Chapter 4
Map Projections and the Internet

**Fritz C. Kessler, Sarah E. Battersby, Michael P. Finn
and Keith C. Clarke**

Abstract The field of map projections can be described as mathematical, static, and challenging. However, this description is evolving in concert with the development of the Internet. The Internet has enabled new outlets for software applications, learning, and interaction with and about map projections. This chapter examines specific ways in which the Internet has moved map projections from a relatively obscure paper-based setting to a more engaging and accessible online environment. After a brief overview of map projections, this chapter discusses four perspectives on how map projections have been integrated into the Internet. First, map projections and their role in web maps and mapping services is examined. Second, an overview of online atlases and the map projections chosen for their maps is presented. Third, new programming languages and code libraries that enable map projections to be included in mapping applications are reviewed. Fourth, the Internet has facilitated map projection education and research especially with the map reader's comprehension and understanding of complex topics like map projection distortion is discussed.

F.C. Kessler (✉)
John A. Dutton e-Education Institute, Department of Geography,
Pennsylvania State University, State College, USA
e-mail: fck2@psu.edu

S.E. Battersby
Tableau Software, Seattle, WA, USA

M.P. Finn
Center of Excellence for Geospatial Information Science,
U.S. Geological Survey, Denver, CO, USA

K.C. Clarke
Department of Geography, University of California, Santa Barbara, USA

4.1 Introduction

This chapter presents an overview of how map projections have been used for Internet cartography. The first section provides a general overview of map projections. The second section covers the map projections that are used by Web maps and map services. This section is divided into two parts and covers map projections adopted for both global and local-global mapping scales. The third section presents a review of online atlases. Specifically, this section examines the common map projections that are selected for thematic and general purpose maps appearing in online world atlases. The fourth section considers online map projection software. For instance, there are several useful code libraries that can be incorporated into a Website that facilitate map creation and projection. The fifth section discusses topics related to map projection research and education. Of particular importance in this section is the level to which map readers understand map projection distortion and how this understanding enhances or detracts from map learning.

4.1.1 Map Projection

Map projection is the mathematical way the Earth's two-dimensional curved surface is transformed and mapped onto a planimetric surface. Hundreds of map projections have been developed. Many were created from mathematical curiosity or as a means to reduce the inevitable distortion that results from the projection process (Snyder 1993). For instance, the Eisenlohr projection is conformal (preserves local angles) and rarely used. The Eisenlohr was mathematically contrived so that conformality does not fail at any point (Eisenlohr 1870). Despite the many projections that have been developed, only a handful have seen wide-spread use. The Gall stereographic is one projection that has appeared in many atlases as the basis for world maps of thematic data. In some instances, a few map projections were developed to meet the specific needs of a map purpose. For example, the American (or ordinary) polyconic projection was developed by Hassler (1825) for large-scale topographic mapping of the United States. On the other hand, the Robinson projection, developed by Robinson (1974), was designed specifically to show the appearance of the world's landmasses as if looking on a globe.

Map projections can be generally categorized based on the properties that are preserved in the transformation process. The properties that are preserved make particular types of projections useful for specific purposes. For instance, equal area projections preserve areas measured on the Earth's surface. When using symbolization methods, such as dots, to show the distributions of a phenomenon across space, an equal area projection is preferred for thematic mapping. Using an equal area projection in global-scale mapping ensures that each country is shown with the same area as on a globe. Preserving area allows for visual comparisons of a distribution of a data set across the geographic area of interest.

If the map purpose calls for preserving distances, then an equidistant projection should be considered. This property allows distances to be preserved along all lines of longitude or from a single point to all other points following great circles. Like azimuthal projections, equidistant projections are beneficial for navigational purposes. If an angle is measured on the Earth's surface and that angle needs to be preserved on a map (e.g., for navigational purposes), then a conformal projection is appropriate.

Some projections do not preserve any specific property. These projections are referred to as "compromise" and balance the distortion levels across the projected area. The result is a projection that attempts to preserve the visual appearance of Earth's landmasses as much as possible. Due to this characteristic, compromise projections are suitable for general reference or political maps. As will be described through this chapter, not all projections and their properties are correctly matched to the map purpose.

4.2 Map Projection Use in Web Map Services

In this section we will discuss common map projections as used in Web maps and map services. We will start with a discussion of global-scale mapping options (largely focusing on those tailored for tiled map services to be used across scales), and then present general discussion of projections for online local-scale mapping.

4.2.1 Global-Scale Maps

For general purpose online maps designed to be panned and zoomed across scales, from global to local, we generally see use of cylindric map projections. Cylindric projections allow for easy tile creation and the rectangular shape makes it easier to facilitate continuous panning without discontinuities on the map periphery. Though projection choice for online maps has varied over the years (Battersby et al. 2014), most online maps now utilize Web Mercator. Though we do not know the exact cartographic and/or computational reasons behind the choice of Web Mercator for online tiled map systems, it has become the de facto standard for global-scale tiled maps since Google Maps was introduced in 2005 using this system. For reference, the Web Mercator projection may also be referred to as Spherical Mercator, Google Mercator, or WGS84 Web Mercator, and is formally referenced by the European Petroleum Survey Group (EPSG), now the International Producers of Oil and Gas) definitions as EPSG:3857 (Battersby et al. 2014).

Web Mercator is a projection related to the cylindric projection introduced by Gerardus Mercator in 1569. The significant difference with the Web variant of the projection is that it uses the spherical form of forward equations with an Earth model radius of 6,378,137.0 m. Ellipsoidal latitude and longitude values from the

World Geodetic Survey of 1984 (WGS84) ellipsoid are then projected using the spherical form of the equations. Using the spherical equations with the ellipsoidal values (namely, the semi-major axis) makes the Web Mercator non-conformal (it does not preserve local angles), unlike the conformal Mercator projection), though visually this difference at the global scale is not detectable.

4.2.2 Web Mercator Issues and Controversies

The adoption of Web Mercator has been fairly controversial for Web mapping. Much of this controversy is related to the general need to use a map projection that is appropriate for the scale, data, and application. Unfortunately, for general purpose mapping (thematic and reference) across scales that we see in Web map services there is *no* single best projection that will be appropriate for all uses. Though we discuss several issues and controversies surrounding the adoption of Web Mercator, we note that these issues would not be eliminated with the selection of any other single projection. We also note that we are only presenting a few notable issues with the Web Mercator projection; for reference, Battersby et al. (2014) provide a more detailed discussion of the challenges of the Web Mercator projection for online mapping.

4.2.3 Mapping Accuracy

While there is no visual difference between Mercator and Web Mercator in global-scale mapping, from a geodetic standpoint the difference in calculated measurements can be substantial—up to 50 km at the extreme north and south latitudes (Battersby et al. 2014). Because of these differences, agencies such as the US National Geospatial-Intelligence Agency (NGA 2014) have indicated that the Web Mercator is not acceptable for global-scale intelligence mapping. Related to this, NGA (2014) has issued an advisory notice indicating that "this erroneous geospatial positioning information poses an unacceptable risk to global safety of navigational activities… that require accurate and precise positioning and navigation information" and has explicitly stated that it does not endorse or support the Web Mercator projection for any geospatial intelligence activities (NGA Office of Geomatics 2014). The NGAs concern about the distortion of the Mercator projection is not a new development in discussion of appropriate global-scale projections, as can be seen in the 1989 resolution (American Cartographic Association 1989) rejecting all rectangular projections (such as the Mercator projection) for global-scale mapping.

Another map distortion consideration is how scale distortion exists across the Web Mercator projection and how Web mapping services account for and communicate this distortion. As discussed earlier, the Web Mercator is approximately

conformal; no scale distortion is present along the equator. Thus, distances measured between two points that fall exactly on the equator are identical to the true Earth distance. As one moves away from the equator, scale distortion begins to increase gradually. As one nears the poles (around 60°N/S) scale distortion increases rapidly. Although scale distortion increases with higher latitudes, distortion is constant along all lines of latitude. The way in which scale changes across the Web Mercator projection is an important consideration when using Web mapping services to measure, for example, distances.

Web mapping services such as Google Maps and OpenStreetMap use zoom levels (0 to 20) to allow users control of the geographic extent shown on screen. Zoom levels range from very large map scales showing street-level views (approximately 1:1000) to very small map scales showing the entire world (approximately 1:600,000,000). Associated with each zoom level are graphic scale bars (e.g., showing miles and kilometers) that appear inside the mapping service window and change in size according to the zoom level. Using the scale bars as reference, users can take approximate measures of distances or areas on the map. As users zoom in on and out from a single point the scale bars automatically adjust in size to account for the changing zoom level and thus map scale. Additionally, as one pans north or south across the map (not changing zoom levels) the scale bars also adjust to accommodate the changing scale distortion across the Web Mercator's surface with different latitude. However, as one pans east or west along a line of latitude (not changing zoom levels), the scale bars remain fixed in size accounting for the fact that scale distortion is constant along all parallels. By incorporating the Web Mercator and changing scale bars Web Mapping services have minimized the problems of accounting for scale distortion that was problematic by the presence of a single scale bar commonly found on printed map. Note, however, that the accuracy of the scale bar across the entire viewing window and thus the geographic extent shown will vary depending on the map's zoom level. Since scale distortion varies with changing latitude the scale bar will be correct only along a single parallel in the view. For large scale mapping changes in scale across a small geographic extent are generally inconsequential, however for small scale mapping, the changes in scale will be substantial.

Additionally, it is important to note the relative importance of the map projection and scale as an influence on visual analysis or when computing a spatial metric. For large scale mapping, the impact is likely to be minimal regardless of projection as the relative change in distortion across the area will be small; for small scale mapping the distortions present significant issues (e.g., a tightly clustered set of points at high latitude on the Earth may appear as a widely distributed set of points in Web Mercator; distances between these points as measured in projected space will be exaggerated).

4.2.4 Map Distortion

While projection distortion in general is an accuracy issue, the controversy sur-
rounding distortion in the Mercator and Web Mercator projections is a cognitive
issue as well. Numerous scholars have suggested that frequently seeing distorted
maps will warp our global-scale cognitive maps (e.g., Robinson 1990; Monmonier
1995) providing worldviews in which regions at higher latitudes are given a "false
connotation of importance" (Vujakovic 2002).

