REVISED COASTAL RELIEF MODEL OF SOUTHERN CALIFORNIA: PROCEDURES, DATA SOURCES AND ANALYSIS

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1. INTRODUCTION

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed a revised regional bathymetric-topographic model for the area of Southern California. This model incorporates the most recent, publicly available bathymetric data to update the Southern California volume of NGDC's U.S. Coastal Relief Model (CRM), which provides a comprehensive view of the U.S. coastal zone by integrating offshore bathymetry with land topography. The Southern California CRM includes data from a variety of sources, including multibeam swath sonar bathymetry surveys from various academic institutions; NDGC’s digital elevation models of the coastline; the U.S. Geological Survey (USGS) topographical datasets; and other federal government agencies and academic institutions. The data are assembled in a gridded format referenced to a vertical datum of Mean Sea Level (MSL), and a horizontal datum of North American Datum of 1983 (NAD 83). First, 1 arc-second grids of areas 1° in longitude by 1° in latitude were developed for the areas close to the shoreline, providing high-resolution representation of the bathymetry and topography of the seafloor in coastal waters. For areas deeper than 1500 meters, 3 arc-second grids of 1° by 1° areas were developed. The resulting model provides an improved bathymetric representation of Southern California that will support a wide variety of applications, including coastal processes, ecosystems and habitat research, coastal resource management, community development planning, coastal hazard mitigation and community preparedness.

This report provides a summary of the data sources and methodology used to develop the Southern California CRM.

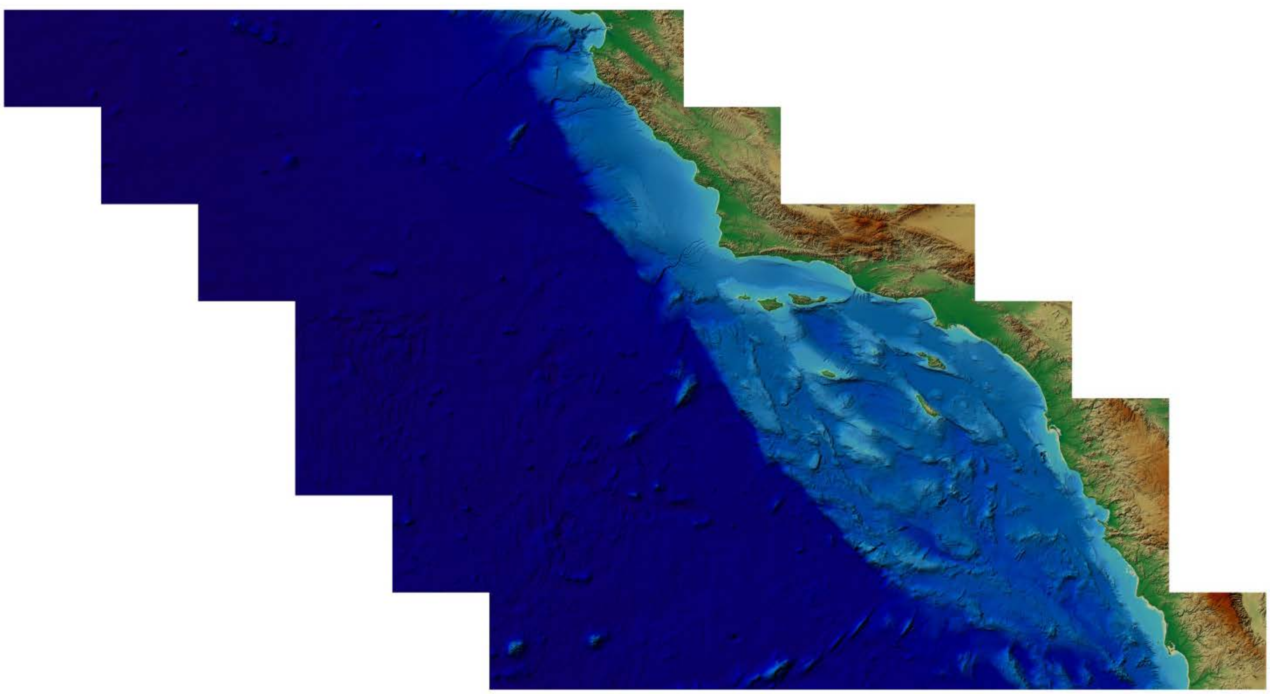

Figure 1: Shaded relief image of the Southern California CRM.

2. STUDY AREA

The Southern California CRM provides regional coverage of the area from 30° to 37° N latitude, and 155.5° to 128° W longitude. The CRM integrates bathymetry and topography to represent Earth's surface and covers the cities of Monterey, San Luis Obispo, Ventura, Santa Monica, Los Angeles and San Diego, as well as coastal areas in Baja California. The area also includes multiple points of interest, including two National Marine Sanctuaries at Monterey Bay and Channel Islands National Park, as well as the San Clemente U.S. Navy Station and Camp Pendleton Marine Corps Base in Oceanside (Fig. 2).

The Southern California region features a wide variety of coastal environments, including sandy beaches, rocky headlands, and sheltered embayments. These environments are extremely dynamic due to the region's long history of tectonic activity. The San Andreas Fault system forms a complex boundary between the North American and Pacific plates, extending more than 1,300 km from the Gulf of California to the offshore region of Mendocino County in Northern California. Within this zone are hundreds of strike-slip faults, making Southern California extremely prone to earthquakes, landslides, and tsunamis. Some areas of Southern California also show evidence of recent volcanic activity.

The offshore area between the coast of Southern California and the continental slope is known as the Continental Borderland. This series of generally northwest-trending basins and ridges are characterized by a variety of features, including volcanic islands, undersea calderas, atolls, craters, and fault lines. This region is home to highly diverse marine life, and has been an area of ecologic and historical interest for decades. The Patton Escarpment marks the edge of the continental shelf, and is a relict accretionary wedge from a subduction zone that was active in the Mesozoic into the Cenozoic Eras.

