International Journal of Environmental & Science Education
Vol. 8, No. 1, January 2013, 163-174

Undergraduate students' mental models of hailstone formation

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Received 13 September 2012; Accepted 5 December 2012

The objective of this research is to investigate students' mental models of the hailstone formation and explore factors that may affect their mental models. The sample chosen for the study was composed of a total of 84 students. The students attended the 1st to 4 th grade classes of the Social Studies Teaching Programme at Giresun University in Turkey. The data in relation to the students' mental models of hailstone formation were collected from the administration of a structured interview consisting of open-ended questions. The students' responses were scrutinised and categorised to gather similar mental models into a group. The choice of categories was based on the students' responses. Four groups mental models have been determined, one is scientifically acceptable and the others scientifically unacceptable. The prevalence of scientifically unacceptable mental models was attributed to the students' lack of pre-knowledge of hailstone formation. Considering the results of the study, recommendations for the teaching of hailstone formation have been made to teachers, textbook authors and programme developers.

Keywords: Atmospheric science; hailstone formation, mental models

Introduction

Hailstones are large pieces of ice that fall during powerful thunderstorms. They are formed in huge cumulonimbus clouds, commonly known as thunderheads. Cumulonimbus clouds contain vast amounts of energy in the form of updrafts and downdrafts. Updrafts bring raindrops from the bottom to the top of the cloud where they freeze into ice pellets. They then fall only to be blown back up where another coating of rain freezes to the hailstone and thus grows larger, layer-by-layer. This layering affect can increase the size of hailstones, sometimes to the size of baseballs. Typically the stronger the updraft, the more times a hailstone repeats this cycle and consequently, the larger it grows. Once they reach a weight sufficient enough to overcome the updrafts, they fall to the ground. The hailstone reaches the ground as ice, since it is not in the warm air below the thunderstorm long enough to melt before reaching the ground.

During the spring semester in 2011, I explored the undergraduate students' pre-knowledge about hailstone formation at the beginning of the course "Natural Hazards Education". I discovered that most of the students possessed incorrect mental models despite previously being instructed on hailstone formation. According to the Turkish National Curriculum, hailstone formation firstly appears under the topic of "Types of Precipitation" in grades 9 in the Geography

ISSN 1306-3065

http://www.ijese.com/

course. Geography is a compulsory subject for students in grades 9-12 at high schools. The Curriculum of Social Studies Teaching at undergraduate level suggests that students need to understand the atmospheric systems and related phenomena. At the first year of the Social Studies Teaching programme, the curriculum includes the subject of “Introduction to Physical Geography”. In this course, the students are given more detailed explanations of hailstone formation. The students’ unexpected pre-knowledge pushed me to explore their mental models of hailstone formation.

The term “mental model” has been used in many contexts and for many purposes. It was originally postulated by the psychologist Kenneth Craik (1943) who proposed that people carry in their minds a small-scale model of how the world works (Jones, et.all 2011). Norman (1983) defined the mental model as the mental representation constructed through interaction with the target system and constantly modified throughout this interaction. Vosniadou (1994) explained that mental models “refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning” (p. 48). Throughout her study, Vosniadou called her interpretations of students’ conceptions of the Earth, force, and heat, mental models. In this article, we have consistently used the term “mental models” to describe our interpretations of individual student’s conceptions of hailstone. From this perspective, mental models may be unstable, inaccurate, inconsistent, and incomplete, and they may change continually as more information is noticed, acquired, or remembered (McClary and Talanquer, 2011).

Determining students’ mental models are particularly important for instructional design (Gentner, 2002; Winn, 1990), overcoming students’ misconceptions in order to meet the learning objectives (Smith, 2009) and students’ conceptual development and conceptual change (Vosniadou & Brewer, 1992). Understanding mental models is also a central issue for cognitive science because they appear to be important in reasoning about complex physical systems, in making and articulating predictions about the world, and in discovering causal explanations for what happens around us (Norman, 1988). Referring to the importance, the role mental models play in learning and instruction has become a significant topic for researchers and instructional designers worldwide (Seel, 1999).

