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1 Impacts of tides on tsunami propagation due to potential Nankai Trough 2 earthquakes in the Seto Inland Sea, Japan

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14

15 Abstract

16 The impacts of tides on extreme tsunami propagation due to potential Nankai Trough earthquakes
17 in the Seto Inland Sea (SIS), Japan, are investigated through numerical experiments. Tsunami
18 experiments are conducted based on five scenarios that consider tides at 4 different phases, such as
19 flood, high, ebb, and low tides. The probes that were selected arbitrarily in the Bungo and Kii
20 Channels show less significant effects of tides on tsunami heights and the arrival times of the first
21 waves than those that experience large tidal ranges in inner basins and bays of the SIS. For instance,
22 the maximum tsunami height and the arrival time at Toyomaesi differ by more than 0.5 m and nearly
23 1 hr, respectively, depending on the tidal phase. The uncertainties defined in terms of calculated
24 maximum tsunami heights due to tides illustrate that the calculated maximum tsunami heights in the
25 inner SIS with standing tides have much larger uncertainties than those of two channels with
26 propagating tides. Particularly in Harima Nada, the uncertainties due to the impacts of tides are
27 greater than 50% of the tsunami heights without tidal interaction. The results recommend to simulate
28 tsunamis together with tides in shallow water environments to reduce the uncertainties involved with
29 tsunami modeling and predictions for tsunami hazards preparedness.

30 **Keywords:** Tsunami-Tide interaction, the Tokai-Tonankai-Nankai-linked earthquake, the Nankai
31 Trough, the Seto Inland Sea, adaptive mesh refinement

32 1. Introduction

33 The tsunami on 11 March 2011, which was induced by the Tohoku Earthquake, Japan, brought an
34 unprecedented and unexpected level of disasters. Since then, the coastal defenses have been required
35 to be revised against possible very large earthquakes, tsunamis and storm surges all over Japan. In
36 the western part of Japan, potential earthquakes and consequential tsunamis that are expected to
37 occur along the Nankai Trough over the next 30 years are a formidable coastal disaster to be
38 considered.

39 The Nankai Trough extends from Suruga Bay to the Hyuga Nada with a total length of
40 approximately 800 km (**Fig. 1**). The history of Nankai Trough earthquakes can be traced through 11
41 events from the Hakuho Nankai earthquake in AD684 to three recent earthquakes: (a) the 1707 Hiei
42 (M_w 8.4) earthquake, (b) the 1854 Ansei Nankai (M_w 8.4) and Ansei Tokai (M_w 8.4) earthquakes,
43 and (c) the 1944 Tonankai (M_w 7.9) and the 1946 Nankai (M_w 8.0) earthquakes [Ando, 1975;
44 Furumura *et al.*, 2011; Ishibashi, 2004]. Among these great interplate earthquakes along the Nankai
45 Trough, the 1707 Hiei earthquake was the largest, causing more than 20,000 casualties due to strong
46 ground motion and the ensuing tsunami. These great interplate earthquakes show a recurrence

47 interval of approximately 100 to 150 years. Three fault segments, namely, the Tokai, the Tonankai
48 and the Nankai, stretch from east to west along the Nankai Trough. The three segments exhibited
49 simultaneous or individual rupture patterns during the historical earthquakes, and the 1707 Hōei
50 earthquake was the largest shock in modern Japanese history [Furumura *et al.*, 2011; Tanioka and
51 Satake, 2001].

52 **Figure 1** illustrates the source rupture and tsunami source area, which was revised and issued in
53 March 2012 by the Central Disaster Prevention Council (Chuo Bousai Kaigi in Japanese; hereinafter
54 CDPC) of the Japanese government. The previous source rupture and tsunami source area that was
55 issued in 2003 was largely based on the 1707 Hōei earthquake data. The revised source rupture
56 region in 2012 extended further to the north and west, covering Shikoku, the Hyuga Nada and the
57 southeastern part of Kyushu. Moreover, additional source rupture and tsunami source areas (shaded
58 pink in **Fig. 1**) south of the Nankai Trough are considered for future disaster prevention for potential
59 extreme tsunamis.

60 In the CDPC's first report released on 31 March 2012 and in their second report released on 29
61 August 2012, the tsunami height and arrival time along the Pacific coast of Japan were numerically
62 estimated for 11 worst-case scenarios with M_w 9.0 and 7.6 m of average slip over all segments (both
63 reports are available in Japanese at <http://www.bousai.go.jp/jishin/nankai/model/index.html>). In the
64 second report, the sequential rupture of fault segments with 5, 10, 15, 20 and 40 min intervals were
65 considered for the tsunami source in the numerical simulations, while only a concurrent rupture was
66 considered in the first report. The numerical estimations of tsunami propagation were performed in
67 multi-nested domains with 10 m spatial resolution for the smallest domain in the second report by
68 using a non-linear shallow water equation model. In the results of the second report, inundated area
69 maps are provided along the shoreline with detailed information of the coastal structures, which were
70 incorporated together with the most updated topography and bathymetry data. The maximum
71 tsunami heights in 5 scenarios are over 30 m and, in all scenarios, the maximum tsunami heights are
72 estimated to be over 20 m along the coastline. Additionally, the maximum tsunami heights are
73 obtained at the maximum high tides by linearly superposing the two values. The explicit physical
74 interactions between the tsunamis and tides are not taken into account in the CDPC reports.

75 The Seto Inland Sea (SIS) is the largest channel-shaped enclosed coastal sea in the western part
76 of Japan, with a size of approximately 23,000 km², a length of approximately 500 km and an average
77 depth of approximately 38 m [Tsuge and Washida, 2003; Yamamoto, 2003; Yanagi *et al.*, 1982]. The
78 SIS is connected to the outer Pacific Ocean via the Kii Channel and the Bungo Channel and to the

79Korea Strait via the Kanmon Strait. In addition to its mild climate and beautiful scenery of sandy
80beaches, tidal flats, and historical heritage, it includes approximately 700 islands and a number of
81narrow waterways/straits (Seto in Japanese) that connect the basins (Nada in Japanese) and bays
82(Fig. 2). Thus, unlike in the other coastal regions in Japan, the tide and tidal currents are high and
83very strong and are dominant physical processes in the SIS's coastal environment. Therefore, taking
84the impacts of tides and tidal currents on extreme tsunami propagation in the SIS into account is
85critical for coastal protection and disaster prevention [Lee and Kaneko, 2015; Lee et al., 2010;
86Shimoyama and Lee, 2014].

