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Spanish Preservice Primary School Teachers' Understanding of the Tides Phenomenon

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Abstract

In this study, we analyzed the descriptive knowledge and mental models of the phenomenon of tides manifested by 111 preservice primary teachers. The instrument employed is an open-ended questionnaire, analyzed by means of an approach that explores the descriptions, explanations, and predictions in respect of this phenomenon by our subjects. First, we made a descriptive study of the kinds of ideas applied across different dimensions of analysis, and, subsequently, a cluster analysis was performed to check how those ideas were articulated and modeled. By means of this analysis, we were able to identify the mental models underlying the responses of preservice primary teachers. Furthermore, the results showed that the models they did have were not used when it came to making predictions in local situations. Instead, they employed heuristic rules based on everyday assumptions, not always consistent with tidal cycles of approximately 12 h. However, faced with situations that required thinking on a global scale, they did use their models, normally based on alternative conceptions. Lastly, from the results obtained, we consider some of the possible difficulties that preservice primary teachers may have in learning about the phenomenon of tides, and the implications for future teaching–learning designs aimed at overcoming those difficulties.

Keywords Descriptive knowledge · Models · Modeling · Preservice teachers' models · Tides

Introduction

The movements of heavenly bodies and their cycles have been the subject of scientific study throughout history. Events such as the day/night cycle, the seasons, and the ocean tides have called for rational or scientific explanation in the past and are today taught to children at school. The phenomenon of tides, in particular, was not

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satisfactorily explained until thinkers such as Newton and Laplace appeared and used classical mechanics to develop models that allowed the phenomenon to be understood. It therefore provides us with the opportunity to put Newton's concept of gravity and mechanics in a specific context (Fazio & Battaglia, 2019; Viiri & Saari, 2004). Moreover, this phenomenon is one of the most familiar astronomical events for students, especially those living in places on an ocean coast.

Nevertheless, constructing a scientific model of this astronomical phenomenon is not easy. In fact, according to Solbes and Palomar (2011), its difficulty is determined by several factors, including the intrinsic complexity of the phenomenon, its conceptualization in terms of dimensions and scales, a generalized lack of interest in scientific topics among students, and the decontextualized image of science. Other reasons are offered, such as the difficulty in forming a space view of the phenomenon, and the change in system of reference (Black, 2005; Wilhelm et al., 2018, or the existence of alternative ideas different from those taught in school (Hegarty, 2010; Parker & Heywood, 1998; Slater et al., 2018). In particular, these difficulties also affect the phenomenon of the tides. This is demonstrated by the large number of studies aimed at clarifying the scientific interpretation of the phenomenon (Härtel, 1995; Norsen et al., 2017), at explaining the basis of the tides in a way that is understandable to non-specialists (Armario et al., 2019; Viiri & Saari, 2004), and at characterizing the misconceptions regarding the phenomenon in students of different educational levels (Ucar et al., 2011; Viiri, 2000).

In Spain, the phenomenon of the tides is studied from primary education onwards, when students are aged 10 to 12 years (EEP, 2015). Hence, it is important for their teachers to have a good knowledge of this phenomenon and to have developed a model to explain it. The purpose of our study is to characterize the descriptive knowledge and the models regarding the phenomenon of tides, utilized spontaneously by Spanish student teachers in initial training. Taking into consideration the results obtained, our intention is to foresee the possible difficulties that may be encountered in their learning processes on this topic and to develop proposals for future action orientated to assisting students to advance their mental models towards those more in accordance with the school science.

Models in Science Learning

Both in daily life and through school learning, an individual constructs representations of reality that are useful in the same way that a scientific model is useful to the scientist: they are constructed in order to describe, explain, or predict situations and phenomena (Adúriz-Bravo, 2012; Grosslight et al., 1991). These representations are based on causal relationships that allow connections to be made between causes and effects, thus linking abstract knowledge with real-world phenomena (White, 2009).

These representations, known as mental models, are structural analogs of the world; and employing these models allows the individual to adapt and to interact with it (Johnson-Laird, 1996). It is assumed that, when a question is put to someone, that person constructs a mental model in order to respond to the question; and that model is later evaluated, revised, and modified if necessary (Gobert & Buckley, 2000). In this context, it is expected that these models get organized and structured, taking as reference the school science model.

Mental models are internal and implicit and for that reason are not directly accessible to others (Gilbert & Boulter, 1995). Hence, the means by which one can obtain information on students' mental models is through their explanations and symbolic representations used when the students are applying their models (Blanco et al., 2019; Monteira & Jiménez-Aleixandre, 2019; Passmore & Svoboda, 2012). However, when a student responds to a question, generating an explanation, a drawing, or some other type of representation, that response is only a partial manifestation of their mental model. Consequently, more than one question may be needed in order to identify the particular model used by that student.

A necessary condition for constructing models is that students should have some knowledge of the reality that is to be modeled. But it is also possible that students construct their explanations on the basis of information that is merely memorized and not well-understood. Regrettably, that is what often happens, since the models studied at school frequently become converted into canonical representations that are provided to students in the hope that they might be memorized, rather than being employed as a tool for helping the child make sense of natural phenomena (Guy-Gaytán et al., 2019). To avoid this, learners need to participate in the construction and review of their own explanations and to connect these with the phenomena they represent (Odden & Russ, 2018).

The School Science Model and Student Models of the Tidal Phenomenon

To characterize the descriptive knowledge and models utilized by a student requires us first to define a school science model of reference. This reference model will serve to assess how distant or close the student's existing model is with respect to the correct model and allow us to establish possible progression routes in the learning. Above all, the reference is very important when we are intending to use this characterization subsequently, as in our own case, to develop proposals for future action orientated to assisting students to advance their mental models. For this, we consider a simplified model similar to that provided in many Spanish school textbooks for use in obligatory teaching (Armario et al., 2021). In this model, the surface of the Earth does not have continents but is covered by an unbroken hydrosphere. The gravitational force exerted by the Moon, and by the Sun less evidently, deforms the planet and its oceans, resulting in a water mass (with the Earth "encased" within it) that is not spherical but rather ellipsoid in shape, with two "bulges", on opposite sides to each other. This deformation is due to the difference in force (tidal force) generated between the points on the planet's surface closest and most distant, respectively, with respect to the Moon (Fig. 1). The gravitational force acts with different strengths and in different directions on the volumes of different matter—liquid and solid—comprising the planet as a whole (Simanek, 2015). The resulting deformation causes tidal cycles of approximately 12 h because the Earth turns completely on its axis once every 24 h. This necessarily implies that there are two tides per day, and that, at two points at the same latitude, separated by 180° of longitude, the state of the tide will be the same.

This is a static and very simplified representation of the reality, since the rotation of the Earth-Moon system as a whole generates a drag effect on the two bulges, displacing them slightly from where they would otherwise be situated, with the result that the bulges are not aligned symmetrically with the axis. Furthermore, the existence of the continents impedes the uniform lateral displacement of the oceans' water towards the two sides of the planet. Thus the global pattern of tides actually generated is the result of many factors, including the depth and shape of the ocean basins, the friction due to the irregular sea bottom, and the topography of the coastlines (Simanek, 2015). In fact, because of these diverse factors, there are some places on the planet that experience only one tidal cycle per day.

However, working with such a complex scientific model is beyond the objectives of this study. Hence, we resort to the simplified version of the scientific model as sketched above.

Significantly, the existing literature on students' understanding of this phenomenon indicates the existence of mental representations very different from the simplified model described above. For example, Ballantyne (2004) detected that children aged 10–11 years tend to explain the tides in terms of the action of the wind, currents, or waves. Viiri (2000) studied Finnish secondary-level students and teachers in initial training, and later Corrochano et al. (2017) researched Spanish subjects.

