[CV-01-001] Cartography and Science

Abstract

"Science" is used both to describe a general, systematic approach to understanding the world and to refer to that approach as it is applied to a specific phenomenon of interest, for example, "geographic information science." The scientific method is used to develop theories that explain phenomena and processes. It consists of an iterative cycle of several steps: proposing a hypothesis, devising a way to make empirical observations that test that hypothesis, and finally, refining the hypothesis based on the empirical observations. "Scientific cartography" became a dominant mode of cartographic research and inquiry after World War II, when there was increased focus on the efficacy of particular design decisions and how particular maps were understood by end users. This entry begins with a brief history of the development of scientific cartographic approaches, including how they are deployed in map design research today. Next it discusses how maps have been used by scientists to support scientific thinking. Finally, it concludes with a discussion of how maps are used to communicate the results of scientific thinking.

Keywords: cartographic theory, History and Trends, history of cartography, science, science communication, visual thinking

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Explanation

1. Definitions

cartography: the process of designing the graphical marks that comprise a map

epistemology: a theory of how we can know something and that shapes the set of methods that can (acceptably) be used within a subject area

map: a representation of spatial relationships

positivism: a set of philosophical approaches, often associated with science, that seeks to develop theories and laws that explain phenomena and processes through empirical observations and inductive reasoning

post-representation: a cartographic theory that holds that there is no distinction between the map and the world – that is, the map and the world make each other

post-structuralism: a set of philosophical approaches that question whether signs and the things they stand for have fixed relationships with each other

representation: a cartographic theory that holds that symbols on a map stand for something in the world

science: the systematic study of phenomena and processes using experiments, measurements, and observations

theory: a set of propositions that explains something; scientific theories are evidence-based explanations

2. Science

"Science" is used both to describe a general, systematic approach to understanding the world and to refer to that approach as it is applied to a specific phenomenon of interest, for example, the "science of economics" or "geographic information science." The specific ways in which these systematic approaches are put into practice have evolved over time and vary depending upon the object(s) or phenomena of interest. With a narrow focus on the "sciences of" meaning of the word, it is possible to identify some philosophical underpinnings (ontologies, epistemologies, theories) that can be found across all sciences, no matter the phenomenon upon which a specific science focuses.

Understanding the philosophical underpinnings of a science is important because **epistemologies** shape what questions are asked and how researchers and practitioners of that science try to answer these questions (i.e., by what methods). The philosophical tradition that is typically associated with "science" in the sense of a general approach to understanding the world is **positivism**. A positivist approach, which is also associated with the quantitative revolution in geography, holds that it is possible to develop theories that explain phenomena and processes via a process of proposing a hypothesis, developing a way to make empirical observations that test that hypothesis, and then refining the hypothesis based on the empirical observations. This process, also known as the scientific method, eventually leads to a **theory**, which is a broad, general explanation that has been tested and not (yet) been proven to be untrue. The scientific method relies on both inductive and deductive reasoning; the former to generate hypotheses and the latter to test the validity of hypotheses through experimentation or further observation.

3. A Brief History of "Scientific Cartography"

German cartographers began thinking about **cartography** as a science as early as the 19th century (Table 1). The basis for the idea that cartography is a science was that thematic map design required both deduction and induction, thinking processes that are typically associated with scientific practice. In other words, thematic maps are carriers of science. Central to this understanding of maps as the product of scientific inquiry was the concept of “map logic”, the rules that constrain the personal, subjective (by implication "artistic") design decisions a cartographer might make. One proponent of considering cartography to be a science noted: “the dictates of science will prevent any erratic flight of the imagination and impart to the map a fundamentally objective character in spite of all subjective impulse” (Eckert, 1908: 347). However, Eckert acknowledged that artistic approaches to cartography still have a role in design as maps are “products of art clarified by science” (ibid) (see Cartography & Art). In other words, "scientific cartography" constrains artistic imagination in ways that effectively communicate the map’s content – through the process of establishing and following design laws or rules.

A key source that developed this map logic was an extensive empirical survey of cartographic practice, a 1500 page, two-volume tome entitled Die Kartenwissenschaft (1921, 1925), which might be translated as "The Map Science" or, perhaps more precisely, "The Map Knowledge." It aimed to outline a cartographic theory that could be used to guide practice. This theory was derived from inductive analysis of the empirical material presented in the volumes. Pápay (2018) suggests that the theory had little practical impact because other, more general theories (e.g., semiotics, information theory, communication theory) that could have contextualised this empirical synthesis were insufficiently developed at that time.

The Second World War was pivotal for cartography. It interrupted the work of the German cartographers who were working towards developing scientific cartographic theory. It also heavily shaped the experiences of some North American cartographers who spent the war making maps for the OSS. Cartographers noticed how propagandists designed visual characteristics of maps to present deliberately distorted and biased views of information, and some believed that design rules could be used to highlight these manipulations as well as to assist cartographers to make effective small-scale thematic maps (Robinson, 1952; Montello, 2002; Edney, 2005; Crampton, 2010; Kent, 2018).

This led to a functionalist theory of scientific cartography in which the goal is to understand the function of a given visual characteristic of the map in communicating information to a map reader. To investigate these functions, cartographers would apply the scientific method: “Cartography is neither an experimental science in the sense that chemistry or physics are nor is it searching for truth in the manner of the social sciences. Nevertheless, it employs the scientific method in the form of reason and logic.” (Robinson 1953: 11). The functionalist concept of logic is distinct from the earlier concept of map logic, which was criticized directly in The Look of Maps, the first exposition of functionalist scientific cartography (Robinson, 1952: 12), where the author noted that the map logic rule "brown is the best color for terrain, contours, and land representation" was merely a convention whose validity needed to be established through objective investigation. Functionalist map logic is established through systematic, empirical study of map users and their maps rather than empirical study of maps alone, thereby providing "objective" evidence of a design rule’s efficacy.