87 Tsunami waves propagate in the ocean as a short-term event, interact with other processes and
88can be influenced or modified by these interactions. However, the water motions associated with
89tsunamis are much stronger than other background motions [Dixon and Tawn, 1997; Kowalik and
90Proshutinsky, 2010]. For example, tides in the open ocean do not have a significant influence on
91tsunami propagation such that a linear superposition can be applied for sea level variation. However,
92in shallow coastal zones, tsunamis are usually amplified by water shoaling. Additionally, tsunamis
93can remain in near-shore regions for a long time as ringing oscillations due to either local resonance
94or the local trapping of the tsunami's energy [Kowalik et al., 2006].

95 With respect to tsunami-tide interactions, tidal elevations can theoretically influence the speed
96and magnitude of tsunami waves in shallow regions with dominating tidal signals by changing the
97water depth [Weisz and Winter, 2005]. Moreover, Kowalik et al. [2006] and Androsov et al. [2010]
98illustrated through numerical experiments that the non-linear interaction between tides and tsunamis
99in shallow water becomes very significant such that the amplification of tsunami height is mainly
100associated with the strong amplification of tsunami currents, while the linear superposition of sea
101surface heights from separate tide and tsunami simulations is still valid in deep water. Kowalik and
102Proshutinsky [2010] also drew a conclusion analogous to previous works through idealized and
103regional studies, stating that the non-linear tsunami-tide interactions in terms of tidally induced water
104depth and enhanced currents is the main cause of the changing conditions of tsunami propagation,
105amplification and dissipation. In particular, the non-linear interaction of tsunamis and tides is critical
106for an accurate estimation of tsunami run-ups and inundations in coastal, river mouth and estuarine
107areas [Kowalik and Proshutinsky, 2010; Zhang et al., 2011].

108 Therefore, in this study, we investigated the impacts of tides and tidal currents on potential
109extreme tsunami propagation due to Nankai Trough earthquakes by numerical experiments in the
110SIS, where the tidal ranges are high and the tidal currents are strong. In the following, a brief

111 introduction of the numerical model is given in Section 2. Sections 3 and 4 illustrate the validations
 112 of the numerical model for tides in the SIS and for the 1707 Hwei Earthquake tsunami with historical
 113 observation records, respectively. Section 5 shows the set-up of the numerical experiments. The
 114 experimental results are described in Section 6, and discussions on the tsunami-tide interactions are
 115 presented in Section 7. Finally, conclusions are provided in Section 8.

1162. Open source flow solver: Gerris

117 Gerris is an open source computational fluid dynamic code that solves non-linear shallow water
 118 equations. In this section, Gerris is described briefly in terms of the governing equations, the
 119 numerical scheme, and the adaptive mesh refinement method. For full details on Gerris and its
 120 various applications, please see *Popinet* [2003; 2011; 2012] and *Lee et al.* [2013].

1212.1 Governing equations

122 Tsunamis are most commonly modeled using a long-wave approximation of the mass and
 123 momentum conservation equations for a fluid with a free surface. In this approximation, the slopes of
 124 both the free surface and the bathymetry are assumed to be negligibly small. However, these
 125 assumptions are often violated in the case of tsunamis, particularly those close to shore; somewhat
 126 surprisingly, the long-wave approximation still gives reasonable results in practice. Simple scaling
 127 arguments show that the vertical velocity of the fluid is also negligibly small in this context. Fluid
 128 motion can thus be described by only using the vertically averaged components of the horizontal
 129 momentum and the free-surface elevation. The non-linear shallow water equations in conservative
 130 form with additional terms for the Coriolis Effect and bottom friction can be described as

$$131 \quad \frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0 \quad (1)$$

$$132 \quad \frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2}gh^2\right) + \frac{\partial}{\partial y}(huv) - fv = -hg\frac{\partial z}{\partial x} - C_f|u|u \quad (2)$$

$$133 \quad \frac{\partial(hv)}{\partial t} + \frac{\partial}{\partial x}(huv) + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2}gh^2\right) + fu = -hg\frac{\partial z}{\partial y} - C_f|v|v \quad (3)$$

134 where h is the free surface elevation, $\mathbf{u}=(u, v)$ is the horizontal velocity vector, g is the acceleration
 135 due to gravity, z is the depth of the bathymetry, f is the Coriolis coefficient, and C_f is the friction
 136 coefficient, which is set to 10^{-3} for all the numerical experiments.

1372.2 Numerical scheme

138 Numerical methods for hyperbolic systems of conservation laws have been extensively
 139 developed in the context of compressible gas dynamics, particularly with applications in aeronautics.
 140 Many of these schemes are suitable for solving the Saint-Venant equations provided that two
 141 important specificities are taken into account: the solver needs to properly account for vanishing
 142 fluid depths and needs to exactly verify the lake-at-rest equilibrium solution. The Saint-Venant solver
 143 used in Gerris is based on the numerical scheme that was analyzed in detail by *Audusse et al.* [2004],
 144 which verifies both properties. The scheme uses a second-order, slope-limited Godunov
 145 discretization. The Riemann problem necessary to obtain Godunov fluxes is solved using an
 146 approximate Harten-Lax-van Leer Contact (HLLC) solver, which guarantees the positivity of the
 147 water depth. The choice of slope limiter is important as it controls the amount of numerical
 148 dissipation required to stabilize the solution close to the discontinuities. Based on *Popinet* [2011], the
 149 Sweby limiter is a good compromise between stability of short waves and the low dissipation of long
 150 waves. A MUSCL-type discretization is used to generalize the method to second-order time-stepping.
 151 The time-step is constrained by the Courant-Friedrich-Levy condition for stability:

$$152 \quad \Delta t < \frac{1}{2} \min \left(\frac{\Delta}{|u| + \sqrt{gh}} \right)$$

153 (4)

154 where Δ is the mesh size.

155 To summarize, the overall scheme is second-order accurate in space and time, preserves the
 156 positivity of the water depth and the lake-at-rest conditions and is volume- and momentum-
 157 conserving.