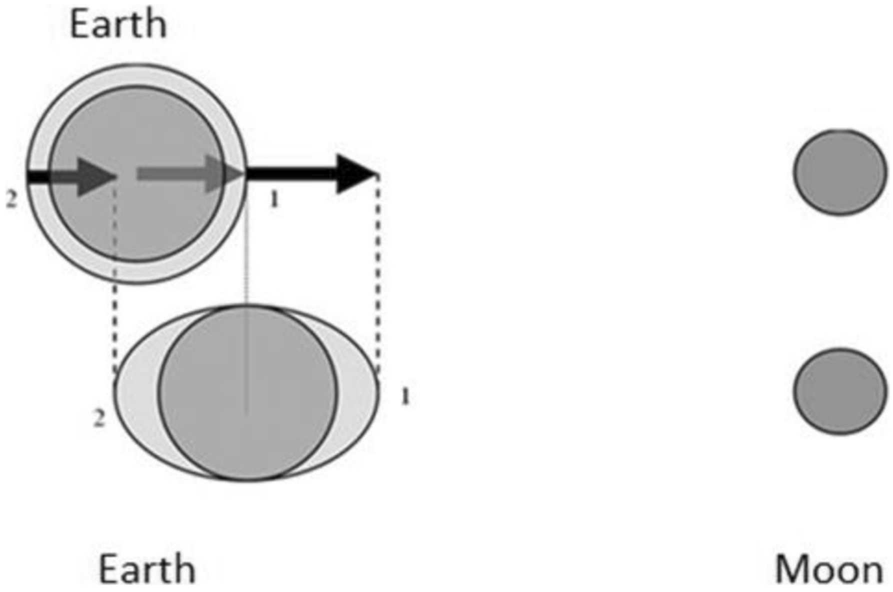


Fig. 1 Generation of the tidal bulges (Armario et al., 2019)

These authors analyzed how the phenomenon is understood, with the object of delimiting typical categories of responses, and analyzing their differences with respect to the scientific explanation of the phenomenon. In particular, Viiri (2000) identified several categories of ideas. In a first category, two bulges of water mass appeared, although hardly any of the students managed to explain this configuration in terms of a gradient of forces. In a second category, in which the majority of explanations were grouped, the idea expressed was that of only one bulge, that was normally argued as resulting from gravitational attraction exerted by the Moon. Furthermore, in a third category, the students focused their attention on the movement of the sea's shoreline during the rise and fall of the tide. That study reveals that the pupils may be able to understand that the tide results in a bulge of water mass on the side of the planet closest to the Moon, but not in a similar bulge that occurs on the opposite side.

In effect, in the studies not only of Viiri (2000), with Finnish subjects, but also of Corrochano et al. (2017) in Spain, of Oh (2014) in the Republic of Korea, and of Ucar et al. (2011) in the USA, the explanations given by student teachers in training seem to consider that the gravity of the Moon tends to make the oceans' waters accumulate on one side of the Earth and recede on the other. In the best of the cases, students do understand the second bulge of water, but in function either of the possible centrifugal effect of the Earth spinning on its axis, or of the presence of the Sun, that exerts a pull from the opposite side (Oh, 2014).

But despite their undoubted interest, the two cited studies of Viiri (2000) and of Corrochano et al. (2017) employ a questionnaire with only one single question; this prevents the possibility of integrating the information obtained from different responses. Moreover, in the study of Ucar et al. (2011), the questionnaire employed served only to quantify the number of correct responses of the participants, and not to delimit the reasoning models used. It is, therefore, considered of interest to take up again the study of this topic but to collect and organize information obtained from different explanations in order to delimit mental models. Similarly, it is of interest to gather information on the descriptive knowledge they employ when asked to describe and predict the tides.

This study forms part of broader research concerning the ideas that students offer on tides in terms of models. Specifically, we propose to respond to the following two questions:

1. What descriptive knowledge on the phenomenon of tides is possessed by Spanish primary-level teachers in initial training, in a coastal location?
2. What models do they employ to explain that phenomenon?

Methodology

Data Collection Instrument

The instrument used was an open-ended questionnaire (Table 1 and Appendix). This comprised two parts: the first part sought information about the student's environment and familiarity with the phenomenon studied; the second comprised seven questions dealing with aspects of the phenomenon corresponding to the three dimensions of modeling: description, prediction and explanation (Table 1). In most cases, the questions formulated required a verbal response, and in some cases, the response sought was also a drawing by the student or work by the student on a given drawing. For example, in question 5, both kinds of response were sought at the same time. The questionnaire had previously been validated by consultation with experts and by conducting a pilot test (Armario et al., 2018).

Participants

The sample studied comprises 111 Spanish primary school teachers in initial training (86 females and 25 males), belonging to two class groups of the University of Cádiz. At the time of the study, they were beginning the subject didactics of natural sciences I (third year); this was the first time they had studied any science subject in their university-level course of studies.

Of these students, 70.3% are residents of various localities in the Province of Cádiz, on the south coast of Spain. The University's School of Education where they were studying is situated only a few meters from the sea. For that reason, we can assume that the participants ought to be familiar with the phenomenon of tides. In fact, 89.8% of them state that they visit a beach very frequently, sometimes three or four times a week during the whole year, and 95.5% of the students are aware of the tidal changes that take place during a complete day on the beach. Further, 58.5% undertake some kind of activity involving the sea, such as surfing or fishing, which requires them continuously to make use of tidal tables as a means of predicting this natural phenomenon. Studying the tides is also a topic of interest and motivation for the participants in this questionnaire, as 89.2% of them state that they want to learn more about this natural process. Furthermore, considering that the majority of participants had not had any formal studies of science subjects since their 9th

Table 1 Research purposes of each question of the questionnaire

Q	Purpose
1	To study how the students define the phenomenon of tides
2	To characterize their ideas on the periodicity of the phenomenon
3	To identify their ideas about the variations of the tides in function of factors such as the wind and the littoral geomorphology of the ocean
4	To find out if the student has associated the phenomenon of tides with the natural processes taking place in the Sun-Earth-Moon system
5	To explore the reasons why the student believes that the tides are produced
6	To analyze the prediction formulated by the student: (a) with respect to the state of the tide at another point on the globe and (b) about whether one or two tidal mass bulges are believed to occur
7	To analyze the prediction formulated with respect to the phenomenon for a particular assumption (*)

(*) On the south coast of Spain, in the region from which these students came, there are two tides every day.

year in education at secondary level, aged 13 to 14 years, the current course should contribute significantly to their scientific education. The students were informed that they were participating in a research study; their informed consent was requested and given.

Data Analysis Procedure

To answer the first research question requires information obtained from the responses to questions 1, 2, 3, 6, and 7. The information obtained was analyzed according to four dimensions: *definition of the phenomenon of tides; periodicity of the phenomenon; comparison of the tides in different parts of the world;* and *prediction of the phenomenon.* For each dimension, categories were created in function of the responses obtained (Table 2). The information obtained from each of the questions is complementary to the rest, since different dimensions are alluded to; hence, there are no inconsistencies in the responses.

The second research question was intended to determine how the participants explain the phenomenon studied. For this, information from responses to questions 1, 3, 4, 5, and 6 was used. In this case, the information obtained was analyzed in a holistic way. It was classified in accordance with an inductive system of emergent categories, based on an analysis of the survey responses. The process started with a first reading of the students' responses, with the object of seeking dimensions that would serve to organize the data, and regularities that would allow us to group the information in categories and subcategories. The analysis was carried out in three rounds, such that in each round new categories were created and others eliminated, in function of the data, with the object that all the responses would fall logically into one or other of the categories proposed.

As the final result of that process, our analysis has evaluated the explanations and arguments put forward by the subjects in relation to three dimensions of the phenomenon: the *causal agent*, internal versus external; the use of the concept of *force as the mechanism of actuation*; and the *effect produced* on the tidal mass (Table 3).

