ARTICLES

Implications of Web Mercator and Its Use in Online Mapping

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ABSTRACT

Online interactive maps have become a popular means of communicating with spatial data. In most online mapping systems, Web Mercator has become the dominant projection. While the Mercator projection has a long history of discussion about its inappropriateness for general-purpose mapping, particularly at the global scale, and seems to have been virtually phased out for general-purpose global-scale print maps, it has seen a resurgence in popularity in Web Mercator form. This article theorizes on how Web Mercator came to be widely used for online maps and what this might mean in terms of data display, technical aspects of map generation and distribution, design, and cognition of spatial patterns. The authors emphasize details of where the projection excels and where it does not, as well as some of its advantages and disadvantages for cartographic communication, and conclude with some research directions that may help to develop better solutions to the problem of projections for general-purpose, multi-scale Web mapping.

Keywords: online mapping, Web Mercator, map projections, GIScience, cartography

RÉSUMÉ

Les cartes interactives en ligne sont devenues un moyen populaire de communiquer au moyen de données spatiales. Dans la plupart des systèmes de cartographie en ligne, la projection de Mercator sur le Web est devenue la projection dominante. La projection de Mercator soulève depuis longtemps des discussions sur son caractère inapproprié en cartographie générale, particulièrement à l'échelle de la planète, et elle semble avoir à peu près disparu des cartes imprimées à l'échelle mondiale d'usage général, mais on a constaté un regain de popularité de la projection de Mercator sur le Web. Cet article présente une théorie sur la façon dont la projection de Mercator sur le Web s'est généralisée pour les cartes en ligne et sur ce que cela pourrait signifier pour l'affichage des données, les aspects techniques de la production et de la distribution de cartes, la conception et la cognition des tendances spatiales. Les auteurs mettent en évidence des détails sur les aspects où la projection excelle et sur ceux où elle n'excelle pas, ainsi que certains de ses avantages et inconvénients pour la communication cartographique. Ils concluent par des pistes de recherche qui peuvent aider à trouver une meilleure solution au problème des projections destinées à la cartographie générale à échelles multiples sur le Web.

Mots clés : cartographie en ligne, Mercator sur le Web, projections cartographiques, science SIG, cartographie

Introduction

> *Persistent misuse of the equatorial Mercator projection, especially for world maps having nothing to do with navigation, taunts cartographically savvy geographers.*
>
> —Monmonier (2004, *121*)

As Monmonier (2004) suggests, misuse of the Mercator projection has taunted cartographers and geographers for decades, perhaps centuries. Cartographers and geographers seem to have kept a trained eye out to find and report inappropriate uses of the Mercator projection in print form; nonetheless, the cartographic community has now seemingly turned a blind eye to the return of the projection as Web Mercator.

In this paper, we discuss issues of relevance to the cartographers, geographers, map users, and map designers who are producing and using Web maps based on the Web Mercator projection. We emphasize several positive, negative, and sometimes questionable aspects related to technical map projection characteristics, data processing and delivery, map design, and the cognitive and educational challenges specific to the Mercator and Web Mercator projections. Our goal is not to vilify the projection but to discuss what it is and why it is being used and to raise issues with the applicability of the projection in a cartographic environment that is becoming increasingly focused on simple, accessible Web-based map creation and delivery.

This particularly time-relevant discussion arises as the last decade has seen a major shift in the way that Web maps are being used, the purposes for which they are being designed, and the increase in accessibility of the maps for almost any end user to customize and distribute. Judging from the number of online mapping applications currently available, a noticeable shift has occurred from Web maps as local-scale, reference maps to a ubiquitous, all-purpose, all-scale reference *and* thematic map product. With this shift to general purpose and thematic mapping across scales, the Web Mercator projection presents new challenges that need to be addressed – and critically evaluated – to understand the implications of the projection for communicating spatial information.

The Basics of Mercator and Web Mercator

The Mercator projection is a cylindrical map projection introduced by Gerardus Mercator in 1569. Mercator depicted the map projection on a huge world map of 21 sections, and the projection became essential in the development of projections (Keuning 1955; Snyder 1987). This projection is one of the most widely known and has a long history of use for global-scale mapping. The Mercator projection is a conformal projection, preserving local angles around points. Although conformality is, in itself, a desirable property for certain map uses (e.g., navigation), preservation of this property comes at the expense of distorting other potentially desirable map properties – such as area. In the Mercator projection, the lack of area preservation manifests in massive inflation of area (relative to other regions) in the areas toward the poles. This inflation is most noticeable (and most often discussed) in the land areas in the northern hemisphere.

On the other hand, the Web Mercator projection is a more recent introduction, probably from the early twenty-first century, that we discuss more in a later section. While the Web Mercator projection has many similarities with the traditional Mercator projection, some notable differences exist. In this section we provide a technical introduction to Web Mercator and its applicability for digital mapping. We also discuss in more detail the differences, benefits, and problems with Web Mercator versus Mercator.

A MATHEMATICAL LOOK AT MERCATOR VERSUS WEB MERCATOR

We follow Snyder (1987) in presenting the rectangular coordinates (map coordinates) for the Mercator projection. The coordinates based on a sphere can be found in Equations 1 and 2.

$$x = R(\lambda - \lambda_0) \tag{1}$$

$$y = R \ln \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \tag{2}$$

where R is the radius of the sphere (at map scale), and φ is latitude and λ is longitude (both in radians). Note that if φ is $\pm\frac{\pi}{2}$ then y is infinite.

To use φ in latitude and λ in degrees, Equations 3 and 4 are employed:

$$x = \frac{\pi R(\lambda^0 - \lambda_0^0)}{180^0} \tag{3}$$

$$y = R \ln \tan\left(45^0 + \frac{\varphi^0}{2}\right) \tag{4}$$

Note that if φ is $\pm 90°$ then y is infinite.

The rectangular coordinates (map coordinates) for the Mercator projection based on an ellipsoid of revolution (sometimes called the spheroid) can be found in Equations 5 and 6.

$$x = a(\lambda - \lambda_0) \tag{5}$$

$$y = \frac{a}{2} \ln\left[\tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)\left(\frac{1 - e\sin\varphi}{1 + e\sin\varphi}\right)^{\frac{e}{2}}\right] \tag{6}$$

where a is the semi-major axis of the ellipsoid and e is the ellipsoid's eccentricity (more technically, its first eccentricity), defined by Equation 7.

$$e = \frac{\varepsilon}{a} \tag{7}$$

where ε equals the linear eccentricity and is calculated by Equation 8.

$$\varepsilon = \sqrt{a^2 - b^2} \tag{8}$$

where b equals the semi-minor axis of the ellipsoid.

With respect to how Mercator and Web Mercator differ, basically Web Mercator is just a special case of Mercator on a sphere (with radius 6,378,137.0 m) and projected from latitude and longitude coordinates from the World Geodetic System 1984 (WGS 84) ellipsoid. From the perspective of developing this "new" projection for use in Web mapping, how did this come about? Somewhere in the evolution of Web Mercator from Mercator, it was decided to make Web Mercator the same as Mercator except with an R (radius) that is equal to a, the semi-major axis of the ellipsoid of revolution, as opposed to a nominal R

Figure 1. Mercator and Web Mercator. At this scale the shapes of the two projections appear identical.

for the radius of Earth modelled as a sphere. Thus, in some communities, Web Mercator is also known as Spherical Mercator. The Spatial Reference Organization (http://spatialreference.org) uses the term "Spherical Mercator" and states,

> Used by certain Web mapping and visualization applications. Uses spherical development of ellipsoidal coordinates. Relative to an ellipsoidal development errors of up to 800 meters in position and 0.7 percent in scale may arise. It is not a recognized geodetic system. (Spatial Reference Organization 2014)

Furthermore, by the current convention the value of the Web Mercator radius is equal to the semi-major axis of the WGS84 datum (National Imagery and Mapping Agency 2000). So why does confusion exist between Mercator and Web Mercator? Aitchison (2011) notes that the Web Mercator projection, as commonly used by most online mapping systems (e.g., Google Maps, Bing Maps, and ArcGIS Online), defines the underlying geographic coordinates using WGS84 but projects them as if they were defined on a sphere.