Much research has been done on students’ mental models in physics education (Borges & Gilbert, 1999; Hubber, 2006; Özcan, 2011), chemistry education (Adboa & Taberb, 2009; Chittleborough, 2004; Coll & Treagust, 2003; Lin & Chiu, 2010; Taber, 1997), biology education (Chang, 2007; d’Apollonia, Charles & Boyd, 2004; Patrick, 2006), environmental education (Bostrom, Morgan, Fischhoff & Read, 1994; Reinfried, 2006; Shepardson, Choi, Niyogi, & Charusombat, 2011), earth sciences education (Gobert, 2000; Herbert, 2005; Marques & Thompson,1997; Panagiotaki, Nobes, & Potton 2009), astronomy education (Cin, 2007; Samarapungavan, Vosniadou & Brewer, 1996; Vosniadou & Brewer, 1994) and atmospheric sciences education (Alkış, 2007; Ben-zvi-Assarf & Orion 2005; Dove, Euerett, & Preece, 1999; Levins, 1992; Saçkes, Flevares, & Trundle, 2010). However, no particular study has been conducted to explore students’ understanding of hailstone formation and studying students’ mental models of this will also fill the gap in the literature.

Hail growth is an example of a complex and dynamic environmental process as explained above. Much research has been performed showing that students have difficulty in understanding phenomena that have complex and dynamic characteristics. Marques and Thompson (1997) found that sixteen and seventeen years-old Portuguese students held incorrect mental models containing misconceptions about the Earth's continents, magnetic field, and tectonic plate movements. Gobert (2000) has found that when students attempt to produce causal explanations about the interior of the Earth and the causal mechanisms of volcanic eruptions, they tend to demonstrate incomplete or distorted mental models. Ben-zvi-Assarf and Orion (2005) explored junior high school students' perceptions of the water cycle. Findings of the study indicated that the students understand various hydro-bio-geological processes, but most of them lack the dynamic, cyclic, and systemic perceptions of the system.

These studies suggest students' mental models might not be always complete, accurate and meaningful. Hailstone formation might also present a cognitive difficulty to students because of its dynamic and complex features. Considering the complexity of this phenomenon, it is important to determine students' difficulties in constructing their mental models of hailstone growth and factors that would affect the construction of their mental models. If this is determined, instructional design could be developed to improve their understanding of hailstone formation.

Method

The participants for this study were 84 prospective teachers enrolled in Social Studies Teaching Programme at Giresun University in Turkey. The sample consisted of 42 females and 42 males. Their ages ranged from 18 to 24 years. Only voluntary students in grades 1–4 were included in the study. The students came from different regions of Turkey. Most of them have had the experience of hailstone precipitation and all of them had had instruction on hail formation in previous classes.

The data in relation to the students' mental models of hailstone formation were collected from the administration of a structured interview consisting of open-ended questions. The interview was conducted by the researcher in a quiet room in the faculty. It was carried out individually with all the students who participated in the research. Each session took about forty minutes and was tape-recorded with the permission from the students.

Information on the source of the students' knowledge about hail formation was collected at the beginning of the interview session. Each student was asked questions such as: 'have you experienced a hail storm?', 'where did you experience it?', 'how strong was it?', 'have you studied hail formation in the school?', 'have you researched it for any reason?', 'have you searched other sources of information (Internet, television, journals, and so on)' about hailstone formation?

Afterwards, the students were asked questions about the formation of rain and snow to assess their factual knowledge of two major precipitation forms. Following this, they were interviewed about hail formation. They were asked 'could you explain how hailstone is formed?', 'in which seasons is it mostly likely to occur?', 'how long do hail storms last?', 'do they affect large or small areas?', 'what kind of clouds produce hailstones?', 'what are their general features?'