Each category considered was, in turn, coded by means of an ordinal scale of three or four values (in function of the dimension analyzed) (Table 4).

In this case, a separate analysis of answers to each question was not made: instead, there is a joint analysis of the information obtained from each of them. In fact, the responses referring to explanations of the phenomenon were concentrated above all on questions 4, 5, and 6, although information was also compiled from answers to questions 1 and 3. It was also considered that the various subcategories of each dimension were not mutually exclusive. For example, if a student attributed the cause of the phenomenon to both the wind and the moon, in responses to different questions or to one single question, we resolved this situation by attributing that response to both categories (in this example, to IC4 and EC4). In addition, the highest score presented by the student over the whole questionnaire was taken as the value of each rubric. Therefore, it was considered that, if the student managed to achieve the highest score in a particular context, this would be possible because the idea in question was

Table 2 System of categories for the analysis of knowledge, description, and prediction of the phenomenon, with an indication of the question of reference in the questionnaire

Dimensions	Categories and subcategories	
Definition of the phenomenon of tides (Q1)	a). Changes produced in the tidal water mass	
	b). Movements of the water	
Periodicity of the phenomenon (Q2)	a). 2 cycles/day	
	b). 1 cycle/day	
	c). Other periods	
	d). Indefinite	
	e). Not known	
Comparison in different parts of the world (Q3)	a). The tides are the same all around the world (with or without justification)	
	b). The tides differ from one place to another (with or without justification)	
Prediction of phenomena	a). In the antipodes, at the same moment (Q6)	• High tide
		• Low tide
		• Not defined
	b). Twelve hours later in the same place (Q7)	• Adequate (with or without justification)
		• Incorrect (with or without justification)
		• Indeterminate (Not coherent or not answered)

Table 3 System of categories for evaluating the causality of the phenomenon

Dimension	Category and subcategory			Brief description
Causal agent	Internal cause	Geomorphology of the oceans/littoral	IC1	Differences in the shape of the coastline and ocean/sea basins
		Tectonic plates	IC2	Internal movements of the Earth (tectonic plates of the Earth)
		Movements of the sea	IC3	Natural processes associated with this movement: marine currents, waves, or level of the sea
		Wind	IC4	Includes all movements of air capable of moving sea and ocean water
		Atmospheric factors	IC5	Such as temperature, pressure, humidity, cloud formation
		Natural catastrophes	IC6	This cause covers phenomena like tsunamis, storms, and/or floods
	External cause	Position/movement of the Earth	EC0	Category of transition between the internal and external factors causing the phenomenon
		Phases of the Moon	EC1	Causes referring to the different states of the lunar cycle
		Eclipses	EC2	Tides are associated with eclipses
		Sun-Earth-Moon system	EC3	Astronomical phenomena, like the seasons of the year or the day-night cycle
		Presence and/or position of the Moon	EC4	Unlike the category EC1, these responses do not explicitly contain words like lunar cycle, phases of the Moon, full Moon, or new Moon
		Dual presence of the Moon and the Sun	EC5	Responses incorporating the two astronomical bodies in the explanations
Mechanism of actuation	Force/gravity as cause		FC	Responses that refer to the process by which the phenomenon of tides is produced, normally defined in terms of force
Effect produced	Number of tidal bulges		NB	Relative to the effect on the tidal water mass

Note. *IC* internal cause; *EC* external cause; *FC* force as cause; *NB* number of tidal bulges.

Table 4 Ordinal scales for different dimensions

Dimension	Level	Definition
Causal agent	2	Principal cause-effect relationship
	1	Secondary relationship: complementary factor to the principal cause or relationship of co-variation
	0	No relationship is presented
Mechanism of actuation	3	The phenomenon is attributed to a gradient of forces*
	2	The idea of force/gravity is employed, and the causal object is stated
	1	The idea of force/gravity is employed, but without naming the causal object
	0	Forces are not mentioned
Effect produced	2	The deformation of the tidal water mass is conceived in terms of two bulges
	1	Only one bulge is postulated
	0	No reasoning at all is offered in terms of bulges

* This specific explanation was not found in the sample, as will be seen later, but it is considered of interest to include, for future studies on learning progressions.

available in the mind of the student. For example, if in the case of one question the student explained clearly the phenomenon in terms of gravitational force exerted by an astronomical body while in another only influence was mentioned without any more detail of the mechanism, the level of reference or score attributed to the rubric FC was “2.”

The categorization applied in the study was done independently by two researchers who had previously agreed the criteria to be employed. After two preliminary rounds of categorization and comparison of results, in the third and definitive round, a level of agreement of 98.5% was reached, with a kappa coefficient (Cohen, 1960) that ranged between 0.79 and 1, in function of the specific category, and a mean value of 0.95. In the few cases in which there was a discrepancy, a third researcher intervened.

Lastly, we thought that having a limited number of models for categorizing the responses of the students would facilitate the process of data interpretation Stewart et al. (2012) and the future construction of progression paths to guide student learning. Thus, from the data obtained in respect of each different dimension, a hierarchical cluster analysis was carried out in order to identify groupings of students with similar responses. The Ward method (measured with the square of the Euclidean distance) was used for this analysis (Ward, 1963). Many methods can be used to choose the optimal solution in hierarchical clustering (Battaglia et al., 2019; Stewart et al., 2012). In this case, we employ the RMSSTD and RSQ statistics (Sharma, 1996): RMSSTD is a measure of homogeneity within clusters, and RSQ indicates the extent to which clusters are different from each other. A marked change in the trend of the RMSSTD and RSQ curves indicates that a satisfactory number of clusters have been obtained.

Results

In this section, we analyze the descriptive knowledge of the participants on the phenomenon of the tides, and the models employed for the interpretation of the phenomenon.

Descriptive Knowledge

Description of the Phenomenon

The analysis has revealed two main kinds of definition formulated by the participants: one referring to changes produced in the tidal water mass, and the other formulated in terms of movements of water. In the first case, most spoke of changes referring to the rise and fall of the level of the sea (49.2%), whereas others spoke simply of "changes in the level of the sea" (32.3%), "changes in the sea" (13.9%), or even "changes in the water" (4.6%). Considering the second kind of definition, "movements", these respondents (32.4%) all coincided in describing the phenomenon as a process in which the movement of the water takes place. Of that second group, those more precise in their definition described the phenomenon in terms of "the movement of currents of water or marine currents" (65.2%), whereas others spoke of the "movement of the waves" (34.8%). The remainder, 10.8% of participants, gave undefined responses.

In relation to the periodicity of the phenomenon, Table 5 shows the wide variety in the responses. A relatively large number of students (37.8%) showed they have adequate knowledge, stating that this change takes place approximately every 6 h, i.e. by means of two daily cycles. However, many (23.4%) considered there is only one tidal cycle each day; this notion is made explicit in a wide variety of ways. For example, 12 of those 26 students stated that there is "a change of tides every 12 h," while others spoke of "a complete cycle of low tide and high tide per day." There are also participants who referred to other periods, and some who gave undefined or blank responses. Thus, one group of participants (13.6%) specified other frequencies, such as "the tides take place every eight hours" or "every four hours." Another significant group (17.1%) offered ambiguous responses or with wide margins of imprecision: "between 3 and 6 h" or "one or two times a day." Lastly, 8.1% of respondents were not capable of giving a specific response.

Table 5 Distribution of the responses on the periodicity of the phenomenon of tides

Periodicity	%	Example
2 cycles/day	37.8	"The changes of the tide take place every six hours"
1 cycle/day	23.4	"There is one low tide and one high tide a day"
Other periods	13.6	"The tides take place every eight hours"
Undefined	17.1	"Once or twice a day," "Every so often," "Constantly"
Not known	8.1	"I don't know"

From the responses of the participants to question 3, we were able to analyze how they compare the effect of the tide in different parts of the world. Almost all the participants (94.6%) recognize that the rise and fall of the tide is not the same in all parts of the world, although most did not explain their response, and among those who did so, a wide variety of arguments are observed. There are some respondents who point to differences in the tides existing between geographic zones with a sea-water coast and those with an ocean coast: “they are not the same, it depends on whether you are on a sea or an ocean.”