158 2.3 Adaptivity

159 Gerris uses a quadtree spatial discretization, which allows efficient adaptive mesh refinement. An
 160 example of the quadtree structure is exhibited in **Fig. 3** together with its logical (tree) representation.
 161 This tree can be conveniently described as a “family tree”, where each parent cell can have zero or
 162 four children cells.

163 An important parameter is the level of a given cell in the tree. The root cell has level zero by
 164 convention and the level increases by one for each successive generation in the tree. A further
 165 simplification is obtained by constraining the quadtree so that the levels of adjacent cells cannot
 166 differ by more than one. This simplification reduces the number of configurations for neighboring

167 cells to two: (1) neighboring cells are on the same level, which is identical to a regular Cartesian grid
168 discretization; and (2) two fine cells neighbor the same coarse cell (**Fig. 3**).

169 Choosing a refinement criterion is necessary to refine or coarsen the mesh dynamically. This
170 choice is not trivial and depends on both the details of the numerical scheme, which control the
171 discretization errors, and the physics of the problem considered, which control how the discretization
172 errors will influence the accuracy of the solution. Gerris provides a variety of refinement criteria,
173 which can be flexibly combined depending on the problem. In this study, the gradient of the free
174 surface elevation was used as the refinement criterion. Cells also need to be coarsened when a high
175 spatial resolution is not required anymore. When cells are coarsened, the values of the fields are set
176 by default to the averages over their children, which also ensures the conservation of quantities.

1773. Tides in the Seto Inland Sea

178 The SIS has three outlets: the Bungo Channel, the Kii Channel, and the Kanmon Strait (**Fig. 2**).
179 The Kanmon Strait has such a small cross-sectional area that the water mass in the SIS is mainly
180 exchanged through the former two channels, and the existence of this strait does not influence the
181 main tidal features of the SIS.

182 Based on tidal observations analyzed by *Yanagi and Higuchi* [1981] and *Yanagi et al.* [1982], as
183 shown in the left column of **Fig. 4**, the M_2 tide from the Pacific Ocean propagates into the SIS
184 through the two channels with a tidal range of approximately 90 cm and a phase of approximately
185 180° . Then, the M_2 tidal range decreases down to approximately 30 cm at the Akashi Strait and
186 increases up to approximately 200 cm at the Suo Nada and the Hiuchi Nada. The tidal phases at the
187 Akashi Strait and the Naruto Strait are 90° (approximately 3 hrs) and 130° (approximately 4.5 hrs)
188 behind that at the Kii Channel. The Bisan Strait experiences a high tide approximately 5 hrs (155°)
189 later than the channels. In the Suo Nada, the high tide appears in the whole area at the same time,
190 exhibiting the characteristics of a standing wave due to a potential interaction between the incidence
191 and reflection of the M_2 tide. Because the M_2 tide propagates from the two channels in the eastern
192 part of the Hiuchi Nada and the Bisan Strait, the M_2 tide at the Hiuchi Nada behaves like a standing
193 wave, while those in the two channels and the Iyo Nada behave like a progressive wave.

194 In terms of tidal currents, the M_2 tidal currents vary within 80 cm/s in the two channels, while
195 those in the nadas in the SIS are approximately 50 cm/s. The phase difference in the tidal currents
196 between the two channels and the center of the SIS is approximately 40° (approximately 1 hr).

1973.1 Verification of tides in the SIS

198 The tides in the SIS was modeled and validated with Gerris. A numerical simulation was
199 performed with tidal open boundaries for the three major constituents, M_2 , S_2 , and K_1 . No normal
200 flux and no-slip conditions were applied to the bottom and coastal boundaries. Open tidal boundary
201 conditions were imposed from the global ocean tide model, FES2004 [Lyard *et al.*, 2006]. FES2004
202 is a combined product based on a hydrodynamic model, which assimilates tide gauges and altimeter
203 data from Topex/Poseidon and ERS-2 on a $1/8^\circ \times 1/8^\circ$ grid (available at
204 <http://www.aviso.altimetry.fr/en/home.html>). The bathymetry data for the experiments is taken from
205 the GEBCO 30 arc-sec database [IOC *et al.*, 2003], which is referenced with respect to the mean sea
206 levels. The refinement level of the adaptive meshes varies from level 6 to level 12, which are
207 equivalent to 31.25 km and approximately 488 m in distance, respectively. The simulation period
208 was more than 6 weeks, covering spring-neap tidal cycles. The right column of **Fig. 4** illustrates the
209 co-amplitude, co-phase, and tidal ellipse charts that were obtained for the M_2 tide by Gerris
210 simulation. Compared with the previous studies in the left column, the characteristics of the M_2 tide,
211 such as tidal amplitudes and phases in the SIS described above, agree well. The Suo Nada and the
212 Hiuchi Nada appear to have almost the same tidal phase, indicating rising and falling water levels
213 that resemble standing waves within each nada. The simulated tidal harmonic constants of the tides
214 are also compared with the observed harmonic constants as shown in **Table 1**. Harmonic analyses of
215 the simulated tides were carried out by following *Msadek* [2005], while the observed values were
216 obtained from the National Institute of Advanced Industrial Science and Technology (AIST), Japan.
217 The observed harmonic constants are the 40-yr (1970 ~ 2010) mean values of the annual harmonic
218 constants.

2194. The 1707 Hiei Earthquake tsunami

220 The historical 1707 Hiei Earthquake tsunami was also modeled for its validation. **Figure 5**
221 illustrates the 1707 Hiei Earthquake's tsunami source region (middle panel) based on the revised
222 fault parameters proposed by *Furumura et al.* [2011], as shown in **Table 2**. The 1707 Hiei
223 Earthquake's tsunami simulations were conducted with varying friction coefficients, and the
224 simulation result with a friction coefficient of 0.001 showed the best performance compared with the
225 historical tsunami records (the top and bottom panels in **Fig. 5**). The historical tsunami records are
226 indicated as "inundation heights" in the original documents, namely, *Hatori* [1974; 1985] and
227 *Murakami et al.* [1996] and are actually the maximum inland run-up (inundation) heights, while the
228 simulated values are the calculated maximum tsunami heights at the given probe locations in shallow
229 water regions. The locations of the probes are not the same locations where the tsunami run-up
230 records were taken. Therefore, the simulation with a rather small friction coefficient value results in

231the best performance because we directly compare the maximum inland run-up heights to the
232maximum tsunami heights in the shallow water regions from the simulations. The same bathymetry
233from GEBCO 30 arc-sec was also used for the tsunami simulation. The minimum and maximum
234levels of mesh refinement are the same as those for the tide simulation.