In line with this newly influential, positivist approach to cartographic research, academics developed theory to explain how maps are read. This theory, commonly known as the map communication model, was founded on information communication theory (Shannon, 1948) and quantitative geography's view of maps as models. The map communication model's aim was to transmit the mental model of the cartographer to the mental model of the map reader while losing as little information as possible, in effect transforming cartographic design into a problem of map engineering (Figure 1). Information communication theory proposed that information was fungible (i.e., it can be transformed between one form and another – in the cartographic case from a mental model to a map). It also proposed that communication could be improved by maximizing the signal and minimizing noise.

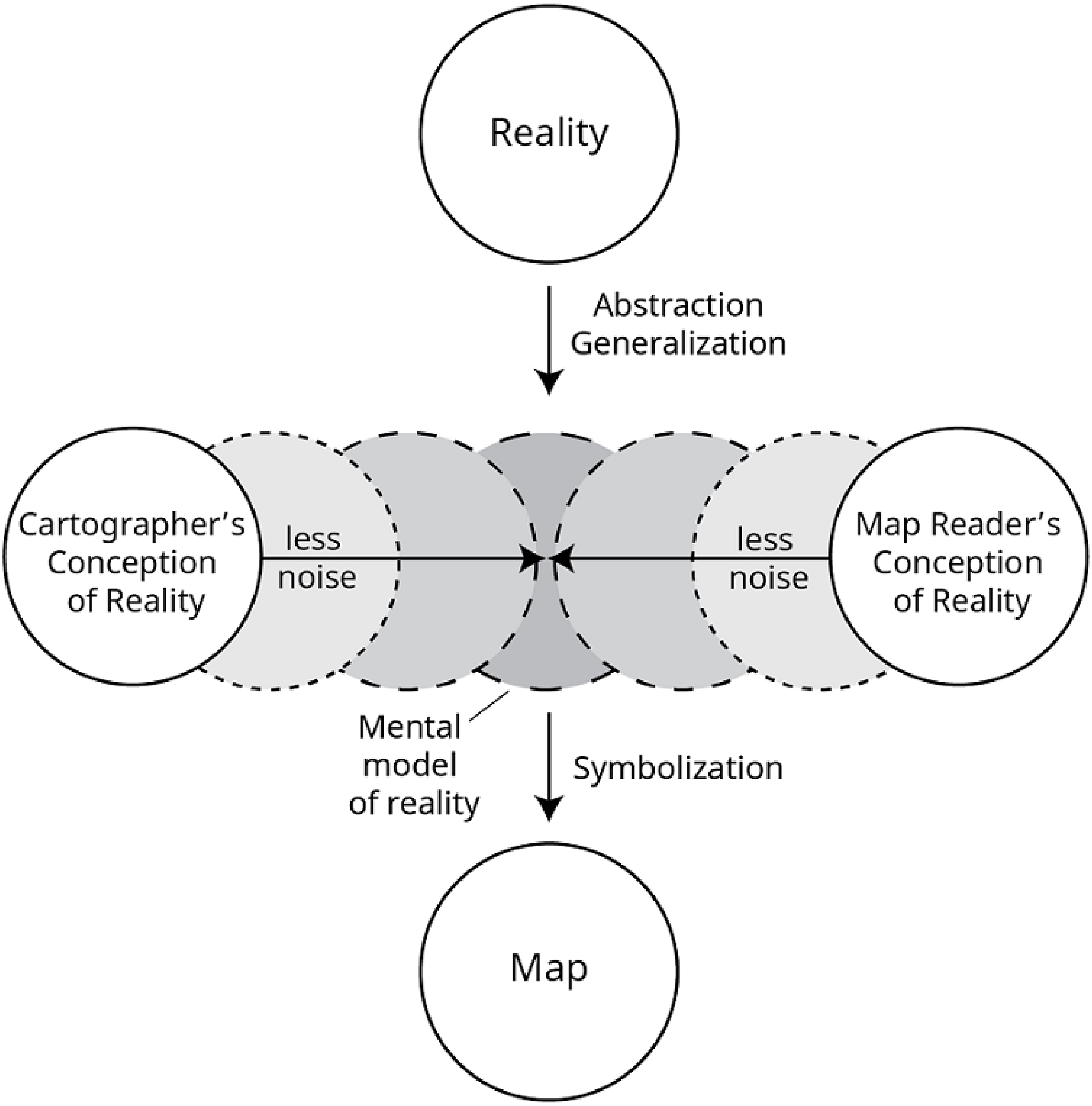

Figure 1. A schematic depiction of common components of map communication models and their functional relationships to each other. Many different cartographic communication

models were proposed by different authors in an attempt to describe the process by which information was communicated from the map maker to the map reader. Some influential examples include those developed by Board (1967), Koláčný (1969), Ratajski (1973), and Robinson and Petchenik (1976). All contained some common elements, such as reality ("the world"), a map, and someone's mental model that intermediated between reality and the map. What was common across models was the idea that a 'good' map had the result of increasing the similarity between the cartographer's and the map reader's mental models of the world, and that the product of cartographic communication is a mental model of reality in the mind of the map reader. Source: author.

Cartographers attempted to operationalize communication theory by identifying cartographic grammars that could be used to guide map design decisions (see **Symbolization & the Visual Variables**). Some of these, such as graphical semiology (Bertin, 1967), were proposed by researchers outside of cartography and were derived intuitively rather than from empirical studies with map users. Graphical semiology provided a general theory of information graphics (including maps) that matched information characteristics to graphical characteristics. Other authors suggested grammars that arrayed graphical characteristics against map reading tasks, with supporting evidence provided by psychophysical studies (Morrison 1974, 1977). Taken to its logical extreme, the communication model should be able to create expert systems that could automate the production of the 'optimal map' – that is the map that transmits the most information – at the click of a button (Forrest, 1993).