Following this session, the students were presented with four different photographs. The first photograph depicted various cloud types, one of which was cumulonimbus. After giving the students an opportunity to look at these pictures, they were asked 'which one brings hail?' and 'what is its name?' If they managed to give the correct answer (cumulonimbus), they were asked, 'how do you know that?', 'what tells you it brings hail storm?', 'what are the features of this cloud?' They were asked similar questions even if they indicated the other incorrect clouds. The second photograph represented a baseball-sized hailstone. The students were told that this is one of the largest hailstones recorded. Afterwards, they were asked, 'could you explain how this big hailstone formed in the air?', 'how does this big object remain in the air' and 'how do they resist the Earth's gravity by the time they grow so large?' The third picture depicted the inner structure of a hailstone. They were told that when a hailstone is cut in half, a series of concentric rings, like that of an onion, is revealed. After that they were asked the reasons for these layers occurring. The forth picture depicted different shapes of hailstones. They were asked such questions as "why is this one circular and the others different?'

Data Analysis

The students' oral answers were transcribed. In order to identify students' mental models the data were content analysed using methods of inductive analysis (Patton, 2002; Shepardson, Wee, Priddy, & Harbor, 2007) that is; instead of searching for pre-determined patterns, themes were allowed to emerge from the data as the authors interpreted the students' conceptions of hailstone growth. The determined students' mental models were tabulated and interpreted. Geography and science textbooks in secondary and higher education were also examined through the content analysis method. Texts, illustrations (drawings, graphs, and tables), activities proposed, and everything connected with hailstone in the textbooks were scanned and analysed. Data obtained from the textbooks were used to interpret students' explanations.

Findings

The students indicated that geography courses of the high school were their major source of information about hailstone formation, followed by mass media and the Internet. Only a few students stated that they have researched it using scientific books and journals. 82 % of the students had experience of hailstones. 48 students out of 84 (57 %) knew the name of the cloud that brings hailstones, but only 14 students (17 %) had correct understanding of its common features. 72 students (85 %) knew that hail forms in the spring, autumn and summer seasons. Many of the students stated that size of a hailstone would not grow bigger than a walnut. Concerning the shape of a hailstone, almost all students stated that its shape is spherical. The findings indicate that eight students were able to hold a scientifically accepted model. The remaining 76 students had incorrect mental models. These models have been categorized into three groups and are shown below.

Mental Model 1: Water Vapours Become Frozen Resulting from a Sudden Decreasing of the Air Temperature

38 students (45 %) offered explanations that can be categorized as Model 1. The students had the idea that when a warm air mass rises into the atmosphere, its temperature suddenly decreases and therefore, water droplets or water vapours in the air freeze and fall as hailstones. A typical protocol from the interview is shown below:

> Researcher: Could you explain the hailstone formation mechanism?
>
> Student: A cloud with plenty of vapour rises up to top of the atmosphere. Sudden rising of the cloud causes sudden cooling of vapour inside the cloud. This causes the vapour to freeze into blocks of ice.
>
> Researcher: As you can see in the picture, this hailstone is as large as a baseball. How it is possible for such a big hailstone to resist the gravitational pull?
>
> Student: Clouds rise upward through the atmosphere. Water vapours in the cloud could remain in the air. If there is a sudden cooling, these vapours freeze and become a mass of ice.

Researchers: If you place water vapours into a deep freezer, do they become hailstones? Is this the same with the hailstone formation process?

Students: Let me think.....I don't think so (Student 68).

Table 1. Excerption from Students' Responses Categorized as Mental Model 1

Student 12	It occurs as a result of sudden freezing of the moisture inside of a rising cloud.
Student 26	It falls to the surface as an ice crystal resulting from sudden cooling of water vapour. In other words, it occurs because of decreasing water vapour below zero degrees.
Student 67	Clouds loaded with water vapour rise to the upper parts of the atmosphere swiftly. Water vapour freezes and falls hailstone-like as a consequence of the raising of the clouds instantly.

