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Predicting Tidal Heights for New Locations Using 25 h of In Situ Sea Level Observations plus Reference Site Records: A Complete Tidal Species Modulation with Tidal Constant Corrections

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(Manuscript received 10 February 2014, in final form 17 October 2014)

ABSTRACT

A hybrid technique for predicting tides for new locations, based on as little as 25 h of concurrent temporary and reference site sea level observations, plus up to a year of reference records, is evaluated using 2-yr South Korean and New Zealand case studies. Comparisons are made between the existing prediction methods of conventional standard harmonic analysis and prediction (CSHAP) and tidal species modulation with tidal constant corrections (TSM + TCC). Building on these approaches, a new procedure is developed to produce a complete tidal species modulation (CTSM) equivalent of CSHAP, with the added inclusion of nodal factors and angles, astronomical arguments, and tidal species tidal constant correction terms (+ TCC), to generate results for temporary sites. The CTSM + TCC approach described here overcomes the record length limitations of traditional standard harmonic-based prediction methods, making the technique more useful to diverse coastal and hydrographic researchers.

The CTSM + TCC method is refined using yearlong input and comparative data from contrasting hydrographic settings, revealing spring periods, specific months, and conditions devoid of nontidal residual extremes (e.g., storms) as the most appropriate sample periods for collecting temporary site data in order to maximize prediction accuracy. CTSM + TCC represents a viable alternative to tidal prediction methods using multiconstituent inferences, for those wishing to make predictions for new sites based on established conventional tidal prediction software, with the added benefits of efficient input data collection and no need for a decision process regarding multiconstituent inference calculations. CTSM + TCC could, without compromising accuracy, support the spatial and temporal proliferation of tidal predictions across coastal oceans, where fieldwork funds and instruments currently hinder predictions for new locations.

1. Introduction

Most contemporary industrial uses of the world’s coastal oceans, including navigation, pollutant-dispersion modeling, and tidal energy prospecting, require the accurate generation of detailed tidal predictions across extensive spatial areas. In shallow tide-dominated regions, tides also constrain human activities such as recreation, and coastal development and management. The first step in understanding the role of tides in such activities and places is to acquire sufficiently long sea level records to make accurate tidal predictions. This step is typically expensive and time consuming, particularly when off-shore gauges are involved. Meanwhile, short sea level records are commonly produced by coastal researchers and hydrographic officers using pressure gauges, current meters, and/or wave gauges. Detailed sampling and intensive memory requirements mean that these sorts of instruments are usually deployed for periods less than a week, oftentimes only a few days of sea level record being produced per site if instruments are moved or batteries fail.

In the past, tides have been commonly predicted via conventional standard harmonic analysis and prediction methods (CSHAP), which require a minimum of 15 days
TABLE 1. List of tidal prediction methods reviewed in this paper. Note that CSHAP is a conventional standard harmonic analysis and prediction method; TSM is a tidal species modulation; TSM+TCC is a tidal species modulation with tidal constant correction; CTSM is a complete tidal species modulation; CTSM+TCC is a complete tidal species modulation with tidal constant correction; TPMI is tidal prediction using multiconstituent inferences.

<table>
<thead>
<tr>
<th>Prediction method</th>
<th>Data length required from new site for predictions</th>
<th>Notable characteristics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSHAP</td>
<td>≥15 or 28 days</td>
<td>Possible separation of the $K_2$ and $P_1$ tides from the $S_2$ and $K_1$ tides using inferences; no multiconstituent inferences from a single reference constituent</td>
<td>IOS tidal package (Foreman 1977); T_Tide (Pawlowicz et al. 2002)</td>
</tr>
<tr>
<td>TSM</td>
<td>≥1 month</td>
<td>Use of harmonic least squares fitting; increase in errors due to no consideration of nodal modulation effects</td>
<td>Kang (1997)</td>
</tr>
<tr>
<td>TSM+TCC</td>
<td>1 month</td>
<td>Need monthlong observations from the reference tidal station per prediction month; better to use concurrent monthlong observations from a reference and a temporary tidal station to obtain $M_2$ and $K_1$ tidal constituents</td>
<td>Kang (1997)</td>
</tr>
<tr>
<td>CTSM</td>
<td>≥15 or 28 days</td>
<td>Use of a conventional standard harmonic analysis; similar prediction ability to CSHAP</td>
<td>This study</td>
</tr>
<tr>
<td>CTSM+TCC</td>
<td>≥25 h</td>
<td>Need concurrent 25-h observation or prediction data from a reference tidal station, plus a reference station 28-day-plus record from any time period</td>
<td>This study</td>
</tr>
<tr>
<td>TPMI</td>
<td>≥25 h</td>
<td>Use of multiconstituent inferences from a single reference constituent</td>
<td>UTide (Codiga 2011)</td>
</tr>
</tbody>
</table>

of sea level observations to predict spring–neap tides. Common observation-derived tidal prediction methods are based on time and height differences or the ratio of tidal ranges and time differences between a reference tidal station (R) and a temporary or secondary station (O). These methods are only suitable for paired sites characterized by similar tidal regimes. The latter methods also have well-known accuracy limitations (Simon 1991). These cumbersome constraints on tidal predictions for new sites form the motivation for the present study. Accordingly, we have developed a general observation-based tidal prediction method that is able to produce relatively accurate tidal height predictions for temporary stations based on 25 h of concurrent temporary and reference station sea level observations, plus a minimum 28 days or, ideally, 1 year of reference station observations from any time period (note: yearlong reference records are preferred for the most accurate results).

Table 1 summarizes the characteristics of the main tidal prediction methods reviewed, developed, and evaluated in this paper. We first explore the two existing tidal height prediction methods based on tidal harmonic constants: CSHAP (Foreman 1977; Pawlowicz et al. 2002) and tidal species modulation (TSM) with tidal constant correction (TCC) to overcome sea level record limitations [i.e., Kang’s (1997) TSM+TCC method]. Next, we explain a complete tidal species modulation (CTSM) equivalent of the CSHAP methods: the new hybrid technique integrates conventional tidal harmonic prediction factors (nodal factors and angles, astronomical arguments) into TSM, hence CTSM. Third, in order to overcome sea level record limitations inherited from TSM, like Kang (1997), we introduce tidal constant correction terms (+TCC) for the tidal species, producing CTSM+TCC. Fourth, we refine our method using yearlong South Korean and New Zealand reference site input observations, plus yearlong comparative observations, to show that spring periods, specific months, and sea level conditions devoid of nontidal residual extremes are the most appropriate sample periods for collecting the 25-h sea level observations in order to produce the most accurate predictions via CTSM+TCC methods. Next, we compare the prediction accuracy of CTSM+TCC with the improved conventional standard harmonic analysis and prediction method of Codiga (2011), which includes multiconstituent inferences derived from a single reference constituent, and synthetic time series sets predicted from tidal harmonic constants. The latter method is referred to as tidal prediction using multiconstituent inferences (TPMI; Table 1). Last, we compare patterns of accuracy variability for both the CTSM+TCC and TPMI methods in order to understand the tidal constituent factors that cause certain sample periods during the year to produce better results.