Even while the communication model was in vogue, critiques of its utility began to appear. Some scholars questioned its goal of producing the "optimal map," suggesting that single-map solutions suffered from both overt and hidden biases that might color their design (Monmonier, 1991). Other scholars critiqued the communication model's focus on information transmission, given that some maps have no predetermined message. For example, what is the "message" of a road map other than that "these things are here"? In much of the research conducted within the communication paradigm, understanding map perception was prioritised over map cognition. This is perhaps because the communication model presupposed that knowledge exists, instead of understanding it as something that is constructed through the process of reading a map. The constructivist theory of scientific cartography suggests that successful maps are vehicles for making meaning (i.e., constructing knowledge) about a phenomenon. Some of the earliest discussions of this theory claimed that it was primarily the cartographer, through her understanding of the geographical phenomenon being mapped, who added meaning to the map (Guelke, 1976). Others argued that meaning making is not limited to cartographers. These authors suggested that not every interaction with a map leads to meaning making and even coined a term, the "percipient," to distinguish those whose interactions with a map resulted in meaning making from the more pedestrian 'map readers' or 'map users' (Robinson & Petchenik, 1976: 20).

A more fully developed theory of maps as a means for creating new knowledge can be found in the cognitive-semiotic approach to understanding "how maps work", as described in a major cartographic text with that title (MacEachren, 1995). Founded on the ontological view that maps are representations of the world, not the world itself, the cognitive-semiotic approach tries to describe both how "meaning is derived from maps and how maps are imbued with meaning.” (ibid, p. vi). As **representations**, maps are abstractions of the world, and the marks on the map stand for something in the world. A particular map design is one possible representation of the world, and some representations work better than others for some purposes. New knowledge (i.e., meaning) is created both by making and using maps, and this paradigm uses lexical, functional, and cognitive approaches to understanding how maps work in different mapmaking and map use contexts (Figure 2). The widespread availability of computer technologies that made making maps much easier and quicker presented new opportunities for designing multiple cartographic representations to support thinking.

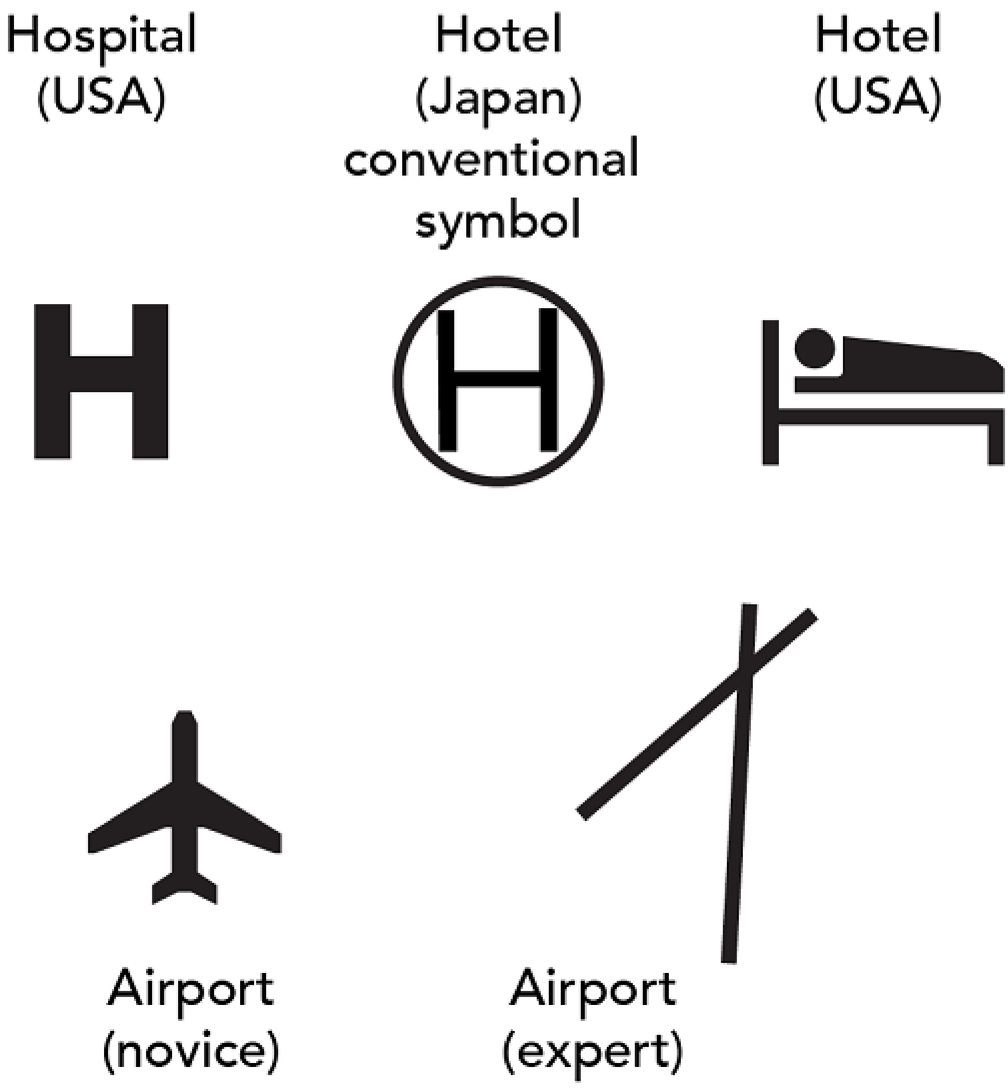

Figure 2. Lexical approaches to map representation attempt to answer the question of what symbols might legitimately mean. This varies among symbols. A set of arbitrary or geometric symbols might have a broader range of possible meanings than do pictorial symbols. Depending on the location being mapped and the organization or cartographer doing the mapping, the symbol at the left can represent two rather different types of building: either a hospital (as in the U.S. map symbol) or a hotel (as in many Japanese maps). The lexical approach shows how the meaning of symbols can at least in part be socially and culturally determined. Functional approaches to representation ask questions about how symbols provide meaning at both the level of individual symbols and that of sets