2355. Numerical experiments

236 Numerical experiments based on the scenarios in **Table 3** were conducted to investigate the
237impacts of tidal currents on tsunami propagation in the SIS. The 4 tidal phases that were defined
238(**Fig. 6(a)**) and considered in the experiments are based on those at Hayasuido because the tidal
239current at Hayasuido is one of the fastest currents in the SIS. Based on the observational charts by
240the Japan Coastal Guard (JCG), the maximum north-going current at Hayasuido is approximately 4.6
241m/s. Therefore, the phases at Hayasuido were selected as the baseline in the experiments. In addition,
242the maximum currents in the SIS are observed during the inward flooding tide, with currents of
243approximately 2.5 – 4.5 m/s at narrow straits (setos), such as Hayasuido, Naruto, Akashi and Bisan,
244and currents of less than 1.0 m/s at nadas and bays. The tidal phases in the Kii and Bungo Channels
245are almost the same, and the tidal phase difference between the Bungo Channel and the center of the
246SIS, such as the Hiuchi Nada and the Bisan Strait, is approximately 5 to 6 hrs, as described above.
247Thus, if we have a high tide at Hayasuido, we will approximately have an ebb tide in the center of
248the SIS. For the tidal open boundary, the four major constituents M_2 , S_2 , K_1 and O_1 are imposed from
249the same FES2004 global tide model. The same GEBCO bathymetry is used for the experiments.
250Variable resolutions are also applied to implement “sponge layers” on the open boundaries of the
251domain. Along all the boundaries of the domain, the spatial resolution is coarsened to level 5.
252Therefore, the resulting numerical dissipation dampens waves before they exit the domain, thus
253minimizing spurious tsunami wave reflections at the boundaries.

254 First, the tsunami-only simulation was conducted for 10 hrs without tidal boundaries. Then, a
255tide-only simulation with the 4 tidal components at open boundaries was conducted for 7 days. We
256found that the tides in the SIS reach a periodic stationary state solution after approximately 6 cycles
257(approximately 3 days). Therefore, the joint tsunami-tide simulations were then conducted for 10 hrs
258with added tsunamis, restarting from the results of the tide-only simulation at different tidal phases
259(**Fig. 6(a)**) after approximately 6 cycles. **Table 3** shows the scenarios and conditions of the numerical
260experiments. These joint tsunami-tide simulations allow us to investigate how the tides and tidal
261currents affect tsunami propagation in the SIS depending on different tidal phases.

262 The added tsunami shown in **Fig. 6(b)** was adopted from the first of eleven scenarios describing
263 the Tokai-Tonankai-Nankai-linked earthquake of M_w 9.1 that was released in the CDPC's first report
264 on 31 March 2012. In the CDPC's first report, the results from the first scenario produced the
265 maximum tsunami heights in many places along the coastline in the SIS. Therefore, we chose the
266 first scenario for the tsunami source in our experiments. The whole area of the SIS exhibits initially
267 negative tsunami displacements. In the Bungo Channel, the negative displacement is lower than -1
268 m. In the center of the SIS, such as the Hiuchi Nada and in the Kii Channel, it is relatively small
269 compared to that in the Bungo Channel. It is less than -50 cm in the Suo Nada, the Harima Nada, and
270 the Osaka Bay. This initial tsunami surface profile was generated using *Okada's* [1992] model with
271 5,773 asperities. The rupture times of all the asperities are the same in the Tokai, Tonankai, and
272 Nankai segments. For a further discussion of the results, we arbitrarily selected 27 probes in the SIS,
273 as indicated in **Fig. 6(b)**. **Figure 6(c)** illustrates the time-varying time step (dt) due to the mesh
274 adaptivity from all the experiments. The time step decreases after approximately 1 hr of elapsed time,
275 when the tsunamis arrive at most shorelines and interact with tides in the shallow coastal zone.

2766. Results

277 **Figures 7** and **8** illustrate synthesized maps of the calculated maximum tsunami heights (bottom
278 panel) and occurrence time of maximum tsunami heights (top) along the Honshu and Shikoku
279 coastlines (middle) in the SIS, respectively. The SIS is divided into 7 sections, such as the Bungo
280 Channel (BC), the Suo Nada and Iyo Nada (SI), the Hiroshima Bay and Aki Nada (HA), the Hiuchi
281 Nada (HUN), the Harima Nada (HRN), the Osaka Bay (OB), and the Kii Channel (KC). **Figure 9**
282 shows the calculated tsunami heights with time at the selected probes (see **Fig. 6(b)**) from the five
283 experiments. In each panel of the figures, the legend, *Tsunami*, indicates the result from the tsunami-
284 only case, while the others, such as *at Flood*, *at High*, *at Ebb*, and *at Low*, represent the tsunami
285 heights with time that were obtained by the difference between the joint tsunami-tide simulations and
286 the tide-only simulation. **Table 4** shows the summary of the calculated maximum tsunami heights
287 from the numerical experiments at all the probes in the SIS. The baseline of the tidal phases equals
288 that at Hayasuido. The results are described in the following.

289 The maximum tsunami heights with tidal interactions at 3 probes in the Bungo Channel (BC) are
290 lower compared to the tsunami height from the tsunami-only case, except at Saikisi, which is 33 cm
291 higher. However, the tsunami heights of the first waves at Uwajimasi are even lower compared to
292 those at other probes. The maximum tsunami heights from the joint tsunami-tide simulations at

293Uwajimasi appear between 5 and 6 hrs of elapsed time and are amplified due to tsunami-tide
294interactions.

295 In the Suo and Iyo Nadas (SI), the maximum tsunami heights from the joint simulations are
296higher at Houfusi, Toyomaesi, Kunisakisi and Oitasi and lower at Matsuyama, Iyonagahama, Hikari
297and Shimonoseki-Oki. The arrival times of the first peaks depending on the tidal phase are slightly
298earlier than those of the tsunami-only case. At Simonoseki-Oki and Toyomaesi, the tsunami heights
299of the first peaks are considerably higher or lower depending on the tidal phase compared to those
300without the influence of tides. The first peaks at Shimonoseki-Oki and Toyomaesi arrive
301approximately 30 min earlier than those of the tsunami-only case. Overall, the impacts of tides on the
302calculated tsunami heights, particularly, to the west of 131.5°E in Suo Nada, are significant,
303exhibiting an almost 1 m difference depending on the tidal phase (**Fig. 7**). Moreover, in the middle
304coastline of Suo Nada between 131.25°E and 131.5°E, **Fig. 7** illustrates that the maximum tsunami
305heights are not due to the first waves but possibly due to reflected waves according to the occurrence
306time of maximum tsunami heights.