Mental Model 2: Raindrops Become Frozen While Falling towards the Earth

20 students' (23%) responses can be categorized as Mental Model 2. The students had the idea that when water drops fall from a cloud towards the Earth, they freeze on their way down. The following is a typical example of a student who categorised as model 2.

Researcher: Could you explain the hailstone formation mechanism?

Student: When a warm air mass rises into the atmosphere, its temperature decreases and rain droplets occur. While they are falling towards to the Earth's surface, they pass into a cold air layer. Since the cold air temperature is below freezing, rain droplets become ice and fall as hailstones" (Student 45).

However, most of the students in this category could not correctly respond to a question regarding raindrop size being as a baseball. The following is an example of this response type.

Researcher: As you can in the picture, this hailstone is as large as a baseball. Is it possible that a raindrop size could be baseball size?

Student: Science cannot explain it. It is very illogical. It can only be explained by the principles of metaphysics (Student 80).

Researcher: Why are hailstones different shapes?

Student: They are the shape of raindrops (Student 52).

Table 2. Excerption from Students' Responses Categorized as Mental Model 2

Student 7	A cool current of air makes raindrops freeze in the course of raining.
Student 39	Normally, water vapour becomes a raindrop after condensation, but it turns into a hailstone because the raindrop freezes while passing into a cold air mass where the temperature is below zero degrees.
Student 42	In the course of raining in spring and autumn a sudden change occurs in the air temperature. This in turn makes the raindrops solid and therefore, a hailstone is formed.

Mental Model 3: The Meeting of Warm and Cold Air Masses Causes Hail Formation

15 students' (18%) responses can be categorized as Mental Model 3. The students had the idea that when the warm air encounters the cold air upward in the atmosphere, water vapour in the hot air freezes. The following is an excerpt from the protocol of one student who was placed in this category.

> Researcher: Could you explain the hailstone formation mechanism?
>
> Student: When a warm air mass encounters a cold air mass, vapour and water droplets inside the warm air mass freeze.
>
> Researcher: As you can see in the picture, this hailstone is as large as a baseball. Can the confrontation of cold and warm air mass produce such a big hailstone?
> Student: It sometimes could be so (Student 60).

Table 3. Excerption from Students' Responses Categorized as Mental Model 3

Student 9	When water vapour inside the warm air rises up to the sky, it meets with the cold air mass and therefore, it becomes cold.
Student 76	It's an abnormal precipitation form. It might be formed as a consequence of the meeting of a warm air mass with a cold air mass on a sunny day. Apparently, the meeting takes place pretty high up from the Earth's surface.
Student 73	The formation mechanism of a hailstone is similar to the formation mechanism of snow. But, the warm air mass meets a much colder air mass in the case of hail formation than in the case of snow formation.

Mental Model 4: Explanations Consistent with the Scientific Model

8 students' (9,5%) responses were placed in this category. They had the idea that a hailstone is formed as a result of growing small particles in the upper part of clouds where strong updrafts and downdrafts took place. Since this idea is similar to the scientifically accepted idea, it was affiliated as a correct mental model. Here is a typical example from the protocol of a student who was classified as holding a correct model.

> Researcher: Could you explain the hailstone formation mechanism?
>
> Student: Rain droplets and water vapours are very small. When they freeze, they become small hailstones. Such a big hailstone can only be formed by the joining rain droplets.
>
> Researcher: How they join each other?
>
> Student: There are strong currents in upper parts of a cumulonimbus cloud. Rain driblets and water vapours move up and down because of the currents.
> Researcher: And then?
>
> Student: When they reach a big enough size, they fall down (Student 22).