   In addition to the general issue of the distortion patterns potentially influencing
our cognitive understanding of global-scale geography, we must also consider that
most map users do not recognize the influence of distortion on areas or angles
across a map. This presents an issue for both designers and map readers. Designing
online maps using the application programming interfaces (APIs) from Web map
providers is often seen as more an issue of understanding the coding to control map
symbology than understanding the nature of map distortion. This means that
unknowingly a map designer may introduce significant geographic errors. For
instance, we may see "shortest" routes that are straight lines connecting locations
(instead of a great circle route) or buffers around points that are a consistent circular
shape and size (instead of the varying size and shape expected due to distortion in
Web Mercator). The map reader may make the same mistake—interpreting these
symbols as truth in their representation of spatial relationships. On the other hand,
readers may interpret *accurate* representations on the map as incorrect because they
do not follow their intuitive, but incorrect, understanding of spatial relationships
because the spatial relationships that are expected to be true in a Cartesian coor-
dinate system are not always true in a map projection because the projection
transforms the Earth's curved surface to the 2-dimensional plane. This educational
issue is a significant problem that must be overcome as online maps with a Web
Mercator projection become our most familiar global-scale map.

4.2.5 Non-web Mercator Options

Web Mercator is not the only option for zoom and pannable multi-scale maps. As
we stated earlier, no single projection can meet all mapping needs at all scales and
for all purposes. To address this problem, Jenny (2012) has suggested that we need
adaptive composite map projections that can seamlessly morph between projections
as a user pans and zooms around a map. Figure 4.1 depicts the variety of projec-
tions used based on zoom level and central latitude of a map. Though this system
for Web maps to adapt on-the-fly based on user location and zoom level (and, one
would assume, map purpose) presents benefits, it has not yet been adopted for
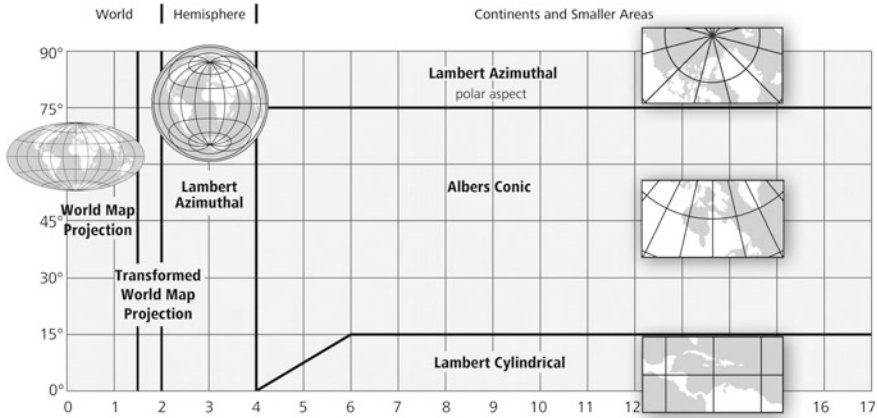widespread use.

Fig. 4.1 Bernhard Jenny's adaptive map projection matrix. The horizontal axis shows zoom factor and the vertical axis shows central latitude of map. (Figure courtesy of Bernhard Jenny)

4.2.6 Non-global Scale Map Projections

At the global scale map projections, such as Web Mercator, are usually based on treating the Earth as a sphere and simply converting latitude and longitude pairs into the projected coordinate system of the map display window. An alternative to this is use of three axis (x, y, z) coordinates or Earth Centered Earth Fixed, as is common in geodesy, space geometry and computer graphics. This type of transformation would provide a more accurate view of local-scale geographic data.

By far the majority of Web maps have a regional or continental focus, especially in thematic mapping. This is true of Web mapping applications with a national focus such as Baidu Maps for China (http://map.baidu.com/) and Bhuvan for India (http://bhuvan.nrsc.gov.in/bhuvan_links.php), and for more local applications such as state geographic information systems (GISs) (http://www.kansasgis.org/). In most cases, projections are chosen that suit a local map extent, meet various distortion minimization criteria for the region, or fit a local grid. General guidelines for scales larger than global-scale map projection exist, for example Snyder (1987, Appendix B) provided a list of projections used in National mapping for the United States and its territories, and Bugayevskiy and Snyder (1995, pp. 238–9) provided such a list for Russia and the former Soviet Union. Practically, these guidelines seem little used in Web mapping with the exception of national reference maps and some demographic mapping. For example, the Lambert conformal conic has long been standard for mapping demographic data from the United States Bureau of the Census, for example on the Census Data Mapper (http://tigerWeb.geo.census.gov/datamapper/map.html). It also does not seem that much attention in Web mapping has been paid to the research on projection optimization based on geographic

extent. Hopefully, the use of better matched projections will expand as Web-based map dissemination becomes more widespread, both geographically and intellectually.

4.2.7 Local- and Global-Scale Grid Systems

In addition to the named projections mentioned above for non-global-scale mapping, the Web also provides extensive support for standard grid systems at both the local- and global-scale. There are many benefits to grid systems. The many benefits of global grid systems include universality (fitting into existing alternative Earth models such as geodetic and astronomical models); authority (being supported by a permanent and credible agency, standard or law); succinctness (using as few codes as possible to ensure location); definitiveness (providing reference to one and only one unique location); exhaustiveness (applying to the whole Earth); being hierarchical (allowing references to multiple scales depending on the desired level of detail); intuitiveness (easy to understand and use); and tractability (able to be used computationally) (Clarke 2002). Not all commonly used grids share these properties, and consequently there exist multiple grid systems, in spite of national efforts at standardization around "National Grids" as in the United States (FGDC 2015) and the United Kingdom (Ordinance Survey 2015).

The Universal Transverse Mercator (UTM), Military Grid Reference System (MGRS), and the United States National Grid (USNG) and other popular global grid coordinate systems are modified versions of the Universal Transverse Mercator or Gauss-Kruger coordinate system. The basic division of the globe into 60 6-degree-wide UTM zones is common, although other systems use 3 degree zones such as China (Yang et al. 2000). Other referencing systems exist for satellite imagery such as the World Geographic Reference System (WGS), and sometimes underlie Web-based map projection systems as data structures, such as tessellated triangles and hexagons (e.g. Quaternary Triangular Mesh). National grid systems are standardized in many countries such as the Map Grid of Australia, the British Ordnance Survey National Grid, the Irish National Grid, the Qatar National Grid (QND95), and in the United States, the National Grid (Cavell 2005). Wikipedia uses a hybrid UTM/MGRS reference somewhat reflective of the USGS Civilian UTM system. In almost all cases, the Web also provides a forum for grid conversions, including geographic to projected and datum to datum transformations. Datums common to national grids are the International Terrestrial Reference Frame and the World Geodetic Datum of 1984 (Maling 1992). At a third level, there is a host of special purpose grids such as the Maidenhead Grid Square system (amateur radio), United States Public Land Survey system, Canadian Dominion Land Survey (cadastral), and the Universal Polar Stereographic, which completes the Military and Civilian versions of the UTM system for the two polar regions. Often local geospatial data servers, for example state and provincial data clearinghouses, use these projections for maps and data.

Lastly, there are highly localized projections for small areas. As an example, Egypt uses the Helmert 1909 ellipsoid and three mapping zones localized to the Purple, Red and Green zones defined colonially (see www.digitaleg.com). Perhaps the best examples of local projections are the 123 zones of the State Plane Coordinate system of the United States (Stem 1989). These are grouped by state and follow either the Transverse Mercator or Lambert conformal conic projections, with some cases using both, and one zone (Alaska Zone 1) using the oblique Mercator. The U. S. Geological Survey (www.usgs.gov) and the National Geodetic Survey (www.ngs.noaa.gov/TOOLS/spc.shtml) provide extensive Web support for conversion from other coordinate systems into the state plane system, which was extensively revised and metrified after adoption of North American Datum of 1983.

4.3   Web-Based Atlases and Map Projections

In this section we review issues of map projection selection for Web-based atlases. An atlas can be thought of as a bound collection of maps which are organized around a common theme and share a standard design. In most cases, an editor is responsible for the layout, choice of data to include, and the overall map design— including map projection. Two editors from the late 1500s share some historical significance with respect to map projections in the history of the atlas: Gerardus Mercator and Abraham Ortelius. Mercator's *Atlas sive Cosmographicæ Meditationes de Fabrica Mundi et Fabricati Figura*, published in 1595, is credited as the first publication to include 'atlas' in the title, and relied on the Mercator projection. Monmonier (2004) argues that Mercator's application of the term atlas had more to do with giving credit to the mythological figure Atlas than to a cartographic innovation of a book of maps. Ortelius'*Theatrum Orbis Terrarum*, published in 1570, is more consistent with the modern concept of an atlas but did not include "atlas" in the title, and utilized an oval-shaped projection with straight parallels and curved meridians.

During the infancy of the Web, online atlases were often no more than a collection of static paper maps that could be viewed and printed. However, the atlas has evolved from a purely print-based format to a Web-based interactive environment. For instance, since the late 1900s, the National Geographic Society has published their *World Atlas* in print version, but it is now also a Web-based world atlas titled *National Geographic's Atlas Explorer* (maps.nationalgeographic.com/maps/atlas-explorer.html). As technology increased, so have the interactivity levels of a Web-based environment (e.g., linking videos, animation, and querying data). As a result, more sophisticated Web-based atlases are now common, with options to select from an infinite number of map projections. Despite the atlas' evolution in the Web environment, one question remains challenging to cartographers: Which map projection should be selected to map the data?

4.3.1 A Review of Web-Based Atlases and Their Map Projections

What follows is a brief review of the projections that are used in Web atlases. The atlases included in this review are divided into three categories: World, specialty thematic, and individual countries. For each category, the review will first summarize the map projections that appear in atlases, examine the data sets that are being mapped, the associated projection properties, and then comment on their appropriateness for the data set mapped. All of the atlases reviewed here are freely available online and do not require any installation on a local computer.