2. Observations

The south and west coasts of South Korea are dominated by predominantly semidiurnal tidal regimes, including semidiurnal and mixed mainly semidiurnal tidal forms (Table 2). These shallow coasts are characterized by
TABLE 2. The five main tidal harmonic constants and mean spring tidal ranges (MSTR) estimated using harmonic analyses of yearlong sea level observation records from 2008 for five South Korea sites, and from 2011 for two New Zealand (NZ) sites. Note that \( F = (H_{K_1} + H_{O_1})(H_{M_2} + H_{S_2}) \) and MSTR = \( 2(H_{M_2} + H_{S_2}) \).

<table>
<thead>
<tr>
<th>Tidal station</th>
<th>( H_{M_2} )</th>
<th>( H_{S_2} )</th>
<th>( H_{K_1} )</th>
<th>( H_{O_1} )</th>
<th>MSTR (cm)</th>
<th>Form factor ((F)) and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Korea</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incheon</td>
<td>283.8</td>
<td>114.6</td>
<td>39.3</td>
<td>29.2</td>
<td>796.8</td>
<td>0.17, semidiurnal</td>
</tr>
<tr>
<td>Daechoegdo</td>
<td>104.8</td>
<td>41.0</td>
<td>34.4</td>
<td>25.4</td>
<td>291.6</td>
<td>0.41, mixed, mainly semidiurnal</td>
</tr>
<tr>
<td>Geomundo</td>
<td>83.5</td>
<td>37.5</td>
<td>22.5</td>
<td>16.6</td>
<td>242.4</td>
<td>0.32, mixed, mainly semidiurnal</td>
</tr>
<tr>
<td>Tongyeong</td>
<td>73.6</td>
<td>34.0</td>
<td>14.5</td>
<td>9.8</td>
<td>215.2</td>
<td>0.23, semidiurnal</td>
</tr>
<tr>
<td>Busan</td>
<td>36.6</td>
<td>17.1</td>
<td>4.4</td>
<td>1.6</td>
<td>107.4</td>
<td>0.11, semidiurnal</td>
</tr>
<tr>
<td>NZ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyttelton</td>
<td>86.0</td>
<td>5.8</td>
<td>4.5</td>
<td>2.7</td>
<td>183.6</td>
<td>0.08, semidiurnal</td>
</tr>
<tr>
<td>Kaingaroa</td>
<td>50.9</td>
<td>4.0</td>
<td>3.6</td>
<td>1.1</td>
<td>109.8</td>
<td>0.09, semidiurnal</td>
</tr>
</tbody>
</table>

well-developed intertidal mudflats and sand ridges several tens of kilometers long (Byun and Wang 2005). Five tidal stations with stilling-well float gauges operated by the Korea Hydrographic and Oceanographic Administration (KHOA) were selected for this study: Incheon, Daechoegdo, Geomundo, Tongyeong, and Busan (Fig. 1). The mean spring tidal ranges at these stations range between about 1 and 8 m, and the values of the form factors are from 0.11 to 0.4, revealing semidiurnal to mixed mainly semidiurnal tidal characteristics (Table 2). Two-year-long (2008–09) hourly sea level records from each tidal station were used to test and evaluate our tidal prediction method. For the purposes of evaluation, we classified Tongyeong Tidal Station as R and Incheon, Daechoegdo, Geomundo, and Busan Tidal Stations as O.

In addition, 2-yr-long (2011–12) hourly sea level records measured by pressure gauges mounted on harbor structures in Whakaraupou Lyttelton and Kaingaroa Harbors, New Zealand, were used to test our prediction method in a tidal environment heavily influenced by perigean–apogean cycles. Lyttelton Harbor is a long (15 km), shallow (<16 m deep), rock-walled inlet with a mean spring tidal range of 1.84 m and a semidiurnal tidal form (Table 2). Kaingaroa Harbor, 880 km to the east and on the wave-dominated coast of eastern New Zealand, comprises a small (0.9 km × 1.2 km), shallow (<9 m) embayment on the easternmost peninsula of Chatham Island. The Kaingaroa tide gauge represents a key instrument in New Zealand’s tsunami alert network, since it receives far-field waves traveling from the eastern Pacific before they reach the mainland Canterbury coast. In contrast to the South Korean tidal stations, the Lyttelton and Kaingaroa areas experience tidal regimes where perigean–apogean variations are more pronounced than spring–neap variations: that is, the \( N_2 \) tides are their second largest constituent next to the \( M_2 \) tide (Table 2).

For all of the 2-yr tidal observation datasets from South Korea (2008–09) and New Zealand (2011–12): tidal harmonic analysis was conducted on the full-year 2008/2011 observation data, the results of which were used as input data to generate tidal predictions for the subsequent 2009/2012 periods. Then, using CTSM+TCC (method development explained below and characteristics summarized in Table 1), we estimated the tides at hourly intervals throughout 2009 for the four South Korean temporary tidal stations (Geomundo, Busan, Daechoegdo, and Incheon) using daily \( M_2 \) and \( K_1 \) amplitude ratios and phase-lag differences with station R (Tongyeong) for each 25-h period. These results were compared with the 2009 observations (Obs) from the same temporary tidal stations using root-mean-square errors (RMSEs). Note that the mean and solar annual \( S_2 \) components were removed to increase the validity of these 1-yr comparisons. The harmonic analysis and prediction programs T_Tide (Pawlowicz et al. 2002) and UTide (Codiga 2011) were used to produce the input values for CTSM+TCC as well as to evaluate its tidal height prediction accuracy.

3. Background on existing tidal harmonic prediction methods

a. Tidal predictions based on harmonic constants

Traditionally, the tidal amplitudes and phase lags needed for accurate tidal predictions are determined via conventional tidal harmonic analysis of sea level records spanning a year or more. The tidal height \( h \) at any time \( \tau \) can then be predicted from the superposition of the sinusoidal tidal constituent amplitudes \( (H_I) \) and phase lags \( (g_I) \), along with their astronomical arguments \( (\nu_I) \), nodal factors \( (f_I) \) and nodal angles \( (u_I) \), as given by

\[
\begin{align*}
h(\tau) &= \sum_{i=1}^{N} f(\tau)_{I} H_{I} \cos[\nu_{I} t + V(t_{0})_{I} + u(\tau)_{I} - g_{I}] \\
&= \sum_{i=1}^{N} f(\tau)_{I} H_{I} \cos \left[V(\tau)_{I} + u(\tau)_{I} - g_{I}\right]
\end{align*}
\]