Table 4. Excerption from Students' Responses Categorized as Mental Model 4

Student 2	A moist air mass rises up in the atmosphere. There are strong up and downdrafts in this part of the atmosphere. The moist particles freeze and grow by moving up and down.
Student 41	When there are strong air currents in cumulonimbus clouds, small ice pellets get bigger and bigger.
Student 75	It comes from thunderstorms. The updrafts and downdrafts in the thunderstorm cause the particles to be cycled by being blown upwards, falling in the downdraft, captured by an updraft again, and so on.

Results and Discussion

Four mental models have been determined, one scientifically acceptable and three scientifically unacceptable. Scientifically unacceptable mental models showed the characteristics that they are mainly incomplete and they contain error and contradictions. The data provided evidence for the reasons of the incorrect mental models. One piece of evidence was that the students' lacked the prerequisite knowledge. Two important prerequisites have been detected for the students to be able to give a correct explanation of hailstone formation.

The first one is that the upper parts of the cumulonimbus clouds carry ice crystals where temperatures are below zero degrees Celsius. Some of the students did not know this prerequisite. Students are likely to have difficulty accepting that water vapours and other particles become ice crystals unless they know the characteristics of the upper part of the cumulonimbus cloud. Some students explained the phenomenon of freezing by the meeting of a cold air mass with a hot air mass. This kind of explanation is mainly referred to as Mental Model 3 which was the meeting of warm and cold air masses causing hail formation.

The second prerequisite is that there is strong vertical motion of air in the upper parts of the cloud. If the students do not have this prerequisite knowledge they could not know about the developing of ice crystals by the strong up-down currents. The data showed that a very small number of students knew this prerequisite. The students who did not know this prerequisite and knew the previous prerequisite mentioned above mostly possessed Mental Model 1. Model 1 was water vapours become frozen resulting from the sudden decreasing of the temperature.

The students who lacked knowledge about the first and the second prerequisites gave explanations which mainly referred to the category of Mental Model 2. The category of Mental Model 2 was raindrops become frozen while falling towards the Earth. The students in this category probably transferred their knowledge of rain formation to hailstone formation. They firstly explained the rain formation mechanism. Afterwards, they explained hailstone formation as the raindrops freezing since they pass into a cold air mass. This kind of explanations implied that the students did not know what happens in the upper parts of the cumulonimbus clouds.

Students with an inadequate knowledge of the relation between the strong motions in the cloud and growing super cooled particles by their coalescence are unlikely to explain hailstone formation. All students who knew this prerequisite could explain the formation of hailstones correctly. A very small number of the students had these prerequisites resulting in the scientifically correct mental models. There could be several reasons for the students' lack of prerequisite knowledge. One reason could be attributed to the textbooks. Many researchers have suggested that textbooks play a predominant role in the teaching process (Stinner, 1995) and teachers rely heavily on the textbooks (Driscoll, Moallem, Dick & Kirby, 1994; Yore, 1991).

An examination of geography textbooks in secondary and higher education showed that explanations of hailstone formation are very inadequate. Textbooks at the secondary school level (9th grade) deal with the explanation of a hailstone. The explanation was that "hailstone is big ice which is formed by sudden freezing of water droplets below 0 degrees Celsius in the clouds. It is common in spring and summer". The textbook also presented a picture of hailstones. No further explanation was given in the textbook. Although the textbooks at the tertiary level have greater explanations about the formation of hailstones, they do not take these prerequisites into account as mentioned above. The textbooks also do not include colour diagrams and models showing the process of hailstone formation. Therefore, the textbooks are to some extent responsible for students' incorrect mental models.

Although textbooks largely determine what topics and ideas are taught in the classrooms and how these topics are taught, they should not singly blamed for the students' erroneous mental models of hailstone formation. Teachers play an important role in students' learning. The results of the interview in the study contained some evidences that the teachers taught the topic of the hailstone formation superficially. One of the interview questions was that "have you been taught hailstone formation". Most of the students' response were that we were instructed it very broadly. If the students were not taught soundly they probably use their personal experience and knowledge that is related to other kind of precipitation, such as rain and snow, to explain hailstone formation. In fact, the students showed evidence of using mental models of hailstone formation that related to their understanding of rain and snow formation. Rain and snow formation were viewed by most of the students as actual constituents of hailstone formation.