of symbols. For example, a common way in which symbols indicate that they stand for something is through iconicity – looking like the phenomenon they represent. The example of the symbol used in many countries to represent hotels looks like a person sleeping in a bed, an activity that typically occurs in hotels. Cognitive approaches shed light on how what the map reader already knows interacts with map symbolization decisions to shape the meaning the reader constructs from reading the map. A novice might do better with a pictographic or iconic symbol, as in the typical symbol used for airports on tourist maps. An expert, on the other hand, may be able to easily recognize an airport from a symbol depicting the typical orientation of two runways. Source: author.

Critical theories of cartography share some common features and even some methodologies with the semiotic component of the cognitive-semiotic approach, though they differ in how they understand the intentions of cartographers. Critical theoretical frameworks seek to expose how power relationships are reflected in the meanings carried by map symbols (see **Cartography & Power**) while the cognitive-semiotic approach proposes that these same symbol meanings are unintentional. Both critical and cognitive-semiotic approaches see maps as representations of the world, though many critical theories allow for fewer legitimate meanings to arise from a given set of map symbols than does the cognitive-semiotic approach. As Crampton (2010: 9) writes, “Maps produce knowledge in specific ways and with specific categories that then have effects (i.e., they deploy power).”

Around the turn of the millennium, some cartographic theorists began to question the separation between the map and the world, challenging the notion that maps are representations. This thinking has become known as post-representational cartography and it is a break from scientific and positivist philosophical approaches to cartography. In **post-representational** cartographic theory, the focus is on how maps act in the world rather than on the map itself or the map user. It proposes that the map and the world are co-constituted – that is, that maps are simultaneously created by the world and act to create the world. This view sees the map itself as active, fluid, and without fixed meanings, but rather having meanings that are negotiated through their use. Post-representational theorists thus believe that understanding cartography requires a scholarly focus on mapping processes rather than the map product (Kitchin & Dodge, 2007; Kitchin et al., 2013).

Processual approaches to understanding maps continue to evolve. Edney (2019) recently declared that ‘cartography’ is a fictional concept that unnecessarily constrains map scholarship by implying that mapping is a universal process. Instead, he argued forcefully for a focus on the on the specific and varying circumstances in which maps are produced, circulated, and consumed. Like the work of scholars who apply a critical theoretical framework, Edney’s work demonstrates that not all ‘work’ done by maps can be studied through the theoretical tools of the scientific method.

Cartographical Theoretical Frameworks	Epistemological Basis	Timeframe	Key Thinkers
Map logic	Historical empirical analysis of cartographic practice	Late 1800s-1930s	Emil von Sydow Karl Peuckert Max Eckert
Functional	Behaviorist/positivist	1952-late 1960s	Arthur Robinson
Communication	Behaviorist/positivist	Late 1960s-late 1970s	Christopher Board Anton Kolacny Jacques Bertin Joel Morrison
Critique of communication	Cognitive/critical realist	Mid-1970s-early 1990s	Leonard Guelke Barbara Petchenik Mark Monmonier
Representation	Cognitive-semiotic/ critical realist	Early 1990s-today	Alan MacEachren
Critical	Deconstruction/ post-structuralist	Late 1980s-today	Brian Harley Jeremy Crampton
Post-representation	Phenomenological	Early 2000s-today	Rob Kitchin Martin Dodge

Table 1: Major cartographic theoretical frameworks. Frameworks colored in purple are those that could be classified as taking a scientific approach, in the sense of science as a systematic approach that involves an iterative cycle of hypothesis generation and testing. The map logic framework, while systematic, did not involve the testing of hypotheses. The critical and post-representational frameworks draw primarily on methods that are used more commonly in the humanities: criticism and interpretation.

4. Scientific Approaches to Map Design

Scientific approaches to map design focus on understanding maps, map making, and map use with a goal of making improvements (however they are measured) in map design and use (Montello, 2002). This body of research sometimes implements the scientific method directly, using controlled experiments to test a hypothesis about how maps of a particular type or design are read, used, or understood (e.g., MacEachren et al., 2012; Hegarty et al., 2010). Other research projects seek to develop empirical evidence of map-making- or map-use-practices in order to spur further development of hypotheses about the nature of maps or map use that can later be tested experimentally (e.g., Perkins & Gardiner, 2003; Morrison et al., 2011; Schöning et al., 2014). A third type of research links the user-centered design approach to participatory action research and seeks to collaboratively solve practical problems and co-design maps that work for communities (Lloyd & Dykes, 2011; Hennig & Vogler, 2016). Importantly, each of these types of research aims to generate knowledge about maps, map making, and map use that is either generalisable or transferrable to other contexts. The concept of transferability, while well developed in the context of qualitative methods, has recently been suggested to have potential to improve the predictive capacity of findings from scientific map design research when applied to cartographic practice (Griffin et al., 2017).

A range of different methodological approaches, including both quantitative and qualitative methods, is used across these different types of map design research. Frequently, multiple methods are combined within a given investigation. In controlled experiments, behavioral study designs are often used to measure whether map readers draw correct inferences or extract the relevant information from a map or visualization with one or more design implementations. Other information that is frequently measured in such studies includes the time taken to complete a task, where a reader is looking through measurement of eye gaze, what is clicked on (for interactive and digital maps), and the reader's subjective preferences or level of satisfaction with a given design. Other empirical studies that use less experimental control might use approaches such as qualitative content analysis to code a sample of maps, observation (recorded or in situ) of map readers working with a map, or verbal protocols, which ask map readers to verbalize their thoughts while working with a map. User-centered design approaches use a still wider range of methods, including ethnographic participant observation, interviews, card sorting, scenario generation, sketching, and prototyping. The wide range of methods employed in map design research are addressed in detail in **Usability Engineering & Evaluation**, and Roth et al. (2017) provide a recent delineation of some of the methodological challenges of map design research.