(Godin 1972; Foreman 1977), where \( \tau \) equals the reference time \( (t_{0}) \) plus the \( t \) elapsed since \( t_{0} \) (i.e., \( \tau = t_{0} + t \));
\( \omega_I \) are the angular speeds (° h\(^{-1}\)) of the tidal constituents and the subscript \( I \) denotes each tidal constituent; \( N \) is the number of constituents; and \( V_I, f_I \) and \( u_I \) are calculated from the astronomical variables [refer to Schureman (1958) and Byun and Cho (2009) for a detailed description of the astronomical variables]. Similar to this tidal-harmonic-constant-based method, there is another way to predict tidal heights for
the combined diurnal and higher-frequency constituents, based on the modulated amplitudes and phase lags of each tidal “species” or group of constituents with similar frequencies (e.g., the semi-diurnal or diurnal or short-period constituents) (Kang 1997). Note that even though the earlier species concordance method (SCM) of George and Simon (1984) and Simon (1991) had the same tidal constituent group starting point, their method was different from that of Kang (1997). SCM expressed the tidal height formula differently, using orthogonal exponential functions with reduced vectors derived from the Euler formula. Unlike Kang’s (1997) method, and akin to Munk and Cartwright’s (1966) “response method,” SCM involves a convolution.

Kang’s (1997) method predicts tidal heights using the modulated tidal harmonic constants, derived from harmonic least squares fitting applied to less than a month of sea level elevation data, whereby

\[
h(\tau) = \sum_{k=1}^{m} \sum_{i=1}^{n} Y_{ik} \cos(\omega_{ik} \tau - \phi_{ik})
\]

\[
= \sum_{k=1}^{m} A(\tau)^{k} \cos[\omega_{k} \tau - \theta(\tau)^{k}],
\]

where superscript \(k\) denotes the tidal species, \(m\) is the number of tidal species, \(n\) is the number of tidal constituents, the subscript \(i\) denotes each tidal constituent, and \(\omega_{ik}\) can be expressed using the angular speed (\(\omega_{k}\)) of a representative tidal constituent for each species as given by \(\omega_{k} = \omega_{k} + \delta \omega_{k}\). For example, the dominant \(M_{2}\) and \(K_{1}\) tides can be used to represent the angular speeds of the representative semidiurnal (\(\omega_{M_{2}}\)) and diurnal tidal species (\(\omega_{K_{1}}\)), respectively. The amplitudes \(Y_{i}\) and phase lags \(\phi_{i}\) of the tidal constituents are estimated using harmonic least squares fitting alone. In the present study, this method of Kang’s (1997) is referred to as TSM.

The solution to Eq. (2) for each tidal species is given by

\[
A(\tau)^{k} = \left\{ \frac{\sqrt{\sum_{i=1}^{n} (Y_{ik}^{2}) + 2 \sum_{i \neq j} Y_{ik}^{2} Y_{jk}^{2} \cos[(\omega_{ik} - \omega_{jk}) \tau - (\phi_{ik} - \phi_{jk})]}}{1/2} \right\}
\]

for the modulated amplitude \(A(\tau)^{k}\), while for the modulated phase lag \(\theta(\tau)^{k}\),

\[
\theta(\tau)^{k} = \tan^{-1} \left[ \frac{\sum_{i=1}^{n} Y_{ik}^{2} \sin(\delta \omega_{ik} \tau - \phi_{ik})}{\sum_{i=1}^{n} Y_{ik}^{2} \cos(\delta \omega_{ik} \tau - \phi_{ik})} \right].
\]

Kang (1997) was able to ignore the nodal modulation effect, since variations in \(f_{n}^{k}\) and \(u_{n}^{k}\) over less than a month are negligible (Byun and Cho 2007), and since the use of real-time \((\tau)\) data means that \(V_{n}^{k}\) does not need to be considered. Thus, the tidal constituent amplitudes and phase lags used in Eq. (2) are calculated from harmonic least squares fitting alone, without nodal modulation and astronomical argument corrections. In the absence of such corrections, the accuracy of predictions made using this incomplete method decreases gradually for predictions made over time periods longer than 1 month and fluctuates according to the 18.61-yr tidal nodal cycle (Byun and Cho 2007).

b. Including tidal constant correction in tidal species modulation

It is expensive and time consuming to establish long-term reference tidal stations. Accordingly, temporary tidal stations are often set up to record sea levels for a month or longer, so that tidal predictions can be made for new sites of interest and greater spatial coverage. Reasonably accurate tidal predictions can be made for a temporary station based on monthlong observation data and the CSHAP method in Eq. (1), along with inference parameters (i.e., the ratio of inferred amplitudes to reference amplitudes, and the difference between reference phase lags and inferred phase lags) to separate out the main pairs of constituents including \((S_{2}, K_{2})\) and \((K_{1}, P_{1})\).

Tides at a temporary observation station can also be predicted reasonably easily using monthlong data-derived correction factors for amplitudes and phase lags from a reference tidal station, under the assumption of linear changes in amplitudes and constant differences in phase lags (Kang 1997). The amplitude correction factor \([fc(\tau)_{R}^{k}]\) for each tidal species at station \(R\) is calculated from the ratio of the species amplitude \([A(\tau)^{k}_{R}]\) and the amplitude of representative tidal constituents \([Y_{k}^{R}]\) for each tidal species (e.g., \(M_{2}\) for semidiurnal tide and \(K_{1}\) for diurnal tide), as given by

\[
fc(\tau)_{R}^{k} = \frac{A(\tau)^{k}_{R}}{Y_{k}^{R}}.
\]

Similarly, the phase-lag correction factor \([pc(\tau)_{R}^{k}]\) for each tidal species at station \(R\) is calculated from the difference between the species phase lags \([\theta(\tau)_{R}^{k}]\) and

\[
\theta(\tau)_{R}^{k} = \tan^{-1} \left[ \frac{\sum_{i=1}^{n} Y_{ik}^{2} \sin(\delta \omega_{ik} \tau - \phi_{ik})}{\sum_{i=1}^{n} Y_{ik}^{2} \cos(\delta \omega_{ik} \tau - \phi_{ik})} \right].
\]
the phase lag of the representative tidal constituent ($\phi_k^R$) for each tidal species, as given by

$$pc(\tau)^k_R = \theta(\tau)^k_R - \phi_k^R.$$  \hspace{1cm} (6)

Note that $A(\tau)^k_R$, $\theta(\tau)^k_R$, $Y_R^k$, and $\phi_k^k$ are derived from monthlong observation data at station R using harmonic least squares fitting. Inserting Eqs. (5) and (6) into Eq. (2), the tides ($h_O$) at station O can be estimated by

$$h_O(\tau) = \sum_{k=1}^m f(\tau)^k_R Y_O^k \cos[\omega_k^R \tau - pc(\tau)^k_R - \phi_k^O].$$  \hspace{1cm} (7)

The tidal constants, ($Y_R^k$, $\phi_k^R$) and ($Y_O^k$, $\phi_k^O$), are representative tidal constituents for each species at the reference and temporary tidal stations, respectively, estimated using harmonic least squares fitting of monthlong sea level elevation data over the same observation period at both tidal stations. In this study, this method is referred to as tidal species modulation with tidal constant correction (TSM + TCC).