What is the difference in radius between the Mercator and Web Mercator? The mean radius, R_1, as defined by the International Union of Geodesy and Geophysics (IUGG) is as follows:

$$R_1 = \frac{2a + b}{3} \tag{9}$$

where a equals the semi-major axis of the Earth and b equals the semi-minor axis of the Earth.

For the Earth, according to Moritz (2000), the mean radius is equal to 6,371,008.7714 m. The Earth's authalic ("equal area") radius is the radius of a hypothetical perfect sphere which has the same surface area as the reference ellipsoid, and further, the volumetric radius is defined as the radius of a sphere of volume equal to the ellipsoid (equations are available for both of these radii in Moritz 2000, 130). The authalic mean radius is equal to 6,371,007.1810 m, and the volumetric radius is equal to 6,371,000.7900 m. Interestingly, perhaps, is the value that the commonly used GCTP (General Cartographic Transformation Package) uses for the sphere, which is 6,370,997.0 m (Finn and others 2012).

What this means in terms of Mercator and Web Mercator is simply that different measurements of the Earth exist for each of these projections used today. While historically the Mercator projection was developed on a spherical Earth model, subsequent implementation may be based on either the sphere or ellipsoid. Implementations of the Mercator projection typically rely on the best Earth model available. Web Mercator, in contrast, always uses a spherical Earth, with a radius equal to the semi-major axis of the ellipsoid of revolution. This difference manifests itself as a function of latitude. Further, if or when the standard Mercator projection is used on a sphere, the value for the radius of that sphere is important to recognize because, as a fundamental component of functions used to calculate angles and distances, different values for the radius will provide differences in derived values for cartographic measurements.

It is impossible to say what value of R is used by current online mapping/Web mapping services with any certainty because of the myriad of programs, application programming interfaces (API), and individual programmer preferences available. A single value of R is not likely, but in addition to the values mentioned in this section, two of the more commonly used values come from Esri's projection definition for "WGS 1984 Web Mercator" and the definition of the European Petroleum Survey Group (EPSG) 3785 (Popular Visualization Sphere). Both use the radius value of 6,378,137.0 m, which matches the published WGS84 ellipsoid parameters of Subirana and others (2011).

From a cartographic and mathematical perspective, scale factor, defined as the ratio of the scale at a particular location and direction on a map to the stated scale of the map, is another notable difference between Mercator and Web Mercator. For a conformal map projection, the scale factor at a point is undeviating in all directions. This is the case for the Mercator projection (a conformal projection) but it is not for Web Mercator (Lapaine and Usery 2013).

A PERCEPTUAL LOOK AT MERCATOR VERSUS WEB MERCATOR

From a purely visual perspective, at the global scale, the difference between the two projections is impossible to identify (Figure 1). But although the visual difference at the global scale is not apparent, a substantial distortion

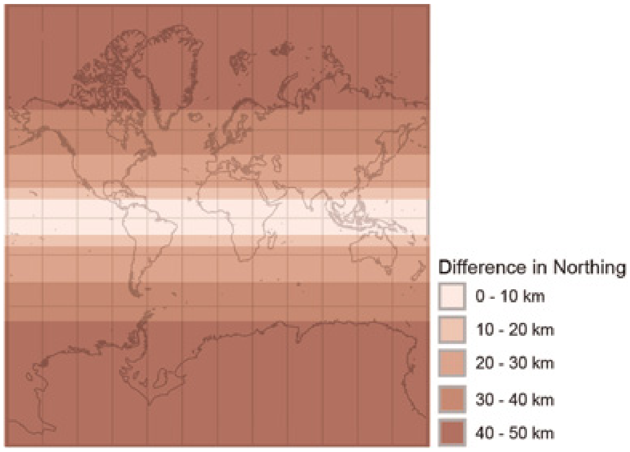

Figure 2. Approximate difference in northing for coordinates between Mercator and Web Mercator.

still exists between the two projections, up to a 50-km difference in location coordinates at the extreme north and south latitudes (Figure 2 and Figure 3). For a global-scale wall map, if one assumes a fairly typical world wall map size of approximately 50 inches by 32 inches, and with a map scale of 1:32,000,000, this would be a difference of about 1.5 mm in location (with $R = a$, as noted in the last section). With this small potential difference in location, from a perceptual standpoint Mercator and Web Mercator projections can be considered the same.

At a global scale, identifying the difference between the two projections with the naked eye is virtually impossible. But as mentioned previously in the technical evaluation, the projections have some notable mathematical differences that are still of importance when it comes to data display and analysis.

WHY WEB MERCATOR?

Given that cartographers and geographers have long discussed the inappropriateness of the Mercator projection for general purpose global-scale mapping, why has the Web Mercator variant been embraced so thoroughly by the mapping community? Inherent issues with representing the three-dimensional irregular Earth onto two dimensions continue to plague geographers and cartographers just as they did with those from centuries past. Ideally, a projection that is conformal, equal area, and equidistant will be used to solve our mapping needs; however, without such a perfect model of the world, sacrifices must be made, and Web Mercator has been selected as a "good enough" solution that has persevered. In some respects, this solution may have been a convenient choice made by someone, and the online mapping systems designed with Web Mercator became popular enough to become the standard to which everyone else conformed. In this section we discuss some of the reasons why the Web Mercator projection works well and describe where it does not.

In general, Web Mercator is a good choice for online mapping, particularly at the global scale because, as previously explained, it simplifies the standard Mercator projection by mapping the Earth to a sphere, which allows