Prediction of the Phenomenon

The analysis of the responses given to questions 6 and 7 indicates that the students made more adequate predictions when the context is a situation close to them. That is the case in respect of question 7 (Table 6), in which a real situation on the beach is the context proposed and the students were asked to predict the state of the tide 12 h later. Here, the most frequent responses were of the type: “It would be the same level, since a change of tide takes place every six hours” and “The tide would be the same, since it has completed its cycle.” Specifically, 41.4% of the participants made an adequate prediction, although only three quarters of them provided an explanation for it. In these cases, the explanations offered were based on memory rules (tidal cycles of approximately twelve hours) learned through the student’s experiences of everyday life or on information obtained at school. These results are consistent with those reported for question 2 about the periodicity of the phenomenon (Table 5). In fact, by dichotomizing the responses into “adequate” or “inadequate,” we obtained a statistically significant degree of association between the two questions ($\chi^2 = 17.71$, $df = 2$, $p = 0.000$, $phi = 0.40$).

However, this does not coincide with the responses given to question 6, in which they were asked about the state of the tide at a point on the equator knowing that, at the opposite side of the globe, at that time, there was high tide. In this case, only 4.5% of the participants responded adequately, stating that the tide would be also high; a substantial majority of responses (70.3%) to this question indicate, to the contrary, that the tide there would be low. In fact, the predictions were normally based on a model and not on descriptive knowledge, such as: “it would be low, since that point would be located at a greater distance from the Moon.” The consequence

Table 6 Distribution of the responses given to question 7 of the questionnaire

Types of response		%
Adequate*	With explanation	30.6
	Without explanation or incomplete/ inadequate justification	10.8
Incorrect	With or without explanation	48.6
Indeterminate	Not coherent or not answered	10.0

Note. * Responses in which the idea of two complete tidal cycles per day is made explicit.

of this is that there would be no correlation between questions 2 and 6 ($\chi^2 = 0.56$; $df = 2$, $p = 0.439$, $phi = 0.07$).

Next, we consider the criteria of causality employed to interpret the phenomenon.

Causal Analysis: Explanation of the Phenomenon of Tides

We employ the system of categories (Table 3) to analyze holistically the explanations given by the participants. Figures 2 and 3 provide quantitative information on the distributions of frequencies obtained for the different dimensions, categories and subcategories considered.

In Fig. 2, it may be helpful to recall that in level 2 (red-colored bars), the factor considered is the principal causal agent of the tides, whereas in level 1 (blue-colored bars), the relationship established is only complementary or of covariation. As can be seen, the cause of the tides is attributed or related principally to external factors, such as the position of the Moon (EC4) or the current phase of the Moon (EC1), and, less frequently, with the dual presence of the Moon and the Sun (EC5), or the position/ movement of the Earth itself with respect to other astronomical bodies (EC0). However, in some of the students' responses, the cause is attributed to internal factors, principally to movements of the sea (IC3), the wind (IC4), or to atmospheric factors (IC5). Some of their responses were: "I believe that the tides are produced by the intensity of the wind" and "[The tides] are produced by the movements of tectonic plates and the movement of the waters." In addition, other internal factors such as the geomorphology of the ocean or of the littoral (IC1), or natural catastrophes (IC6), are cited as having influence on the phenomenon; however, in these cases, they are considered not so much as the principal cause but rather as a secondary factor (level 1).

On the other hand, Fig. 3a indicates that 47.8% of the participants make no reference to any mechanism of actuation in their explanation of the phenomenon of the tides (level 0). A few students (5.4%) make some allusion to the force of gravity as a mechanism without mentioning any causal agent (level 1), and almost half (46.8%) of the explanations cite the astronomical body that gives rise to that force (level 2). Lastly, it is notable that none of the participants explains the phenomenon in function of a gradient of force (level 3). These data are consistent with the number of bulges indicated in their drawings and explanations (Fig. 3b). It can be appreciated that almost a quarter of the participants (23.4%) have no conception of even a single bulge (Level 0), at least not explicitly. Further, almost three quarters of them (71.2%) conceive of the existence of only one bulge (Level 1); and only a small minority of responses (5.4%) identify two bulges (Level 2).

With the object of reducing the volume of information and to reveal the mental models that underlie the categories of analysis considered, we performed a hierarchical cluster analysis using each of the subcategories of Table 3 as variables and levels given in Table 4 as values. Figure 4a shows the RMSSTD and RSQ statistical indicators in function of the number of distinct clusters proposed. It can be seen that the inflection points occur for seven as the optimum number of clusters; this solution is reflected in the dendrogram (Fig. 4b).

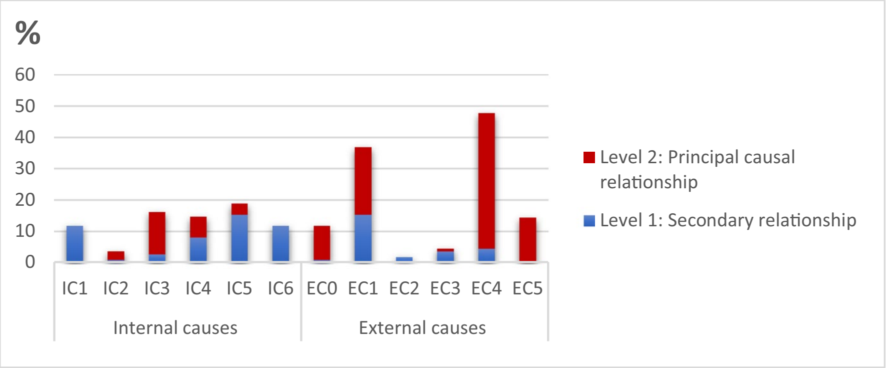


Fig. 2 Students' responses assigned to each of the categories of analysis for the dimension: c*ausal agent*

Once the sample had been segmented, it was possible to calculate in each cluster the median values of the rubrics used for each (sub)category (Table 3). From these values, we were able to establish which of the (sub)categories were implicated in each cluster and the corresponding value of the rubric (Table 7).

Cluster 1 groups together those students (27.9%) who explain the phenomenon of tides as a natural process produced by the force exerted by the Moon (EC4); they conceive the final effect of this force in terms of displacement of all the tidal water mass towards the part of the Earth's surface closest to the Moon (Fig. 5). This is the situation that Viiri (2000) described in terms of existence only one tidal bulge.

The responses assigned to cluster 2 suggest a more complex, albeit incomplete, conception (9.9%). These are the only responses in which the phenomenon is conceived as a consequence of the effect produced by the gravitational forces exerted by the Moon and the Sun in combination (EC5): "In previous primary and secondary courses, it was explained to me that [the tides] are produced by the forces exerted by the Moon and the Sun on the Earth."

Grouped in cluster 3 (18.0%) and in cluster 4 (11.7%) are those students' responses in which the lunar phases (EC1) or the Moon itself (EC4) are taken, respectively, to be the principal causal agents of the phenomenon. Unlike clusters 1 and 2, the responses in these groups consider that it is the mere presence of the Moon/Phase that determines the rise and fall of the sea level, without specifying any causal mechanism of interaction. For example, one of the students commented the following: "[The sea level] will be low because the Moon will be closest to the circle [the symbol marked on the drawing of the globe directly facing the Moon] and furthest from the triangle [a second symbol marked on the drawing situated on the opposite side of the globe to the first symbol]" (Question 6). As can be seen, this student's conception again corresponds to the idea of only one bulge.