To predict tides outside the observation period at station O, the modulated amplitude and correction factors in Eqs. (5) and (6) for station R must be recalculated for periods of 1 month or less for the duration of the prediction time in order to minimize errors due to nodal modulation effects. This requirement for iterative calculations is the main drawback of the approach for making predictions over many months.

c. Tidal harmonic analysis and prediction using multiconstituent inferences

The T_Tide package (Pawlowicz et al. 2002), a MATLAB version of the Institute of Ocean Sciences (IOS) tidal package (Foreman 1977) is widely used by the physical oceanographic community in the application of CSHAP. However, since the T_Tide package is theoretically based on the IOS tidal package (Foreman 1977), it includes the same fundamental multiconstituent inference limitation (Table 1).

More recently, a new and improved classical harmonic method, TPMI, has become available, including the versatile harmonic tidal analysis of Foreman et al. (2009) and the UTide of Codiga (2011). Both of these packages are capable of calculating multiconstituent inferences based on a single reference constituent, including a nodal modulation solution built into the harmonic analysis procedure. This improvement means these TPMI packages can be used to predict tides at a temporary tidal station based on the $M_2$ and $K_1$ tidal constants resolved from 25-h temporary tidal station records, plus inference parameters derived from a nearby reference tidal station; that is, many other semidiurnal (e.g., $S_2$, $N_2$, $K_2$, $T_2$) and diurnal constituents (e.g., $O_1$, $P_1$, $Q_1$, $J_1$) for a temporary tidal station can be simultaneously inferred from the $M_2$ and the $K_1$ tidal constituents, respectively, with inference parameters (amplitude ratios and phase-lag differences between referred and reference constituents) derived from the long-term harmonic analysis of records from a nearby reference station. Note that the UTide harmonic analysis program uses exact times to accurately calculate the nodal factors and angles and astronomical arguments, unlike T_Tide, which uses a less accurate linearized time approach.

In this study, harmonic analysis of yearlong 2008 Tongyeong tidal station data was used to derive the inference parameters for 20 diurnal tidal constants inferred from the $K_1$ tide and 17 semidiurnal tidal constants inferred from the $M_2$ tide (Table 3) in order to predict tidal heights from 25-h sea level data using UTide.

4. Modified tidal species modulation technique

To avoid the cumbersome iterative tidal prediction process of Kang's (1997) approach [Eq. (7)], we have introduced the nodal modulation effect and astronomical arguments, with the amplitudes ($H_k^R$) and phase lags ($g_k^R$) of the tidal constituents computed from a conventional standard harmonic analysis, into Eq. (2) as

$$h(\tau) = \sum_{k=1}^m \sum_{i=1}^n f(\tau)^k_i H_k^i \cos[\omega_k^i \tau + V(t_0)^k_i + u(\tau)^k_i - g_k^i].$$

$$= \sum_{k=1}^m B(\tau)^k \cos[\omega_k^i \tau - \phi(\tau)^k].$$  \hspace{1cm} (8)

The correct, modulated amplitude [$B(\tau)^k$] for each tidal species in Eq. (8), including the nodal modulation and astronomical argument corrections, can then be given by

$$B(\tau)^k = \left( \sum_{i=1}^n \left| f(\tau)^k_i H_k^i \right|^2 + 2 \sum_{i \neq j} \left| f(\tau)^k_i H_k^i \right| \left| f(\tau)^k_j H_k^j \right| \cos\left( (\omega_k^i - \omega_k^j) \tau + [V(t_0)^k_i + u(\tau)^k_i - g_k^i] - [V(t_0)^k_j + u(\tau)^k_j - g_k^j] \right) \right)^{1/2}$$

$$= \left( \sum_{i=1}^n \left| f(\tau)^k_i H_k^i \right|^2 + 2 \sum_{i \neq j} \left| f(\tau)^k_i H_k^i \right| \left| f(\tau)^k_j H_k^j \right| \cos\left( [V(\tau)^k_i - V(\tau)^k_j] + [u(\tau)^k_i - u(\tau)^k_j] - (g_k^i - g_k^j) \right) \right)^{1/2}.$$  \hspace{1cm} (9)
TABLE 3. Inference parameter values $[\alpha(i,j)$ of related amplitude ($H_i$) to reference amplitude ($H_j$) and phase-lag difference $[\beta(i,j)$ between reference phase lag ($g_i$) and referred phase lag ($g_j$)] for semidiurnal and diurnal constituents calculated from full-year 2008 harmonic analysis of Tongyeong tidal station.

<table>
<thead>
<tr>
<th>Pair of tidal constituents $(i,j)$</th>
<th>$\alpha(H_i/H_j)$</th>
<th>$\beta(g_i-g_j)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semidiurnal $(17)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(S_2, M_2)$</td>
<td>0.4621</td>
<td>-35.3°</td>
</tr>
<tr>
<td>$(N_2, M_2)$</td>
<td>0.2006</td>
<td>12.8°</td>
</tr>
<tr>
<td>$(K_2, M_2)$</td>
<td>0.1314</td>
<td>-27.6°</td>
</tr>
<tr>
<td>$(\mu_2, M_2)$</td>
<td>0.0514</td>
<td>24.7°</td>
</tr>
<tr>
<td>$(M_2, M_2)$</td>
<td>0.0326</td>
<td>11.4°</td>
</tr>
<tr>
<td>$(T_2, M_2)$</td>
<td>0.0322</td>
<td>-35.7°</td>
</tr>
<tr>
<td>$(N_2, M_2)$</td>
<td>0.0232</td>
<td>7.7</td>
</tr>
<tr>
<td>$(L_2, M_2)$</td>
<td>0.0221</td>
<td>-5.7°</td>
</tr>
<tr>
<td>$(R_2, M_2)$</td>
<td>0.0116</td>
<td>17.8°</td>
</tr>
<tr>
<td>$(e_2, M_2)$</td>
<td>0.0209</td>
<td>38.7°</td>
</tr>
<tr>
<td>$(n_2, M_2)$</td>
<td>0.0150</td>
<td>-40.8°</td>
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<tr>
<td>$(a_2, M_2)$</td>
<td>0.0072</td>
<td>78.9°</td>
</tr>
<tr>
<td>$(H_1, M_2)$</td>
<td>0.0068</td>
<td>149.6°</td>
</tr>
<tr>
<td>$(MN_{62}, M_2)$</td>
<td>0.0059</td>
<td>-82.2°</td>
</tr>
<tr>
<td>$(MSN_{2}, M_2)$</td>
<td>0.0045</td>
<td>214.7°</td>
</tr>
<tr>
<td>$(OQ_{2}, M_2)$</td>
<td>0.0039</td>
<td>-27.7°</td>
</tr>
<tr>
<td>$(O_{1}, K_1)$</td>
<td>0.6770</td>
<td>32.8°</td>
</tr>
<tr>
<td>$(P_{1}, K_1)$</td>
<td>0.3268</td>
<td>1.3°</td>
</tr>
<tr>
<td>$(Q_{1}, K_1)$</td>
<td>0.1339</td>
<td>49.4°</td>
</tr>
<tr>
<td>$(S_{1}, K_1)$</td>
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</tr>
<tr>
<td>$(NO_{1}, K_1)$</td>
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</tr>
<tr>
<td>$(J_{1}, K_1)$</td>
<td>0.0655</td>
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<td>$(SO_{1}, K_1)$</td>
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<tr>
<td>$(OO_{1}, K_1)$</td>
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<tr>
<td>$(\psi_{1}, K_1)$</td>
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<td>$(2Q_{2}, K_1)$</td>
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<tr>
<td>$(h_1, K_1)$</td>
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</tr>
<tr>
<td>$(n_1, K_1)$</td>
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<td>49.3°</td>
</tr>
<tr>
<td>$(\theta_1, K_1)$</td>
<td>0.0143</td>
<td>-27.9°</td>
</tr>
<tr>
<td>$(t_1, K_1)$</td>
<td>0.0118</td>
<td>82.0°</td>
</tr>
<tr>
<td>$(\beta_1, K_1)$</td>
<td>0.0070</td>
<td>110.5°</td>
</tr>
<tr>
<td>$(\phi_{1}, K_1)$</td>
<td>0.0060</td>
<td>-48.9°</td>
</tr>
<tr>
<td>$(\phi_{1}, K_1)$</td>
<td>0.0002</td>
<td>-171.5°</td>
</tr>
<tr>
<td>$(\alpha_{1}, K_1)$</td>
<td>0.0005</td>
<td>-36.5°</td>
</tr>
</tbody>
</table>