Southern California is home to more than 18 million people, and the coastal region provides a large tourism outlet and economic niche for local residents. Southern California is also home to some of the nation's most prestigious Universities and research institutes. However, despite ongoing research in the field, the geologic history of the region is still poorly understood, and the development of detailed coastal relief and digital elevation models of the offshore region is of great interest. It is through these models that researchers can gain a better understanding of the tectonic history and seafloor processes of Southern California.

Figure 2: Points of interest in the Southern California region. Image courtesy the Perry-Castañeda Library, University of Texas at Austin.

3. METHODOLOGY

The first version of the Southern California CRM (NOAA NGDC) was published in 2003 and was available for download from the NGDC website (http://www.ngdc.noaa.gov/mgg/coastal/crm.html). This model only provided coverage from 114º to 124º W, and 32º to 37º N (Fig 3). The data were gridded to a resolution of 3 arc-seconds, or approximately 90 meters, and had poor or missing coverage in large portions of this extent.

To develop a better model of the bathymetry of the region, the revised Southern California CRM was developed to meet the specifications in Table 1. This new model would provide a larger coverage area, extending past the limit of the U.S. Exclusive Economic Zone (Fig. 4). Data close to the shoreline were gridded to a resolution of 1 arc-second, or approximately 30 meters, and provided higher-resolution bathymetry in areas shallower than 1500 m. Data father offshore, past the 1500 meter isobaths, and in regions with less coverage were gridded to a resolution of 3 arc-seconds.

Using previously analyzed multibeam data as well as new survey data available through various resources, the best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: the North American Datum of 1983[1] (NAD 83) and Mean Sea Level (MSL). Data were gathered in an area slightly larger (0.1°) than the boundary extents. This data "buffer" ensured that gridding occurred across, rather than along, the CRM boundaries to prevent edge effects. Data processing and evaluation, and CRM assembly and assessment are described in the following subsections.

Table 1: Specifications for the Southern California CRM.

Grid Area	Southern California
Coverage Area	115.5º to 128.0º W; 30.0º to 37.0º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	North American Datum of 1983 (NAD 83)
Vertical Datum	Mean Sea Level (MSL)
Vertical Units	Meters
Cell Size	a) 1 arc-second
	b) 3 arc-second
Grid Format	NetCDF

1. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the CRM. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant. NAD 83 is restricted to North America, while WGS 84 is a global datum. At the scale of this CRM, WGS 84 and NAD 83 geographic are effectively identical and may be used interchangeably.

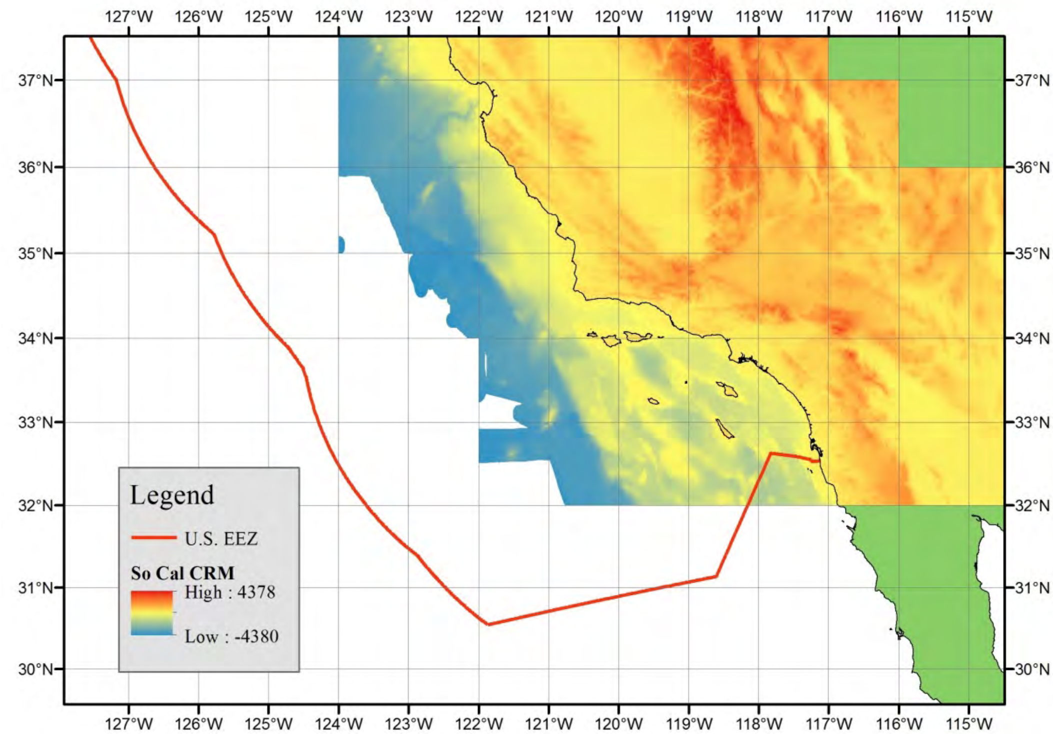

Figure 3: Color relief image of the first version of the Southern California CRM. The limit of the U.S. Exclusive Economic Zone for the Pacific Ocean is depicted in red.