Cluster 5 represents the responses of students (6.3%) whose ideas about the cause of the phenomenon seem to be a mixture of internal and external causes. In some of the responses, explanations based on internal causes (IC5) appear, while in others the phenomenon is also attributed to the presence/position of the Moon (EC4). In this cluster, the students' responses do not specify a mechanism that generates

Fig. 3 Students' responses assigned for the dimensions: *mechanism of actuation* (**a**) and *effect produced* (**b**)

the phenomenon by means of a force or forces. For example, in Fig. 6, the idea of force or gravity as the mechanism of action is not mentioned. In this same student's responses to another of the questions, the phenomenon is also associated with internal factors: "[the phenomenon is associated] with anticyclones, storms and phenomena that are similar and alter the course of the water" (Fig. 6).

Clusters 6 and 7 group together the responses of those participants (11.7% and 14.4%, respectively) who characterize the tides as a natural process influenced only by internal factors of the Earth itself. For example, in one case, the student explained the cause of the tides in the following terms: "…by the movement of the water and of the winds" (question 5). In one response of cluster 7, the student's answer to question 6 refers to the quantity of water on the planet: "I suppose it would be low because all the water has gone towards the other side."

We must state that the characteristics indicated for each cluster are only prototypical perspectives at the level of one group of students' responses with respect to the school science model described at the beginning of this article: readers should not understand that all those characteristics are shared by all the responses assigned to that group or cluster.

On reviewing the significance found in the clusters, regularities among them are observed. These regularities, in turn, enable us to make new groupings of four representative models in accordance with an order of progression (Table 8).

The first of these groupings (clusters 6 and 7), designated *internal causes*, is the simplest model, representing the conceptions of those participants who attribute the principal cause of the phenomenon to factors internal to the Earth: movements of the sea, the rain, the wind, etc. Previous research studies (Ballantyne, 2004; Corrochano et al., 2017; Viiri, 2000) also found this type of explanatory model although, unlike the study reported here, none of the studies published previously were performed with subjects from coastal populations.

In second place is the model that we designate *latent influence* (clusters 3, 4, and 5), in which the causal agent is considered to be the presence of the Moon or one of its phases, without any explanatory mechanism being established; rather, the phenomenon is described in terms of the accumulation of water on the part of the

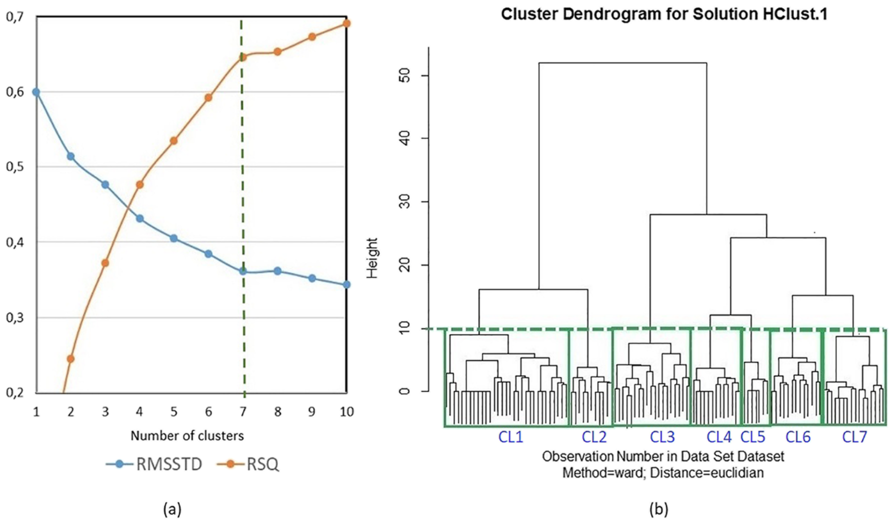


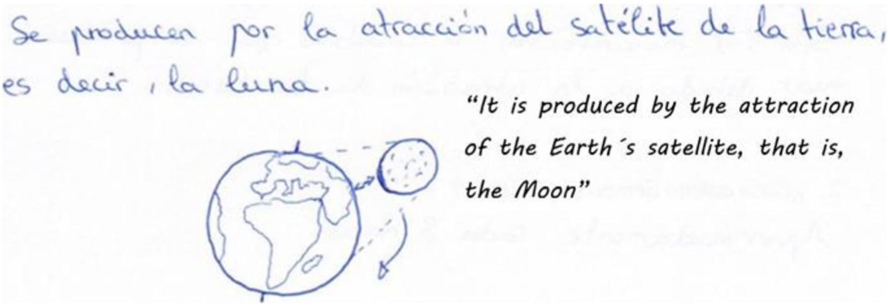
Fig. 4 Statistical indicators and dendrogram of the cluster analysis

Earth closest to the Moon. This reflects an astronomical conception of the phenomenon, albeit extremely simplistic, which is the predominant model among the participants of the study. It must be noted that cluster 5 is exceptional, in the sense that the students hold two different conceptions of the phenomenon together, which is explained by both internal causes and external causes. Hence, in the dendrogram, clusters 4 and 5 are closer to clusters 6 and 7 than to cluster 3, as would be expected of this new classification, since cluster 5 acts as a link between them.

In the next model, *gravitational pull*, the participants interpret the tides in some terms similar to those of the *latent influence* model, but their conception is that gravitational force is the factor responsible for the displacement of water. In this case, the phenomenon is described as an accumulation of water at the part of the Earth closest to the Moon.

Table 7 *(*Sub)categories implicated in each cluster, represented by the median values of rubrics.

Cluster	(Sub)categories														
	IC1	IC2	IC3	IC4	IC5	IC6	IC7	EC0	EC1	EC2	EC3	EC4	EC5	FC	NB
CL1												2		2	1
CL2													2	2	1
CL3									2						1
CL4												2			1
CL5					2	1						2			1
CL6				2											1
CL7						1									1



Se producen por la atracción del satélite de la tierra, es decir, la luna.

"It is produced by the attraction of the Earth´s satellite, that is, the Moon"

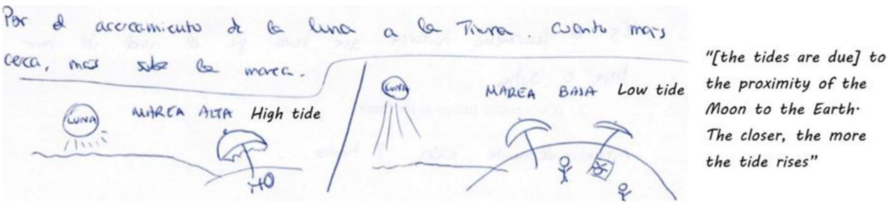
Fig. 5 Explanation and representation of the phenomenon of tides, corresponding to cluster 1

Lastly, a small group of responses are found in which the phenomenon is interpreted as caused by the gravitational action of the Moon and Sun jointly, designated *complex gravitational pull*; the effect this produces is also translated as a displacement of the ocean mass towards one single area of the Earth's surface, specifically towards the area closest to the astronomical body of reference, the Moon. It should be noted that this conceptualization of the phenomenon as displacement of the tidal water mass towards the area of the Earth closest to the Moon is common to the last three models discussed above.

Discussion

Our study has enabled us to analyze the descriptive knowledge and mental models of a group of Spanish primary-level teachers in training, about the phenomenon of the tides. The results suggest that the participants could encounter difficulties with respect to the teaching and learning of a school-level model of this scientific phenomenon.

Firstly, the participants in this study encountered difficulties when asked to describe and make predictions about the phenomenon of tides. This is despite the students living in locations on or near the Atlantic coast, and studying in a University School of Education situated only a few meters from the sea. This point is relevant because it seems reasonable to expect that their day-to-day first-hand experience of the coast and beaches would contribute to basic knowledge of the tides such



Por el acercamiento de la luna a la Tierra. Cuanto mas cerca, mas sube la marea.