and the correct modulated phase $\phi(\tau)^k$ for each tidal species in Eq. (4) can be given by

$$\phi(\tau)^k = \tan^{-1}\left\{\frac{-\sum_{i=1}^{n} H_i \sin[\delta \omega_i t + V(t_0)_i + u(\tau)_i - g_i]}{\sum_{i=1}^{n} H_i \cos[\delta \omega_i t + V(t_0)_i + u(\tau)_i - g_i]}\right\}. \tag{10}$$

Here, $H_i$ and $g_i$ are calculated from $T_{\text{Tide}}$ (Pawlowicz et al. 2002), and $V(t_0)^i$, $f(\tau)^k$, and $u(\tau)^k$ are computed at $t_0$ each time of $\tau$ and from the $t_{\text{yuf}}$ function in $T_{\text{Tide}}$.

Like the CSHAP method of Eq. (1), the CTSM method of Eq. (8) cannot be used with fewer than 15 days of observations, since shorter-term data are insufficient to harmonically resolve the tidal constituent constants. For example, at least 15 consecutive days of hourly data are required to separate out the $M_2$ and $S_2$ tides, which generate spring–neap variations. In addition, at least 28 consecutive days of hourly data are required to separate out the $N_2$ constituent, which produces the perigean–apogean differences between subsequent spring–neap tides, from the $M_2$ constituent.

Figure 2 clearly shows that the accuracy of CTSM...
The Eq. (11) input values, including the harmonic tidal constants and modulated amplitudes and phase lags, can be derived from tidal harmonic analysis results using any standard harmonic analysis program, such as the IOS tidal package (Foreman 1977), T_Tide (Pawlowicz et al. 2002), and UTide (Codiga 2011). In this study, we first used the traditional standard harmonic analysis method of T_Tide. We then used the more recent and improved harmonic analysis technique of Codiga (2011), including the ut_FUV function in UTide, for additional tidal prediction experiments examining the 25-h sea level records.

When compared to Eq. (7), Eq. (11) has several advantages for station O predictions. First, as explained earlier, Eq. (7) necessitates the recalculation of modulated phases and angles for each tidal species at station R for iterative periods of 1 month or less for the duration of the prediction time in order to predict tides at station O. Second, when employing Eq. (7), the longer the station R sea level record that is used to predict tides at station O via harmonic least squares fitting, the larger the prediction error will be due to the increasing problem of not considering the nodal modulation effect.

In contrast, Eq. (11), which takes into account the nodal modulation effect, simply requires a one-off 28-day (minimum) to 1-yr (ideal) record of sea level observations from station R in order to predict any period of station R–modulated amplitudes and phase lags for each tidal species. The longer the sea level record from station R, the more stable and accurate the modulated amplitude and modulated phase-lag predictions will be for this site. Along with these merits, tidal prediction at station O is possible using the minimum 25 h of concurrent sea level data from this and a reference site, plus 28–369 days of data from any time period from station R. The minimum length of concurrent records needed to obtain the tidal constants of the M2 and K1 constituents is 25 h, representing the semidiurnal and diurnal tidal species, respectively, which is for calculating the ratio of modulated amplitudes $[fc'(\tau)_R^K]$ and the difference between the modulated phase lags $[pc'(\tau)_R^K]$ in Eq. (11).

To examine the performance of the T_Tide-based CTSM+TCC method of Eq. (11), we harmonically analyzed 25-h sea level observations (starting at 0000 UTC 1 January) in 2008 from Tongyeong (station R) and Geomundo (station O) tidal stations and in 2011 from Lyttelton Harbor (station R) and Kaingaroa Harbor (station O). Along with the calculated representative tidal constituent harmonic constants ($M_2$ and $K_1$), the station R modulated amplitudes and phase lags for the diurnal and semidiurnal tides were calculated for the full-year prediction periods of 2009 (Figs. 4a,c) and 2012 (Figs. 4b,d) using harmonic analysis results from
the full-year station R observation records of 2008 and 2011. Figures 4e,f clearly shows that station O tides can be predicted to various levels of accuracy using 25 h of sea level data from both stations O and R, plus a long-term record (>28 days–1 year) from station R. In particular, test results reveal that the CTSM+TCC method is applicable even in perigean–apogean-dominated tidal regimes based on just 25 h of concurrent tidal station data (Fig. 4f).

5. Discussion

a. Performance of the CTSM+TCC method

In the previous section, we showed that our method (T_Tide-based CTSM+TCC) could predict tides using the modulated species amplitudes and phase lags derived from long-term station R data, plus amplitude ratios and phase-lag differences for the $M_2$ and $K_1$ tides derived from as little as 25 h of concurrent sea level data from stations O and R. Questions arose as to how much variation in the $M_2$ and $K_1$ tidal amplitude ratios and phase-lag differences was attributable to spring–neap and perigean–apogean cycles and, in turn, what effect this had on tidal prediction accuracy. Accordingly, we explored these questions as explained below.

