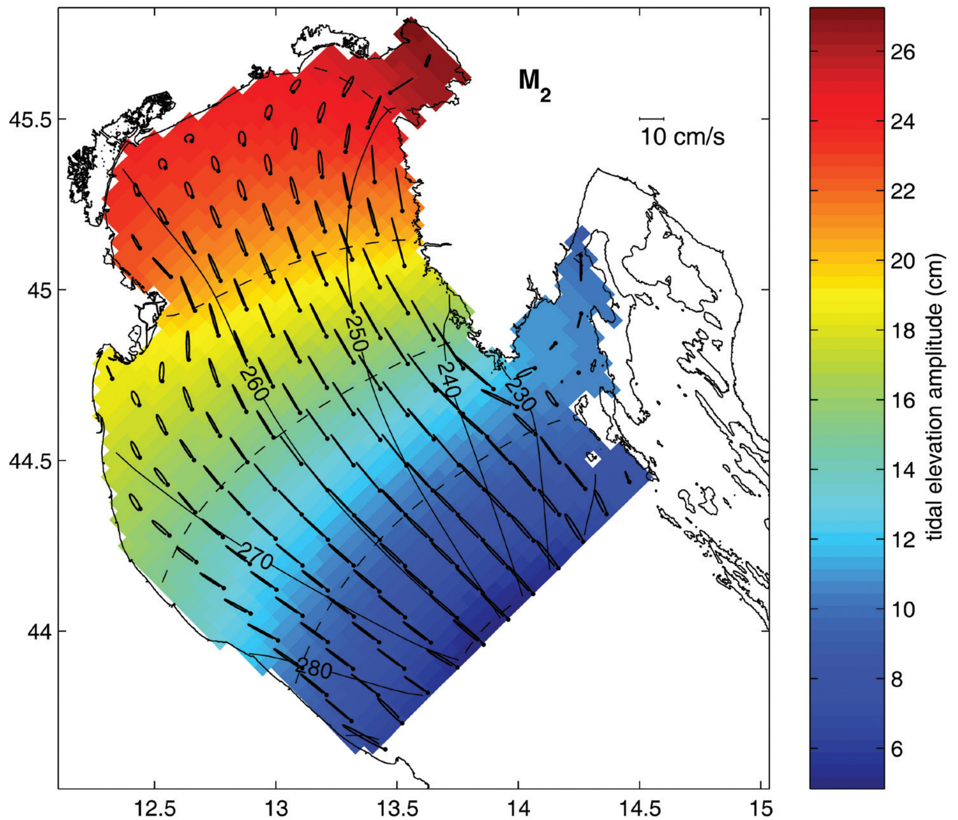

Figure 5. M_2 co-range and co-tidal map and tidal current ellipses from the data-assimilation model. Dashed lines are co-range lines (contour interval 5 cm) and bold solid lines are co-phase lines with GMT phase lag labels in degrees. M_2 sea-surface elevation amplitudes are also indicated by the color field. Only every third ellipse in both the along- and across-axis directions of the Adriatic is shown for graphical clarity. The velocity scale for the ellipses is indicated in the upper right. Tidal currents rotate from the dot (time of the transit of the fictitious star) to the gap.

time shift in the pressure time series records used by the model. At some sites (SS2, SS5, SS6, SS9, CP2, and KB1) the two shifts almost canceled each other leading to net time shifts in the pressure records of less than 2 minutes. At other sites (SS8, CP3, VR2, VR4, VR5, and VR6) the two shifts added together to produce net time shifts in the pressure record of 13–17 minutes. Pressure at sites SS4, SS10, and VR1 were not affected by these errors because they used 15 minute time steps aligned with the current measurements.