307 The calculated tsunami heights in the Hiroshima Bay and the Aki Nada (HA) exhibit a similar
308tendency: the impacts of tides on the tsunami heights are relatively large, approximately 0.25 cm.
309The maximum tsunami heights with tidal interactions are lower at Hiroshima (**Table 4**), and the
310impacts of tides are clearly observed in the arrival times of the first waves (**Fig. 9**). Particularly in
311Hiroshima Bay, the arrival times are delayed by more than 1 hr due to the many islands between the
312at *high* and at *ebb* tides (**Fig. 7**).

313 In Hiuchi Nada (HUN), the center of the SIS, the maximum tsunami heights calculated with tidal
314interactions are lower at 4 probes compared to the tsunami-only case (**Table 4**). The sea level
315variations for the beginning 4 hours at Fukuyama-Oki and Shikoku-Chuo are oscillations due to the
316negative initial displacement of the surface, and the tsunami waves that are caused by positive
317displacement from the outer SIS arrive at the Hiuchi Nada after approximately 4 hours (**Fig. 9**). The
318calculated tsunami heights are generally less than 0.5 m in Hiuchi Nada. Overall, in Hiuchi Nada, the
319greatest tsunamis arrive earlier in the *at Ebb* and *at High* tides, which are the high and flood tides in
320the local phases, than in the *at Low* and *at Flood* tides (**Figs. 7 and 8**). Because the tsunami heights
321are lower with the same order of tides in Hiuchi Nada, the occurrence times of the maximum tsunami
322heights depend greatly on the tidal phases. The occurrence times of the maximum tsunami heights
323along Shikoku's coast in **Fig. 8** also exhibit the presence of normal oscillation modes in the Hiuchi

324Nada, which affect the maximum tsunami heights. Moreover, the tsunamis in the Hiuchi Nada, which
325propagated from both sides, are clearly present in the occurrence times.

326 In Harima Nada (HRN), the maximum tsunami heights are higher at Takamatsu, Higashi-
327Kagawasi, and Narutosi, and lower at Setouchisi and Himeji (**Table 4**). The arrival times of the first
328waves calculated with tidal interactions are also higher or lower depending on the tidal phases. The
329probes in the Harima Nada show relatively large differences in the maximum tsunami heights with
330and without tidal interactions, for example, a 40 cm reduction at Setouchisi (**Table 4 and Fig. 9**).
331Interestingly, in the Harima Nada, the occurrence times of the maximum tsunami heights in **Fig. 7**
332depend on the oscillation modes of the nada.

333 In Osaka Bay (OB), the calculated maximum tsunami heights are nearly 4.0 m and increase by 12
334cm at Osaka-Oki due to interactions with tides (**Table 4**). Analogously, the maximum tsunami
335heights in Osaka Bay depend on the natural oscillation modes of the bay, which is clearly exhibited
336in the occurrence times of the maximum tsunami heights (**Fig. 7**). Therefore, continuous long-term
337monitoring is necessary to measure a potential local maximum tsunami height, particularly in Osaka
338Bay.

339 At the probes in the Kii Channel (KC), such as those in Wakayama-Oki, Anansi, Aritasi, and
340Tanabe (**Table 4**), the maximum tsunami heights are higher, with a maximum difference of 40 cm at
341Aritasi. The arrival times of the first waves are more or less the same as for the tsunami-only case
342because the probes are located close to the positive tsunami source area.

343 In general, the probes located at the borders between the nadas and bays in the SIS, such as Uno-
344Oki, Takamatsu, Imabari-Oki, Wakayama-Oki and Hayasuido, exhibit small differences in the
345maximum tsunami heights between the *tsunami-only* and *at phase*.

3467. Tsunami-Tide interactions

347 In terms of the tidal impacts on tsunami propagation in shallow water, the water depth (H)
348changes that are induced by the tide (ζ) affect the tsunami magnitude and propagation speed ($C = \sqrt{g(H + \zeta)}$) and, thus, the travel times. In previous research from numerical experiments on
349tsunami-tide interactions in the long narrow shelf break of Alaska [Kowalik and Proshutinsky, 2010],
350the travel time of tsunamis to Anchorage varies from 5 to 6 hrs depending on the tidal phase in Cook
351Inlet, which stretches approximately 290 km from the Gulf of Alaska to Anchorage. The tsunami
352magnitude is also affected by tidal phases in Cook Inlet such that the maximum tsunamis occur
353

354 approximately 70-90 min after high tide, while the minimum tsunamis occur approximately 70-90
355 min after low tide.

356 From observations in the tide-dominant Columbia River mouth [Tolkova, 2013], tsunami
357 attenuation during ebb tides has been found, but no enhancement during flood tides or variations in
358 the tsunami arrival time occur with tidal phases, which probably occurs because the relatively short
359 propagation distances are not enough to observe the arrival time differences of tsunamis.

360 **Figure 10** presents the calculated sea level variations from the numerical experiments at
361 Hayasuido in the Bungo Channel and at Shimonoseki-Oki in the inner part of the Suo Nada. Each
362 panel exhibits the sea level variations caused by the tide-only, tsunami-only, and joint tsunami-tide
363 simulations and the difference between the joint tsunami-tide and tide-only simulations.

364 First, the results at Hayasuido in **Fig. 10(a)** are dominated by tsunamis such that the impacts of
365 tides are not significant during the first three peaks until 1.5 hrs of elapsed time. The tidal range is
366 less than 2 m. At the time of the fourth peaks at 2 hrs of elapsed time, the tsunami height *at Low* (at
367 flood in local) is the highest, the tsunami height *at Ebb* (at low) is second, that *at High* (at ebb) is
368 third and that *at Flood* (at high) is the lowest. In terms of the arrival time, the fourth peaks are
369 ordered *at Low*, *at Ebb*, *at Flood*, and *at High*, even though the differences are fairly small. After the
370 four tsunami peaks at approximately 2 hrs of elapsed time, the differences in the tsunami heights
371 between the tsunami-only and the joint tsunami-tide simulations becomes significant. After 5 hrs of
372 elapsed time, in particular, the tsunami-tide interactions result in large differences among the
373 experiments.