To evaluate variability in the accuracy of the T_Tide-based CTSM+TCC predictions based on the choice of 25-h field sampling period, we created 365 separate datasets of paired station R and station O records from the 2008/2011 AU11 data: that is, each individual day was used as a “start date” for a 25-h data “slice.” These sliced datasets were then used to calculate 365 sets of CTSM+TCC input values (amplitude ratios and phase-lag differences for the $K_1$ and $M_2$ tidal constituents between stations R and O) per temporary tidal station. For comparison, the calculation of the diurnal and semidiurnal tide modulated amplitudes and phase lags from station R for the 2009/2012 predictions were based on station R 2008/2011 full-year harmonic analysis results.

To examine the characteristics of the $M_2$ (semidiurnal species) and $K_1$ (diurnal species) tidal amplitude ratios...
and phase-lag differences, two pairs of Korean tidal stations (stations R and O) characterized by different tidal peculiarities (Table 2) were selected: Tongyeong versus Incheon tidal stations exhibit large tidal amplitude differences, whereas Tongyeong versus Geomundo tidal stations exhibit small amplitude differences. In general, the $M_2$ and $K_1$ daily tidal amplitudes and phase lags at Tongyeong and Incheon tidal stations (Fig. 5) and at

Fig. 5. Daily (a),(c) $M_2$ and (b),(d) $K_1$ amplitudes and phase lags derived for Tongyeong and Incheon tidal stations based on harmonic analysis of daily 25-h data slices starting at 0000 h each day of the 2008 sea level record. Note the several small gaps correspond to periods when sea level observations failed.
Tongyeong and Geomundo tidal stations (Fig. 6) exhibited very similar variations over time. Specifically, the $M_2$ and $K_1$ daily amplitudes varied with spring–neap tidal cycles, amplitudes increasing during spring tides, and decreasing during neap tides (Figs. 5a,b and 6a,b). However, the $M_2$ and $K_1$ daily amplitudes exhibited different variation patterns in terms of the modulation of the half-year amplitude envelope. For example, during the
specific periods between days 1 and 15 (during January), days 132 and 210 (from mid-May to July 2008), and days 312 and 365 (from November to December), the daily $M_2$ amplitude ranges were relatively small, while the $M_2$ minimum amplitude values were relatively large; however, the daily $K_1$ amplitude ranges were relatively large over the same periods, while the $K_1$ minimum amplitude values were relatively large. Interestingly, these periods are consistent with those of the lower $S_2$ amplitudes calculated from harmonic analysis of monthly 29-day

![Graphs showing daily amplitude ratios and phase lag differences for $M_2$ and $K_1$ tides between different stations.]

**Fig. 7.** The daily amplitude ratios and phase lag differences for the (a),(c) semidiurnal species ($M_2$) and (b),(d) diurnal species $K_1$ between Tongyeong and Incheon tidal stations and Tongyeong and Geomundo tidal stations, derived from the daily 25-h harmonic analyses of 2008 data. Thick solid lines in each panel indicate the amplitude ratio and phase-lag differences for the $M_2$ and the $K_1$ tides, derived from results of full-year 2008 harmonic analyses of the tidal station data.
records over 23 months (Byun 2011). The daily phase lags for the $M_2$ and $K_1$ from both tidal stations tended to have less variation over these same periods (Figs. 5c,d and 6c,d).

Figure 7a shows that the daily $M_2$ amplitude ratios and phase-lag differences between Tongyeong and Incheon tidal stations varied with spring–neap tidal cycles. They tended to be significantly larger, for example, during neap tides (indicated by the smaller $M_2$ amplitudes occurring approximately every 15 days in Fig. 5a). The magnitude of these large neap tide ratios and differences reduced significantly during the periods of small $M_2$ daily amplitude ranges (days 1–15, days 132–210, and days 312–365), as shown in Fig. 5a. In contrast, the daily $K_1$ amplitude ratios and phase-lag differences between Tongyeong and Incheon tidal stations did not exhibit such a consistent spring–neap tidal pattern of variation, although the magnitude of the larger values was also reduced during the same periods (Fig. 7b).

Comparisons between Tongyeong and Geomundo, two stations with similar tidal characteristics, revealed contrasting patterns of variation compared to the above-mentioned comparisons between Tongyeong and Incheon, two stations with large differences in tidal characteristics (note the amplitude y-axis scales in Figs. 7a,b vs Figs. 7c,d); that is, the Tongyeong and Geomundo comparisons revealed no consistent spring–neap tidal variation in the daily $M_2$ amplitude ratios, whereas the daily $M_2$ phase-lag differences did vary with spring–neap tidal cycles. The latter pattern of variation was characterized by large values during neap tides and small values during spring tides (Fig. 7c). In addition, the daily $K_1$ amplitude ratios and phase-lag differences showed no clear spring–neap tidal variation, but the variation that did occur tended to be dampened during the periods May–July and November–January (Fig. 7d). Overall, the range of variation in the $M_2$ amplitude ratios and phase-lag differences were smaller than those of $K_1$ for both paired tidal station comparisons (Fig. 7).

These results indicate that we can obtain relatively stable daily $M_2$ and $K_1$ amplitude ratios and phase-lag differences if the 25-h concurrent station O and station R data are collected during spring tides or specific annual periods. Such data produce more accurate tidal predictions than if neap tide sea level data or data from outside the ideal annual periods were used.

This finding is supported by comparisons between the tidal predictions estimated from full-year harmonic analysis results and tidal predictions derived from our method. Figure 8 clearly shows that RMSEs for all four temporary tidal stations tended to be smaller during spring tides than during neap periods. Encouragingly, the RMSEs for the spring tides predicted using our method were close to (Incheon, Daecheongdo, and Busan), or even smaller than (Geomundo), the RMSEs between the observed data and 2009 predictions derived from full-year harmonic analyses of 2008 observations. Along with these RMSEs (thick gray line in Fig. 8c), the RMSEs between the 2009 observations and predictions derived from full-year harmonic analyses of those same 2009 observations (thick black line in Fig. 8c) indicate the strength of nontidal residuals, which cannot be predicted by this traditional harmonic method.

In comparisons between the predictions generated versus the observations, the RMSE values were relatively small for the Geomundo and Busan temporary tidal stations (Fig. 8). These results are due to the small $M_2$ amplitude ratios and phase-lag differences between each of these temporary stations and the reference site, Tongyeong (e.g., Fig. 7c). In contrast, large RMSE spikes occurred in comparisons between station R and the Incheon and Daecheongdo temporary stations, where large $M_2$ amplitude ratios and phase-lag differences existed (e.g., Fig. 7a). The spikes in Fig. 8 coincided with neap tide periods characterized by relatively large $M_2$ and $K_1$ amplitude ratios and phase-lag differences (Fig. 5). As expected, variations in the RMSEs range were relatively small during the periods from May to July (days 132–210) and November to January (days 312–15), when variations in the daily $M_2$ and $K_1$ amplitude ratios and phase-lag differences were also small (days 1–15, days 132–210 and days 312–365).