All the data were re-analyzed with the correction applied to the i/o code and the nearest neighbor interpolation in the synthesis of model input time series replaced with piecewise cubic spline interpolation to remove the random time shifts. All model runs presented in Book et al. (2009a) were redone with these corrected inputs. The final model solutions were not very different than the ones shown in the original paper. The main difference was a nearly uniform 6–7 min-

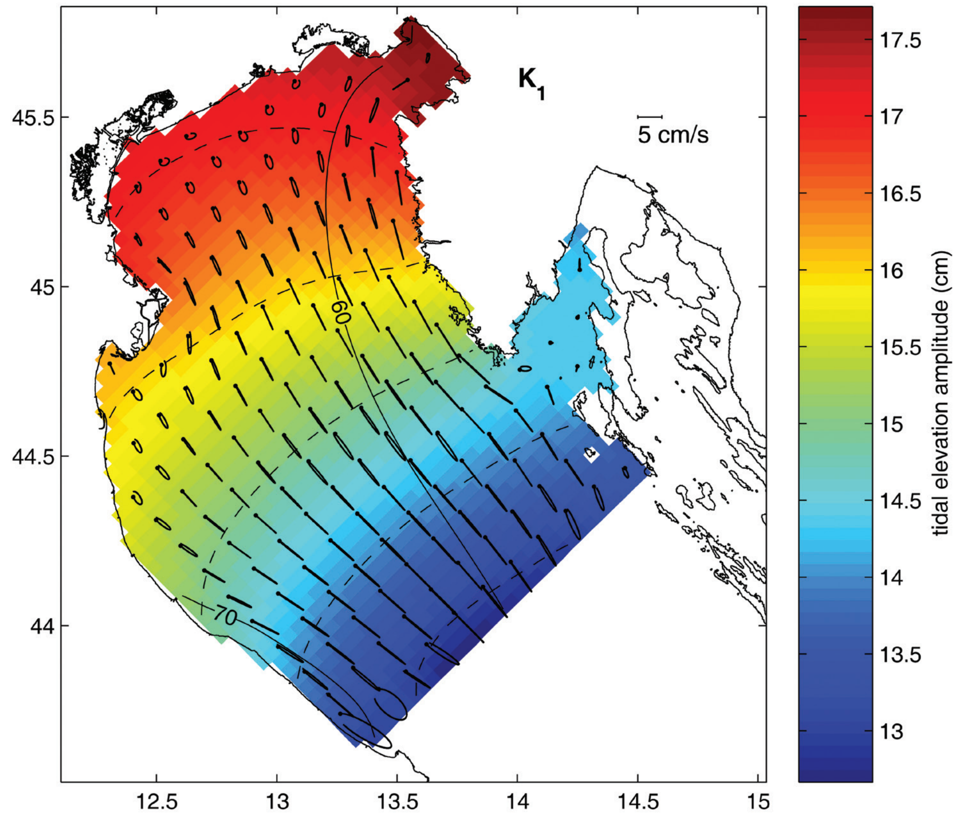

Figure 6. As in Fig. 5, but for the K_1 tide (with co-range contour interval 1 cm, and different velocity and color scales).

ute lag in sea elevation phase arrival, equivalent to a 3.5° decrease in phase for M_2 and a 1.6° decrease in phase for K_1 throughout the corrected model solutions. Figures 5–7 are reprinted here with these corrections. Changes for the lesser tidal constituents (not shown here) matched those of their stronger diurnal or semidiurnal counterparts.

The most dramatic change in the model results was a large decrease in average rms error for tidal elevations (not shown), going from the prior value of 0.81 cm to a new value of 0.40 cm. This is not surprising and together with the relatively minor changes in model solution suggests that a significant portion of the original rms error was due to error in the data rather than error in the model. The strong changes in rms error also changed the frictional tuning of the model (not shown). The friction that yielded the lowest final cost function