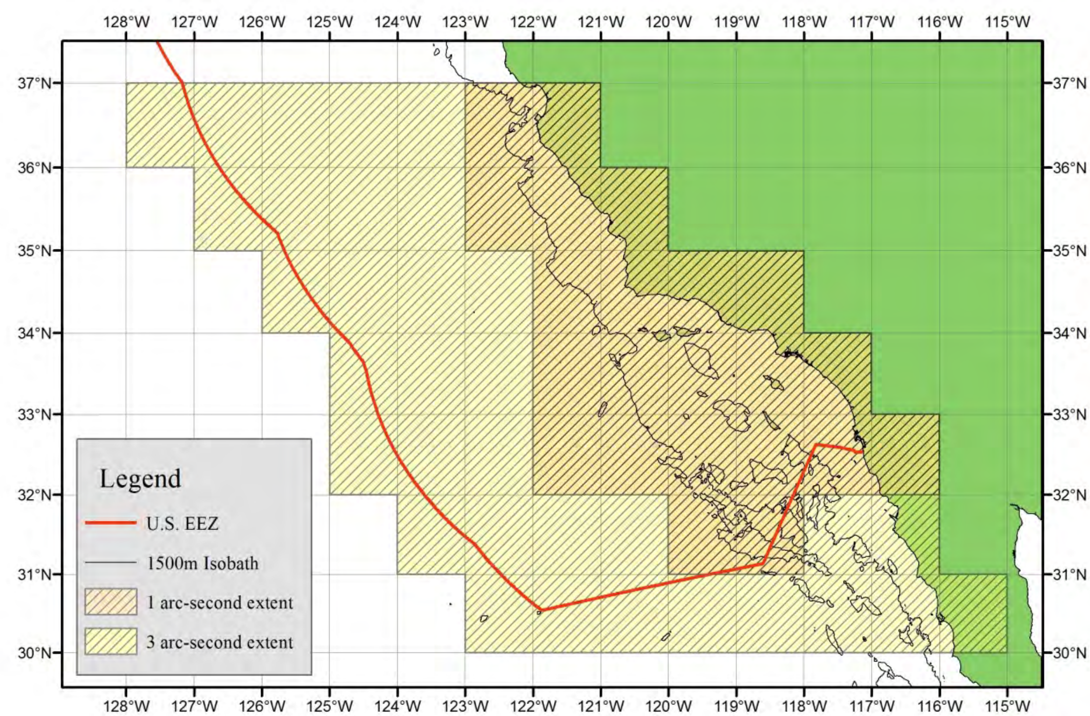

Figure 4: Extents for the revised Southern California CRM. The limit of the U.S. Exclusive Economic Zone for the Pacific Ocean is depicted in red. The 1500 meter isobath is depicted in black.

3.1 Data Sources and Processing

Bathymetric and topographic digital datasets (Fig. 5) were obtained from several U.S. federal, state and local agencies, and academic institutions including: NGDC; Scripps Institute of Oceanography (SIO); Woods Hole Oceanographic Institute (WHOI); the Marine Geoscience Data System (MGDS) at Lamont-Doherty Earth Observatory; and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Topographic datasets were obtained from the U.S. Geological Survey National Elevation Dataset (NED), the NASA space shuttle radar topography mission (SRTM) processed by the Consultative Group for International Agriculture Research (CGIAR). These datasets were then converted to ESRI *ArcGIS* shapefiles for viewing in the *ArcGIS* program. After visual inspection, individual surveys were displayed in Applied Imagery's *Quick Terrain Modeler (QT Modeler)* for data quality assessment and manual editing. Bathymetric data were gridded using MB-System (Caress and Chayes 1993) and Generic Mapping Tools (GMT) (Wessel and Smith 2005). *QT-Modeler* was used to evaluate processing and gridding techniques.