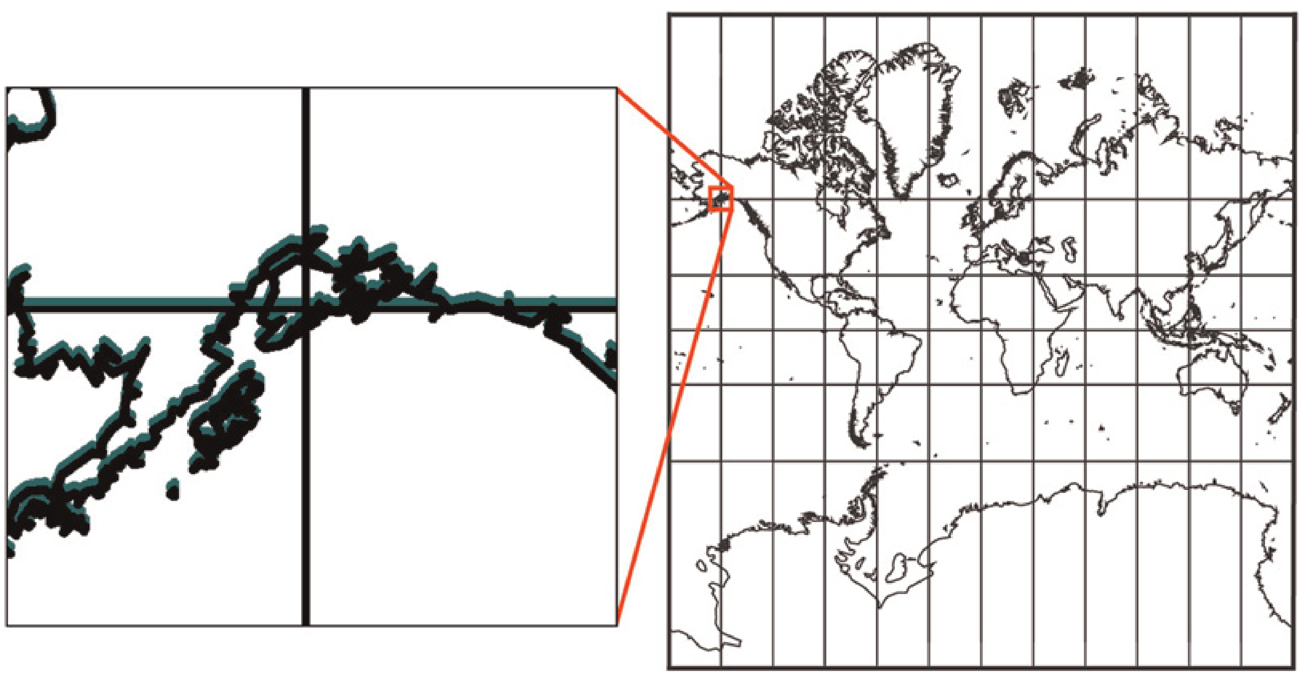

Figure 3. Close-up look at the difference between Mercator (black) and Web Mercator (green).

for simpler (and therefore quicker) calculations; Web Mercator also readily supports Web map service requirements for indexing "the world map" and allowing for continuous panning and zooming to any area, at any location, and at any scale. Note that these beneficial characteristics are the same for other conformal, cylindrical projections, but unlike Web Mercator, these other projections are not in general use for online mapping.

Web Mercator also has benefits because the Mercator projection is a conformal projection. Although Web Mercator is not technically conformal (see Zinn 2010), the visual difference between Web Mercator and Mercator is nonexistent, and for most *general purpose* mapping the distortions to local angles are minimal. This distinction between the two projections is most important for large-scale mapping. As a cylindrical map, the Mercator projection has the property that north is always the same direction anywhere on the map, a characteristic that is not preserved on non-cylindrical map projections. For online mapping these properties of maintaining a north-up orientation and (close to) conformality allow us to implement seamless panning and zooming using a single projection (Strebe 2009). While equal-area projections are often suggested for global-scale thematic mapping, this is impractical for Web maps because angular distortion would vary across the location or the projection would have to be recalculated on the fly based on the zoom/pan location.

So how important is the conformal/"not conformal" issue to online mapping? The essence is the point that we mentioned about Web Mercator using a spherical Earth model with ellipsoidal coordinates. To some this concept is apples and oranges, whereas to others it is oranges and tangerines (shades of the same fruit) – meaning the difference is either important or not depending on the use and the user. So the "well-informed user" becomes a more important participant. For a well-informed user who *understands* the difference between the projections, he/she can assess the importance for the task at hand. But for users who are unaware that a difference even exists, they cannot critically assess the accuracy and validity of the mapped data. The conformal/"not conformal" point is, at its heart, a cartographic versus geodetic issue. Professionals in these realms understand the issues of each projection; however, for the non-professionals designing Web maps and for the end users interpreting the maps, understanding or even being aware of these issues can present a major challenge. Zinn (personal communication, 15–16 March 2012) opines that "the argument for the Web Mercator is that it's suitable for the web. I agree. My argument against the Web Mercator is that it's become a bona fide projection in GIS where it can do harm in the hands of the uninformed."

One should note that Web Mercator is not computationally faster than Mercator if using Mercator (spherical) with a nominal radius; it is only faster than Mercator on the ellipsoid. In other words, computationally faster means latitude and longitude are used from the ellipsoid, but instead of the ellipsoidal equations, the spherical equations are used, because this computation is faster. If the ellipsoidal equations are used, the electrical costs (for an enterprise, for example) could be very high (Strebe 2009 suggests that this calculation would be millions of dollars per year), with associated environmental issues, not to mention the ever-present issues and concerns associated with compatibility and interoperability with the "mashup" community (mashup maps combine a user's data and existing Web-based maps to create a new map application or display). Furthermore, Strebe (personal communication, 15–16 March 2012) contends, "We've always had a 'Web Mercator' and a 'Web-any-thing-else' projection. Small-scale projections assume a sphere [. . .] When a small-scale map goes into preparation, nobody bothers to transform the ellipsoidal coordinates to spherical-datum coordinates before projecting to the sphere because the difference would be imperceptible [. . .] [Google and the like] represent (perhaps) the first widespread use of the spherical Mercator for large scale maps."

As discussed in more detail later, substantial issues related to the use of Web Mercator must be addressed, even if it does express a notable benefit for online mapping purposes. One of the most important issues arises when the map is "zoomed" to a large-scale mapping of a local area and calculations are made from that scale rendering (Zinn, personal communication, 15–16 March 2012).

A History of Web Mercator

In this section we discuss the transition to Web Mercator for Web mapping. We first provide a short overview of map projection choices for navigational Web map applications in the last few decades (mid-1990s to present) and then discuss in more detail justifications for Web Mercator as a solution to several Web mapping problems that arose as Web maps transitioned from primarily local-scale mapping solutions to more global-scale interactive maps.

THE EARLY YEARS: LOCAL-SCALE COMPUTER-BASED MAPPING

In exploring the history of Web Mercator, we initially theorized that the projection (or another Mercator variant) may have been used as early as the 1980s with the distribution of CD-ROM or other computerized pan/zoomable commercial maps. This hypothesis seemed plausible because of the benefit of a projection that was always north-up, which eliminates issues of north moving as the user panned around the map. Granted, other options would provide the same characteristic (e.g., an equirectangular projection); however, we hypothesized that

Figure 4. Microsoft Streets '98 zoomed to the smallest scale available.

Figure 5. As the user pans around the map in Microsoft Streets '98, the map rotates to maintain a north-up perspective. In this graphic, note the rotation of Washington State compared to the angle shown in Figure 4.

the added benefit of Mercator's conformality would have been of interest because of an early focus on local-scale mapping (e.g., in Microsoft Streets, Delorme's Simply Streets, etc.).

We evaluated the Microsoft Streets '98 (released in 1998) and Delorme Simply Streets (released in 1997) software packages to gain some insight on early automated mapping software and the projection used. At this time (late 1990s), apparently, no clear standard or preference existed for projection or implementation of interactivity for panning and zooming. So in retrospect, likely during product design for each software package, the cartographic team would simply fit the solution to the problem.

For Microsoft Streets '98, the projection used was clearly *not* Mercator based and, in fact, was not even a cylindrical projection – which is surprising since cylindrical projections are generally better when the area needs to be divided into regular-sized tiles. Likely the projection used is either Lambert Conformal Conic or Albers Equal Area (Figure 4), as these projections are a more traditional cartographic choice than a Mercator-related projection for mapping the entire US region. Additionally, the Microsoft Streets '98 system did not rely on tiling but instead appears to have used one large graphic for the entire mapped area (US-focused) and rotated the graphic to north-up as the user panned around the map using slippy-map functionality, which is the ability to dynamically pan the map by grabbing and sliding it in any direction (Figure 5). This ability eliminated the need for a cylindrical projection that maintained a constant north-up perspective.