4.3.2 Web-Based World Atlases

Table 4.1 lists five online world atlases (1) World Atlas, (2) Holt, Rinehart, and Winston Atlas, (3) Maps of World, (4) Swiss World Atlas, and (5) Grolier World Atlas. According to Table 4.1, when mapping the world, the following projections were selected by these atlases: Mercator, Miller, Plate Carrée, Mollweide, Eckert V, Robinson, and Aitoff. General reference maps were found in all of world atlases. These maps show political borders of individual countries or simple outline of the world's coastlines. With these maps, no specific projection property is required. Yet, these general reference maps include a mix of projection properties. General reference maps typically do not attempt to preserve angles, directions, distances, or areas correctly. The conformal property of the Mercator projection (Fig. 4.2) is not appropriate for maps showing the outline of the world's coastline (e.g., the WorldAtlas.com). There is gross distortion in the appearance of the landmasses in the upper latitudes and measuring angles is not the purpose of this general reference map. A compromise projection would be a better choice for this map purpose. It is interesting to note that the world time zones map presented in WorldAtlas is illustrated through the Mollweide projection (Fig. 4.3). This projection represents lines of longitude as curved lines that converge to points that denote the poles. Time zone maps are usually based on a cylindric projection with equally spaced meridians such as the Miller (Fig. 4.4) or Plate Carrée (Fig. 4.5) that suggest zones of equal time.

The Swiss World Atlas and Grolier World Atlas include more diverse thematic topics than the world atlases discussed previously. The Swiss World Atlas maps many thematic topics on the Plate Carrée projection. This cylindric equidistant projection shows all lines of longitude as equally spaced straight lines and at true scale (which is not a necessary projection property for thematic data). Lines of latitude are shown straight and of the same length as the equator which creates considerable distortion in the upper-latitude landmasses. Despite the distortion, this projection is a popular choice for Web mapping since its rectangular dimensions fit a computer screen well. The Grolier World Atlas maps its thematic data sets on the

Table 4.1 A listing of web-based atlases of world-wide data

World atlases of general thematic topics

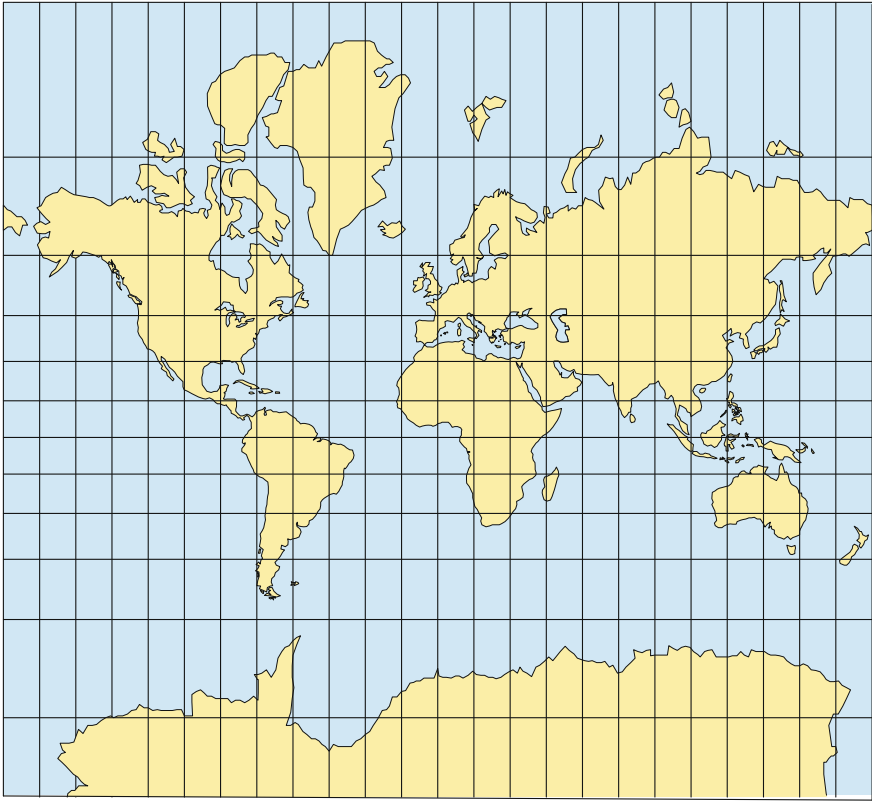| Atlas name	Geographic region mapped	Data set mapped	Projection name	Projection class	Projection property	Projection identified
World atlas (www.worldatlas.com)	World	Regional boundaries	Mollweide	Pseudocylindric	Equal area	Yes
	World	Major latitudes	Mollweide	Pseudocylindric	Equal area	Yes
	World	Time zones	Mollweide	Pseudocylindric	Equal area	Yes
	World	World coastline outline	Mercator	Cylindric	Conformal	Yes
	World	Political borders	Robinson	Pseudocylindric	Compromise	No
Holt, Rinehart, and Winston (go.hrw.com/atlas/norm_htm/world.htm)	World	Political borders	Robinson	Pseudocylindric	Compromise	No
Maps of world (www.mapsofworld.com/world-atlas/)	World	Political borders	All maps are available in one of five projections: Miller, Mercator, Robinson, Eckert V, or Aitoff	Miller & Mercator: cylindric Robinson & Eckert V: Pseudocylindric Aitoff: modified Azimuthal	Mercator: conformal Miller, Robinson, Eckert V, Aitoff: compromise	All projections are identified
	World	Physical landforms				
	World	Various thematic themes				
	World	Various historical themes				
	World	Satellite imagery				
	World	Various weather/environment/natural resources themes				
Swiss world atlas (schweizerweltatlas.ch/?lang = en)	World	Various thematic themes	Plate Carrée	Cylindric	Equidistant	No
Grolier world atlas (go.groiler.com/atlas?id = mtps018)	World	12 broad thematic themes	Robinson	Pseudocylindric	Compromise	No
	World	Time zones	Miller	Cylindric	Compromise	No

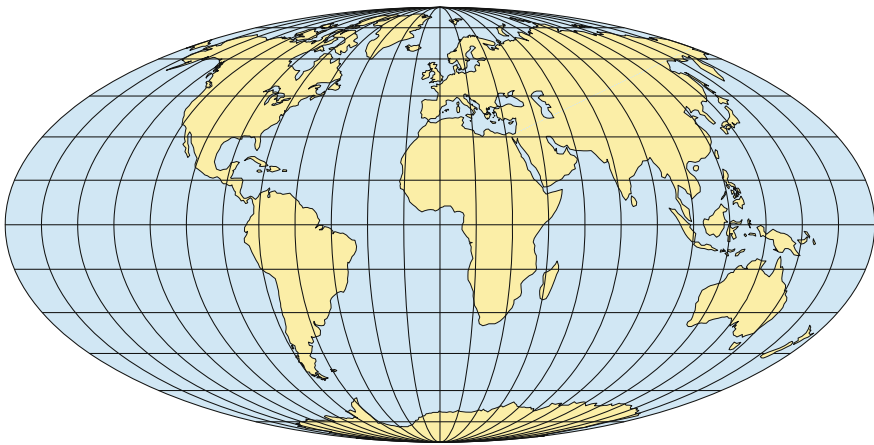**Fig. 4.2** The Mercator conformal cylindric projection

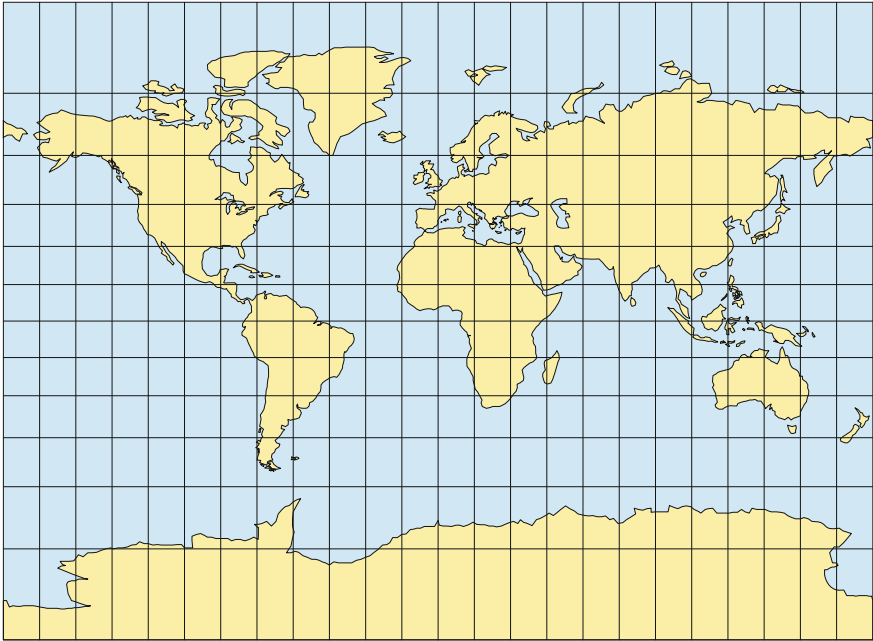**Fig. 4.3** The Mollweide equal area pseudocylindric projection

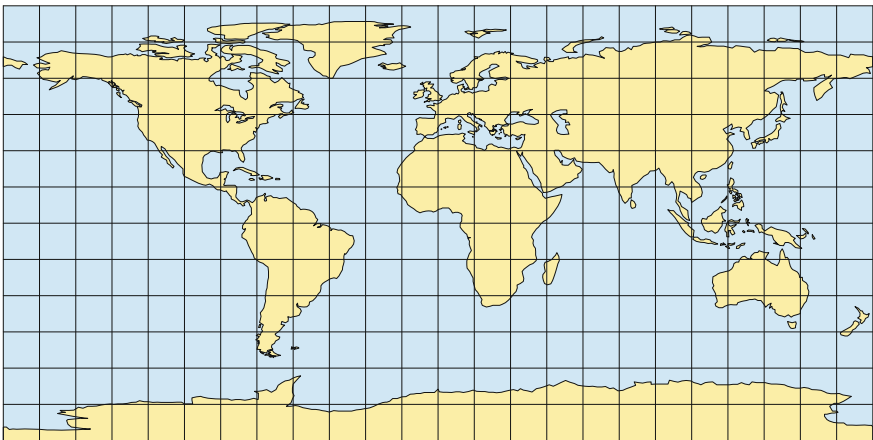**Fig. 4.4** The Miller compromise cylindric projection