374 The results at Shimonoski-Oki in **Fig. 10(b)** clearly show the effects of the tides. The tidal range
375 is nearly 5 m at the probe. The first peaks of the tsunami waves are ordered *at Flood*, *at Low*, *at*
376 *High*, and *at Ebb*, which are approximately at high, at flood, at ebb and at low tides in the local
377 phase. The Simonoseki-Oki is located approximately 400 km from the entrance of the Bungo
378 Channel, and the difference in the arrival times of the first waves is approximately 1 hr, which
379 coincides well with previous findings [Kowalik and Proshutinsky, 2010]. The order of the tsunami
380 heights of the first peaks is *at Flood*, *at Low*, *at Ebb*, and *at High*, which are at high, at flood, at low
381 and at ebb tides in its local tidal phase. The water depth changes at high and low tides clearly depict
382 its influence in the propagation speeds and the heights of tsunami waves such that a tsunami at high
383 tide appears earlier and higher than that at low tide. Moreover, the maximum tsunami height among
384 the four experiments occurs *at Flood* (at high in local) approximately 50 min after the peak of high
385 tide, which agrees well with previous findings.

386 In the Bungo Channel and Kii Channel, the effects of tsunami-tide interactions are not significant
387 compared to those at the probes in the Suo Nada, Hiroshima Bay, and Hiuchi and Harima Nadas
388 (**Fig. 9**). Particularly, the probes in the Suo Nada, such as Toyomaesi and Shimonoseki-Oki, and the
389 probes in the Harima Nada, such as Setouchisi and Himeji, where the tides are standing waves, show
390 distinctive tsunami signals after experiencing high tide at approximately 5 hrs of elapsed time.

391 The results show that the larger the tidal range is at a probe, the more distinct the influence of
392 tides is in the tsunami propagations. For example, the tidal range at Fukuyama-Oki is less than 0.8 m.
393 The maximum difference in the wave amplitude at Fukuyama-Oki is approx. 0.5 m and that in the
394 arrival time is nearly 0 hrs. However, the tidal range at Shimonoseki-Oki is approximately 4.5 m, and
395 the maximum difference in the wave amplitude and arrival time at Shimonoseki-Oki is
396 approximately 0.5 m and 1 hr, respectively.

397 To further investigate the impacts of tides on tsunami propagation, we define the relative
398 uncertainty as follows by using the calculated tsunami heights from the numerical experiments in
399 **Table 4**.

$$400 \quad \text{uncertainty}(\%) = \frac{(\text{maximum difference of calculated tsunami heights})}{(\text{maximum tsunami heights by Tsunami-Only case})} \times 100 \quad (5)$$

401 From this relative uncertainty, we can evaluate how much tides affect the calculated maximum
402 tsunami heights compared to the *Tsunami-Only* case. As observed in **Table 4** and in **Fig. 11**, the
403 uncertainties in the Kii Channel (avg.: 6.93%) and Bungo Channel (avg.: 10.18%) are lower than
404 those in the Suo and Iyo Nadas (avg.: 27.27%), Hiuchi Nada (avg.: 122.2%) and Harima Nada (avg.:
405 37.08%). The relative uncertainty in the Hiuchi Nada is large because of the negative initial surface
406 displacement.

4078. Conclusions

408 This paper investigates the impacts of tides on tsunami propagation in the Seto Inland Sea, Japan,
409 based on numerical experiments. Tsunami experiments are conducted based on five scenarios that
410 consider tides at 4 different phases, such as flood, high, ebb, and low tides. The initial tsunami
411 displacement is adopted from the first case scenario announced in the CDPC's first report in Japan
412 for potential extreme tsunamis due to Tokai-Tonankai-Nankai-linked earthquakes along the Nankai
413 Trough. The numerical experiments are conducted using an open-source non-linear shallow water
414 equation model with an adaptive mesh refinement method.

415 Based on the results of numerical experiments, the general effects of changing water depth due to
416 tides on tsunami propagation indicate that higher tsunami heights and earlier tsunami arrivals at high
417 tide are obtained compared to those at low tide. The probes in the Bungo and Kii Channels, where
418 the tides are propagating waves, show less significant tidal effects on tsunami propagation. However,
419 the probes in the Suo Nada, Hiroshima Bay, Hiuchi and Harima Nadas, and Osaka Bay in the SIS,
420 where the tides are standing waves and the tidal ranges are relatively large compared to those
421 elsewhere, depict large differences in the maximum tsunami heights and in the arrival times of the
422 first waves. For example, the differences in the maximum tsunami height and the arrival time of the
423 first peaks at Shimonoseki-Oki and Toyomaesi are 0.37 m and 0.52 m, respectively, and nearly 1 hr
424 among the joint tsunami-tide results. Moreover, the relative uncertainties, which are defined as the
425 ratio between the difference in the maximum tsunami heights and the maximum tsunami heights in
426 the Tsunami-Only case, show higher uncertainties in the inner nadas and bays in the SIS.

427 The main conclusion of this study is that tsunami-tide interactions have a wide range of impacts
428 on tsunami propagation in the SIS, where the tides are high and strong in this shallow water
429 environment, which also depends on the individual basin and bay bathymetry and coastline
430 configuration. Therefore, simulating tsunamis together with tides in shallow water environments is
431 strongly recommended to reduce the uncertainties involved with tsunami predictions and coastal
432 defenses and management. Based on the uncertainty analysis of the calculated tsunami heights,
433 Hiroshima Bay and the Harima Nada show up to or greater than 50% uncertainty due to the impacts
434 of tides. Thus, providing qualitative and quantitative uncertainty information is also recommended
435 when presenting tsunami simulation results because the people living near the tsunami-prone coastal
436 area deserve to have more information for self-decision and self-evacuation plans. The current
437 tsunami hazards and inundation maps are strongly recommended to be revised by considering the
438 impacts of tides. Moreover, the maximum tsunami heights do not appear by the first or second peaks
439 in semi-enclosed bays and basins, where the tides behave as standing waves. Therefore, continuously
440 monitoring sea level changes until the tsunami energy is fully dissipated in specific bay and harbor
441 areas is recommended.