On the other hand, the Delorme Simply Streets 1997 product appears to use multiple projections. At the maximum extent (the conterminous United States), the main map appears to be in a Mercator projection while the overview map is an equirectangular projection (Figure 6).

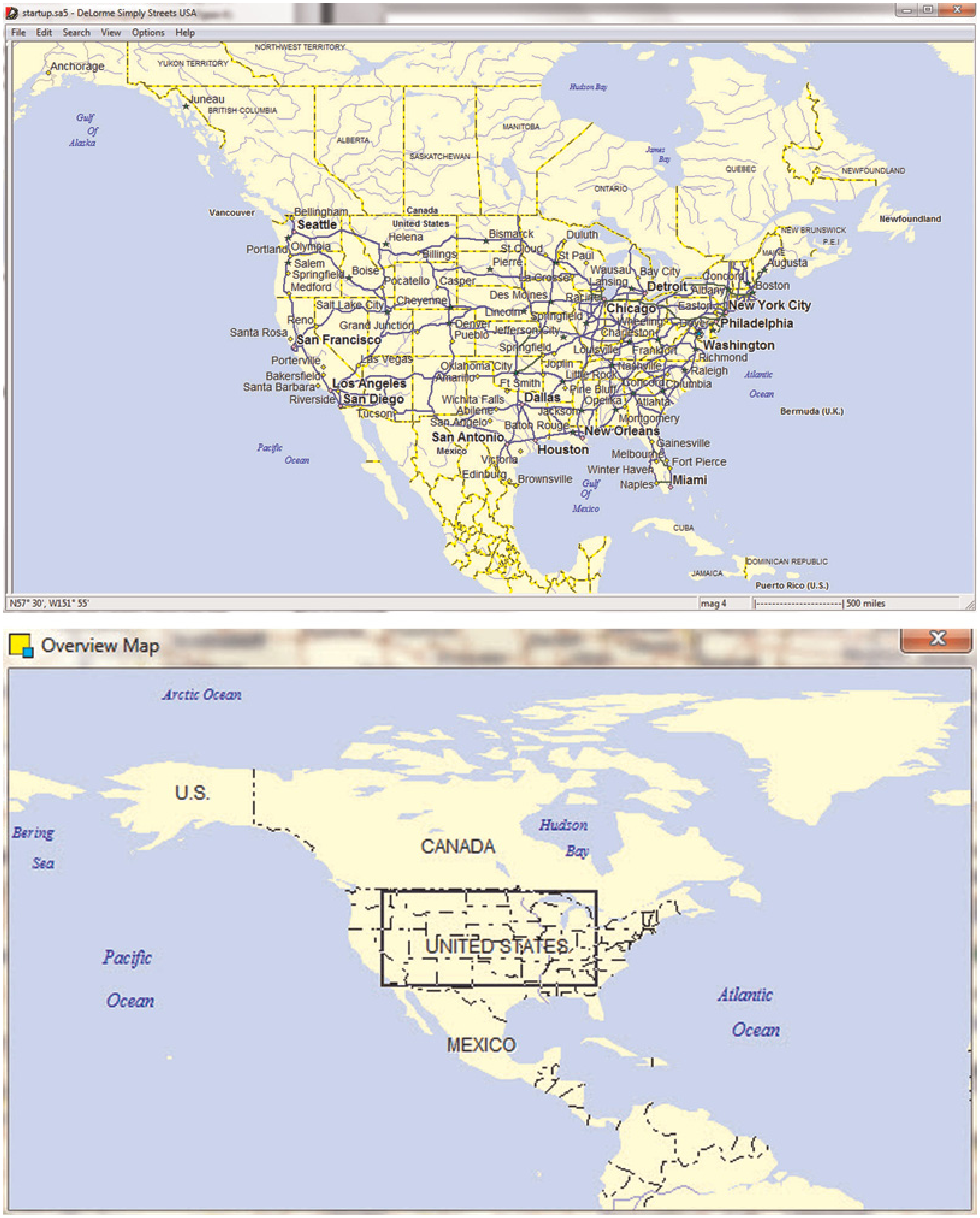

Figure 6. Delorme Simply Streets USA, showing the main window (top) in a Mercator projection and the overview window (bottom) suggesting an equirectangular projection.

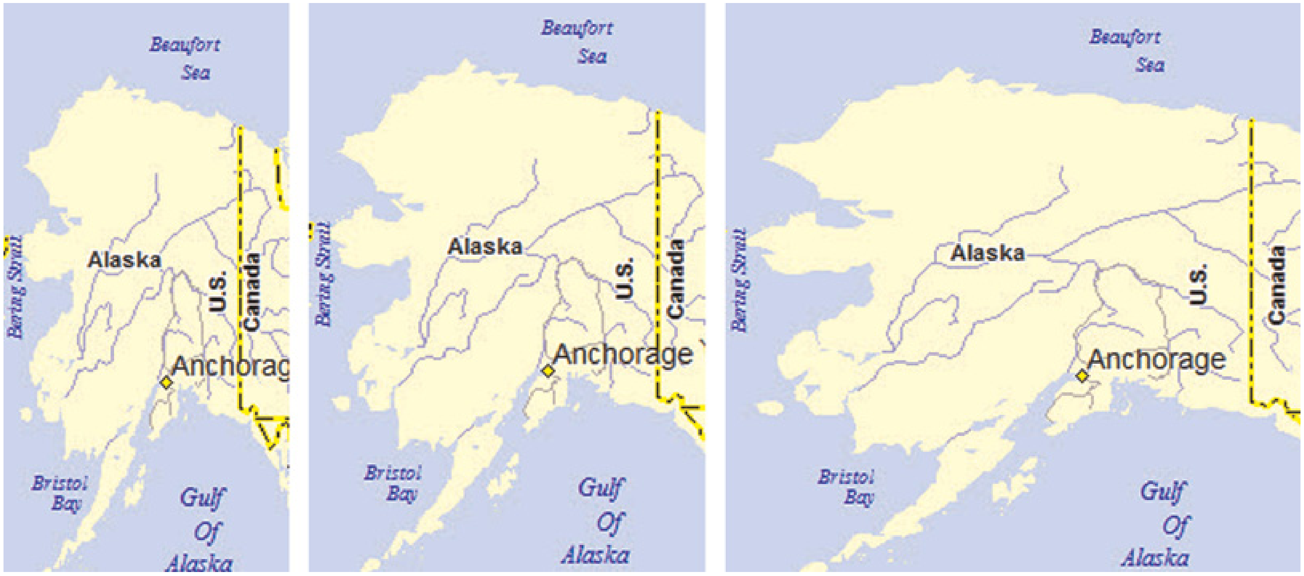

Figure 7. At the same level of zoom, as the map is panned, Alaska drastically changes in appearance in Delorme Simply Streets USA.

But when the user pans in on the main map, the projection changes, perhaps suggesting some projection of vector graphics on the fly – note the differences in the appearance of the state of Alaska shown in Figure 7. Though Delorme Simply Streets 1997 is navigated using an interactive compass rather than a slippy-map interface, insufficient evidence exists to suggest that a tile-based system was used.