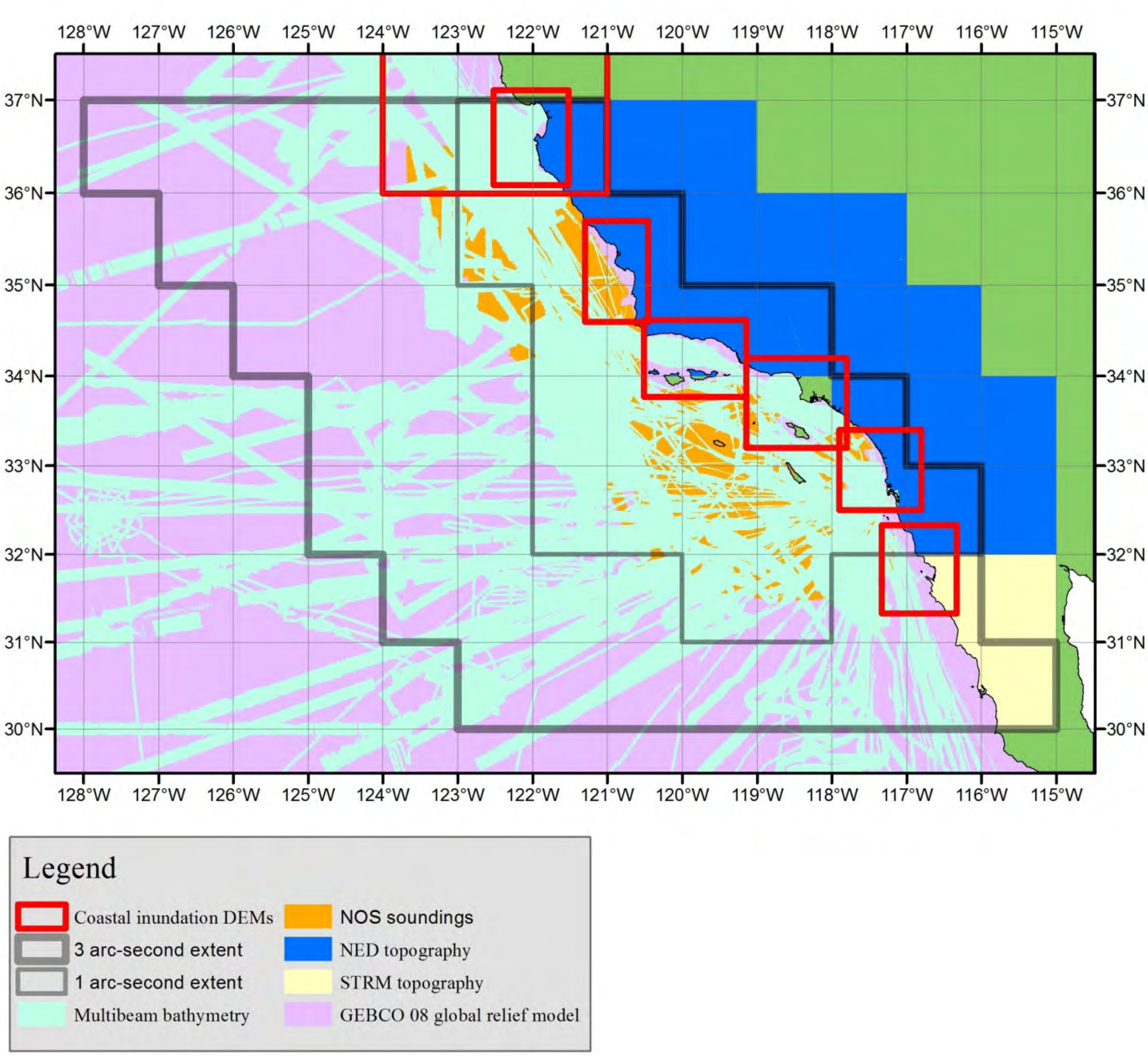

Figure 5: Principle source dataset contributions to the revised Southern California CRM.

3.1.1 Bathymetry

Bathymetric datasets available for use in the compilation of the revised Southern California CRM include 165 multibeam surveys downloaded from the NGDC multibeam database, multibeam surveys from CSUMB, SIO, MGDS, WHOI, and JAMSTEC; NOS hydrographic soundings; and the 2010 General Bathymetric Chart of the Oceans (GEBCO 08) 30 arc-second global relief model (refer to Fig. 5, Table 2).

Table 2: Bathymetric datasets used in compiling the Southern California CRM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*URL*
NGDC	1982 to Present	Multibeam Swath Sonar	Gridded to 1 arc-second	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
SIO	2003 to 2005	Multibeam Swath Sonar	Gridded to 1 arc-second	http://www.marine-geo.org/portals/gmrt/
MGDS	2004	Multibeam Swath Sonar	Gridded to 1 arc-second	http://www.marine-geo.org/portals/gmrt/
WHOI	2007	Multibeam Swath Sonar	Gridded to 1 arc-second	http://dla.whoi.edu/cruises
JAMSTEC	2005	Multibeam Swath Sonar	Gridded to 1 arc-second	http://www.godac.jamstec.go.jp/catalog/data_catalog/index_en.html
NOS	1933-2008	Hydrographic Soundings	Gridded to 1 arc-second	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
GEBCO 08	2010	Global Relief Model	30 arc-second	http://www.gebco.net/data_and_products/gridded_bathymetry_data/

1. **Multibeam swath SONAR surveys**

A total of 173 multibeam swath sonar surveys were available in the Southern California region (Fig. 6). Data were acquired from NGDC's Multibeam Bathymetry Database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html), which is comprised of the original swath sonar surveys conducted principally by the U.S. academic fleet, and 8 additional surveys were acquired from MGDS, WHOI, SIO and JAMSTEC (Fig. 6). A complete list of surveys used in building the revised Southern California CRM is provided in Appendix A.

All surveys have a horizontal datum of WGS 84 geographic and an undefined vertical datum assumed to be equivalent to sea level. The multibeam bathymetry data were gridded at 1 arc-second cell size near the shoreline and 3 arc-second cell size across the entire extent, using *MB-System*. *MB-System* is an NSF-funded, free software application specifically designed to manipulate multibeam swath sonar data (http://www.ldeo.columbia.edu/res/pi/MB-System/). The gridded data were converted to shapefiles and checked for erroneous soundings.

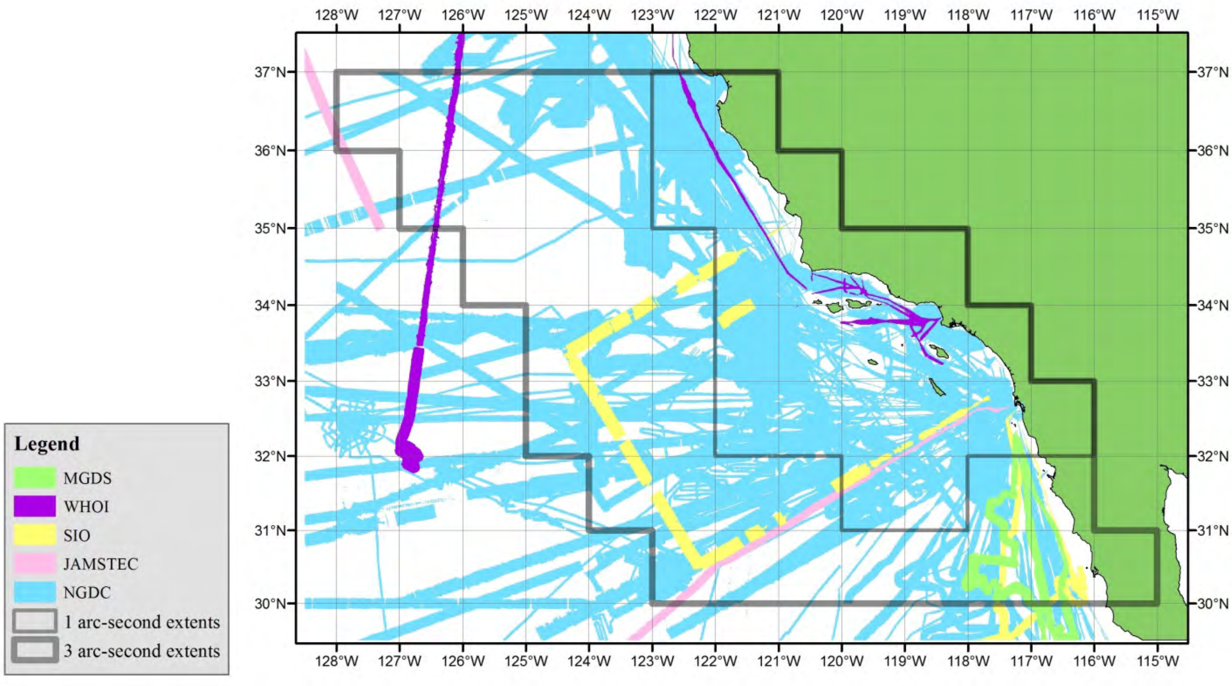

Figure 6: Multibeam coverage for the Southern California region.