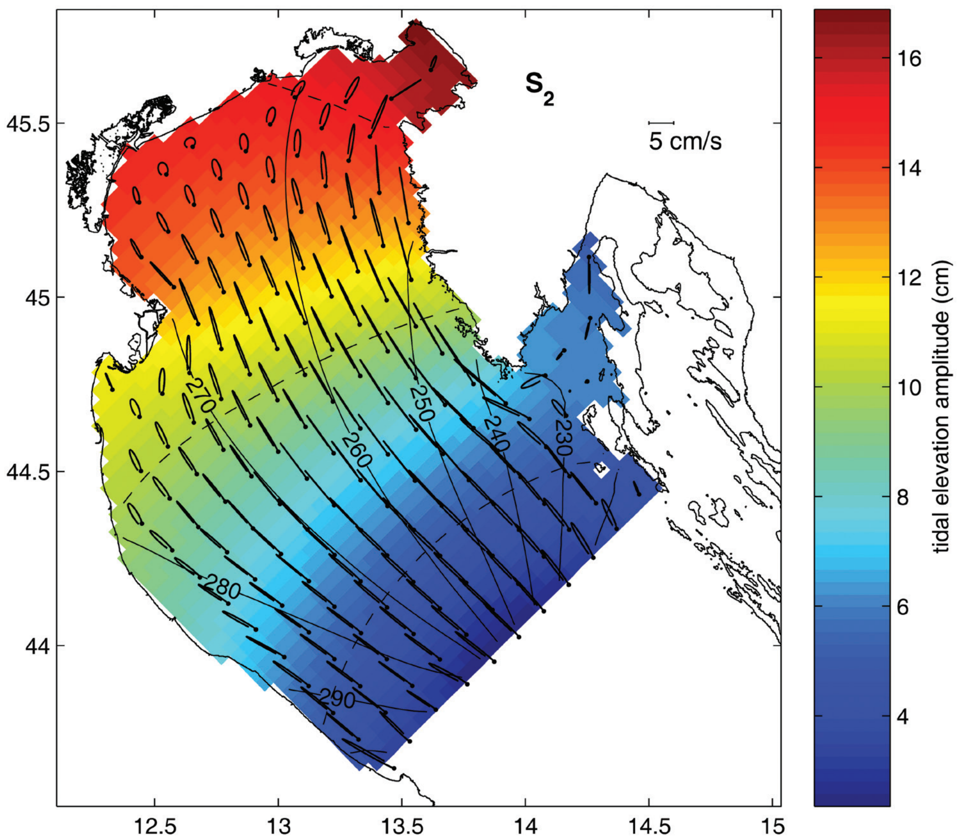

Figure 7. As in Fig. 5 but for the S_2 tide (with co-range contour interval 5 cm, a different color scale, and a velocity scale matching Fig. 6).

changed from $\lambda = 5 \cdot 10^{-4}$ m/s to $\lambda = 4 \cdot 10^{-4}$ m/s. The differences between these two model solutions were small and the cost function value for $\lambda = 4 \cdot 10^{-4}$ m/s was only 1.9% lower, made up of a 25.5% lower contribution from tidal elevations and a 10.0% higher contribution from tidal currents. Friction parameters lower than $\lambda = 4 \cdot 10^{-4}$ m/s all had relatively low rms errors for tidal elevations but produced sharply increasing rms velocity errors as the friction was decreased further.

The final average rms error values for the corrected $\lambda = 4 \cdot 10^{-4}$ m/s model run were 0.40 cm for tidal elevations, 0.41 cm/s for along-axis tidal currents, and 0.43 cm/s for across-axis tidal currents. The Q factors calculated from this