THE MODERN ERA: WEB-BASED MAPPING

As navigation programs moved from an era of being strictly local computer–based to an era where it was more feasible to distribute navigation products in a Web-based format, there was also a (slow) shift in the design to enhance the maps to meet the expectations of a wide range of users with a wide range of mapping interests. Although it is hard to say exactly when and where the Web Mercator projection originated, the popularity of its use definitely seems tied to the era when Google Maps was introduced (2005). Web Mercator has now been readily adopted by Google Maps, Microsoft Bing Maps, Yahoo Maps, Esri's ArcGIS Online, OpenStreetMap, and *The National Map* of the US Geological Survey and therefore has become the de facto standard for online maps.

THE ROAD TO WEB MERCATOR

In the early years of Web mapping (e.g., 1996 with the introduction of MapQuest), just as can be seen with the older CD-ROM-based systems, neither Mercator nor Web Mercator appeared to have been the single projection of choice. Although one cannot go back in time to explore the older Web map implementations of the mid-1990s, sufficient archival material exists to explore the basic structure of the Web maps, including the map projection used. We should note that while several Web mapping sites were available, MapQuest has a fairly well-documented history from the mid-1990s, so we have emphasized MapQuest in our discussion of the transition in map projections – this is not to imply that MapQuest was in some way superior or that the choices for that one mapping option are reflective of all of the mapping sites.

In thinking about appropriateness of projections for Web maps, consider the importance of the initial purpose for which these maps were designed – finding locations and directions for relatively small areas (typically city to country scale). For example, early versions (late 1990s) of the MapQuest site restricted zooming to a scale no smaller than "National" (Figure 8). While we were unable to find examples of these early versions of the MapQuest site zoomed out to this scale, a slightly more modern version of the site (Figure 9; approximately 2005) lists "Country" as the smallest scale and shows a little more than a continental view. In this period of the mid-2000s, MapQuest was still based on an equirectangular projection (MapQuest 2012). This equirectangular projection would allow for the relatively easy creation of a tiling system to cover a mapped area from the local to the global scale, as MapQuest had seemingly implemented for its display.

The switch from equirectangular projections, which were just as suited for global-scale tiling systems, seems to be tied to the introduction of Google Maps in 2005. In 2003, Lars and Jens Rasmussen, with Australians Noel Gordon and Stephen Ma, co-founded Where 2 Technologies, a mapping-related start-up in Sydney, Australia. Their mapping program, which became Google Maps,

Figure 8. MapQuest, unknown date – though this appears to be running in Netscape and Windows 95, so we estimate mid- to late 1990s. Note the scale bar's smallest scale for zoom is "National." (Image courtesy of Computer History Museum; http://www.computerhistory.org/revolution/the-web/20/392/2345.)

was first planned to be downloaded by users. Where 2 Technologies subsequently pitched the scheme for a purely Web-based product to Google management, shifting the method of distribution (CNET 2005; Kiss 2009). Where 2 Technologies was procured by Google in October 2004 to produce the free, browser-based software Google Maps (Taylor 2005). With this switch to browser-based Google Maps, which provided an easy interface for global-scale mapping – including the now common slippy-map interface for panning – there was a larger adoption of the Web Mercator projection for other Web maps.

The shift to the Web Mercator projection is likely tied to the recording of EPSG:90913 in 2007 (OSM 2012), which formalized the choice of projection made by Lars and Jens Rasmussen. This temporary EPSG code was created to define the Spherical Mercator projection being used in Google Maps (see OSGEO 2013). The International Producers of Oil and Gas (OGP), formerly the EPSG, maintains and publishes sets of parameters for coordinate reference systems. This publication provides a standard definition of projections according to EPSG codes, a now common reference for map projections. Currently EPSG:3857 is the code assigned to WGS84 Web Mercator (Auxiliary Sphere), sometimes incorrectly referred to as "Google Mercator" because of its association with Google Maps. After the formalization of the EPSG for Web Mercator, several other online mapping systems switched to Web Mercator. For instance, MapQuest switched to Web Mercator in 2011, to "be more user-friendly, especially for those dealing with multiple data sources and finding that the standard for online mapping has increasingly shifted towards the more popular Mercator Projection" (MapQuest 2011).

Concerns with Web Mercator

For better or worse, Web Mercator is now an accepted standard for online mapping and has been embraced widely by online map creators and developers. In this section we examine issues surrounding this adoption and discuss the potential implications of the projection from technical/mathematical, cognitive, educational, and design perspectives.

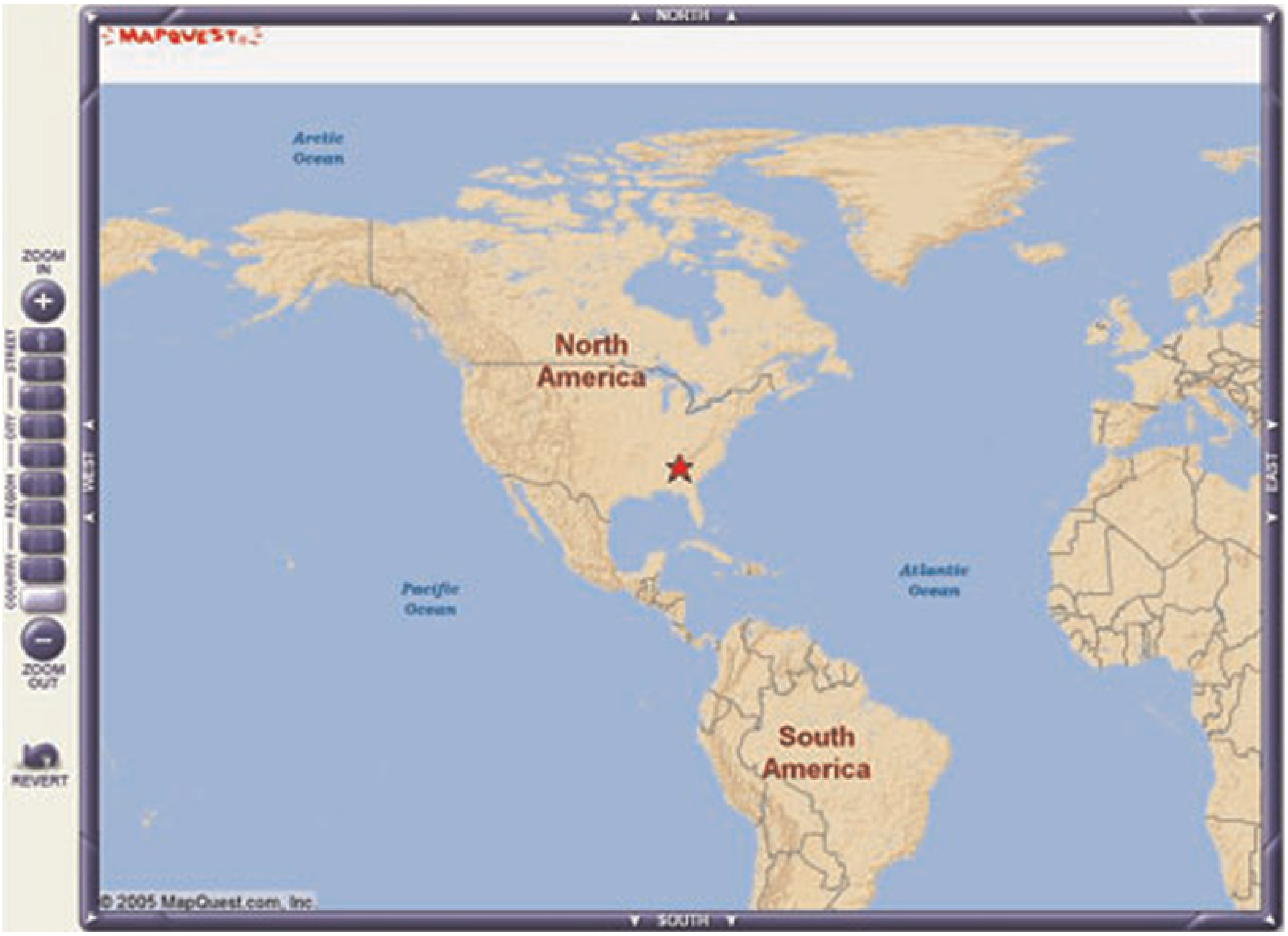

Figure 9. MapQuest, circa 2005. Note that the map did not zoom out much past continental scale and that the projection was clearly not Mercator based. (Source: http://money.howstuffworks.com/mapquest3.htm)