442 The limitations of this study are 1) the uncertainty coming from the water depth changes due to
443 initial sea bottom deformation by fault motions are not considered in all experiments and 2) the
444 potential local maximums which are possibly occurred during all tidal phases in spring-neap tidal
445 cycle might be overlooked because only four tidal phases are considered in numerical experiments.

446 Finally, this study illustrates the importance of the physical interactions between extreme
447 tsunamis and tides during tsunami propagation in the high tide range and strong tidal current
448 environments such as the SIS, Japan. This study intends to supplement the CDPC report in this
449 manner, and neither to compare nor to replace the results of the CDPC report. The locations and
450 names of the probes in the SIS, shown in **Fig. 7** in this study, are arbitrarily determined by the
451 authors and are not the same as those in the CDPC reports.

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458 The CDPC's reports and tsunami initial displacements for 11 cases of potential Nankai Trough
459 earthquakes are available at Cabinet Office of Government of Japan
460 (<http://www.bousai.go.jp/jishin/nankai/model/index.html>). Gerris is freely available at Gerris Flow
461 Solver (<http://gfs.sourceforge.net>). FES2004 is freely available at AVISO by registration
462 (<http://www.aviso.altimetry.fr/en/home.html>). T-Tide is freely available at the developer's site
463 (<http://www.eos.ubc.ca/~rich/>). The observed M_2 tide harmonic constants are available at National
464 Institute of Advanced Industrial Science and Technology (AIST), Japan. The historical tsunami run-
465 up records are obtained by digitizing the Table 1 from *Hatori* [1974] and the Table 1 from *Murakami*
466 *et al.* [1996]. GEBCO 30 arc-sec bathymetry dataset is freely available at General Bathymetric Chart
467 of the Oceans (<http://www.gebco.net/>). The 2011 Tohoku Earthquake tsunami records with 15-sec
468 interval is available for purchase from Japan Meteorological Business Support Center
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538

539 Figure captions

540 **Figure 1.** The potential Tokai-Tonankai-Nankai-linked earthquake and tsunami source region along
541 the Nankai Trough, which was revised and issued by the Central Disaster Prevention Council, Japan
542 (modified from **Fig. V.3** in the CDPC's first report released in 31 March 2012).

543 **Figure 2.** Schematic diagram illustrating the potential tsunami-tide interactions in the Seto Inland
544 Sea.

545 **Figure 3.** Example of quadtree discretization (left) and its local representation together with the level
546 of the cells in the tree (right).

547 **Figure 4.** Comparison of the co-amplitude, co-phase and tidal ellipse chart for the M_2 tide in the Seto
548 Inland Sea between previous studies (left column) and this study (right column). The co-amplitude
549 and co-phase charts of the M_2 tide on the left are obtained from *Yanagi and Hiuchi* [1981], and the
550 tidal ellipses chart on the left is from *Kobayashi et al.* [2006]

551 **Figure 5.** The 1707 Hōei Earthquake tsunami source region (N1 – N5') and observation sites (middle
552 panel), and the simulated maximum tsunami heights compared with the historical tsunami inundation
553 heights (top and bottom panels). The observation sites and their names follow *Hatori* [1974; 1985]
554 and *Murakami et al.* [1996]. The fault parameters are given in **Table 2**. Uncertainties in historical
555 tsunami inundation heights as in references are represented by error bars.

556 **Figure 6.** (a) Definitions of the four different tidal phases considered in the numerical experiments.
557 The tidal phase at Hayasuido (Probe #24) is considered as the baseline in the experiments. (b) Initial
558 surface displacement due to an extreme tsunami (Case 1 from 11 scenarios in the CDPC's first
559 report) induced by a potential Tokai-Tonankai-Nankai-linked earthquake, and 27 probes in the Seto
560 Inland Sea. (c) Temporal variations in the computational time steps (dt) for each numerical
561 experiment.

562 **Figure 7.** The calculated maximum tsunami heights (bottom) and occurrence time of maximum
563 tsunami heights (top) along the Honshu coastline (middle). Each color indicates the results from the
564 tsunami-only run and the joint tsunami-tide runs. The tags indicate the regions of the SIS: the Bungo
565 Channel (BC), the Suo and Iyo Nadas (SI), the Hiroshima Bay and the Aki Nada (HA), the Hiuchi
566 Nada (HUN), the Harima Nada (HRN), the Osaka Bay (OB), and the Kii Channel (KC).

567 **Figure 8.** Same as **Fig. 7**, but along the Shikoku coastline.

568 **Figure 9.** Calculated tsunami heights at selected probes in the Seto Inland Sea. The legend, *Tsunami*,
569 indicates the results from the tsunami-only run. The other legends, *at Flood*, *at High*, *at Ebb*, and *at*
570 *Low*, indicate the modeling results with tidal interactions. The tidal phases are based on the baseline
571 at Hayasuido. Refer to the scenarios in **Table 3** for detailed conditions. The numbers and tags
572 indicate the probe numbers and the regions of the SIS, respectively (see **Fig. 6(b)** and **Fig. 7**).

573 **Figure 10.** Comparisons of the calculated tsunami heights at (a) Hayasuido and (b) Shimonoseki-
574 Oki. The top panels indicate the calculated tsunami heights at 4 tidal phases with the tide-only
575 results. Each panel from the second to the bottom presents the sea level variations from the tsunami-
576 only (*Tsunami*) and joint tsunami-tide simulations (*Tsunami+Tide*), the tsunami height (*at Phase*)
577 obtained by (*Tsunami+Tide*) - (*Tide*), and the tide-only results (*Tide*).

578 **Figure 11.** Uncertainties in terms of calculated maximum tsunami heights as defined in Eq. (5). For
579 locations of the probes and sections in the Seto Inland Sea, refer to **Fig. 6(b)** and **Fig. 7**, respectively.