2. NOS hydrographic soundings

A total of 47 NOS hydrographic surveys conducted between 1933 and 2008 were used in building the revised Southern California CRM. The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to NAD 83 geographic.

All surveys were extracted from NGDC's online database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original datums. The data were then converted to a vertical datum of MSL using NOAA's Vdatum transformation tool, and then were displayed in ESRI *ArcMap* and reviewed for digitizing errors.

3. GEBCO

For regions not covered by multibeam data, seafloor bathymetry was represented by the 2010 General Bathymetric Chart of the Oceans (GEBCO 08) (Fig. 7). GEBCO 08 has a 30 arc-second, or approximately 1 km, cell size and is referenced to WGS 84 coordinates. This model is coarse at the resolution of the Southern California CRM, however, it provides the only digital constraint over areas with sparse or no bathymetric data. To prevent interpolation, the model data were clipped where multibeam swath sonar data were present.

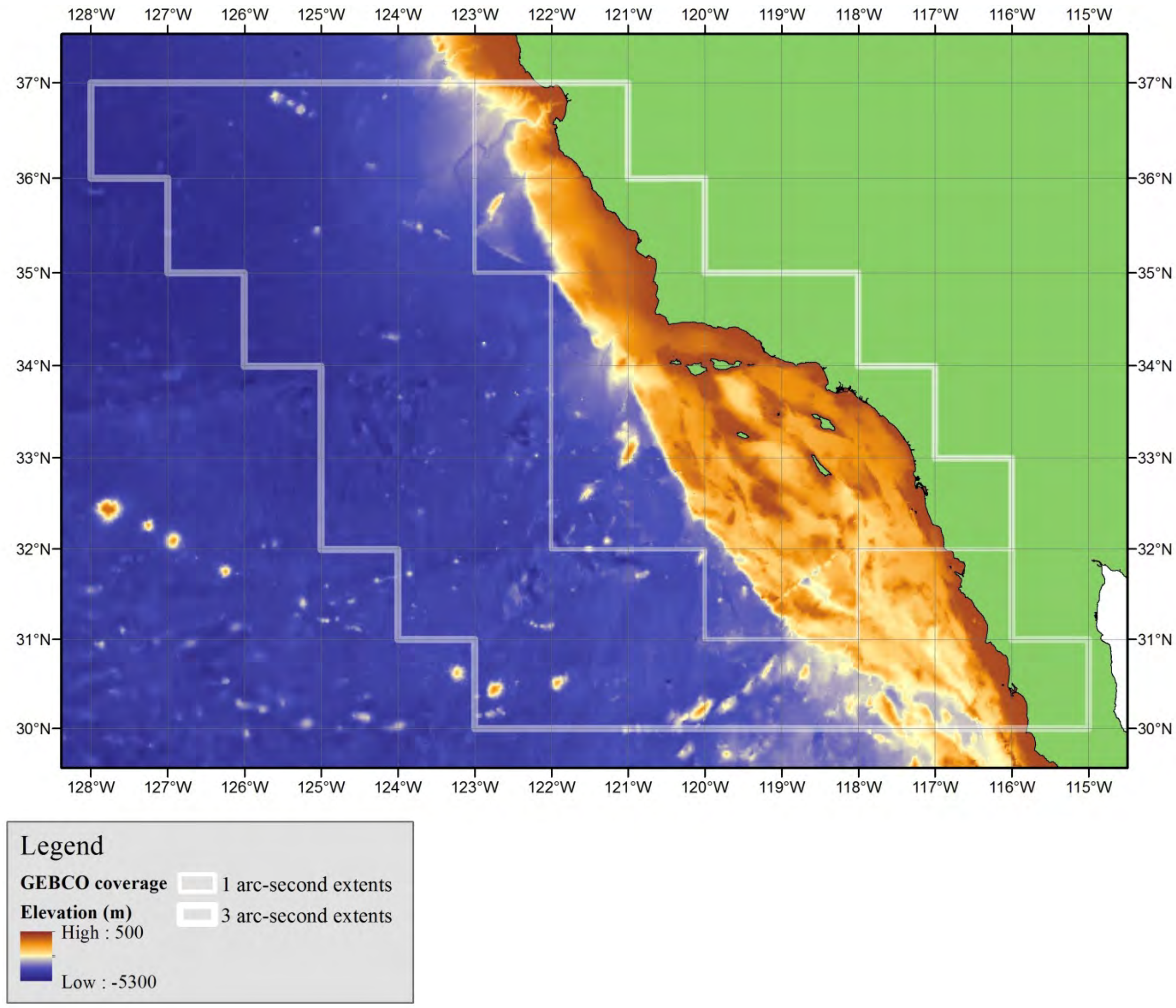

Figure 7: Shaded relief image of bathymetric data extracted from GEBCO 08.

3.1.2 Topography

Topographic datasets for Southern California were obtained from the U.S. Geological Survey: National Elevation Dataset 1/3 arc-second gridded topography (NED), and 3 arc-second NASA space shuttle radar topography (SRTM) processed by the Consultative Group for International Agriculture Research (CGIAR) (refer to Fig.4).

1. **USGS NED topography**

   Topographic datasets for Southern California were obtained from the USGS National Elevation Dataset (NED)[2], which provides a complete 1/3 arc-second coverage of the Southern California region. The data were referenced to a horizontal datum of NAD 83 and a vertical datum of NAVD 88. These data were available for download as raster DEMs on the USGS web site (Fig 8). The bare earth elevations of the NED 1/3 topographic DEM have a vertical accuracy of ± 7 to 15 meters, respectively, but are most likely less than that in low elevation area. Since the resolutions of the NED DEMs are finer than the resolution of the Southern California CRM, the GMT tool *blockmedian* was used as a pre-processor to modify the precision of the DEMs to 1 arc-second. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/).