TECHNICAL ISSUES

Though Web Mercator has become a readily adopted standard for online maps, it is still less than ideal in many instances, especially when considering smaller than global areas and, particularly, high-latitude regions. Unlike Mercator, Web Mercator does not preserve the shape and relative angles at each point, and if scale factor at a point needs to be calculated with a high level of accuracy, then the computational efficiency of Web Mercator is slower than both spherical and ellipsoidal Mercator (Zinn 2010).

The effects of choosing Web Mercator as the projection for online mapping can be empirically seen when running the associated calculations with tile-caching schemes. Early Internet maps habitually used a single large raster file for every zoom level, which was re-rendered with every change to zoom level or direction. The introduction of tile caching for online maps in the first decade of the twenty-first century allowed for a better and faster user experience, as the single image files were carved up into smaller tiles. Although the choice of projection does not affect prime parameters such as the degrees per pixel (DPP), map width, ground resolution, or map scale, it does affect the kilometre per degree (km/deg) measurements. The km/deg measurements can vary considerably from actual ground km/deg values, based on the choice of projection (expanded upon below). The ground km/deg measurement is a function of the arc length of the parallel (Equation 10; Torge 2001).

$$dL = N \cos \phi d\lambda \tag{10}$$

where dL equals arc length of the parallel, N equals the radius of curvature in the prime vertical, ϕ equals the latitude at the parallel in question, and $d\lambda$ equals the difference in two longitudes. The radius of curvature in the prime vertical is calculated by Equation 11.

$$N = \frac{a}{(1 - e^2 \sin^2 \phi)^{\frac{1}{2}}} \tag{11}$$

When calculated on a sphere, Equation 10 becomes Equation 12 because N equals R, the radius of the sphere.

Table 1. Comparisons of radius of curvature in the prime vertical (*N*) and the arc length for one degree of longitude (*dL*) at various latitudes (in kilometres) based on WGS84 ellipsoid parameters.

	0°	10°	20°	30°	40°	50°	60°	70°	80°
N	6378.13700000	6378.17291196	6378.20773314	6378.24040546	6378.26993612	6378.2954277	6378.31610564	6378.33134147	6378.34067220
dL	111.3	19.6	14.6	96.4	85.3	71.6	55.7	38.1	19.3

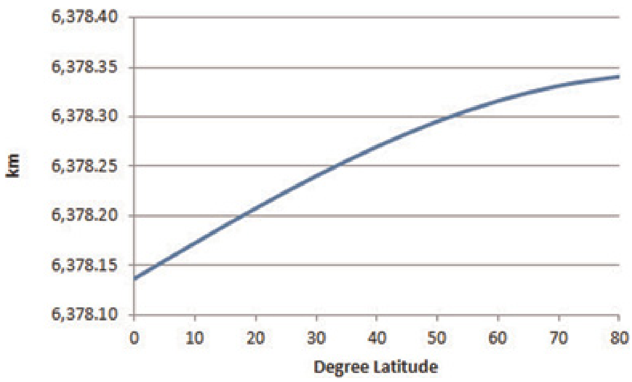

Figure 10. Comparisons of radius of curvature in the prime vertical (*N*) at various latitudes (in kilometres) based on WGS84 ellipsoid parameters.

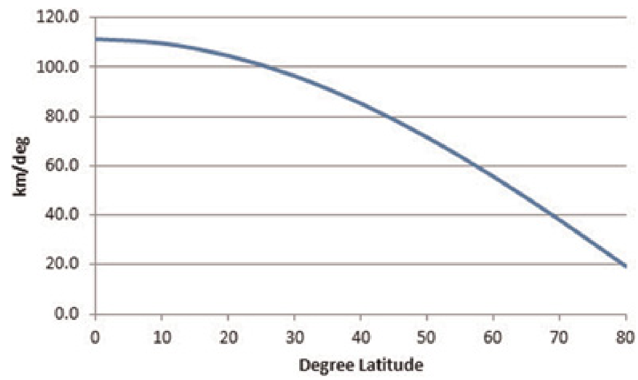

Figure 11. Comparisons of the arc length for one degree of longitude (*dL*) at various latitudes (in kilometres) based on WGS84 ellipsoid parameters.

$$dL = R \cos \phi d\lambda \tag{12}$$

Normally, parameters for a specifically defined ellipsoid are given in terms of the semi-major axis, a, and the flattening factor (sometimes referred to as the geometrical flattening), f. To calculate dL from the above equations, we need to calculate b in terms of f as follows:

$$f = \frac{a - b}{a}$$

And, thus, we can find b as follows:

$$b = a(1 - f) \tag{14}$$

Using Equations 7, 8, 12, 13, and 14 and the published parameters for WGS84, the radius of curvature in the prime vertical and the arc length for one degree of longitude were calculated at various latitudes (in kilometres) (Table 1, Figure 10, and Figure 11). We then compared the results to measured km/deg of longitude per degree of latitude for various maps at different projections and scales as shown in Table 2 and Table 3 to show the comparison of Web Mercator to other projections. Note that these values were derived based on earlier implementations of Web Mercator that presented a constant scale bar across the entire projected area, whereas most newer implementations now contain a variable-width scale bar, which rescales based on the region of the map that is rendered. Though the calculations for a variable-width scale bar would be more accurate than those we calculated using the older constant-width scale bars, this helps show the constant evolution of the implementation of the projection in an attempt to help provide more accurate representation. We used the WGS84 parameters for the refined frame, Reference Frame G1150; 1150 refers to the global positioning system (GPS) Week Number (Snay and Soler 2000; Subirana and others 2011). We used the published WGS84 ellipsoid parameters of Subirana and others (2011) for our calculations, as follows: semi-major axis, a, equals 6378137.0 m and flattening factor, f, equals 1/298.257223563.

As one can see in the above tables, the difference between a map's km/deg calculation and the real-Earth values varies considerably as a direct result of the projection used. While this difference can be small in some cases (e.g., less than 1 km/deg for Sinusoidal Equal Area), the values for Web Mercator can reach nearly 100 km/deg of difference in the high latitudes. Differences between projections are also apparent when comparing the calculated areas. For example, the state of Alaska is listed as having an area of 1,477,953 km^2 (US Census 2013); however, the area differs between projections because of distortion (Table 4). We focus on Alaska in this example because the state is a high-latitude area and familiar to most cartographers as an identifiable region. The purpose of these tables is to show explicitly the quantification of differences in the projection to help readers and mapping practitioners understand the magnitude of error.