5. Using Maps to Support Scientific Thinking

The history of scientific thought is replete with examples of using graphics of various types to support thinking and generate new insights (e.g., Miller, 1986, 2000). Well-designed graphics are thought to be amplify human cognitive abilities in several ways: by offloading the requirement to keep information (Larkin and Simon, 1987) or an internal visualization (Hegarty 2004) in memory because it can be easily perceived and recognised in the visualization; in constraining the kinds of inferences that can be made about a problem; and in restructuring the problem to make particular types of thinking easier to do (Scaife and Rogers, 1996). Specific maps have sometimes been instrumental in prompting the development of new scientific theories, with one clear example being Alfred Wegener's theory of continental drift, a theory that was so revolutionary in its time that it was widely dismissed, the maps becoming objects of ridicule (Figures 3 and 4).

The arrival of the computer greatly altered how maps could be used to visualize geographic information in support of scientific thinking. In particular, computers make it much easier to construct maps on-the-fly to answer questions quickly enough to approximate the speed of thinking (avoiding interrupting the map reader's thinking processes), and in response to the map reader's questions and goals. These goals might include exploring datasets to generate new hypotheses (e.g., as in geovisualization approaches such as those described in MacEachren, 1995; see **Geovisualization**), as well as using visual tools to seek to confirm (or disprove) the validity of a hypothesis. Maps and other visualizations are becoming ever more essential tools for making sense of data in the current environment of big data (see **Big Data Visualization**), often visual methods are now used in conjunction with computational methods that aim to support analytical reasoning (see **Geovisual**

Analytics). This pairing of visualization and statistical computation may in the future quicken the acceptance of map-driven theories that revolutionize conventional thinking about a phenomenon, such as Wegener's theory of continental drift. Finally, critical storytelling approaches are being used to drive the exploration of large geographic datasets, using visualization techniques to identify stories and generate new insights about complex phenomena with drivers that occur at different spatial and temporal scales (Moore et al., 2018). A contribution of critical cartographers to understanding how maps can be used to support scientific thinking lies in raising awareness that when maps are used for sense-making and knowledge construction, the knowledges these activities produce are both historically contingent and partial (Crampton, 2004). An implication of this is that it is important to be aware of how the broader socio-political-historical context might influence what data is available for mapping as well as how the map is constructed.