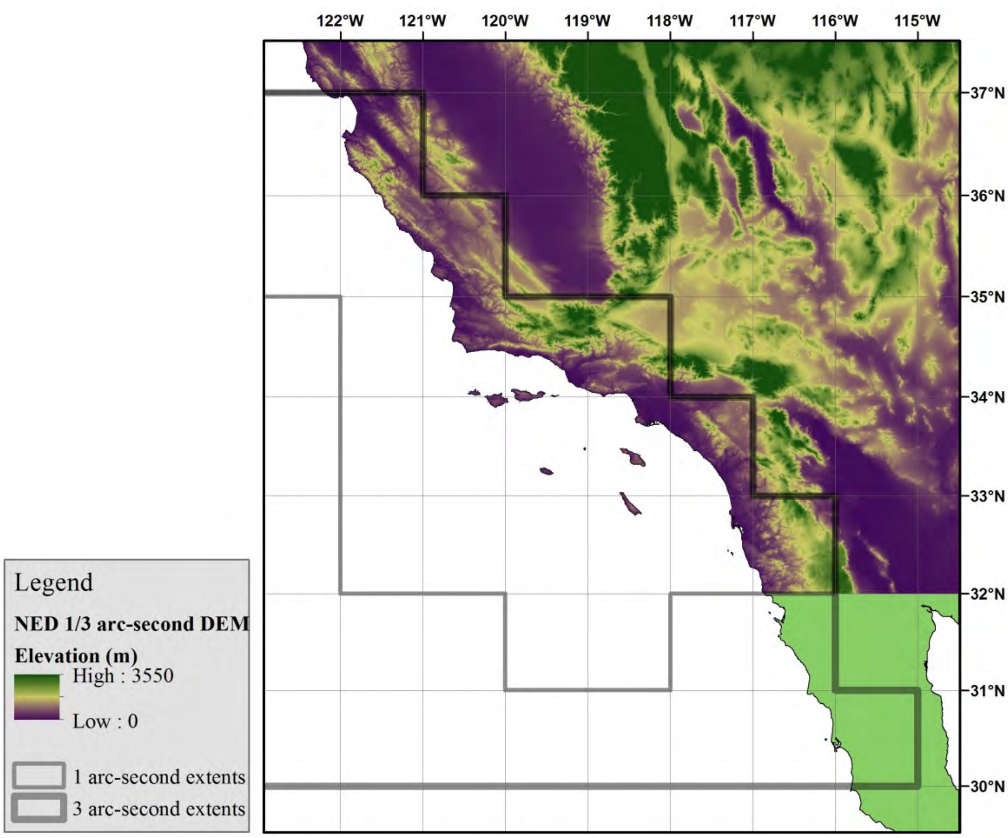

Figure 8: Shaded relief image representing the 1/3 arc-second NED topography used to build the Southern California CRM. The 1/3 arc-second DEMs are only available for the continental U.S., above 32ºN; 1 arc-second data are available for regions extending outside of the U.S.

2. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Alaska. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]

2. NASA space shuttle radar topography

In regions not supported by NED topography and in the Baja California region, topographic datasets were obtained from the NASA space shuttle radar topography (SRTM) mission, which were processed by the Consultative Group for International Agriculture Research (CGIAR) Consortium for Spatial Information (CGIAR-CSI)[3] (Fig. 9). These datasets provide global digital elevation data in 3 arc-second resolution. These data are available for download from the CGIAR website in a variety of different formats. For specific source information, see the CGIAR-CSI website (http://srtm.csi.cgiar.org/).