"[the tides are due] to the proximity of the Moon to the Earth· The closer, the more the tide rises"

Fig. 6 Idea representative of cluster 5 (internal and external factors)

Table 8 Relationship between the models and the clusters found

Model	Clusters	*n*	%
Internal causes	6 and 7	29	26.1
Latent influence	3, 4 and 5	40	36.0
Gravitational pull	1	31	27.9
Complex gravitational pull	2	11	9.9

as the cycle of around 12 h. This was not so: the results obtained indicate that many had problems in correctly answering questions about tidal periods and even more in making predictions based on that.

In addition to this, we also observed that the students gave less adequate predictive responses when the situation put forward requires reasoning at a global (question 6) rather than only a local level (question 7)—that is, when the scenario proposed is more abstract and remote from their everyday experiences. Another factor that could have contributed to this finding is that, in the first case, the comparison they were asked to consider is spatial in nature, whereas, in the second case, it is temporal. Relevantly, in answer specifically to question 7, the participants usually made predictions based on a heuristic rule of duration of the tidal cycle, and consequently those whose descriptive knowledge was appropriate responded correctly to the question. However, in answer to question 6, which required reasoning spatially on a global scale, the participants did not use that rule to make an adequate prediction, even though many of them knew it. Instead, the majority used a mental model that postulates the existence of only one bulge of water: consequently, they offered predictions not corresponding to reality. This suggests there is a problem in connecting a model applicable at the global scale with the descriptive knowledge of the participants. This difficulty would be present in all the students, independently of whether or not they are familiar with the phenomenon, and it would lead to them failing to give adequate explanations of the phenomenon, despite most of them knowing the rule of 12-h tidal cycles. In order for students to achieve any significant learning of a model regarding a natural phenomenon, they need to be able to make the connection between the theoretical and relatively abstract representation of it and their everyday real-world experience.

This finding could also be related to another more general problem, which is their difficulty in changing the reference framework, such as when required to resolve the problem from an astronomical perspective (Hegarty, 2010). This change, which involves switching from the global scale to another local scale, or vice versa, is essential for understanding most notions related to astronomical phenomena (Plummer et al., 2014). In fact, the ability to imagine what a system would look like from different points of view is a core component of spatial ability (Eilam & Alon, 2019) and is an important factor in students' understanding of astronomical phenomena (Black, 2005; Wilhelm et al., 2018. For example, to jump from a local and topocentric system of reference (question 7) to an astronomic system (question 6), it is essential to understand and handle abstract notions like tidal force and even inertial force, if they are applicable. And in a reciprocal way, to jump from an astronomic to a local view, it is necessary to be able to collate the predictions of the model to the realities observed. It is only on this basis that the abstract concepts forming part of the model would make sense and be plausible for the students.

We have found that the models employed by students in this study show notable differences from what would correspond to the science taught at school, something that is frequently observed with children and adolescents faced with astronomical phenomena (Slater et al., 2018), but that also happens with teachers in initial training. In fact, none of the models identified the model that we have defined earlier as appropriate for school science. Thus, some students explained the phenomenon employing a model of internal causes, alluding to local agents like the wind and rain. That internal model is consistent with some of the models described by Viiri (2000), in particular in some of the categories designated "Tides at the seashore."

Other students used a model of *latent pull* of the Moon or its phases, without referring to any specific mechanism. This implies two problems. One is the absence of a causal mechanism that would explain the influence of the Moon or its phases, since the student does not mention the force of gravity; the basic reason for this may be that many students conceive gravity as something that makes physical bodies fall to the ground (Bar et al., 1997), although they then have difficulties in admitting the existence of gravity in and empty space (Berg & Brouwer, 1991). Another problem is the association of this phenomenon with the phases of the moon, as students also usually employ alternative models (Parker & Heywood, 1998). In both cases, it is possible that the ideas developed to construct this model originate from the student drawing on memories of partial ideas acquired in an earlier learning stage.

A third model for the phenomenon of the tides considers it to be an effect exerted by the Moon that attracts the mass of ocean water towards it, producing a single bulge of water (*gravitational pull model)*. Alongside that, we identify a fourth model that is similar but also includes the Sun as a causal agent together with the Moon. These last two models are consonant with those already found (Ballantyne, 2004; Corrochano et al., 2017; Viiri, 2000).

It must be emphasized that not one of the models identified approximates to the model taught in school science (Fig. 1). In other words, none of the models reflects the conception of a double bulge of the tidal water mass generated by a gradient of forces produced by the Moon, which could be added to the four groupings listed in Table 8 to represent the most advanced model. Considering these five groupings together, they would form a sequence of progression to be taken into account in designing a didactic proposal for teaching this topic; the sequence could also be employed as indicators of progression when evaluating the model being used by each student at different stages during their learning.

Conclusions and Educational Implications

This study has enabled us to do two things: first, to identify a series of alternative models employed by these students to explain the phenomenon of the tides. These alternative models, together with the school model of reference (Fig. 1), constitute a logical sequence of progression for students' learning and a useful rubric for evaluating which particular model a student has in mind at any particular moment during the learning process. This sequence of models has been identified inductively from this study; however, in the future, the sequence could be employed as a criterion for categorizing the models presented by students.

Second, the study has also allowed us to foresee some additional difficulties the participants could encounter in learning a school-level model of the phenomenon of the tides. The fact that many students do not know sufficient details of the phenomenon (e.g. duration of the tidal cycles) begins to represent a serious handicap, given that a good previous knowledge is essential for achieving an adequate understanding of it. Moreover, the intrinsic complexity of the tides' model, even in its simplest version, is a factor contributing to the students' retention of simpler alternative models, such as that of *gravitational pull*.

Furthermore, the difficulty many have in thinking about reality in three spatial dimensions, together with the problem students have of changing one reference framework for another, could explain part of the difficulty students have in passing from a local model centered on day-to-day experiences to one of global and astronomical scale.

Lastly, overlying all the above, there is the complexity involved in making connections between descriptions and models. As has been seen, the students find it difficult to relate the facts known with the theoretical models that explain them; hence, it is complicated to persuade a student to question their existing model and consider an alternative. For example, to advance beyond the model of *gravitational pull* requires that the student should understand clearly the incompatibility between the predictions of their model and a 12-h tidal cycle.

All these conclusions should be tested in future research considering the limitations of this study. One limitation is that the explanations of the participants have been obtained from a single instrument. On this point, it would be useful to be able to triangulate the results obtained with answers given by students in individual interviews. It would also be interesting to compare the difficulties that emerge from this study with those encountered by teachers in service.

Despite these limitations, we can infer from this study that for students to make measurable progress in their mental models through their learning requires taking those difficulties into account when designing teaching and learning sequences. On this point, teaching approaches based on modeling could be interesting options when designing sequences of activities directed towards meeting that challenge (Gilbert & Justi, 2016). These sequences would be contemplated as an itinerary of progression that would start from the personal intuitive models of the students, taking as reference others more complex and consistent with the school curriculum (Clement, 2000; Oliva, 2019). Thus, the repertoire of models described in Table 8 suggest a possible progression route towards more advanced models, like that presented in the Introduction of this article as an adaptation of the "correct" scientific model to the school teaching framework required. In order to make possible the desired progression in the students' models, it is essential that the didactic designs prepared comply with several conditions that can also be inferred from the present study.

First, the models taught should not be presented as canonical representations that the students have to learn, but rather as attempts to represent accurately the reality under study, and to explain it causally. On this point, any didactic design must include activities in which the students have to devise their own diagrams (Gobert, 2005).

Second, science teachers should take into account and try to identify explicitly the implicit models that the students bring with them to class. Teachers should aim for those implicit models to evolve by processes of argumentation that guide the students to construct more advanced models in which two tidal bulges are conceived, using as explanation the notion of a gradient of forces (Oh, 2014).