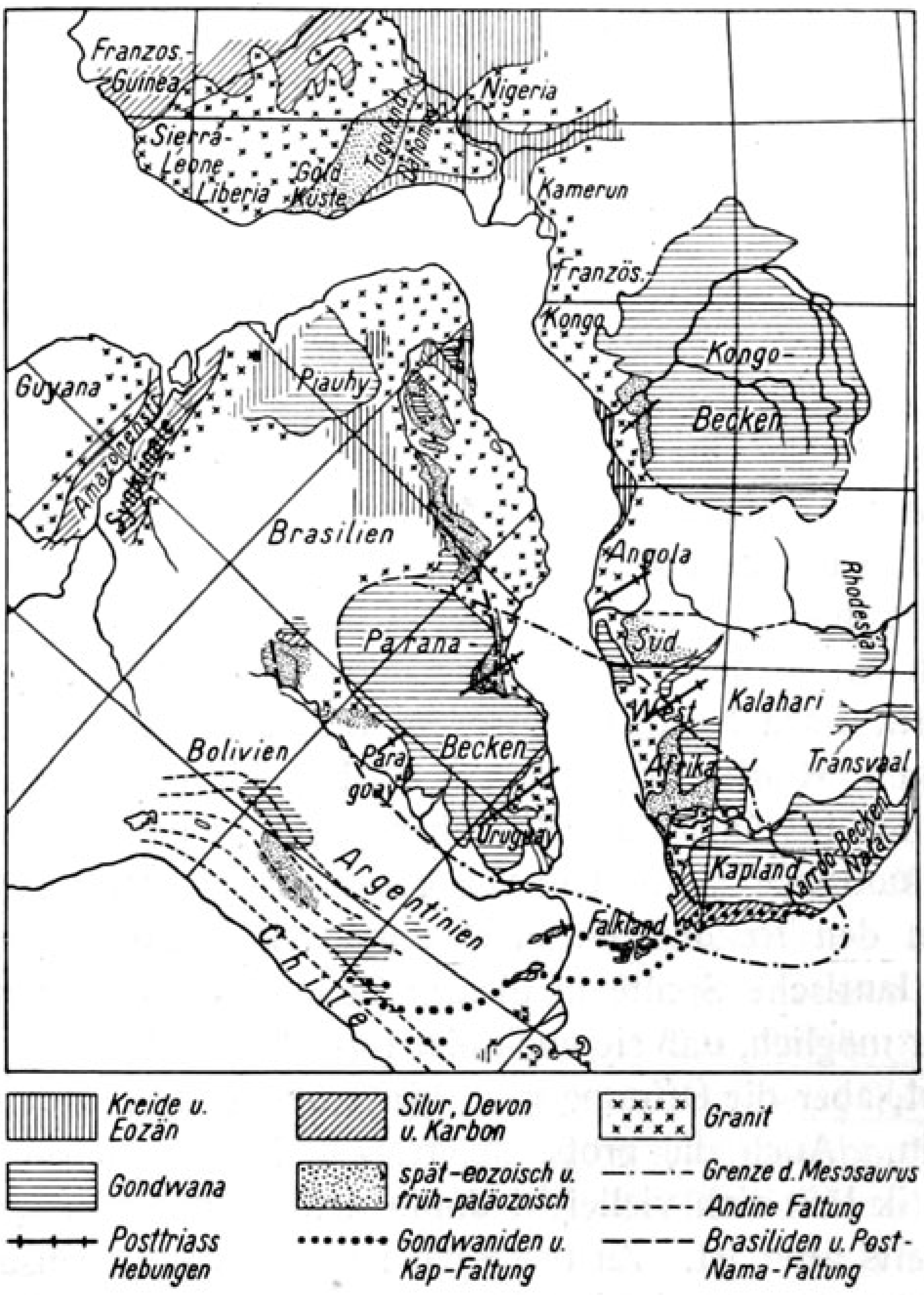

Figure 3. While not the first to make this observation, Wegener noticed the similarity in shape between the coastlines of Africa and South America, the so-called jigsaw fit, and hypothesized that together they once formed a larger continent. His curiosity prompted by the map, Wegener searched for evidence to further develop his theory and uncovered a scientific paper that showed that similar fossils existed on two sides of an ocean. More investigation showed that this was not an isolated incident, but that many such examples existed – too many to be plausibly explained by a land bridge. He also found that other spatial patterns of evidence 'lined up' when mapped across the now distant continents, such as geology (shown in the map above), tectonics, and glacial deposits, lending further support to his theory. Source: Wegener 1929, public domain.

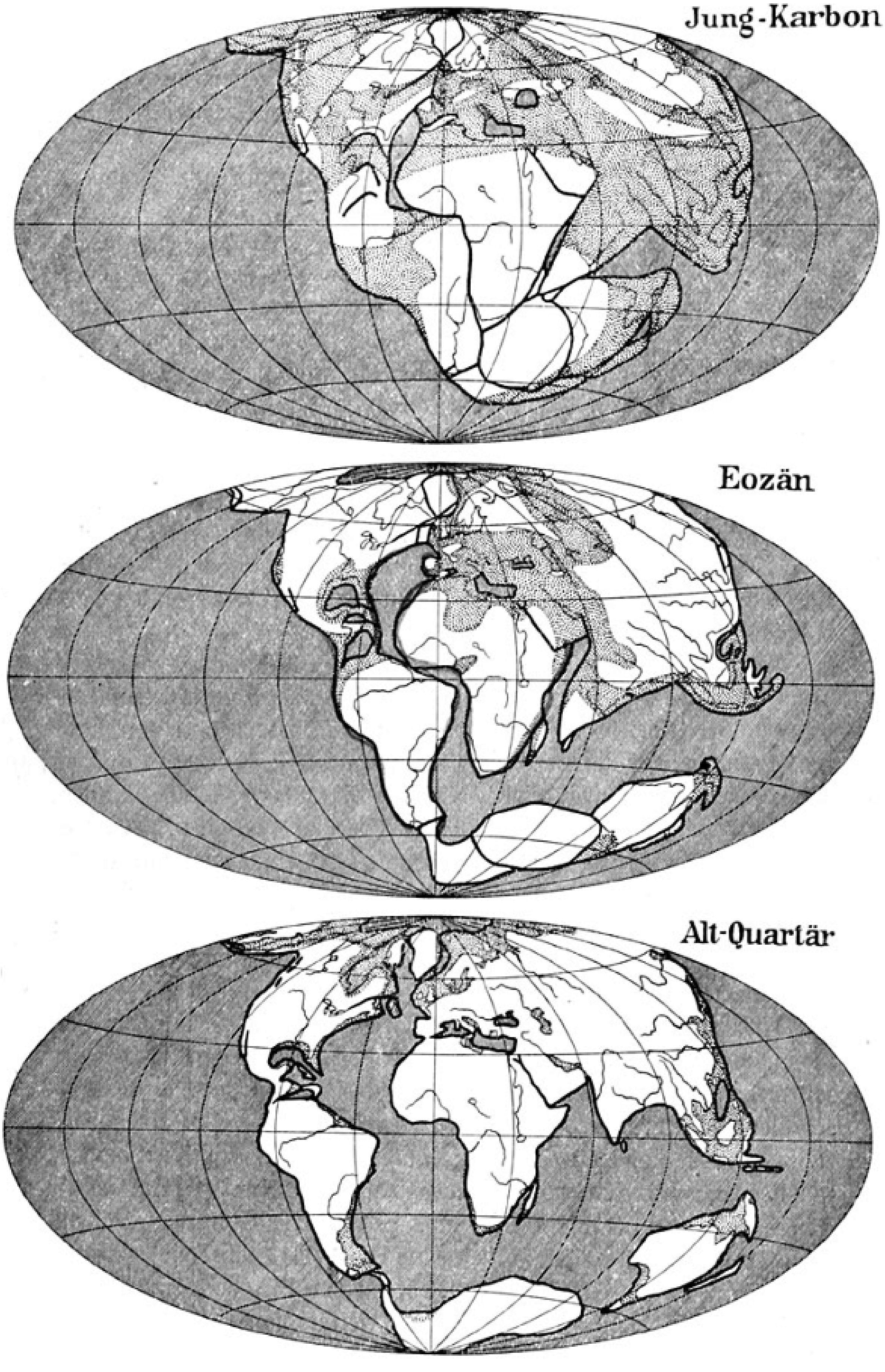

Figure 4. Wegener also used maps to communicate his scientific theory of continental drift, showing the locations where he proposed different continents could be found during

different geological eras. Although the geological mechanism Wegener proposed to explain continental drift was ultimately proven to be incorrect, the subsequent investigations that his original proposal sparked led to the modern theory of plate tectonics. The book that describes his theory is notable for its extensive use of maps to both prompt scientific thinking and to then communicate his theory of continental drift. Source: Wegener, 1929, public domain.