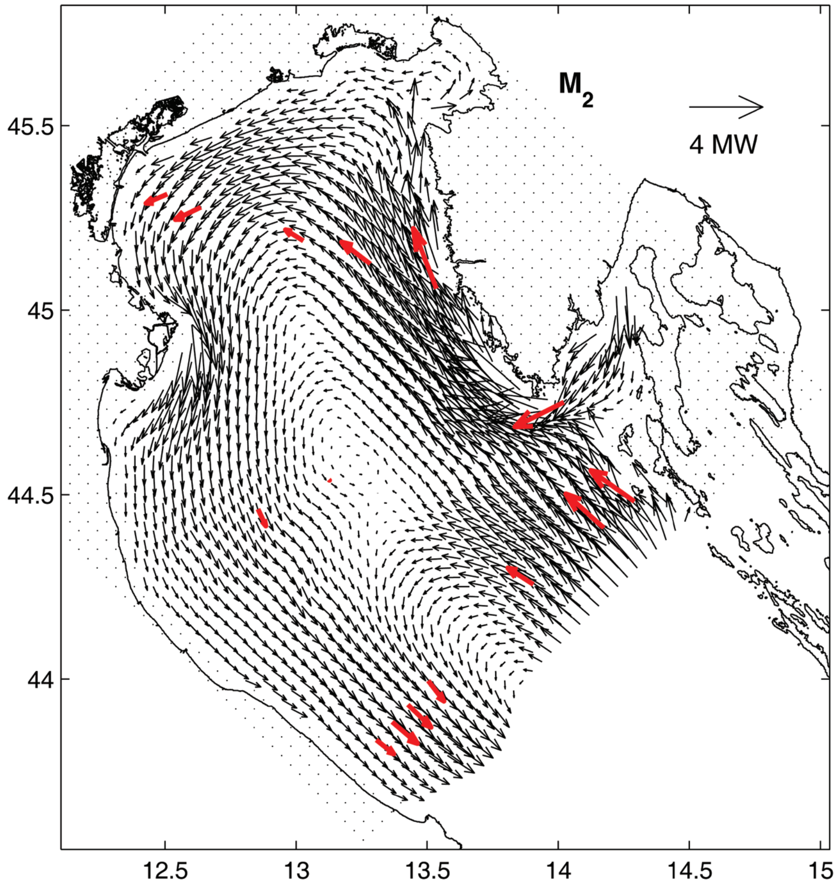

Figure 13. Average M_2 energy flux over a tidal cycle calculated from the observations (red arrows) and model solutions (black arrows). The energy flux scale is given in the upper right. For purposes of model/data comparison, the energy fluxes per meter calculated from the tidal observations were multiplied by 4 km, the length of the model grid spacing, to convert them into total energy fluxes.

model run increased to 17.4 for M_2 and 27.2 for K_1 in line with a decrease in model dissipation to 40 MW. However, the comparison (not shown) of model dissipation to dissipation estimated from the observed vertical structure of the tides from Book et al. (2009b) remains at a consistent ratio to the previous comparison and suggests that a value of 24 MW would be a better estimate of the true average tidal dissipation of the North Adriatic basin. Values for Q factors and dissipation are not tightly constrained by our methodology of determining them using frictional tuning of a strong constraint variational data-assimilation model. In the new model results, energy is not equally partitioned between KE and PE in the basin for either M_2 or K_1 as the PE stored over a tidal cycle is 1.5 times the KE for M_2 and 6.0 times the KE for K_1 in agreement with the previous results.

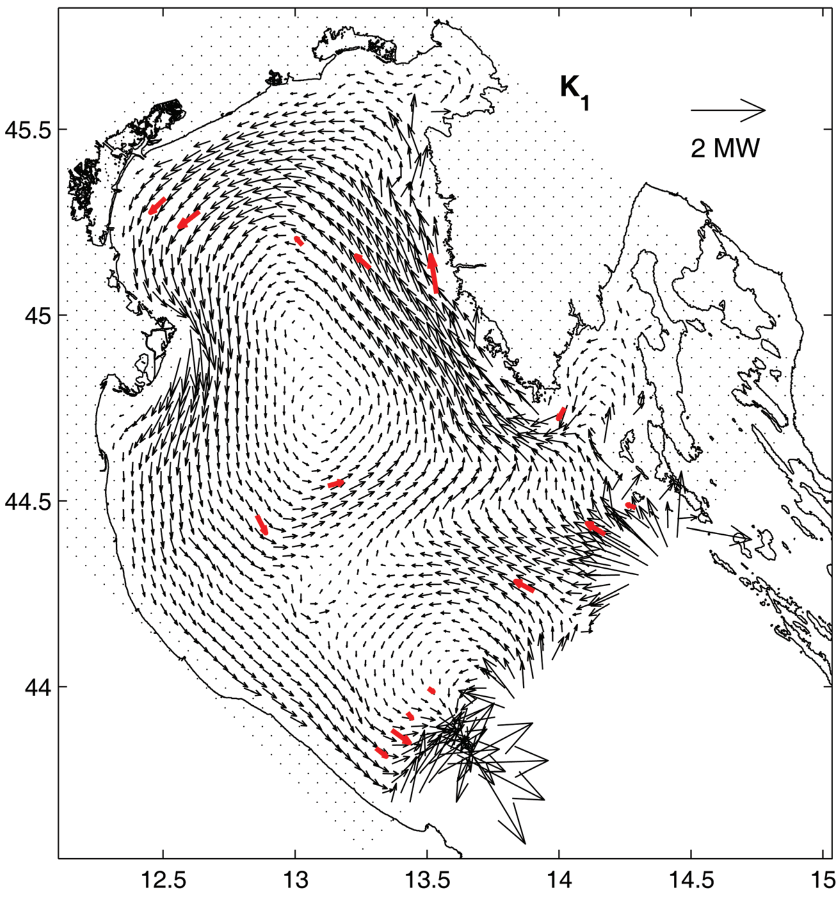

Figure 14. As in Fig. 13, but for K_1 tides with a different energy flux scale.