In addition, the daily semidiurnal species ($M_2$) amplitude ratios and phase-lag differences for Lyttelton versus Kaingaroa tidal stations (Fig. 9a) were of a similarly small magnitude to those produced for Tongyeong versus Geomundo tidal stations (Fig. 7c). Interestingly, the Lyttelton versus Kaingaroa $M_2$ values varied with spring–neap tidal cycles despite their dominance by perigean–apogean ($N_2$ driven) cycles, as indicated in Table 2. However, the daily diurnal species ($K_1$) values did not show clear spring–neap tidal patterns, nor did they exhibit several-month periods of dampened variation (Fig. 9b) as seen between the South Korean stations (Fig. 7). Large $K_1$ amplitude ratio and/or phase-lag differences (e.g., $>3$ or $>100^\circ$ in Fig. 9b) increased the RMSEs (Fig. 9c) even though the $M_2$ values were stable (Fig. 9a). These large differences in the $K_1$ constituent occur because Kaingaroa is located close to the $K_1$ amphidrome, thus making the amplitude ratios and phase differences between Kaingaroa and Lyttelton more erratic. However, the contribution of this effect to the larger RMSE values was relatively weak, since the $K_1$ amplitude is relatively small (Table 2). Overall, these results indicate that meteorological effects can significantly influence the accuracy of predictions, meaning
FIG. 8. Daily time series of the RMSE between 2009 tidal predictions derived from Tide-based CTS+TCC using the 2008 sea level data from station R (Tongyeong, full-year data including 25-h concurrent with temporary site data) and four temporary stations—25-h data from (a) Incheon, (b) Daecheongdo, (c) Geomundo, and (d) Busan—vs 2009 observation data. The thick solid gray (black) lines in each panel indicate the RMSEs between the 2009 predictions derived from harmonic analysis of the 2008 (2009) data vs 2009 observations with their mean removed.
that the best times to gather input data for our CTSM+TCC tidal prediction method are those characterized by small nontidal residuals (e.g., calm weather).

b. Comparison of performance between TPMI and CTSM+TCC methods

In this section, we compare the prediction accuracy of the TPMI and CTSM+TCC methods, with both techniques based on UTide for comparability. The accuracy of the harmonic analysis, which in turn affects the tidal height prediction accuracy, depends on the amount of nontidal energy (noise) in the data as well as on the similarity of the reference station inference parameter relationships with the new tidal prediction site. To compare the tidal height prediction accuracy of the TPMI-based CTSM+TCC method versus UTide-based CTSM+TCC method, without considering noise-induced errors, we first generated synthetic full-year 2008 and 2009 time series based on the tidal constants of 66 constituents, excluding the $S_n$, derived from harmonic analyses of each tidal station’s full-year 2008 records.

As in previous experiments, Tongyeong tidal station was used as the reference station for testing both methods. The prediction experiments for both methods were conducted using daily 25-h “slices” of temporary tidal station data (Incheon, Daecheongdo, Geomundo, and Busan), starting at 0000 h each day of the 2008 sea level records. Results were compared with the 2009 synthetic time series from each temporary tidal station. Comparisons between the prediction accuracy of the TPMI- and UTide-based CTSM+TCC methods are illustrated in Fig. 10, which shows that the daily RMSEs of tidal height results produced using the two methods were very similar. The RMSE results of TPMI were slightly
better than those of CTSM+TCC (Table 4), due to the lower peak values of the former method. The RMSE values of the tidal height means and standard deviations from each station for TPMI (vs UTide-based CTSM+TCC) were 67.3 ± 38.8 cm (vs 70.7 ± 40.0 cm) for Incheon; 21.0 ± 10.4 cm (vs 22.8 ± 12.0 cm) for Daecheongdo; 4.8 ± 1.6 (vs 5.2 ± 1.6 cm) for Geomundo; and 3.8 ± 1.2 cm (vs 3.9 ± 1.3 cm) for Busan. While TPMI was found to be marginally more accurate than CTSM+TCC, we believe that the latter method will prove useful, since it is more convenient and universal (general) in that it does not require decisions to be made regarding the use of particular inferred and reference tidal constituents based on the length of observation records used.

Further analyses revealed that UTide-based CTSM+TCC predictions exhibited slightly lower mean and standard
deviation RMSE values compared to T_Tide-based CTSM+TCC predictions (Table 4). This indicates that UTide is slightly more accurate than T_Tide because the UTide harmonic analysis program uses exact times, whereas T_Tide uses linearized times in calculating the nodal factors and angles and astronomical arguments.

c. Conditions for high-prediction performance

Similar to our Fig. 8 analyses, both methods also reveal spring–neap and semiannual variations in RMSE, including higher RMSEs during neap tidal cycles.

Comparing the full-year 2008 synthetic daily tidal range records (Fig. 11) with the corresponding RMSE records (Fig. 10), it is apparent that the smaller daily tidal ranges of neap periods tend to result in higher RMSE values, resulting in semiannual variations in RMSE. These analyses show that the tidal constants of the constituents are inadequately harmonically resolved for periods with smaller daily tidal ranges when the dominant $M_2$ tide is out of phase with the $S_2$ tide and other constituents, such as what occurs during neap periods. In contrast, the tidal constants can be adequately resolved for spring periods, with their larger daily tidal ranges, resulting from the $M_2$ tide being in phase with other constituents. To identify the main constituent combinations that increase or dampen tidal height variation during certain neap tide periods, producing the highest and lowest daily neap tidal ranges and, thus, minimum and maximum RMSE values for predictions based on data from these periods, 2008 synthetic time series for four different constituent groupings ($M_2+S_2$, $N_2+K_2$, $M_2+S_2+N_2+K_2$, $M_2+S_2+N_2+K_2+O_1+P_1+Q_1$) were generated from the results of the full-year 2008 harmonic analysis of Tongyeong tidal station data (Fig. 12).

Figure 12 shows how the regularly small daily tidal range variations generated across an approximate 15-day cycle by the $M_2+S_2$ tides (Fig. 12a) combine during certain neap periods with the fluctuating $N_2+K_2$ daily tidal range variations (Fig. 12b) to produce maximum daily neap tide ranges, as shown in Fig. 12c (e.g., around days 130 and 180); that is, the small, regular daily tidal range contributions of the $M_2+S_2$ tides (Fig. 12a) are

![Fig. 11. Synthetic time series of the daily tidal ranges for (a) Tongyeong and (b) Incheon calculated from the maximum and minimum values of daily 25-h data slices starting at 0000 h each day of the 2008 sea level record, derived from harmonic analyses of each tidal station’s full-year 2008 records.](image)
transformed into relatively high neap daily tidal ranges (Fig. 12c) when they combine in phase with the high daily tidal range contributions of the $N_2 + K_2$ constituents (Fig. 12b). As such the $N_2 + K_2$ contribution has a large influence on the daily tidal ranges and, thus, on the RMSEs of predictions based on neap tide period sea level data (Fig. 10). The effects of the other constituents ($K_1 + O_1 + P_1 + Q_1$) with $M_2 + S_2$ constituents on the variation in daily tidal ranges were found to be minor relative to the contribution of the $M_2 + S_2$ and $N_2 + K_2$ combinations (Fig. 12d).