Third, being an event close to their daily experiences is not enough for students to be familiar with the phenomenon to be modeled. In addition to that, the students need to acquire sufficient descriptive knowledge on the phenomenon, so that they have accurate knowledge about the reality that they have to model. This, in the specific case of the phenomenon of tides, would imply knowing aspects such as the periodicity of the tidal cycles, the types of tide existing simultaneously in different parts of the globe and, should they advance to it, the periodicity of the cycles of spring and neap tides.

Fourth, it is necessary to address alternative conceptions through new channels, and particularly through a mindful attention to perception (Rollinde, 2019). The teaching activities proposed should promote, if possible, that the students are continuously establishing connections between their mental models and that descriptive knowledge; that is, making connections between formal and informal knowledge (Odden & Russ, 2018). In those cases, where there is contradiction, issues of cognitive conflict will need to be resolved. This is the case, for example, when the model conceived by the student includes only one bulge of water mass, and the student does not appreciate the contradiction implied by that with respect to the existence of two tidal cycles every day (Oh, 2014). Contradictions of this type were frequently seen in responses to the questionnaire; hence, questions similar to those we posed could serve as a basis for resolving such issues by classroom activities.

Fifth and last, diverse resources available for modeling, such as observations, analogies, thought experiments, embodiments, simulations and animations, need to be skillfully combined (Niebert et al., 2012). These resources may be relevant not only in phases of introducing new ideas that encourage the construction of more evolved models, but also when it comes to using the resulting models to make predictions. Hence, on the one hand, with the object of promoting the evolution of the students' thinking from a model of internal causes to others based on external causes, classroom activities such as observation, monitoring, and representation of the periodicity of the phenomenon could be promoted using tidal tables or articles in the press. On the other hand, the transition from a model of *latent pull* to another taking the force of gravity as reference, like the model of *gravitational pull*, could be facilitated by means of some of the thought experiments used by Newton to relate the fall of objects from the air to the ground to the orbital movement of the Moon, which gave rise to his Theory of Universal Gravity (Velentzas & Halkia, 2013). Further, embodiment activities could be very useful for the development and application of different systems of reference in astronomic phenomena (Richards, 2012;

Rollinde et al., 2021). The use of analogies could also help to give plausibility to the inclusion of a second bulge of water, for example, by means of visualization of the stretching of a spring with a steel ball fixed to each end when a magnet is moved closer, in a similar way to how the water mass of the oceans is “stretched” and reshaped by a gradient of the force of gravity. Lastly, to finish this brief outline of possible activities, we could consider the use of digital simulations as a resource to visualize the combined effects of the Moon and the Sun on the tides.

Many of these are elements and criteria that are being considered as a basis for the design of future sequences of teaching–learning on the subject of the tides, and their implementation in secondary education and in the initial training of primary-level teachers. In the near future, we hope to report the results obtained and the corresponding data. Particularly, in the initial training of primary-level teachers, what we are specifically proposing is simultaneous training in both scientific and didactic knowledge. In this proposal, the object would be to develop a scientific education in which the pre-service teachers experience in their own training the same didactic strategy that would be desirable for them subsequently to apply with their own future pupils. We would thus aim to achieve a maximum degree of consistency between their scientific and didactic training.

Within such a framework, it is essential that the preservice teachers should participate in processes of construction, use, review, and development of their own models (Clement, 2000; Gilbert, & Justi, 2016), thus having opportunities to contribute ideas, take decisions, and make progress in their own knowledge, monitored by the teacher. The approaches to teaching based on modeling should also be used in the training of primary-level teachers so that they are able to advance from their initial models towards more appropriate ones.

Lastly, there are many other aspects essential for an adequate training of the future teachers. Thus, existing programs for the initial training of future primary-level teachers may need to be revised, since the findings of this study suggest that, in Spain, the student teachers are faced with the difficult task of learning how to teach science without having sufficient scientific knowledge. This means that it will also be necessary to review the didactic training required for those of us teaching preservice primary-level teachers.

Appendix: Questionnaire

Initial data

First and family names: Age: Sex: Woman/Man: Course: Center and locality:

First part

a) How frequently do you go to the beach or have contact with the sea?

b) Do you have any interest or hobby related to the sea (examples: fishing, collecting shellfish, surfing)? Please indicate which. What about other members of your family?
c) When you spend a whole day on the beach, changes can be observed taking place around you. Could you mention any that appear to you relevant from a scientific point of view?
d) Would you like to know more about these changes?

Second part

1. What are tides?
2. How frequently do they take place?
3. Are the rises and falls of the tides equal in all parts of the world?
4. Do you think the tides have anything to do with other phenomena that you know about? If so, state which, and explain why you think that?
5. Why do tides take place? Use your own words, and draw a sketch that might help you in your explanation.
6. If, at the point on the Earth's surface indicated with a circle, the tide is high, what will be the level of the sea at the opposite point on the Earth, indicated by the triangle? Explain this in your own words and draw a sketch.

7. A fisherman gets to the beach at 20:00 h and observes that there is low tide. If he spends all night there, what will be the level of the sea at 8:00 h? Explain your answer.

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References

Adúriz-Bravo, A. (2012). Algunas características clave de los modelos científicos relevantes para la educación química [Key characteristics of scientific models relevant for Chemistry education]. *Educación Química, 23*, 1–9. https://doi.org/10.1016/S0187-893X(17)30151-9

Armario, M., Oliva, J. M., & Jiménez-Tenorio, N. (2018). *Elaboración y validación de un cuestionario para conocer los modelos expresados de los estudiantes sobre el fenómeno de las mareas* [Elaboration and validation of a questionnaire to know the expressed models of the students on the phenomenon of the tides]. Paper presented at the IV Simposio Internacional de Enseñanza de las Ciencias (SIEC 2018).

Armario, M., Oliva, J.M., & Jiménez-Tenorio, N. (2019). El fenómeno de las mareas y su explicación [The phenomenon of tides and its explanation]. *Alambique. Didáctica de las Ciencias Experimentales, 95*, 31–38.

Armario, M., Jiménez-Tenorio, N., & Oliva, J. M. (2021). *Tratamiento del fenómeno de las mareas en libros de texto de Secundaria* [Treatment of the phenomenon of tides in secondary school textbooks]. Paper presented at the 29 Encuentros de Didáctica de las Ciencias Experimentales "Nuevos horizontes en la enseñanza y aprendizaje de las Ciencias," Córdoba, Spain.

Ballantyne, R. (2004). Young student's conceptions of the marine environment and their role in the development of aquaria exhibits. *GeoJounal, 60*, 159–163. https://doi.org/10.1023/B:GEJO.0000033579.19277.ff

Bar, V., Zinn, B., & Rubin, E. (1997). Children's ideas about action at a distance. *International Journal of Science Education, 19*, 1137–1157.

Battaglia, O. R., Di Paola, B., & Fazio, C. (2019). Unsupervised quantitative methods to analyze student reasoning lines: Theoretical aspects and examples. *Physical Review Physics Education Research, 15*, 020112. https://doi.org/10.1103/PhysRevPhysEducRes.15.020112

Berg, T., & Brouwer, W. (1991). Teacher awareness of student alternative conceptions about rotational motion and gravity. *Journal of Research in Science Teaching, 28*, 3–18.

Black, A. A. (2005). Spatial ability and Earth science conceptual understanding. *Journal of Geoscience Education, 53*, 402–414. https://doi.org/10.5408/1089-9995-53.4.402

Blanco, P., Díaz, J., & Mendonça, P. C. C. (2019). Las destrezas argumentativas en la evolución de modelos en una actividad de geología [Argumentation skills in the evolution of models in a Geology activity]. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 16*(3), 3105. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2019.v16.i3.3105

Clement, J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education, 22*(19), 1041–1053. https://doi.org/10.1080/095006900416901

Cohen, J. A. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement, 20*, 37–46.