6. Using Maps to Communicate Science

Once scientific thinking is sufficiently well developed to communicate it to others, maps often feature prominently in its communication. In other words, these maps are used to bring the map reader's mental model of the phenomenon closer to the scientist's (revisit Figure 1). This communication may be directed to either to the general public or to other specialist audiences like policymakers. Fundamentally, science communication seeks to make "maps that matter" – those that as Robinson et al. (2017, p. 32) define them, "pique interest, are tacitly understandable and are relevant to our society." However, there are a number of different, more specific communication goals in science communication, ranging from seeking to inform policy, to spark behavioral changes, or to increase public understanding of and support for scientific research. The cartographic challenges that accompany each of these goals thus vary.

Scientists know that all measurement is subject to errors of a range of types: measurement, conceptualization, and modelling and methodological choices. Many scientists develop a nuanced understanding of the uncertainties that arise from these errors and how they should be accounted for when interpreting the results of their work. But policymakers and members of the public often have less experience in accounting for scientific uncertainty. Among communication devices, maps have frequently been perceived to be objective and neutral (Kitchin & Dodge, 2007). This perceived authority is why people tend to trust rather than question maps. Thus, one challenge relates to communicating this scientific uncertainty and how it influences the conclusions the reader should draw from a map, whether the reader is a policymaker or member of the public.

When the goal is to stimulate behavior or attitude change, map designers seek to persuade the reader to take one or another action by engaging the reader with arguments for the subject's personal relevance and urgency, though taking care to use ethical persuasion that does not exaggerate the data in scientifically implausible ways (Monmonier, 1991; Sheppard, 2005). This requires truthfully conveying the level of trust the map reader should have in the data, given its uncertainty. This is an active area of research within cartography, with many researchers grappling with how much and what kind of uncertainty information to include as well as how to represent it visually (see Figure 5 and **Representing Uncertainty**).