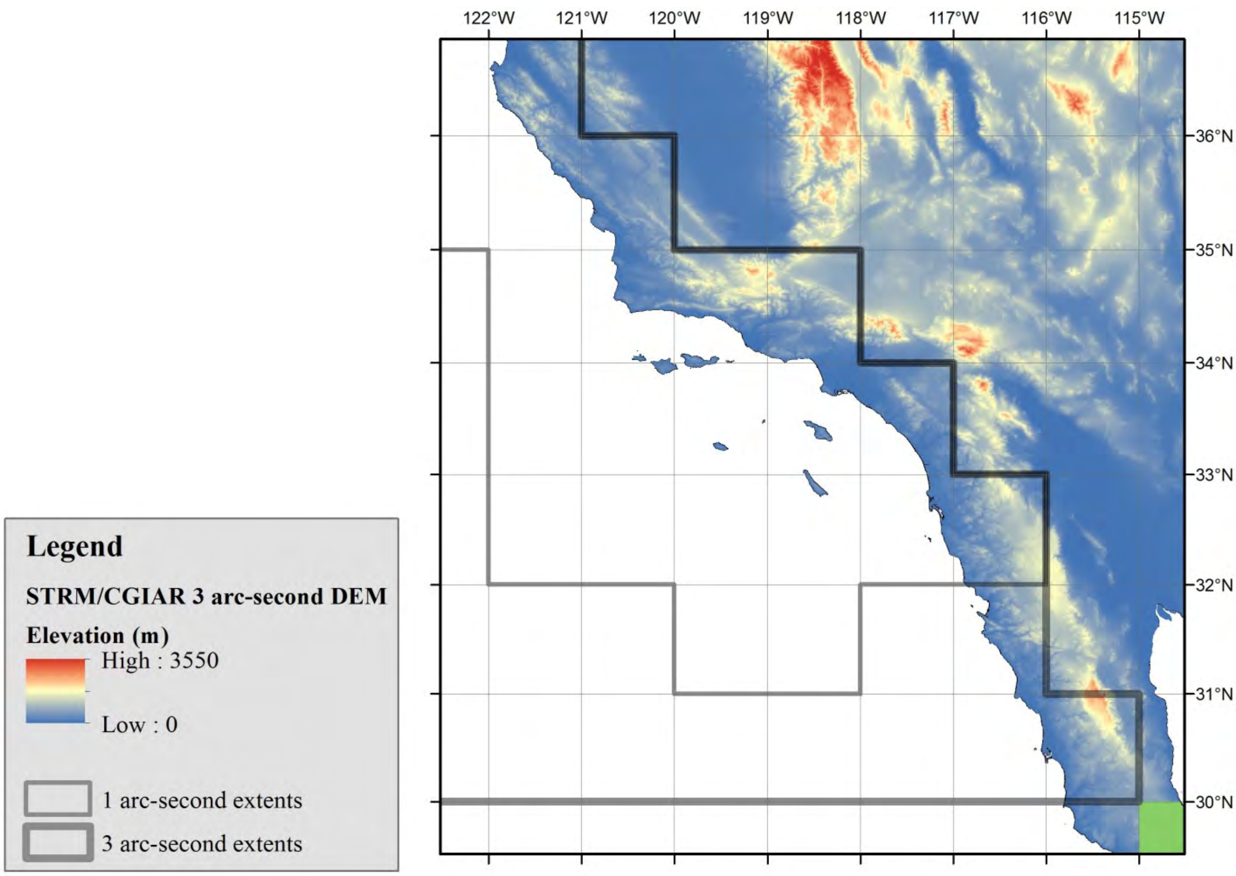

Figure 9: Shaded relief image representing the STRM/CGIAR 3 arc-second topography used to build the Southern California CRM. This dataset was clipped to only include regions not covered by the NED DEMs.

3. The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60 meter long baseline. A description of the SRTM mission can be found in Farr and Kobrick (2000). Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. Length of the acquired swaths range from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take." SRTM was the primary (and pretty much only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected for 222.4 consecutive hours. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending orbit passes) to fill in areas shadowed from the radar beam by terrain. This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. [Extracted from SRTM online documentation]

3.1.3 *Bathymetry-Topography*

NGDC has built high-resolution integrated bathymetric-topographic DEMs for seven coastal regions within the bounds of the Southern California CRM (Fig 10). These DEMs are used to support tsunami forecasting and modeling efforts at the NOAA Center for Tsunami Research, Pacific Marine Environmental Laboratory (PMEL), and the state of California (Table 4). All data were referenced to a horizontal datum of WGS 84. Since the resolutions of the NGDC DEMs are finer than the resolution of the Southern California CRM, the GMT tool *blockmedian* was used as a pre-processor to modify the precision of the DEMs to 1 arc-second.

Table 4: Bathymetric-topographic DEMs used in compiling the Southern California CRM.

Source	*DEM Area*	*Year*	*Data Type*	*Spatial Resolution*	*Original Vertical Datums*
NOAA/ NGDC	Central California	2010	Bathymetric/Topographic DEM	1 arc-second	MHW, NAVD 88
NOAA/ NGDC	Monterey Bay	2012	Bathymetric/Topographic DEM	1/3 arc-second	MHW
NOAA/ NGDC	Port San Luis	2011	Bathymetric/Topographic DEM	1/3 arc-second	MHW
NOAA/ NGDC	Santa Barbara	2008	Bathymetric/Topographic DEM	1/3 arc-second	MHW
NOAA/ NGDC	Santa Monica	2010	Bathymetric/Topographic DEM	1/3 arc-second	MHW, NAVD 88
NOAA/ NGDC	San Diego	2012	Bathymetric/Topographic DEM	1/3 arc-second	MHW, NAVD 88
NOAA/ NGDC	Port Ensenada	2006	Bathymetric/Topographic DEM	3 arc-second	MHW

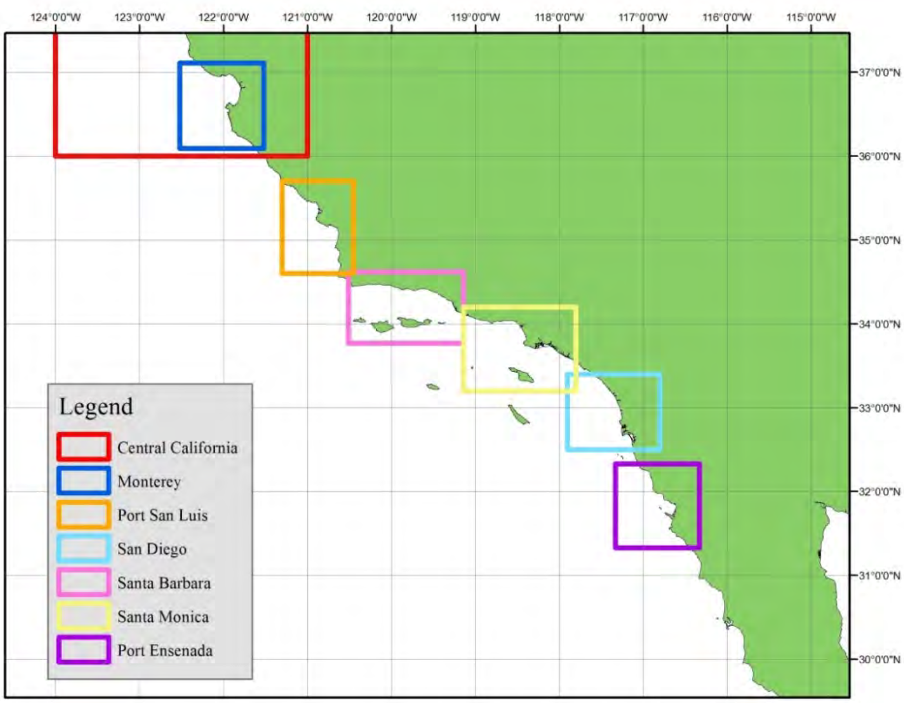

Figure 10: Coverage of high resolution integrated bathymetric and topographic DEMs developed by NGDC.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Southern California CRM were originally referenced to a number of vertical datums including MHW, MSL, and NAVD 88. All datasets were assumed to be referenced to MSL, or were transformed to MSL using a constant offset.