Fig. 4.5 The Plate Carrée equidistant cylindric projection

Robinson projection (Fig. 4.6). This projection was developed by Arthur Robinson at the request of Rand McNally. Since its development, the Robinson projection, although not equal area, is a popular choice for many thematic data sets since it gives a good visual representation of Earth's landmasses. Note that in this atlas, the
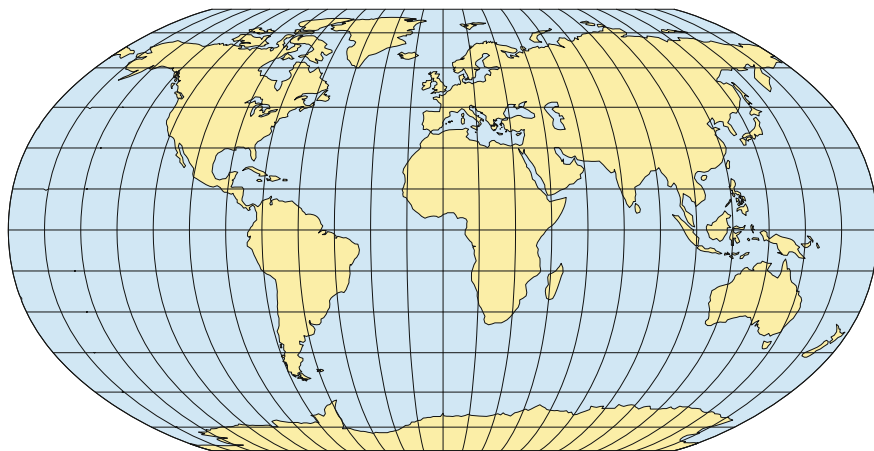
Fig. 4.6 The Robinson compromise pseudocylindric projection

Miller projection with its straight lines of longitude is correctly associated with mapping world time zones.

From Table 4.1, the Maps of World atlas presents many different thematic map topics. An interesting approach taken by Maps of World in mapping these topics is to illustrate each data set using all five of the following projections: Miller, Mercator, Eckert V, Robinson, and Aitoff. In other words, the user can select any data set and view them using any of the five projections. The utility of the Mercator projection and its ability to preserve angular relationships to map thematic data has already been discussed. Although appearing in printed world atlases for thematic data sets, the Miller projection does distort landmasses in the upper latitudes but not to the extent of the Mercator. In fact, the catalyst for developing the Miller projection was to reduce the distortion that was present on the Mercator projection (Miller 1942).

The Robinson, Eckert V, and Aitoff projections are also available in the Maps of World. The Robinson and Eckert V (Fig. 4.7) projections are both pseudocylindric, do not preserve any specific projection property, and have appeared in printed world atlases. The Eckert V is one of six pseudocylindric projections that were developed by Max Eckert (Eckert 1906). Both projections have straight lines representing latitude and curved lines representing longitude that converge to poles represented as lines about half as long as the equator. This combination better reflects the way in which these lines appear on a globe than, for example, cylindric projections. This is an appealing aspect of selecting pseudocylindrics for world maps. On the Robinson projection, the lines of longitude are drawn with elliptical arcs while the Eckert V uses sinusoidal curves (Snyder and Voxland 1989). For this reason, the lines of longitude curve to a greater extent on the Eckert V than on the Robinson. The Aitoff projection (Fig. 4.8) was presented by Aitoff (1899) and is also a compromise projection. However, due to the curved nature of the lines of
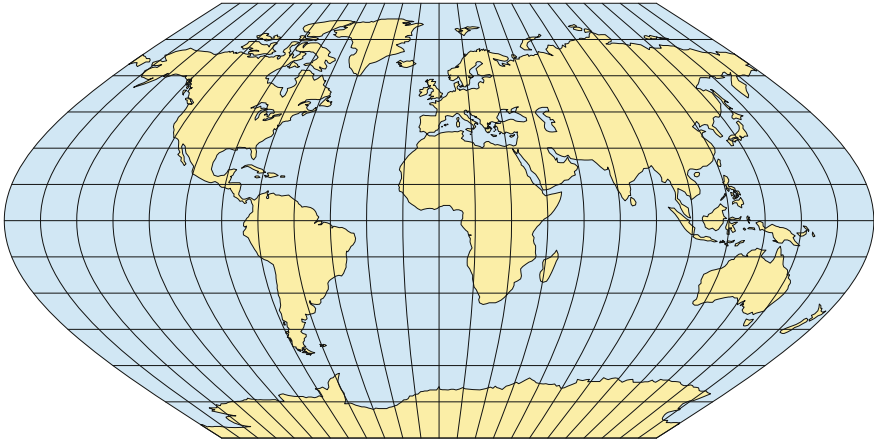
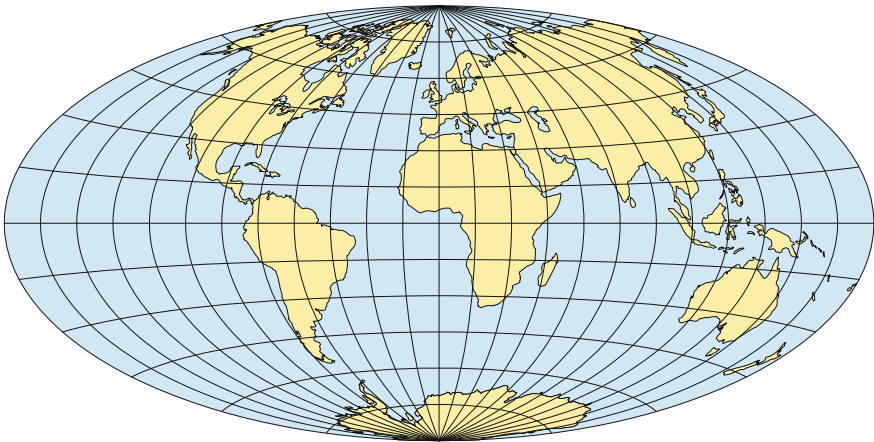**Fig. 4.7** The Eckert V compromise pseudocylindric projection

Fig. 4.8 The Aitoff compromise modified azimuthal projection

latitude, the projection is classified as a modified azimuthal. Although sharing some of the same visual characteristics as the Robinson and Eckert V, the Aitoff projection represents lines of longitude and latitude as complex curves (Snyder and Voxland 1989). In addition, the poles are characteristically represented as points which also mimics the way in which the poles appear on the Earth. However this characteristic results in a considerable compression of landmasses near the polar areas which can be visually undesirable. The Aitoff projection has also been selected for maps in printed world atlases. Collectively, due to their attempt at preserving the overall appearance of the Earth's landmasses and the representation of the lines of latitude and longitude, these three projections are suitable for a range of thematic and general reference world maps.

4.3.3   Web-Based Specialty Thematic Atlases

Table 4.2 lists ten Websites that focus on specific data themes. Seven of these atlases selected the Web Mercator (Fig. 4.9). This projection is commonly selected for Web-based mapping services such as Google Maps, Bing Maps, and Open Street Maps. As mentioned earlier in this chapter, unlike the Mercator map projection, the Web Mercator is not conformal and does not preserve a property. In fact, the Web Mercator makes no attempt to improve upon the gross levels of distortion that appear in the mid- to upper-latitudes as found on the Mercator projection. One apparent advantage of using the Web Mercator comes from the rather computationally simple formulas that are used to calculate coordinates that are then plotted to the computer screen (an important consideration when dealing with the Web environment). Another advantage of this projection is the relative programming ease that comes with panning and zooming on cylindric projections. Non-cylindric projections, such as the Robinson with its curved lines of longitude, need to have the longitude lines re-calculated every time panning takes place.

The Plate Carrée projection appears in the IDF Diabetes Atlas. Although this equidistant cylindric projection represents upper latitudes with distortion, its rectangular shape fits the computer screen better than, for example, a pseudocylindric or conic map projection. As discussed earlier, the Robinson projection's attempt to minimize the visual distortion to the Earth's landmasses makes this projection appropriate for The World Bank to map various thematic data sets displayed through its atlas.

An interesting comparison can be found with two mapping applications created by the U. S. Census Bureau. The bottom two rows of Table 4.2 lists the details of the Small Area Income and Poverty Estimate (SAIPE) and Census Data Mapper. Both of these mapping applications include interactive tools to help users search and map data sets of the lower 48 United States. The SAIPE Website uses the Web Mercator while the Census Data Mapper uses the Albers equal area conic projection (Fig. 4.10). Since the conterminous United States have a considerable east to west extent and is located along the mid-latitudes a conic projection has traditionally been favored. On conic projections in general, the locations of the standard parallels (lines of no distortion) can be specified to coincide over the geographic area of interest (e.g., the mid latitudes) which in turn reduces distortion for that geographic area. Contrary to the standard parallel placement options on conic projections, the equator is assigned as the single standard line on the cylindric Web-Mercator. For this reason, equatorial regions are mapped with lower distortion than landmasses appearing in the mid- and upper-latitudes.