Table 2. Comparisons of the arc length for one degree of longitude (*dL*) (in km) at 10° increments for five different global map projection/scale combinations based on WGS84 ellipsoid parameters*

Degree of latitude	0°	10°	20°	30°	40°	50°	60°	70°	80°
Earth: km/deg latitude	111.3	19.6	14.6	96.4	85.3	71.6	55.7	38.1	19.3
Plate Carrée 1:50,000,000 US map									
Map measurement: cm per 5° long			1.2	1.2	1.2	1.2	1.2	1.2	
km/deg			120	120	120	120	120	120	
Delta			−15.4	−23.6	−34.7	−48.4	−64.3	−81.9	
Plate Carrée 1:200,000,000 world map									
Map measurement: cm per 10° long	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
km/deg	120	120	120	120	120	120	120	120	120
Delta	−8.7	−10.4	−15.4	−23.6	−34.7	−48.4	−64.3	−81.9	−100.7
Mercator scale variable									
Map measurement: cm per 15° long	5.55	5.55	5.55	5.55	5.55	5.55	5.55	5.55	5.55
cm per 100 statute miles	0.5	0.5	0.55	0.6	0.7	0.8	1.00	1.5	3.1
km/deg	119.1	119.1	108.3	99.2	85.1	74.4	59.5	39.7	19.2
Delta	−7.8	−9.5	−3.7	−2.8	0.2	−2.9	−3.9	−1.6	0.1
Web Mercator 1:70,000,000 US map									
Map measurement: cm per 5° long			0.8	0.8	0.8	0.8	0.8	0.8	
km/deg			112	112	112	112	112	112	
Delta			−7.4	−15.6	−26.7	−40.4	−56.3	−73.9	
Web Mercator 1:230,000,000 world map									
Map measurement: cm per 10° long	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
km/deg	115	115	115	115	115	115	115	115	115
Delta	−3.7	−5.4	−10.4	−18.6	−29.7	−43.4	−59.3	−76.9	−95.7

* The Web Mercator entries are based on calculations from initial implementations (constant scale) of the projection. Also, while we have examined comparisons between numerous projections, only cylindrical projections are shown, for simplicity's sake.

Table 3. Comparisons of the arc length for one degree of longitude (dL) and various map projections for Alaska at various latitudes (in kilometres) based on WGS84 ellipsoid parameters. (Note: the Web Mercator entry is based on calculations from initial implementations (constant scale) of the projection.)

	50°	60°	70°
Earth: km/deg latitude	71.6	55.7	38.1
Albers 1:15,000,000 Alaska map			
Map measurement: cm per 10° long	4.8	3.7	2.6
km/deg	72.0	55.5	39.0
Delta	−0.4	0.2	−0.9
Plate Carrée 1:20,000,000 Alaska map			
Map measurement: cm per 5° long	2.9	2.9	2.9
km/deg	116	116	116
Delta	−44.4	−60.3	−77.9
Web Mercator 1:50,000,000 Alaska map			
Map measurement cm per 5° long	1.15	1.15	1.15
km/deg	115	115	115
Delta	−43.4	−59.3	−76.9

Table 4. Comparisons of area of Alaska for different projections.

Projection	Area of Alaska (km^2)
Albers Equal Area Conic	1,517,411.29
Alaska Albers	1,517,411.29
Sinusoidal	1,517,422.58
Lambert Conformal Conic	1,631,416.79
Lambert Azimuthal Equal Area	1,517,412.27
Plate Carrée	3,485,157.46
Mercator	8,181,068.03
Web Mercator	8,191,239.76

To summarize the above equations and calculations, the technical issues with Web Mercator can be seen in the km/deg measurements and area measurements. In addition, these issues increase in severity as one moves closer to the poles. These equations explain in detail the technical issues with distortion in Web Mercator and compare them to distortion in several other common projections for reference. Because distortion is a necessary part of map projections, the calculations presented are relevant to any measurements taken in base maps or for calculations in thematic maps. Map projection distortion affects *every* measurement on the map, and readers and designers need to be aware of these technical details.

COGNITIVE ISSUES

> *[W]e strongly urge book and map publishers, the media and government agencies to cease using rectangular world maps for general purposes or artistic displays. Such maps promote serious, erroneous conceptions by severely distorting large sections of the world, by showing the round Earth as having straight edges and sharp corners, by representing most distances and direct routes incorrectly, and by portraying the circular coordinate system as a squared grid. The most widely displayed rectangular world map is the Mercator.*
>
> —Resolution (1989)

Numerous suggestions have been made that map projections have substantial influence on the shape and structure of cognitive maps, dating back (at least) to the early twentieth century with G.J. Morrison's warning that "people's ideas of geography are not founded on actual facts but on Mercator's map" (quoted in Monmonier 1995, 21). The belief that an individual's general knowledge of geography and cognitive map are based on familiarity with the Mercator projection has been a pervasive theme in geographic literature (e.g., Robinson's suggestion that people have been "brainwashed" by the Mercator projection; Robinson 1990, 103). By the late 1980s, the discussion surrounding the Mercator projection had become heated enough for seven North American cartographic societies to adopt a resolution against rectangular map projections – with the Mercator projection the only one specifically called out by name.

Though suggestions about the impact of distortions from map projections, often specifically focused on Mercator, have been common in the literature, relatively little empirical research can provide a concrete confirmation of the relationship between the Mercator projection and related distortions in peoples' cognitive maps. In a series of sketch mapping studies, Saarinen (Saarinen and others 1996; Saarinen 1999) and others (e.g., Chiodo 1997) have suggested a measurable "Mercator Effect" and have demonstrated that potential Mercator-like artefacts (e.g., size of countries and continents) could be found in children's sketch maps of the world (Saarinen 1999). But these studies provided little to no direct quantitative comparison of the distortions in the sketch maps to the Mercator projection – though some similarities between the sketch properties and the Mercator projection were clearly visible.

In further human subject research, Battersby and Montello (2009) have examined memory-based estimates of land areas for regions around the world. In this study, little evidence was found of an overwhelming Mercator influence on the participants' cognitive maps – implying that the feared Mercator influence was less of an issue than previously suggested. Perhaps this lack of relationship is due to better education about the distortion patterns in the projection and the ability to compensate for it – though Battersby (2009) sheds further light on the challenges of compensating for perceived distortion which makes this seem somewhat unlikely. Perhaps this is simply a sign that at the time at which the data were collected, the participants in the study were not of an age where they had been overly exposed to the Mercator projection and thus had limited opportunity for it to overly influence their cognitive map. This might make sense and help explain potential contradiction in the stated impacts of the Mercator projection between Battersby and Montello's (2009) work suggesting no substantial Mercator influence and earlier studies by Saarinen and others (1996) suggesting a Mercator influence. Saarinen and others (1996) and Saarinen (1999) conducted research in the 1990s, a time when the Mercator projection was more likely to be in use as a classroom reference.

As Web maps have become more prevalent as general purpose references, likely the most widely displayed cylindrical world map is now the Web Mercator. As such, it seems fair that cartographers hearken back to the resolution from 1989 and work to understand better the potential impacts that the prevalence of the map projection may have on our perception of global-scale spaces.

EDUCATIONAL ISSUES

Although the Mercator (and Web Mercator) projections present positive characteristics when used for taking bearings between locations, for most educational purposes this is not a common task for evaluation of global-scale spatial patterns. More likely, global-scale maps are being used for evaluating distance- and area-based spatial relationships – characteristics that are not appropriately represented for many locations and attributes in the Mercator projection (as discussed in Vujakovic 2002 and MacEachren 1995).