To examine longer-term variability in the accuracy of TPMI predictions, we conducted 19-yr experiments using Incheon tidal height predictions for the years 2008–26. Unsurprisingly, these results resembled those of the T_Tide-based CTSM+TCC accuracy analysis (e.g., cf. Figs. 8, 13). As illustrated in Fig. 13, the most appropriate months for gathering temporary tidal station TPMI input data for South Korean sites were from late May to early July (days 139–190) and from late November to mid-January (days 330–15), due to the relatively high daily tidal ranges exhibited by neap tides during these periods. Note that the RMSEs of predictions made using both the CTSM+TCC (Fig. 8) and TPMI (Fig. 13) methods are likely to be minimized when distances between the reference and temporary tidal
stations are small, meaning that reference station selection should still take into account proximity to temporary sites, as advised by Foreman (1977).

Last, we examined the variation in the RMSEs of our UTide-based CTSM+TCC results produced by varying the duration of the concurrent station R and station O hourly input data between 25 and 169 h. To see if lengthening the input records could improve the RMSE values, we chose a 3-day period that included a third day that produced high RMSEs (Fig. 10) for predictions generated from 25-h concurrent input data using both the TPMI- and UTide-based CTSM+TCC methods. For Incheon, Daecheongdo, and Geomundo, this meant using input data from days 59–61, which covered a period with minimum daily neap tidal ranges. The Busan predictions produced using input data from this period did not result in high RMSEs, despite the small daily tidal ranges, so instead we used days 94–96 for analysis of this site. We used the same synthetic 2008 tidal time series data employed in the RMSE comparisons between TPMI and the CTSM+TCC predictions.

As shown in Fig. 14, the RMSEs produced using 25-h input data from days 61 and 96 exhibited high RMSE values, with the error values decreasing gradually as the input data records were lengthened to 169 h. This improvement in prediction accuracy with longer data inputs likely occurred because the 169-h records included days that produced low RMSE values along with the penultimate 25-h record that produced high RMSEs. In contrast, the RMSE experiments based on the starting days 59 (94) and 60 (95) showed a tendency for RMSEs to increase with record length, until the input record duration extended beyond the days that resulted in high RMSE values. These results indicate that for the Incheon, Daecheongdo, and Geomundo sites, when using neap tide input data that include minimum tidal range days, prediction accuracy can be improved by using concurrent input records >4.5 days in length. Using input records >7 days long, however, is unlikely to produce more accurate results compared to simply using the 25-h input data, with RMSEs resembling those illustrated in Fig. 10.

Similarly, the RMSE values of Busan predictions were clearly reduced using >4.5 days of input data, but anomalously high RMSEs were produced using 35- and 50-h-long input records from days 96 and 95, respectively (Fig. 14d). Further analysis using the “day 96 start” experiment as an example (Fig. 15) indicates that the high RMSEs produced using 35-h inputs appear to result from the abnormally high amplitude ratios (12.043) and phase-lag differences (−131.88) of the diurnal tide (K1) compared to those (0.305 and 32.08, respectively) of the 1-yr harmonic analysis, and from the relatively stable amplitude ratios and phase-lag differences (0.495, 7.08, respectively) of the semidiurnal tide (M2) compared to those of the 1-yr harmonic analysis (0.498 and 9.18, respectively). This analysis indicates that input data periods that produce high RMSEs, and thus less accurate predictions, can be identified by checking for variations in amplitude ratios and phase-lag differences for the diurnal (K1) and semidiurnal (M2) tides.

6. Conclusions

This study explains the theoretical construction of a new tidal prediction method, “CTSM+TCC,” that can produce accurate tidal predictions for any time period for a temporary station location based on as little as 25 h of concurrent sea level records from this and a known “reference” site with similar tidal characteristics, plus 28 days (minimum) to 1 year (ideal) of sea level records from any time period from the reference station. The performance of our method based on conventional standard harmonic analysis, CTSM+TCC, is evaluated using data from the tidally dominated coastal regions of south and west South Korea, and from the strongly
influenced perigean–apogean regimes of two wave-dominated sites in southeastern New Zealand. Evaluations reveal that sea level input data sampled during spring tidal periods as well as from specific annual periods (May–July and November–January) are the most appropriate in the tide-dominated South Korean context.

In addition, for the wave-dominated coasts of New Zealand, the accuracy of prediction is adversely affected by the use of recording periods characterized by large nontidal residuals such as those produced by synoptic weather. Together, these comparisons reveal that a sampling-period quality-control process that is adjusted to the coastal environment under consideration can maximize the accuracy of results produced using our short-term tidal prediction method based on input data. Furthermore, the performance of our CTSM+TCC and the recently published TPMI methods are compared using an improved conventional standard tidal analysis and prediction software package (UTide) and synthetic tidal height time series datasets predicted using the tidal constants of 66 constituents from the South Korean tidal stations. Generally, the variability in prediction errors for both methods was similar, particularly during spring tide periods. This analysis identified certain periods of the year with low RMSE values, which equate to preferred times for temporary tidal station data collection. The high values of the $N_2 + K_2$ daily tidal ranges during neap tides

![Figure 14](image.png)

**Fig. 14.** Daily time series of RMSEs between 2009 tidal predictions derived from UTide-based CTSM+TCC using 2008 predicted sea levels from station R (Tongyeong, full-year data) plus concurrent, hourly increment predicted data lasting between 25 and 169 h depending on the start day (i.e., earlier start days in plots indicate longer durations) from station R and four temporary stations—(a) Incheon, (b) Daechegongdo, (c) Geumundo, and (d) Busan—from which the $S_a$ tidal component has been harmonically excluded.
were also identified as the main contributor to the generation of relatively high daily tidal ranges during specific neap periods. In conclusion, our T_Tide- or UTide-based CTSM TCC tidal prediction method represents an alternative to the TPMI methodology for those wishing to make tidal predictions for new sites (i) based on the established conventional standard tidal prediction software and (ii) via a method that offers efficient input data collection for a wide range of potential prediction outputs, and easy and simple automatic operation without the need for a decision process regarding multiconstituent inference calculations. This method could potentially support the spatial and temporal proliferation of tidal predictions across our coastal oceans, where fieldwork funds and instruments have limited past advances, leading to improved navigation, oil-spill dispersion modeling, and tidal energy prospecting, to name but a few applications.

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Fig. 15. The daily amplitude ratios and phase-lag differences for (a),(b) the diurnal species K1 and (c),(d) semidiurnal species M2 between Tongyeong and Busan tidal stations, derived from the harmonic analyses of data using 25–169 h of 2008 sea level input data (with start days between 94 and 96).
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