580

581

582Table 1

583Comparisons between the observed and calculated M_2 , S_2 , and K_1 tidal harmonic constants in the Seto Inland Sea

Stations	Locations		M_2				S_2				K_1			
			Amp (cm)		Phase (deg)		Amp (cm)		Phase (deg)		Amp (cm)		Phase (deg)	
	Lat (°N)	Long (°E)	obs	cal	obs	cal	obs	cal	obs	cal	obs	cal	obs	cal
Kobe	34.68 3	135.18 3	29.0	24.3	216. 0	209. 9	16. 6	7.8	229. 0	230. 8	26. 0	13. 7	204. 0	219.8
Matsuyama	33.86 7	132.71 7	100. 0	67.3	264. 0	257. 7	41. 0	17. 9	292. 6	327. 0	31. 0	16. 4	208. 0	211.6
Murotomisaki	33.26 7	134.16 7	49.4	15.2	174. 0	165. 3	21. 8	2.7	198. 0	203. 4	22. 2	11.5	189. 0	209.5
Oita	33.26 7	131.68 3	58.4	43.6	243. 0	235. 3	24. 0	11.3	271. 0	305. 0	25. 6	14. 2	206. 0	203.4
Tokuyama	34.03 3	131.80 0	88.4	71.0	252. 0	246. 7	37. 6	18. 9	281. 0	284. 1	28. 6	15. 9	207. 6	206.6
Wakayama	34.21 7	135.15 0	44.0	18.3	188. 0	191. 1	21. 0	5.0	209. 6	225. 9	24. 0	12. 2	192. 0	217.8

584

585**Table 2**

586The revised fault parameters for the 1707 Hiei Earthquake's source regions

Segment	Fault Location (Lat (°N)/Lon (°E))	Length (km)	Width (km)	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip (m)
N1	35.120/138.706	120	50	6.4	193	20	71	5.6
N2	33.823/138.235	205	100	4.1	246	10	113	7.0
N3	33.006/136.074	155	100	7.8	251	12	113	5.6
N4`	32.614/134.481	135	120	10.1	250	8	113	9.2
N5`	32.200/133.130	70	80	10.0	250	8	118	9.2

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591

592**Table 3**

593Details of the numerical experiments with different boundary conditions and set-ups

Run	Tsunami	Tidal phase	Tidal boundary	Remark
Tide-only	×	×	○	1) Tides at boundaries: M ₂ , S ₂ , K ₁ and O ₁ 2) Based on the tidal phase at Hayasuido 3) Spin-up: 6 cycles (approx. 3 days) 4) Simulation period for tsunami: 10 hrs 5) Initial water displacement: Case 1 out of 11 scenarios in the first CDPC report 6) (6) ≤ (mesh refinement level) ≤ (12)
Tsunami-only	○	×	×	
Tsunami at High	○	High	○	
Tsunami at Ebb	○	Ebb	○	
Tsunami at Low	○	Low	○	
Tsunami at Flood	○	Flood	○	

594

595Table 4

596Summary of the calculated maximum tsunami heights. The maximum difference in the tsunami
 597height indicates the difference between the *Tsunami-only* and *at Tide* cases. The uncertainty is
 598defined as the ratio between the maximum difference in the tsunami height and maximum tsunami
 599height of the *Tsunami-only* result (Eq. 5). The negative sign in “Remark” represents a decrease in the
 600maximum tsunami height in the Tide cases compared to the *Tsunami-only* case, whereas a positive
 601sign indicates an increase.

No.	Station		Maximum tsunami height (m)					Maximum difference of tsunami height (m) ((<i>Tsunami-only</i>) – (<i>at Tide</i>))	Uncertainty (%)	Remark
	section	name	<i>Tsunami-only</i>	<i>at Flood</i>	<i>at High</i>	<i>at Ebb</i>	<i>at Low</i>			
1	HA	Hiroshima	1.08	0.58	0.78	0.80	1.05	0.50	46.3	-
2	HUN	Fukuyama-Oki	0.13	-0.13	-0.07	0.01	0.02	0.27	207.7	-
3	SI	Matsuyama	0.96	0.79	0.60	0.76	0.85	0.36	37.5	-
4	HUN	Shikoku-Chuo	0.18	-0.07	-0.03	0.07	0.00	0.25	138.9	-
5	HUN	Uno-Oki	0.30	0.27	0.29	0.30	0.24	0.06	20.0	-
6	HRN	Takamatsu	0.60	0.73	0.50	0.56	0.58	0.13	21.7	+
7	HRN	Setouchisi	0.62	0.38	0.32	0.51	0.22	0.40	64.5	-
8	HRN	Higashi-Kagawashi	0.53	0.69	0.51	0.44	0.46	0.16	30.2	+
9	HRN	Himeji	0.70	0.44	0.36	0.35	0.32	0.38	54.3	-
10	OB	Osaka-Oki	1.54	1.53	1.44	1.51	1.56	0.12	7.8	+
11	HRN	Narutosi	2.18	2.24	2.39	2.50	2.48	0.32	14.7	+
12	KC	Wakayamasi-Oki	1.60	1.49	1.51	1.61	1.51	0.12	7.5	+
13	KC	Tanabe	3.41	3.46	3.47	3.41	3.50	0.09	2.6	+
14	KC	Anansi	2.05	2.16	2.11	2.06	2.08	0.11	5.4	+
15	KC	Aritasi	3.28	3.68	3.21	3.35	3.47	0.40	12.2	+
16	SI	Iyonagahama	0.87	0.69	0.70	0.66	0.75	0.21	24.1	-
17	HUN	Imabari-Oki	0.60	0.52	0.42	0.45	0.56	0.18	30.0	-
18	SI	Hikari	1.40	1.20	1.10	1.21	1.36	0.30	21.4	-
19	SI	Houfusi	0.80	0.60	0.50	0.79	0.86	0.30	37.5	+
20	SI	Shimonoseki-Oki	2.08	2.06	1.69	1.69	1.84	0.39	18.8	-
21	SI	Toyomaesi	0.95	0.78	0.72	1.24	1.07	0.29	30.5	+
22	SI	Kunisakisi	1.44	1.30	1.57	1.64	1.45	0.20	13.9	+
23	SI	Oitasi	2.22	2.34	2.27	2.31	2.38	0.16	7.2	+
24	BC	Hayasuido	0.99	0.87	0.90	0.92	0.96	0.12	12.1	-
25	BC	Sukumosi	6.16	5.89	5.73	5.94	5.94	0.43	7.0	-
26	BC	Saikisi	3.12	3.26	3.25	3.34	3.45	0.33	10.6	+
27	BC	Uwajimasi	3.01	2.97	2.68	2.70	2.88	0.33	11.0	-

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