For reference mapping in atlases, Monmonier (1995) reports several (admittedly non-systematic) studies in Britain and the United States which indicated that the Mercator projection was nowhere to be found. Regardless, Monmonier also notes that "the Mercator projection was alive and well, if not thriving, among wall maps" (Monmonier 1995, 21). Since 1995, our own (admittedly non-systematic) evaluation of classroom wall maps indicates that the Mercator projection has largely fallen out of favour in this context as well, with compromise projections such as "the visually accurate Robinson projection" (as Rand McNally describes one of its world map combinations), Winkel Tripel, and Gall Stereographic commonly found in catalogues of global-scale wall maps for educational use. Though Mercator projection maps seem to be less common, we were still able to find a few instances of Mercator projection maps for purchase from educational map resellers.

While Mercator-based wall maps seem to have fallen out of favour as classroom references, the Mercator projection has still managed to maintain a notable place of prominence in the classroom. Perhaps contrary to the desire to minimize familiarity with the Mercator projection as a representation for global-scale space, it appears to have become a favourite example when teaching about map projections. In a cursory review of materials from seven cartography, GIS, and human geography textbooks that include sections focused on map projections and distortion, we found that the only projection common to *all* of the textbooks was the Mercator projection.

Though Mercator does provide a good example for extreme distortion of areas at the global scale, the impact of emphasizing the projection and the two most distinctively exaggerated regions (Greenland and Antarctica) may have had the unintentional effect of enforcing the Mercator distortion pattern as a generic map projection characteristic. For instance, Battersby and Kessler (2012) examined cues used to identify distortion in six map projections (two compromise, two conformal, and two equal area) and found notable patterns of reliance on Mercator-related cues (e.g., Antarctica, Greenland, and general "polar regions" frequently listed as cues for areal distortion) for almost all of the projections examined.

DESIGN CONSIDERATIONS

A common theme in cartography lectures and textbooks is that map projections should be selected based on their *appropriateness* for the user's data, the geographic area being mapped, and the types of measurements that a reader might need to make (Snyder 1987; Robinson and others 1995; Usery and others 2003; Slocum and others 2009; Finn and others 2013). With the rigidity of the online mapping platform, where tiled base maps are typically provided, the average designer does not have any option other than Web Mercator. The designer is thus required to compromise on – or, in the case of the designers who are not aware of the issues surrounding map projections, flat-out ignore – the guidelines suggested for appropriate projection selection. If this projection selection is considered with respect to the map communication process, there are two primary areas of concern – the information source/transmitter (the designer and his/her knowledge of projection distortion) and the receiver (the map reader and his/her knowledge of the projection distortion).

With respect to the understanding of the map designer, there is no choice of projection, so the design decisions are mostly restricted to whether or not the designer understands the implication of map projection distortion so that the map design and implementation can compensate for it. For instance, does the designer understand that while drawing (or coding) a straight line to connect two locations on the map is easy, this action does not imply the shortest path? Or that any map feature defined in size by pixels will not be of equal area in different locations on the map? Fortunately, some mapping APIs now accommodate for Web Mercator–related distortion, though this accommodation requires that all features added to a map are defined appropriately in the API and that the map designer does not rely on graphic features that would not self-modify as the map scale changes (e.g., creating reusable circular buffer graphics of a set pixel diameter).

In addition, from a design standpoint, a cartographer will typically select a projection based on what is appropriate for the map purpose and geographic extent. Unfortunately, with Web maps in their current implementations, limited options are available to select custom projections.[1] Thus, the projection used (Web Mercator) is likely to be considered suboptimal for the display of data. For instance, as Dent and others (2009, 50) state, "the property of equivalency is often the overriding concern in thematic cartography." This sentiment is echoed across other cartography textbooks particularly for global-scale choropleth maps (e.g., Slocum and others 2009) – and equivalency is something the Web Mercator does not provide. Recognizing that this idea of equivalency in map projections has been noted as an "overriding concern in thematic cartography," it is interesting how quickly the idea of equivalent projections for thematic mapping has been pushed aside in favour of easy tools for producing interactive Web map mashups.

With respect to the map reader, there are additional issues to consider – partly because the map reader has no say in how the information on the map is presented (even if he or she can turn layers on/off or contribute in a Web 2.0 situation, the overall look and functionality has already been determined by the designer); the reader is left with the interpretation task. In this interpretation task, the map may become "more real than experience," as suggested in Egenhofer and Mark's (1995, 8) "Naïve Geography." When a person is evaluating maps that present distorted areas, the ability to correctly interpret spatial patterns is hindered; the spatial relationships are incorrect, so how can the interpretation be correct? The projection issue is *somewhat* forgivable for relatively large-scale mapping (such as state/small country), but only for equatorial regions where the distortion is minimized. For large-scale mapping, the distortion in non-equatorial regions can be substantial and can easily mislead the reader. Even though across a single large-scale map the distortion will be relatively consistent within the map, comparisons to any other area may be misleading because of the variance in scale between the maps – unless they are at the same latitude.

Conclusion and Future Research Directions

In this paper we have discussed numerous issues surrounding the use of the Web Mercator projection for general purpose mapping. While there are benefits to the use of the projection, there are also substantial limitations that should be considered by map designers and users. In terms of furthering the state of Web map development and use, several research questions can be addressed:

- A possible risk of democratizing map creation and allowing users to make their own mashup is that more inappropriately designed maps can be distributed farther and faster, as the projection of the base maps is likely going to be inappropriate for most purposes. How do we address this issue? How do we train *designers* who may have little to no training in map projections to address issues of distortion in their maps? How do we design Web maps that are "smarter" and can help guide designers in successful compensation for distortions in the projection? Although the current need for education is with respect to distortion patterns in Web Mercator, these questions are relevant for whatever other projections may become available. All projections present distortion, and the type and pattern of that distortion will vary from projection to projection, so acknowledgement of the distortion and design with a critical eye to the distortion is important for clear and appropriate map communication.
- Can better projections be used? Several tools (e.g., Finn and others 2004) and sets of suggested guidelines exist for selecting appropriate projections for large- and small-scale mapping. Can these projections be incorporated into the base Web maps to minimize distortion in a seamless way, and is this computationally feasible for systems where millions or billions of maps are served every day? For instance, can we incorporate base maps that respond to user panning and zooming as demonstrated in Jenny's (2012) adaptive composite map projections?
- Is the return to a Mercator-type projection going to bring back the feared Mercator cognitive map that was discussed heavily in the 1980s and led to the resolution against "rectangular" map projections for global-scale data?
- In many Web maps, we provide options for satellite views and map views, as well as overlays of traffic, weather, and other themes – would it help if map readers were provided with distortion views or overlays to clarify distortions of values such as area and distances?
- Is a better "replacement" map projection available for online mapping that keeps the desired traits of Web Mercator while, at the same time, improving the fidelity of mensuration associated with high-quality cartographic standards, particularly with respect to large areas (large regions to continental scales)?
- Can this replacement projection for online mapping be consistent with Web mapping tile-caching schemes already in widespread use in the GIScience community and thus meet the larger spatial data infrastructure and interoperability requirements?
- Can APIs using the Web Mercator be designed with intelligence to warn the user of incorrect results because of the projection?

The results from research addressing the above questions, as well as many other related topics, will aid in the development of better, more effective, and less distorted general purpose Web maps.

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Note

1 We note that we have seen examples of polar projections in ArcGIS Online, so perhaps there will be more opportunity to customize projection selection in the future. Granted, this will require that the map designers feel comfortable selecting an appropriate projection.

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