Table 4.2 A listing of web-based atlases showing specialty thematic data

Atlases of specialty thematic data

| Atlas name	Geographic region mapped	Data set mapped	Projection name	Projection class	Projection property	Standard lines	Projection identified
IDF Diabetes atlas 6th edition (www.idf.org/diabetesatlas)	World	Diabetes	Plate Carrée	Cylindric	Equidistant	Equator	No
Ocean data viewer (data.unep-wcmc.org)	World	Ocean-related themes	Web Mercator	Cylindric	None	Equator	No
Global development atlas (atlas.esri.com/Atlas/NGO_Atlas.html)	World	5 Thematic themes	Web Mercator	Cylindric	None	Equator	No
UNESCO atlas of the world's languages in danger (www.unesco.org/culture/languages-atlas/)	World	6 Thematic themes	Web Mercator	Cylindric	None	Equator	No
Health map (healthmap.org/en/)	World	Health-related themes	Web Mercator	Cylindric	None	Equator	No
The world bank (www.app.collinsindicate.com/worldbankatlas-global/en-us)	World	12 Thematic themes on global development	Robinson	Pseudo-cylindric	Compromise	None	No
European environment agency (www.eea.europa.eu/data-and-maps/explore-interactive-maps)	Europe	17 Environmental themes	Web Mercator	Cylindric	None	Equator	No
Michelin route maps (www.viamichelin.com/Web/Maps/Map-Europe)	Europe	Transportation routes	Web Mercator	Cylindric	None	Equator	No
United States census bureau's small area income and poverty estimate (www.census.gov/did/www/saipe/index.html)	Lower 48 United States	Various poverty data	Web Mercator	Cylindric	None	Equator	No
United States census bureau's census data mapper (tigerweb.geo.census.gov/datamapper/map.html)	United States	Various demographic data	Albers	Conic	Equal area	Geographic location dependent	No
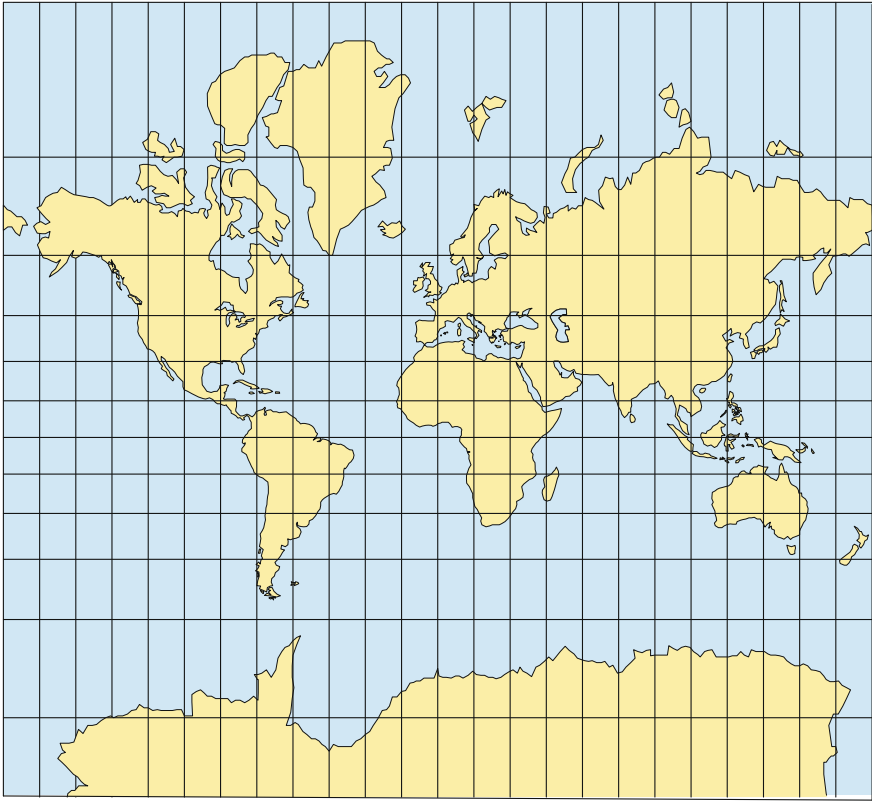
Fig. 4.9 The web Mercator cylindric projection

4.3.4 Web-Based Atlases of Individual Countries

Table 4.3 lists six atlases that focus on topics related to individual countries. Three atlases use the Web Mercator to map various themes. However, the United States National Atlas uses the Plate Carrée; the Atlas of Canada, the Lambert conformal conic (Fig. 4.11); and the Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries, the Albers equal area conic map projection. Canada and Russia have a great east to west extent and by locating the standard parallels over the geographic areas of interest, distortion is reduced. The use of an equal area projection for Russia is logical since the maps show spatial distributions of various thematic topics. The choice of a conformal projection to map Canada does not follow traditional cartographic recommendations of selecting an equal area projection when the map purpose involves showing spatial distributions. However, choosing a projection property is not always the most important consideration. In some cases, the visual appearance of the landmasses or the graticule may take precedence. For example, Figs. 4.10 and 4.11 compare the landmasses and the way
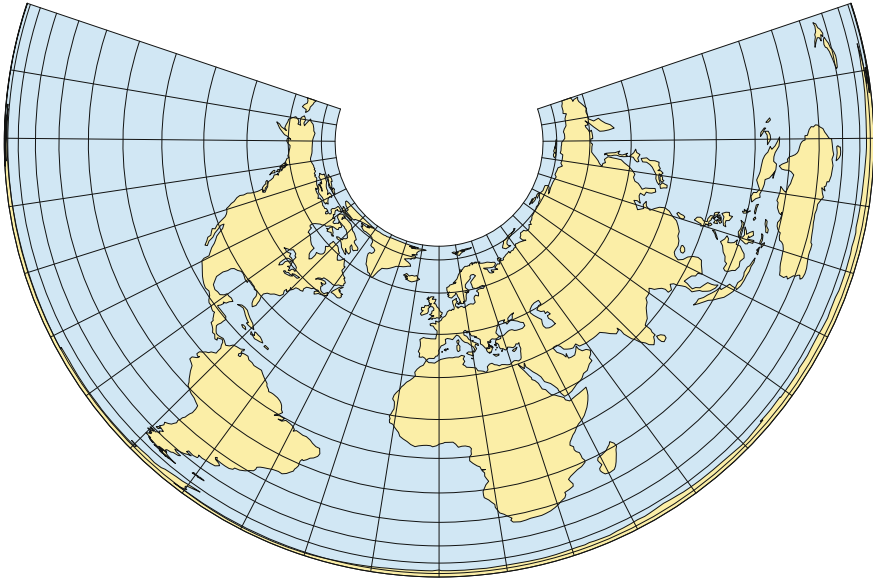
Fig. 4.10 The Albers equal area conic projection

in which the lines of longitude converge in the North Pole region. The lines of longitude converge to an arc that represents the North Pole on the Albers equal area projection (Fig. 4.10) which has the tendency to stretch the landmasses in this area east to west. Since the lines of longitude converge to the North Pole (represented as a point) on the Lambert conformal conic projection (Fig. 4.11) the landmasses are not subjected to this same stretching. The Atlas of Canada designers may have made a conscious decision to forego the traditional recommendation of using an equal area projection for their thematic maps. Instead, they deliberately selected a conformal conic projection for Canada as a result of the pole being represented as a point instead of a line. Showing the North Pole as a point produces landmasses in the upper regions of Canada with less east-west stretching and reflects the way in which the lines of longitude converge to the pole. Both of these characteristics create a visual appearance that is similar to what is shown on a globe.

4.3.5 Summary of Map Projections and Web-Based World Atlases

Based on the review of the Web-based atlases six observations can be made. First, it is apparent that there is disagreement between the data to be mapped and the selection of an appropriate map projection property to preserve. The Web-based atlases in this survey included general reference and thematic maps. According to

Table 4.3 A listing of web-based atlases showing thematic data of individual countries

Atlases of individual countries

| Atlas name	Geographic region mapped	Data set mapped	Projection name	Projection class	Projection property	Standard lines	Projection identified
United States national atlas (http://viewer.nationalmap.gov/viewer)	Lower 48 United States	13 Thematic themes	Plate Carrée	Cylindric	Equidistant	Equator	No
The atlas of Canada (http://atlas.nrcan.gc.ca/site/english/)	Canada	8 Thematic themes	Lambert	Conic	Conformal	49°N and 77°N	Yes
Atlas of living Australia (spatial.ala.org.au/)	Australia	Various thematic themes	Web Mercator	Cylindric	None	Equator	No
Interactive agricultural Ecological Atlas of Russia and neighboring countries (www.agroatlas.ru/en/content/climatic_maps/Pcp/Pcp/)	Russia and former member countries of soviet union	Crops, diseases, pests, weeds, and environment variables	Albers	Conic	Equal area	44°N and 68°N	Yes
Forest Atlas of Cameroon (www.wri.org/tools/atlas/map.php?maptheme=cameroon)	Cameroon	6 Thematic themes	Web Mercator	Cylindric	None	Equator	No
England and Wales Environmental Health Atlas (www.envhealthatlas.co.uk/homepage/gotoatlas.html)	England and Wales	21 Health-related themes	Web Mercator	Cylindric	None	Equator	No
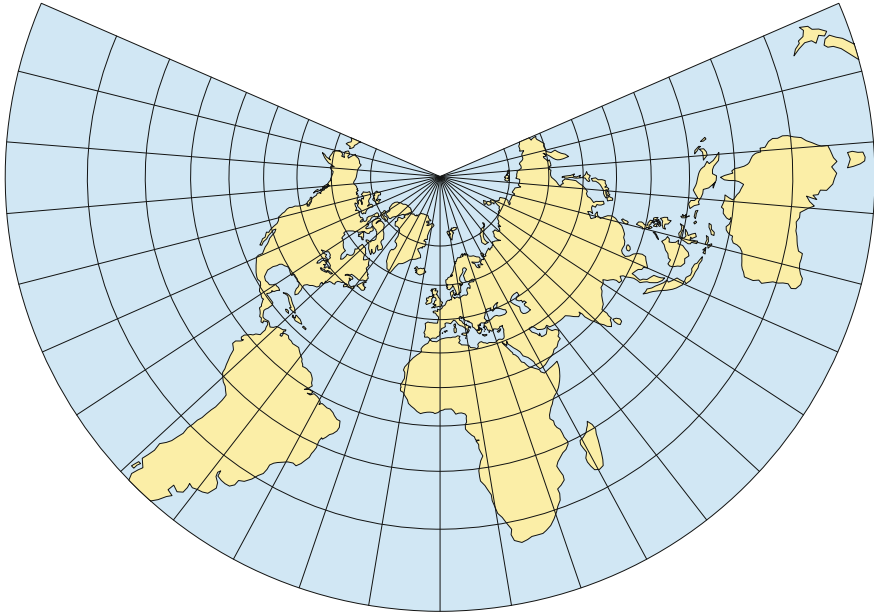
Fig. 4.11 The Lambert conformal conic projection

recommendations present in the cartographic literature, an equal area or compromise projection would be appropriate for these kinds of maps. Yet, those projection properties were not universally found. Second, from Tables 4.1 through 4.3 it is interesting to see that it is uncommon to disclose the projection name to the user. In fact, there was no instance where the Web Mercator was identified by name. Identifying the projection name may help the map reader understand how, for example, the projection's distortion pattern, impacts the spatial distribution represented on the map. At a minimum, providing the projection name would equip users with enough information that they could research the projection in question. Third, the selection of the Lambert conformal conic projection for the Atlas of Canada is contrary to recommendations to use an equal area property for thematic maps. However, this projection choice helped preserve the overall appearance of Canada's landmasses and demonstrates the flexibility to which a map projection can be tailored to meet the needs of a map purpose – provided that those making the selections are equipped with the appropriate knowledge.