Research in the area of alternative conceptions indicates that these scientifically inaccurate notions are often very resistant to change (Driver & Oldham, 1986; Osborne & Cosgrove, 1983; Tobin & Tippins, 1993). However, the students in our study gave the impression that they could change their ideas by probing questions. For example, one student started to think deeply and tried to change his previous ideas related to the question 'how is this big object suspended in the air in the processes of its formation?' The student's previous notion was that a sudden cooling of water particles causes freezing. After the question, he changed his notion into water particles growing as rain; they join each other and get bigger while raindrops are falling towards to the Earth. It was clearly seen that these kinds of questions impacted upon many students' ideas.

Conclusion and Implications

Lack of prerequisite knowledge on hailstone growth is determined one of the most important potential sources of incorrect mental models. The most important prerequisite for the students in the explanation of hailstone formation was determined as the characteristics of the cumulonimbus cloud. These characteristics are that the lower levels of cumulonimbus clouds consist mostly of water droplets while at higher elevations ice crystals dominate and that strong air currents are present in the upper parts of the cloud.

Lack of the prerequisite knowledge pushed them into transferring knowledge of rain and snow formation to assist in their hailstone formation explanation. Transferring knowledge from a familiar context to a new, unfamiliar context is certainly a useful method to learn a context. On the other hand, knowing the distinctive features of a new context is as important as knowing its similar features in the analogical transfer. So the students in the current study who did not know the distinctive features of hailstone formation they constructed scientifically unacceptable mental models. Hailstone is a kind of precipitation like rain and snow. All of them have similar features. Correspondingly, they have critically distinctive features, particularly in the case of their formation. This conclusion suggests that geography and science teachers should take into account that the students could not be aware of the distinctive features of natural phenomena when they tried to use analogical transfer.

The results of the study showed that the Socratic questioning aimed at probing the students' thinking put them in a position of cognitive conflict. Forming conflicts in students' minds could help them revise their ideas, think critically and might alter their previous thoughts. Socratic questions worked well in assessing the students' mental models in this study. These kinds of questions also aroused interest in the students. However, this does not mean that Socratic questions on their own prompt correct explanations. These kinds of questions mostly serve for the creation of cognitive conflict which is important for students to re-examine their previous thoughts. Therefore, well-designed instruction with Socratic questions could help students to develop correct mental models.

The textbooks do not support the attainment of relevant knowledge base which is needed for the explanation of hailstone formation. The statement that 'hailstones are formed as a result of the sudden freezing of water droplets below zero degrees Celsius' is mainly placed in textbooks. This information alone does not provide the adequate knowledge base and might cause rote learning. Therefore, the textbooks should give an adequate knowledge base for students to construct their ideas. The textbooks also do not illustrate the air currents and the process of hailstone growth. Care must be taken that representations included in textbooks should focus on the process of the hailstone formation mechanism. The process could be explained by diagrams showing hailstone growth stage by stage. Therefore, they should be developed in light of the specific difficulties identified in this study and in consideration of the necessary conditions for conceptual change. In addition, audio-visual technologies, including computer graphics, provide opportunities for students to construct sound mental models.

Students may experience difficulties with concepts which are not directly observed and complex in terms of formation process. These difficulties may represent significant problems for atmospheric science educators, but an adequate knowledge base, confrontation of cognitive conflict and well-designed textbook diagrams could overcome these difficulties. The mental models of students in explaining hailstone formation needs further study. Our study has revealed three scientifically unacceptable alternative mental models and determined the reasons behind this. More mental models could be identified and more clarifications could be made if a different sample is used. The results of such research could be used to devise teaching methods and materials which would help students overcome their incorrect mental models of atmospheric science.

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