Corrochano, D., Gómez-Gonçalves, A., Sevilla, J., & Pampín-García, S. (2017). Ideas de estudiantes de instituto y de universidad acerca del significado y el origen de las mareas [The ideas of students of secondary- and university-level regarding the meaning and origin of the tides]. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 14*(2), 353–366. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2017.v14.i2.05

EEP. (2015). *Enseñanzas propias para la educación primaria.* Consejería de Educación de la Junta de Andalucía, España. *Teaching of relevance to Primary Education.* Dept. of Education, Regional Govt. of Andalusia, Spain. Retrieved from http://www.juntadeandalucia.es/educacion/descargasrecursos/curriculo-primaria/areas.html

Eilam, B., & Alon, U. (2019). Children's object structure perspective-taking: Training and assessment. *International Journal of Science and Mathematics Education, 17*(8), 1541–1562. https://doi.org/10.1007/s10763-018-9934-7

Fazio, C., & Battaglia, O. R. (2019). Conceptual understanding of Newtonian mechanics through cluster analysis of FCI student answers. *International Journal of Science and Mathematics Education, 17*, 1497–1517. https://doi.org/10.1007/s10763-018-09944-1

Gilbert, J. K., & Boulter, C. (1995). *Stretching models too far*. Paper presented at the Annual Conference of the American Educational Research Association, San Francisco.

Gilbert, J. K., & Justi, R. (2016). *Modelling-based teaching in science education*. Springer.

Gobert, J. D. (2005). The effects of different learning tasks on model-building in plate tectonics: Diagramming versus explaining. *Journal of Geoscience Education, 53*(4), 444–455.

Gobert, J. D., & Buckley, B. C. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education, 22*(9), 891–894. https://doi.org/10.1080/095006900416839

Grosslight, L., Unger, C., Jay, E., & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799–822.

Guy-Gaytán, C., Gouvea, J. S., Griesemer, C., & Passmore, C. (2019). Tensions between learning models and engaging in modeling. Exploring Implications for Science Classrooms. *Science & Education, 28*, 843–864. https://doi.org/10.1007/s11191-019-00064-y

Härtel, H. (1995). The tides: A neglected topic. *Physics Education, 35*(1), 40–45. https://doi.org/10.1007/978-94-017-0165-5_25

Hegarty, M. (2010). Components of spatial intelligence. *Psychology of Learning and Motivation, 52*, 265–296. https://doi.org/10.1016/S0079-7421(10)52007-3

Johnson-Laird, P. N. (1996). Images, models and propositional representations. In M. De Vega, M. J. Intons-Peterson, P. N. Johnson-Laird, M. Denis, & M. Marschark (Eds.), *Models of Visuospatial Cognition* (pp. 90–127). Oxford University Press.

Monteira, S. F., & Jiménez-Aleixandre, M. (2019). ¿Cómo llega el agua a las nubes? Construcción de explicaciones sobre cambios de estado en educación infantile [How does water get to the clouds? Construction of explanations about changes of state in the education of infants]. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias, 16*(2), 2101. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2019.v16.i2.2101

Niebert, K., Marsch, S., & Treagust, D. F. (2012). Understanding needs embodiment: A theory-guided re-analysis of the role of metaphors and analogies in understanding science. *Science Education, 96*(5), 849–877. https://doi.org/10.1002/sce.21026

Norsen, T., Dreese, M., & West, C. (2017). The gravitational self-interaction of the Earth's tidal bulge. *American Journal of Physics, 85*(9), 663–669. https://doi.org/10.1119/1.4985124

Odden, T. O. B., & Russ, R. S. (2018). Defining sensemaking: Bringing clarity to a fragmented theoretical construct. *Science Education, 103*(1), 187–205. https://doi.org/10.1002/sce.21452

Oh, J. Y. (2014). Understanding the alternative conceptions of pre-service secondary science teachers about tidal phenomena based on Toulmin's argumentation. *International Journal of Science and Mathematics Education, 12*(2), 353–370. https://doi.org/10.1007/s10763-013-9403-2

Oliva, J. M. (2019). Distintas acepciones para la idea de modelización en la enseñanza de las ciencias [Different meanings for the idea of modeling in science Education]. *Enseñanza de las Ciencias, 37*(2), 5–24

Parker, J., & Heywood, D. (1998). The Earth and beyond: Developing primary teachers' understanding of basic astronomical events. *International Journal of Science Education, 20*(5), 503–520.

Passmore, C. M., & Svoboda, J. (2012). Exploring opportunities for argumentation in modelling classrooms. *International Journal of Science Education, 34*(10), 1535–1554. https://doi.org/10.1080/09500693.2011.577842

Plummer, J. D., Kocareli, A., & Slagle, C. (2014). Learning to explain astronomy across moving frames of reference: Exploring the role of classroom and planetarium based instructional contexts. *International Journal of Science Education, 36*(7), 1083–1106. https://doi.org/10.1080/09500693.2013.843211

Richards, T. (2012). Using kinesthetic activities to teach Ptolemaic and Copernican Retrograde Motion. *Science & Education, 21*, 899–910. https://doi.org/10.1007/s11191-010-9265-8

Rollinde, E. (2019). Learning science through enacted astronomy. *International Journal of Science and Mathematics Education, 17*(2), 237–252. https://doi.org/10.1007/s10763-017-9865-8

Rollinde, E., Decamp, N., & Derniaux, C. (2021). Should frames of reference be enacted in astronomy instruction? *Physical Review Physics Education Research, 17*, 013105. https://doi.org/10.1103/PhysRevPhysEducRes.17.013105

Simanek, D. E. (2015). Tidal Misconceptions. Retrieved from https://www.lockhaven.edu/~dsimanek/scenario/tides.htm

Sharma, S. (1996). *Applied multivariate techniques*. Wiley.

Slater, E. V., Morris, J. E., & McKinnon, D. (2018). Astronomy alternative conceptions in pre-adolescent students in Western Australia. *International Journal of Science Education, 40*(17), 2158–2180. https://doi.org/10.1080/09500693.2018.1522014

Solbes, J., & Palomar, R. (2011). ¿Por qué resulta tan difícil la comprensión de la Astronomía a los estudiantes? [Why is it so difficult for students to understand Astronomy?]. *Didáctica de las ciencias experimentales y sociales, 25*, 187–211.

Stewart, J., Miller, M., Audo, C., & Stewart, G. (2012). Using cluster analysis to identify patterns in students' responses to contextually different conceptual problems. *Physical Review Special Topics - Physics Education Research, 8*, 020112.

Ucar, S., Trundle, K. C., & Krissek, L. (2011). Inquiry-based instruction with archived, online data: An intervention study with preservice teachers. *Research in Science Education, 41*(2), 261–282. https://doi.org/10.1007/s11165-009-9164-7

Velentzas, A., & Halkia, K. (2013). From Earth to heaven: Using 'Newton's cannon' thought experiment for teaching satellite physics. *Science & Education, 22*, 2621–2640. https://doi.org/10.1007/s11191-013-9611-8

Viiri, J. (2000). Students' understanding of tides. *Physics Education, 35*, 105. https://doi.org/10.1088/0031-9120/35/2/305

Viiri, J., & Saari, H. (2004). Research-based teaching unit on the tides. *International Journal of Science Education, 26*, 463–481. https://doi.org/10.1080/0950069032000072791

Ward, J. E. (1963). Hierarchical grouping to optimize an objective function. *Journal of American Statistical Association, 59*, 236–244.

White, B. Y. (2009). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction, 10*(1), 1–100. https://doi.org/10.1207/s1532690xci1001_1

Wilhelm, J., Cole, M., Cohen, C., & Lindell, R. (2018). How middle level science teachers visualize and translate motion, scale, and geometric space of the Earth-Moon-Sun system with their students. *Physical Review Physics Education Research, 14*(1), 010150. https://doi.org/10.1103/PhysRevPhysEducRes.14.010150