Fourth, projections that have historically been used in the printed world atlas do not necessarily translate into the digital world atlas. For instance, unlike in the printed world, it is very easy to share data in the digital world (e.g., via map mash-ups—especially at the regional or smaller geographic area extents). The Web Mercator makes this sharing process easier by setting a common map projection which eliminates the need to convert between one projection and another. In another respect, sharing data is also made easier by removing the map projection

altogether and storing vector data (such as Esri shapefiles) in "geographics" or latitude/longitude values based on the World Geodetic System (WGS) 1984.

Fifth, online mapping and the varied interactivity levels present different kinds of restrictions than in the printed world. For example, when using highly interactive tiled-maps that can be panned or zoomed (such as found in Open Street Map), there are more restrictions on the projection choice because of computational and programming needs when users interactively pan or zoom.. In a similar light, global scale data sets that are intended to be panned continuously benefit from a seamless connection along the 180th meridian. This seamless connection is found on cylindric projections whose lines of longitude are straight. On a projection with curved lines of longitude, seamlessly panning across this 180° line causes considerable programming issues and can result in the appearance of non-continuity. Due to their straight lines of longitude, cylindric projections do not suffer from the wrap-around problem. For maps at non-global scale, those that do not need panning (or zooming), or are purely vector maps there are many fewer restrictions to consider when choosing the proper projection.

Sixth, irrespective of the dataset mapped, the Web Mercator appeared to be the most frequently selected projection in this review. However, selecting this projection to map the distribution of a statistical variable is inappropriate. In the cartographic literature, the Mercator (or the visually similar Web Mercator) projection is not recommended for mapping thematic data. For instance, assume one were to symbolize a statistical variable (such as population) on a map using dots. When viewing the map, an important consideration is the interpretation of the visual density of the spatial pattern. The visual density results from the varied nature of the data (and dots) within each geographic region. If the map upon which the dots are plotted is equal area then the impression of the visual density is likely to be correct. Since neither the Web Mercator nor the Mercator are equal area both projections suffer from considerable exaggeration of landmass' shape and size in the upper-latitudes which makes neither projection suitable for representing distributions of a statistical variable. Unfortunately, the inertia of using the Web Mercator for Web mapping has largely been ingrained and its use will likely continue for the foreseeable future. In order for these Web-based atlases to better represent general reference maps or portray the data on thematic maps, projections need to be selected, on which the projection property preserved from the globe is matched to the map purpose.

4.4 Online Map Projection Software and Code Libraries

In this section we review a few of the more popular or practical and downloadable programs (or executables) and software code libraries. Most of these downloadable programs make their source code available under an open source license. In this section we focus on explaining the structure and utility of several commonly available map projection related software packages or online code libraries.

4.4.1   Flex Projector

Flex Projector (http://www.flexprojector.com/), is a cross-platform application for producing custom world map projections and has become a very good tool for practicing mapmakers and students of cartography (Jenny et al. 2008). The development of Flex Projector was inspired by the Robinson projection (Robinson 1974, pp. 147–148; Jenny et al. 2008). It allows users to modify the shape of a projection by altering the length of parallels and their distance from the equator (Fig. 4.12). According to Jenny et al. (2008), the aim of Flex Projector is to democratize the fabrication of world map projections. The program is download-able as an executable for the Windows, Macintosh, and Linux platforms, and, in addition, the source code is available as open source at the Website noted above. From the map projection perspective, Flex Projector focusses on cylindric, pseu-docylindric, and polyconic projections.

4.4.2   Global Map Projector

Global Map Projector (http://www.giss.nasa.gov/tools/gprojector/) is also known as G.Projector, is also a cross-platform application. The program is downloadable as an executable for the Windows, Mac OS X, and Linux platforms available at the Website noted above. It is a Java executable and requires the Java Runtime Environment to be installed on your computer. G.Projector converts an equirect-angular map image into one of over 100 global or regional map projections (Fig. 4.13). It was developed and is being maintained by Robert B. Schmunk of the NASA Goddard Institute for Space Studies.
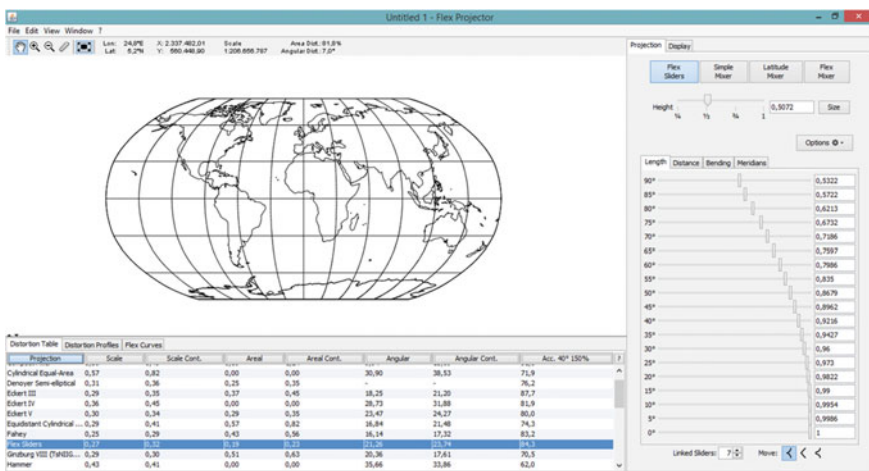

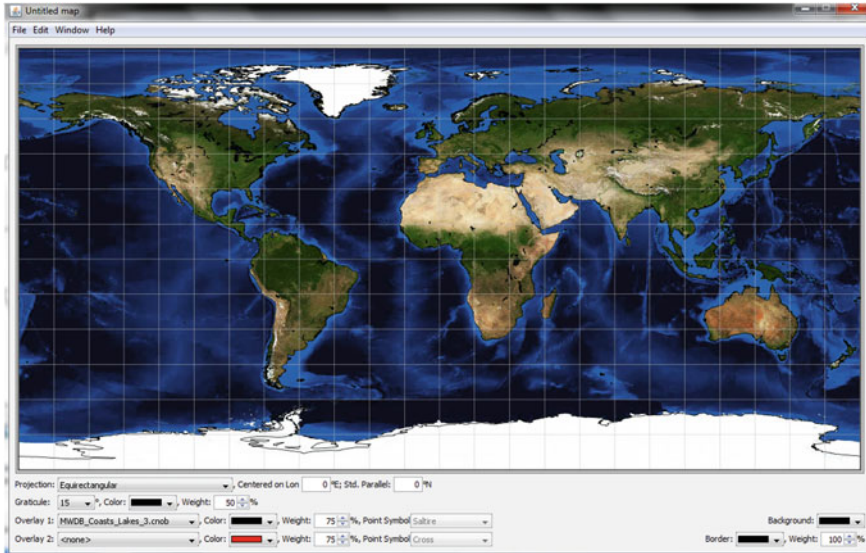**Fig. 4.12**   FlexProjector. *Source* http://www.flexprojector.com/

Fig. 4.13 G.Projector. *Source* http://www.giss.nasa.gov/tools/gprojector/

4.4.3   PROJ.4

Proj.4 (http://trac.osgeo.org/proj/) is a cartographic projections software code library originally written by Gerald Evenden, then of the US Geological Survey (USGS). It is commonly used in conjunction with the Geospatial Data Abstraction Library (GDAL). GDAL is a C++ library for raster and vector geospatial data formats that is released under an open source license (Warmerdam 2008). GDAL presents a data model for both raster and vector available to any calling application for all supported formats (http://www.gdal.org). GDAL supports its own API. PROJ.4 is in active use by many open source GIS/Geospatial technology related programs such as MapServer, Geographic Resources Analysis Support System (GRASS GIS), PostGIS, and Quantum GIS (QGIS).

In addition to supporting over 100 map projections, it supports datum shifting with either a 3-parameter transformation or a 7-parameter transformation. It is presently being maintained by Frank Warmerdam of The Open Source Geospatial Foundation (OSGeo) and Planet Labs. PROJ.4 is a part of OSGeo Meta Coordinate Reference System (MetaCRS) project. The MetaCRS is a project encompassing several projections, and coordinate system related technologies. MetaCRS seeks to improve cooperation among GIScientists and developers by supporting the sharing of similar coordinate system dictionaries, test suites, and mathematical formulations. PROJ.4 supports European Petroleum Survey Group (ESPG) definitions and various Well Known Text (WKT) formats.

4.4.4   JH Labs Java Library

Jerry Huxtable or JH Labs Java Library (http://www.jhlabs.com/java/maps/proj/ index.html) is a Java-based implementation of a portion of the PROJ.4 map projection library. The code is open source and one goal for the library is to eventually incorporate all of the projections included in PROJ.4. In addition, on the Website JH Labs provides "The Globe Applet," which can be used to examine the supported projections. It displays several thematic layers and, importantly, a graticule and Tissot's indicatrix as selectable options. JH Labs also have a Java Map Editor application available for viewing and editing maps in various formats (http:// www.jhlabs.com/maps/index.html). The editor uses Java 1.2 and Swing.

4.4.5   JavaScript Libraries

Java script libraries are becoming more popular, not only for map projections use, but also in the larger online mapping development/application area. JavaScript is a dynamic computer programming language, frequently used in conjunction with Web browsers (Flanagan and Ferguson 2006). Because JavaScript programming, especially advanced programming and associated complex handling of browser differences, can often be very difficult and time-consuming, JavaScript libraries have been developed (Mikkonen and Taivalsaari 2007). A JavaScript library is sometime referred to as a JavaScript framework. These libraries have been developed to deal with issues of advanced JavaScript programming that can be complicated and onerous to work with.