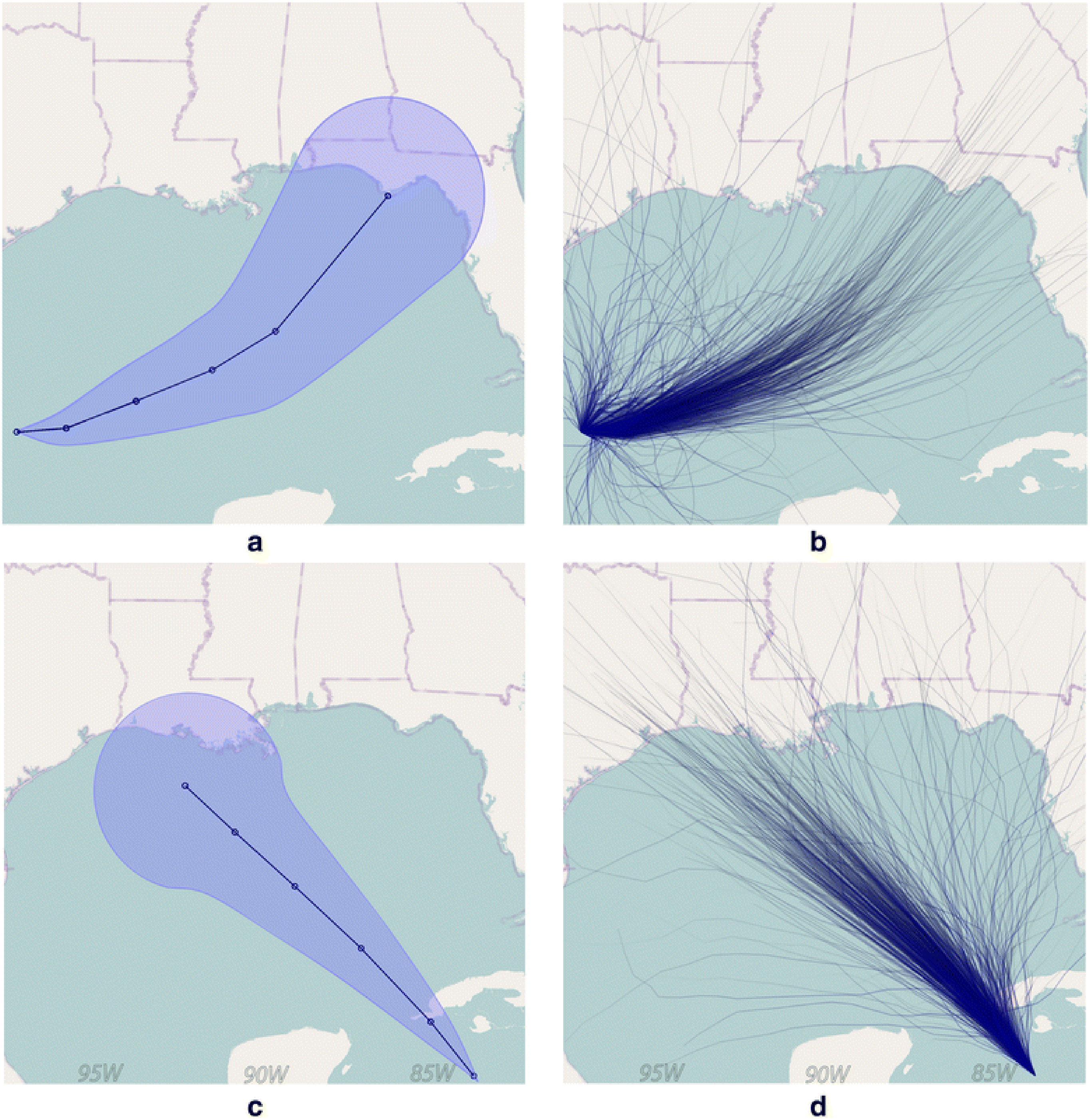

Figure 5. Maps of possible hurricane tracks have the explicit goal of helping their readers to decide what actions to take, including whether or not they should evacuate. However, future hurricane paths are not completely predictable, so it is important to communicate this uncertainty to the map reader. One recent study compared two methods for communicating uncertainty in the predicted future location of a hurricane. The first, the cone of uncertainty, is traditionally used in hurricane location prediction maps and represents a summary of historical hurricane tracks. The second is an ensemble display of potential hurricane tracks produced by different runs of a hurricane prediction model. Participants were more likely to conclude that the hurricane was growing in intensity and size over time when they viewed the cone of uncertainty than when they viewed the ensemble display, leading to an inaccurate understanding of the actual level of risk and where the risks were highest. However, participants were also more likely to judge that the intensity of the storm was lower in locations with a lower density of storm tracks within the

ensemble display, also an inaccurate inference. Image source: Padilla et al., 2017, Cognitive Research, CC BY 4.0.

There are a range of design strategies cartographers can use to persuade map readers. One such strategy places the map reader within an augmented reality map. Lonergan and Hedley's (2015) Tsunamulator interactively simulates the action of a tsunami in situ and displays this simulation on the map reader's mobile phone, depicting the tsunami as it would appear at that location and from that perspective. Other researchers advocate the use of stories and narratives because of their emotional power and memorability, but caution that designers need to think carefully about how the audience might interpret these stories (Grainger et al., 2016).

Cartography also can be used to communicate science in a less goal-oriented fashion, wherein the aim is to share scientific research and provoke the map reader's interest in a topic (Figure 6). In such scenarios, the broad strokes of the scientific story are more important than the details, so communicating nuances such as the uncertainty of the information is less important than an easily interpretable story.

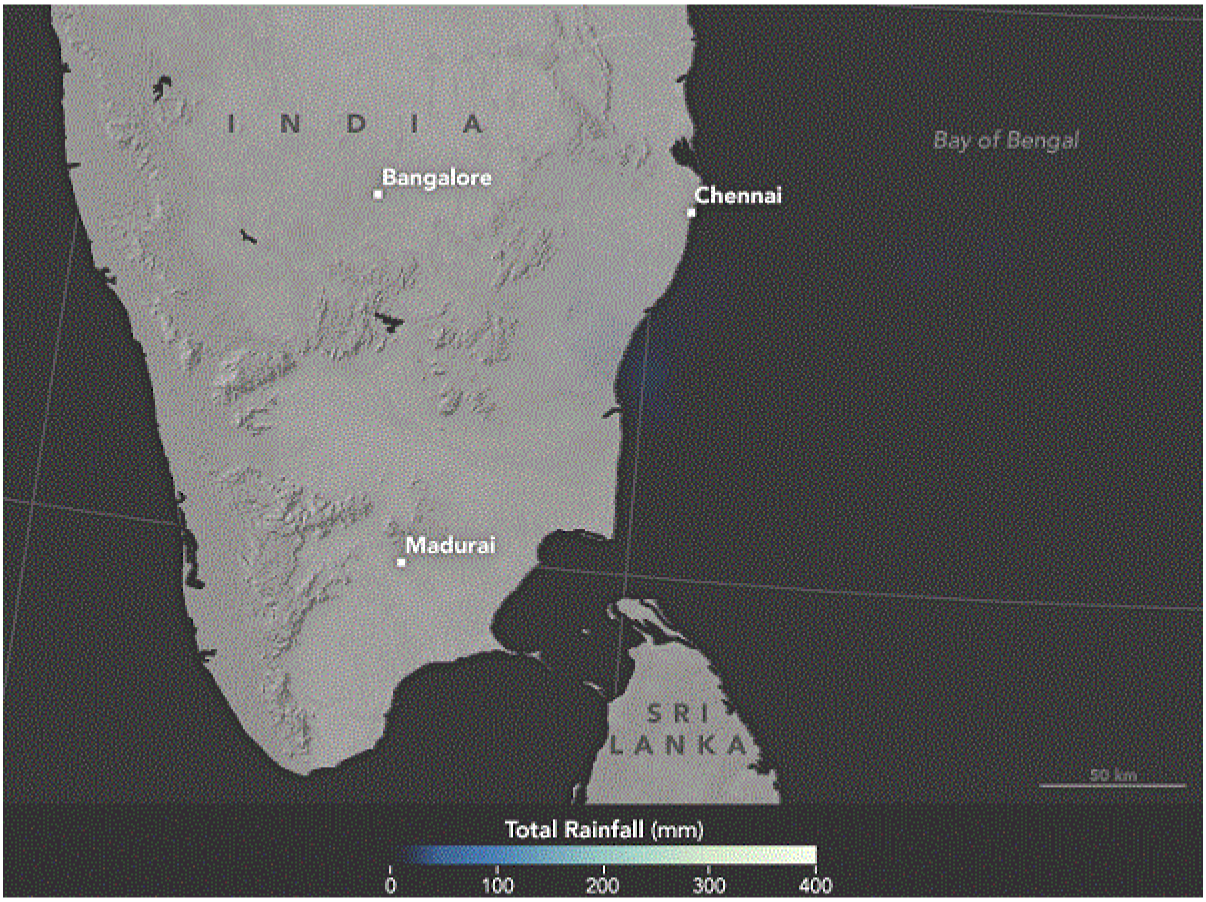

Figure 6. An map of rainfall that caused record flooding in Chennai, India in late 2015. This map is a good example of cartography that aims to increase public support for science. It is part of a series that can be found at NASA's Earth Observatory, which publishes a visualization each day of the year, often a map, derived from NASA's science. An animated

version of this map can be found at NASA's Earth Observatory. Image source: Stevens, 2015, public domain.

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