3. Discussion

Energy flux results are relatively sensitive to small changes in tidal phasing and therefore some corrections are needed for Figs. 13–14. In general the changes were larger in the observed fluxes than in the model solution fluxes because the former had M_2 tidal elevation phases that increased by 7.7° at the 12 affected sites while the latter had tidal elevation phases that decreased by only 3.5°. This correction to the observed tidal elevation phases also changes the location where the maximum M_2 energy flux per unit length was observed. This maximum of 0.88 kW/m is now found at site VR6 just offshore of the Istrian coastline. However, the M_2 energy flux per unit length at site KB1 inside Kvarner Bay is still significant in value, 0.74 kW/m, and remains the second strongest flux per unit length from all the observational sites. Observational and modeling results still suggest that energy fluxes from Kvarner Bay are significant in the North Adriatic tidal energy balance. Changes in K_1 fluxes were smaller due to smaller changes in tidal elevation phases (4.0° increase for the affected observations and 1.6° decrease for the model).

The main conclusions regarding Kelvin waves and TRW dynamics for the North Adriatic basin remain unaltered by these corrections. Observational and modeling results still support the concept of a superimposed incident and reflected Kelvin wave for M_2 tides with modification by friction and some southwestward turning of energy in the middle of the basin. Observational and modeling results for K_1 tides show evidence for both TRW modes (indirectly) and Kelvin-wave modes existing together.

Acknowledgment – We would like to thank Richard D. Ray of the NASA Goddard Space Flight Center for noticing the phase differences in the tables and figures of the original paper and bringing these discrepancies to our attention. We are very grateful for his actions which led directly to this correction.

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SAŽETAK

Ispravak u radu: „Plimne oscilacije u sjevernom Jadranu: opažanja, modeliranje varijacijskom asimilacijom podataka i linearna plimna dinamika“

Jeffrey W. Book, Henry Perkins i Mark Wimbush

Otkrivena je pogreška zaokruživanja u rutinama za plimnu analizu u radu J. W. Book, H. Perkins i M. Wimbush: „Plimne oscilacije u sjevernom Jadranu: opažanja, modeliranje varijacijskom asimilacijom podataka i linearna plimna dinamika“ (*Geofizika*, **26**, 2009, 115–143). Faze plimnih denivelacija, dane u tablicama 4. i 5., za 12 od 15 postaja podcijenjene su u prosjeku 3,9° za dnevne komponente te 7,9° za poludnevne komponente. Ovdje dajemo tablice s ispravljenim vrijednostima.

Greška je utjecala na ulazne podatke koji su korišteni u linearnom modelu za varijacijsku asimilaciju podataka te je, u kombinaciji s interpolacijskom shemom najbližeg susjeda, uzrokovala vremenski pomak unaprijed od približno 15 minuta za 6 od ukupno 43 sintetizirana plimna zapisa. Greška je proizvela konačna modelska rješenja koja su precijenila faze plimnih denivelacija za 3,5° za $M2$ komponentu, 1,6° za $K1$ komponentu, te fazne pomake sličnih iznosa kod drugih poludnevnih i dnevnih komponenti. Greške u ulaznim podacima su ispravljene, interpolacijska shema je promijenjena tako da koristi po dijelovima kubne spline-ove te su ponovno provedeni modelski računi.

Novi rezultati modela sugeriraju malu promjenu u optimalnom parametru trenja, koji dalje mijenja Q faktore modela i disipaciju. Međutim izvorni nalaz, da te vrijednosti nisu dobro određene ovom metodologijom, ostaje nepromijenjen. Rezultati modela i opažanja, izvorno prikazani na slikama 5.–7. i 13.–14., malo su se promijenili i ovdje su nanovo prikazani. Glavni zaključci iz izvornoga rada u vezi s Kelvinovim valovima i TRW dinamikom u sjevernom Jadranu nakon ovih ispravki ostaju isti.

Corresponding authors' addresses: Jeffrey W. Book, Naval Research Laboratory, Stennis Space Center, MS 39529-5004, U.S.A., phone: +1 228-688-5251, fax: +1 228-688-5997, e-mail: book@nrlssc.navy.mil

Mark Wimbush, University of Rhode Island, Graduate School of Oceanography, Narragansett, RI 02882, U.S.A, email: mwimbush@mail.uri.edu