An example of a JavaScript library developed to aid in working with map projections on the Internet is the Geo Projections library (https://github.com/d3/d3-geo-projection/) extending d3 (Data-Driven Documents) and the d3.geo library, specifically. A JavaScript library for manipulating documents, d3 is based on the document object model (Bostock et al. 2011). d3 manipulates data using HTML, SVG and CSS, based on Web standards. The d3.geo library is used to create map projections within a Webpage through a simple function call. The following code example shows the specific d3.geo library needed to compute the plotting coordinates for the Mercator cylindric projection (Fig. 4.14).

```
var mercator = d3.geo.projection(function(λ, φ) {

return [

λ,
Math.log(Math.tan(π/4 + φ/2))

];
});
```
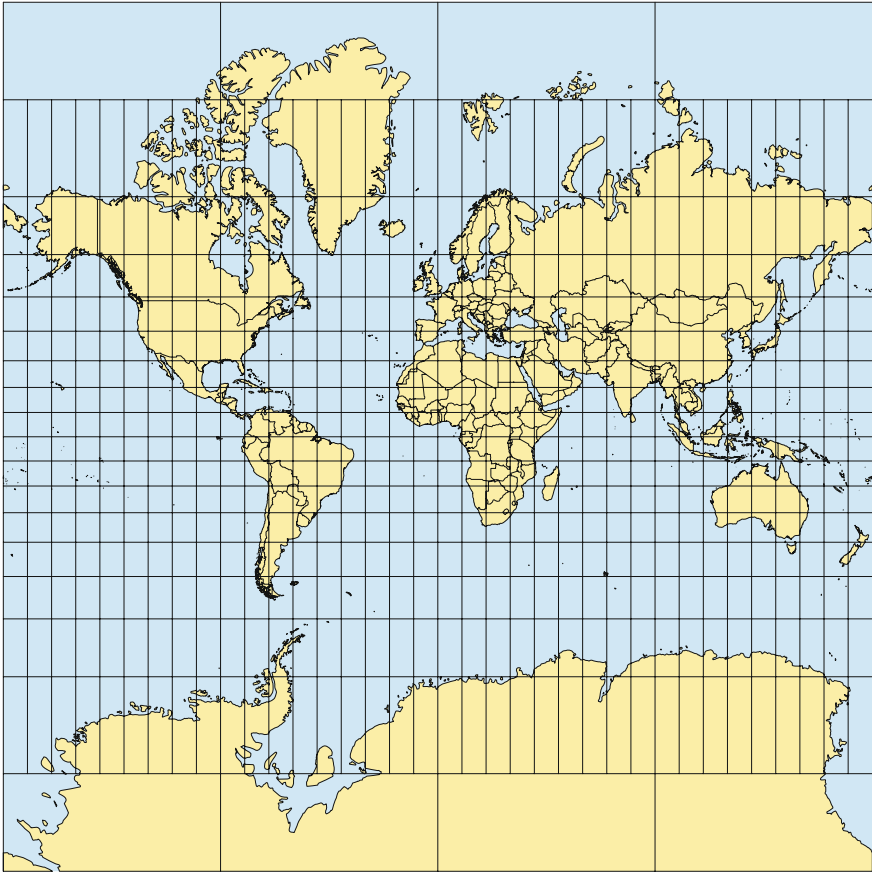
Fig. 4.14 The Mercator projection derived by using the d3.geo d3 JavaScript library (https://
github.com/mbostock/d3/wiki/Geo-Projections)

4.4.6 Generic Mapping Tools (GMT)

Generic Mapping Tools is an open source assortment of approximately 80 core
tools for controlling geographic and Cartesian data and producing PostScript
illustrations, with supplements that add another 40 modules. GMT contains over 30
map projections and transformations (University of Hawaii 2014). It has long been
popular with geophysicists and oceanographers working in the UNIX environment.
GMT was written and is maintained by Paul Wessel (U. of Hawaii) and Walter H.
F. Smith (NOAA) with support from a global set of volunteers, and is subsidized by
the National Science Foundation (Wessel et al. 2013). The latest version is version
5, which added the option to call the code as an API. This API feature allows for
rapid development of custom applications and increase speedup of scripted

workflows. In addition to the standard download package, loaders for OS X and Windows are available (Wessel et al. 2013).

4.4.7 mapIMG

mapIMG is an open source software package that focuses on map projection/re-projection of small scale (coarse) raster data. It is primarily used for mapping raster datasets at continental- to global-scale (Finn et al. 2012). The source code, documentation, test datasets, and executable files (for Windows, Linux, and Solaris) are available at http://cegis.usgs.gov/projection/acc_proj_data.html. mapIMG is tailored to address issues unique to raster datasets such as areal accuracy (as a function of spatial resolution), distortions of cells (pixels or other gridded data like post space for elevation, as opposed to points as in a vector dataset), and the associated resampling that accompanies projection transformations (including alternative resampling methods) (Finn et al. 2012). mapIMG has been further developed as pRasterBlaster to work in a high performance parallel-processing based computing environment, where a separate core library of projection transformation and resampling functions is available for use by both pRasterBlaster and mapIMG (Finn et al. 2014a).

4.4.8 Dynamically Created Vector Maps

Another option for working with projections in spatial data is through dynamic creation and projection of vector data in maps. The intent of vector-based automation tools is to provide, in terms of map projections software, the capability to display multi-zoom datasets over maps. That is, the goal is to load and display data at a full range of map scales. Often Scalable Vector Graphics (SVG) are used to assist this effort (W3C 2010; http://polymaps.org/). SVG is usually encapsulated within a specialized compiled language or interpreted script. SVG is an eXtensible Mark-up Language (XML) based vector image format for two-dimensional graphics with support for interactivity and animation, with behaviors defined in XML text files (W3C 2003; Clarke 2005). This type of multi-scale mapping requires methods for automating generalization (map symbols and map content) to improve communication across scales. Guiding principles have been proposed for symbol selection and map content at related pre-defined scale ranges for maps (Cecconi and Galanda 2002; Brewer and Buttenfield 2007; Samsonov 2011).

  More recently Jenny (2012), Gaffuri (2012) and Lienert et al. (2012) have investigated using variable scale with the related challenge of on-the-fly adjustment of symbology, blending geometries, and adapting projections for dynamic vector mapping, with Samsonov et al. (2013) proposing a new scale-adaptive approach to symbolization of vector data on multi-scale maps. From the perspective of this

chapter, the adaptation of map projections for dynamic vector mapping is a key interest. As previously described in the section on Non-Web Mercator mapping options at the global-scale, Jenny's suggestion (2012) that there is a present requirement for adaptive composite map projections that can seamlessly switch between projections as a user pans and zooms around a map is very relevant. This is an area of active research with many recent developments occurring in a short amount of time (and more expected) and we encourage the reader interested in dynamic vector mapping to check the latest literature.

4.5 Map Projection Research/Education

In addition to the materials discussed above for map projection education, there is also an interesting body of literature related to challenges in teaching about map projections and the resulting misconceptions about projections and distortion. In considering the methods that we use to educate students about map projections, Downs and Liben (1991) examined cognitive challenges behind the concept of shadows and developable surfaces. They found that many college-age individuals do not have sufficient cognitive and spatial skills to understand shadow projections, thus would not be able to effectively understand map projections taught with this method. Olson (2006) suggests that we need to become better "visual detectives" and learn to more closely read the cues in the map graticule.

While Downs and Liben (1991) and Olson (2006) focused on how we learn about projections, Battersby and Kessler (2012) looked at how we apply our knowledge of projections in evaluating distortion. A surprising finding of this study is a substantial reliance on Mercator-based distortion cues (e.g., Greenland, Antarctica, and the general "polar regions") for explaining distortion in *any* of the projections included in the study. Anderson and Leinhardt (2002) also show that angular distortion is not well understood—even by experts. Battersby (2009) further supports this with demonstration that even when a projection is familiar most people have a difficult time adjusting for distortion in the map.

4.5.1 Tutorials and Decision Support Systems

Considering which map projection to choose for a map can be a challenging task. There are few guidelines to assist in the selection of an appropriate map projection. One guideline presented by Snyder (1987) begins the selection process by considering the geographic area of interest (world, hemisphere, or continent, ocean, or smaller region). Once the geographic area to be mapped is determined additional criteria are defined (e.g., projection property, location of geographic landmass, and the location to preserve scale) leading to a named projection. While this guideline is

useful, the one making the selection needs to have a working knowledge of map projections to navigate their way through the guideline.

On the other hand, cartography and GIS texts discuss the specific projection parameters and numerical values that must be carefully specified to ensure that the geographic area of interest is mapped with distortion levels appropriate to the map purpose. Similarly, these texts explain that map projections have specific properties that should be matched to the map's data and purpose. One text (Slocum et al. 2009) discusses the utility of the projection properties (i.e., azimuthal, equal area, equidistant, conformal, and compromise). Directions between two locations on the Earth's surface can be preserved. Assume that a hurricane is brewing in the Central Atlantic and weather forecasters are interested in predicting the storm's direction to warn coastal communities of the impending danger. Azimuthal projections preserve the ability to measure directions from one point to all other points on a map. Since azimuthal projections are suitable for tracking they are often used for navigational purposes.

Additionally, Decision Support Systems (DSS) can serve as an aid to learning about projections. Finn et al. (2014b) discuss a DSS for small-scale map projections to help users identify appropriate map projections and to provide a tutorial detailing the logic guiding appropriate projection decisions for different purposes. This tutorial educates users on the derivation of each suggested projection and supplies a basic explanation of the individual projection design. The DSS is available at http://mcmcweb.er.usgs.gov/DSS/.

4.6   Conclusion

This chapter presented an overview of map projections and how they have been integrated into the Internet. The first section provided a general introduction to projections while the second section covered the map projections that are frequently used by Web maps and map services and addressed projections adopted for both global and local-scale mapping. Many global-scale maps use the Web Mercator map projection. While the cylindric nature of the Web Mercator facilitates the display of mapped data (e.g., panning) there are two major concerns related to the use of this projection. First, unlike the Mercator projection, the Web Mercator is not conformal. Second, like the Mercator, due to the considerable distortion found at the upper latitudes, the Web Mercator is not suitable when mapping at the global-scale. For non-global scale maps, the online map services typically use a variant of the Universal Transverse Mercator coordinate system. Many countries have developed their own national grid systems (e.g., Irish National Grid) and local-level administrative units have created their own coordinate system (e.g., United States State Plane Coordinate System) and distribute data formatted in these coordinate systems. The Web has many sites that are well equipped to handle complex conversions between these different grid and coordinate systems.

The third section presented a review of online atlases. This section examined online atlases of world, specialty thematic and individual countries. World atlases and atlases of individual countries use a greater variety of map projections and properties selected for included maps than the thematic atlases. The thematic atlases almost unanimously use the Web Mercator map projection.

The fourth section considered online map projection software. There is a growing number of Websites devoted to map projection software. Some of the Websites, such as Flex Projector, are interactive and allow users to interactively create a map projection. Other Websites, such as PROJ.4, are a set of useful code libraries that are freely available to the end user for integration into a number of Web-based and other mapping applications.

The fifth section discussed topics related to map projection research and education. There has been progress made in researching the map reader and their understanding of map projections. For instance, research has suggested that the map reader could use the graticule to better understand for example the projection property. In another finding, distortions in the upper latitudes common to the Mercator projection are cues for map. However, the number of research outcomes is still limited and there is much left to investigate regarding the map reader and the map projection.

Disclaimer Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government

References

Aitoff D (1899) Projections des Cartes Géographiques. In: Atlas de Géographie Moderne Paris. Hachette, New York

American Cartographic Association, American Geographical Society, Association of American Geographers, Canadian Cartographic Association, National Council for Geographic Education, National Geographic Society, and Special Libraries Association, Geography and Map Division (1989) Resolution regarding the use of rectangular world maps. Am Cartographer 16(3):223

Anderson KC, Leinhardt G (2002) Maps as representations: expert novice comparison of projection understanding. Cogn Instr 20(3):283–321

Battersby SE (2009) The effect of global-scale map-projection knowledge on perceived land area. Cartographica 44(1):33–44

Battersby SE, Finn MP, Usery EL, Yamamoto KH (2014) Implications of web mercator and its use in online mapping. Cartographica 49(2):85–101. doi:10.3138/carto.49.2.2313

Battersby SE, Kessler FC (2012) Cues for interpreting distortion in map projections. J Geogr 111 (3):93–101

Bostock M, Ogievetsky V, Heer J (2011) D^3: data-driven documents. IEEE Trans Vis Comput Graph (Proc. InfoVis)

Brewer CA, Buttenfield BP (2007) Framing guidelines for multi-scale map design using databases at multiple resolutions. Cartography Geog Informa Sci 34(1):3–15

Bugayevskiy LM, Snyder JP (1995) Map projections: a reference manual. Taylor and Francis, London

Cavell JA (2005) USNG: getting it right the first time. The American Surveyor. June issue. http://www.amerisurv.com/PDF/TheAmericanSurveyor_USNationalGrid-Cavell_June2005.pdf. Accessed 10 Jan 2015

Cecconi A, Galanda M (2002) Adaptive Zooming in Web Cartography. Comput Graph Forum 21:787–799. doi:10.1111/1467-8659.00636

Clarke KC (2002) Criteria and measures for the comparison of global geocoding systems. In: Goodchild MF, Kimerling AJ (eds) Discrete global grids: a web book. http://www.ncgia.ucsb.edu/globalgrids-book/. Accessed 10 Jan 2015

Clarke P (2005) Dynamic web-mapping using scalable vector graphics (SVG). In: Proceedings ESRI user conference 2005. http://proceedings.esri.com/library/userconf/proc05/papers/pap1997.pdf. Accessed 10 Jan 2015

Downs RM, Liben LS (1991) The development of expertise in geography: a cognitive-developmental approach to geographic education. Ann Assoc Am Geogr 81 (2):304–327

Eckert M (1906) Neue Entwürfe für Erdkarten. Petermanns Mitteilungen 52(5):97–109

Eisenlohr F (1870) Ueber Flächenabbildung. Journal für rein und angewandte Mathematik 72 (2):299–307

Federal Geographic Data Committee [FGDC]. Educational resources for the United States National Grid. https://www.fgdc.gov/usng/educational-resources/index_html. Accessed 10 Jan 2015

Finn MP, Liu Y, Mattli DM, Behzad B, Yamamoto KH, Guan Q, Shook E, Padmanabhan A, Stramel M, Wang S (2014a) High-performance small-scale raster map projection transformation on cyberinfrastructure. Wang S, Goodchild MF (eds) Paper accepted for publication as a chapter in CyberGIS: fostering a new wave of geospatial discovery and innovation, Springer, Berlin

Finn MP, Steinwand DR, Trent JR, Buehler RA, Mattli D, Yamamoto KH (2012) A program for handling map projections of small scale geospatial raster data. Cartographic Perspect 71:53–67

Finn MP, Usery EL, Woodard L, Yamamoto KH (2014b) The logic of selecting an appropriate map projection in a decision support system (DSS). In: Lapaine M, Usery EL (eds) Chapter this volume: map projection choice. International Cartographic Association, Springer, Berlin

Flanagan D, Ferguson P (2006) JavaScript: the definitive guide, 5th edn. O'Reilly & Associates

Gaffuri J (2012) Toward web mapping with vector data. LNCS 7478: geographic information science. In: Proceedings of GIScience 2012. Springer, Berlin, pp 87–101

Hassler F (1825) On the mechanical organization of a large survey, and the particular application to the survey of the coast. Am Philos Soc Trans New Ser 2:358–408

Jenny B (2012) Adaptive composite map projections. IEEE Trans Visual Comput Graphics 18 (12):2757–2782

Jenny B, Patterson T, Hurni L (2008) Flex projector—interactive software for designing world map projections. Cartographic Perspect 59:12–27 and 68

Lienert C, Jenny B, Schnabel O, Hurni L (2012) Current trends in vector-based internet mapping—a technical review. In: Peterson MP (ed) Online maps with APIs and mapservices., Lecture notes in geoinformation and cartographySpringer, Berlin, pp 23–36

Maling DH (1992) Coordinate systems and map projections, 2nd edn. Pergamon Press, Elmsford NY

Mikkonen T, Taivalsaari A (2007) Using JavaScript as a real programming language. Technical Report TR-2007-168, Sun Microsystems Laboratories

Miller O (1942) Notes on cylindrical world map projections. Geogr Rev 32(3):424–430

Monmonier M (1995) Drawing the line: tales of maps and cartocontroversy. Holt, New York

Monmonier M (2004) Rhumb lines and map wars: a social history of the mercator projection. University of Chicago Press, Chicago IL

NGA (2014) NGA Advisory Notice on "Web Mercator". http://Earth-info.nima.mil/GandG/wgs84/web_mercator/. Accessed 10 Jan 2015

NGA Office of Geomatics (2014) Implementation practice Web Mercator projection. National Geospatial-Intelligence Agency (NGA) Standardization Document, version 1.0.0, 18 Feb 2014. http://Earth-info.nima.mil/GandG/wgs84/web_mercator/%28U%29%20NGA_SIG_0011_1.0.0_WEBMERC.pdf. Accessed 10 Jan 2015

Olson JM (2006) Map projections and the visual detective: how to tell if a map is equal-area, conformal, or neither. J Geogr 105:13–32

Ordinance Survey (2015) The National Grid. http://www.ordnancesurvey.co.uk/resources/maps-and-geographic-resources/the-national-grid.html. Accessed 10 Jan 2015

Robinson A (1974) A new map projection: its development and characteristics. Int Yearb Cartography 145–155

Robinson A (1990) Rectangular world maps—no! Profes Geogr 42(1):101–104

Samsonov T (2011) Multiscale hypsometric mapping. In: Advances in cartography and GIScience. Lecture notes in geoinformation and cartography (LNGC), vol 1. Springer, Berlin, Heidelberg, pp 497–520

Samsonov T, Podolsky A, Yurova N (2013) Multimapper—prototype system for designing multi-scale maps. In: Proceedings international cartographic conference 2013. http://icaci.org/files/documents/ICC_proceedings/ICC2013/_extendedAbstract/219_proceeding.pdf. Accessed 10 Jan 2015

Slocum T, McMaster R, Kessler F, Howard H (2009) Thematic cartography and geovisualization. Pearson Prentice Hall, Upper Saddle River, NJ

Snyder JP (1987) Map projections: a working manual (U.S. Geological Survey Professional Paper). U.S. Government Printing Office, 1395, Washington DC

Snyder JP (1993) Flattening the earth: 2000 years of map projections. University of Chicago Press, Chicago, IL

Snyder JP, Voxland P (1989) An album of map projections. US Geological Survey, Washington DC

Stem JE (1989) State plane coordinate system of 1983. NOAA Manual NOS-NG-5. U.S. Department of Commerce, Washington DC

University of Hawaii (2014) What is GMT? School of ocean and earth science and technology. http://gmt.soest.hawaii.edu/projects/gmt/wiki. Accessed 10 Jan 2015

Vujakovic P (2002) Whatever happened to the 'new cartography?' The world map and development mis-education. J Geogr High Educ 26(3):369–380

Warmerdam F (2008) The geospatial data abstraction library. In: Hall GB, Leahy MG (eds) Chapter 5 of open source approaches in spatial data handling. Springer, New York, pp 87–104

Wessel P, Smith WHF, Scharroo R, Luis JF, Wobbe F (2013) Generic mapping tools: improved version released. EOS Trans Am Geophys Union 94:409–410

W3C (World Wide Web Consortium) (2003) Extensible Markup Language (XML). http://www.w3.org/XML/. Accessed 10 Jan 2015

W3C (World Wide Web Consortium) (2010) Scalable Vector Graphics (SVG). http://www.w3.org/Graphics/SVG/. Accessed 10 Jan 2015

Yang Q, Snyder JP, Tobler WR (2000) Map projection transformation: principles and applications. Taylor and Francis, New York