1) **Bathymetric data**

Multibeam surveys that fell within the 1 and 3 arc-second extents, as well as the GEBCO 08 global relief model, were assumed to be referenced to MSL, and no vertical datum transformations were applied. NOS hydrographic soundings were originally referenced to MLLW, and were converted to a vertical datum of MSL using NOAA's *Vdatum* transformation tool.

2) **Topographic data**

The CGIAR-CSI topographic data were originally referenced to a vertical datum of MSL, so no transformations were applied.

USGS NED topographic data were originally referenced to NAVD 88, and were converted to a vertical datum of MSL. The same transformation convention that was used on bathymetric data was applied to the topographic data. Each 1° by 1° NED raster was viewed in *ArcMap*, and a vertical shift was applied to each tile, depending on proximity to a given DEM extent. These coastline and inland topographic conversions are summarized in Figure 11 below.

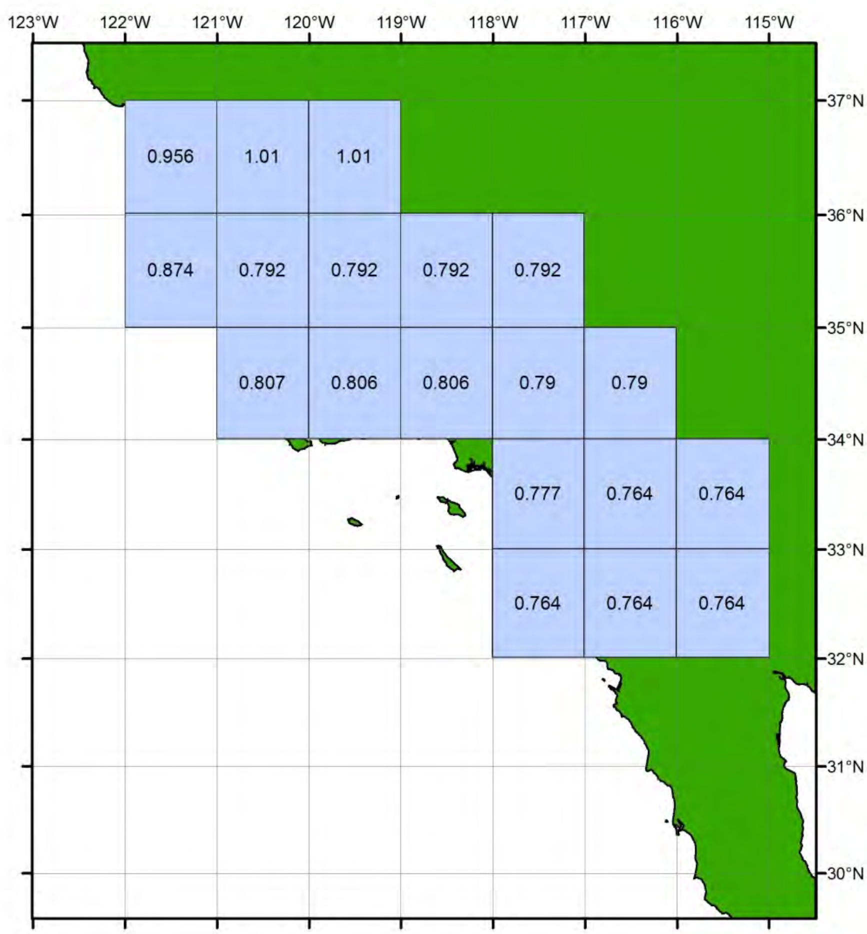

Figure 11: Constant offsets used to convert between MSL and NAVD 88 vertical datums.

3) Bathymetric-Topographic data

Data incorporated from Southern California DEMs were originally referenced to either MHW or NAVD 88. Because the model includes areas that extend inland, the data were converted to a vertical datum of MSL using *ArcCatalog*, by adding a constant offset based on the average difference from MHW or NAVD 88 to MSL at tidal stations within the DEM regions (Table 5). Safe Software's *FME* data translation tool package was used to convert this DEM data into formats appropriate for gridding.

Table 5: Relationship between MSL and other vertical datums used in the Southern California CRM.

DEM	Original Vertical Datum	Difference to MSL
Central California	NAVD 88	1.01
Monterey	MHW	-0.556
Port San Luis	MHW	-0.573
Santa Barbara	MHW	-0.556
Santa Monica	NAVD 88	0.79
San Diego	NAVD 88	0.764
Ensenada	MHW	-0.565

3.2.1 Horizontal datum transformations

Source datasets used in compiling the revised Southern California CRM were originally referenced to NAD 83 or WGS 84 horizontal datums. These horizontal datums are effectively equivalent at this scale, so no horizontal datum conversion was needed.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After datum transformations were applied, the resulting ESRI *ArcGIS* shapefiles were checked in ESRI's *ArcMap* application, and Applied Imagery's *Quick Terrain Modeler* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Data values over the open ocean in the land topography datasets (NED and SRTM/CGIAR). Each dataset required automated clipping to the coastline
- Sparse bathymetric data in the deep ocean
- Sparse bathymetric data at the coastline
- Scattered or inaccurate soundings in some older surveys
- Inconsistencies among overlapping datasets
- Consistent noise in both high- and low-resolution surveys

3.3.2 Smoothing of bathymetric data

Bathymetric data tends to be sparse in regions far offshore, and at the resolution of the 3 arc-second Southern California CRM, little multibeam data is available to grid. In order to cut down on errors due to interpolation with lower-resolution datasets, a 1 arc-second 'pre-surface' was generated using Generic Mapping Tools (GMT), an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The GEBCO 08 30 arc-second bathymetric point data, in xyz format, were combined with the finer-resolution multibeam swath sonar soundings into a single file. To provide a buffer along the entire coastline, the extracted points were limited to elevations below 0 meters. This ensured that the grid only contained bathymetric data. The GMT tool 'surface' was then applied to interpolate values for cells without data. The netCDF grid created by 'surface' was converted into an ESRI Arc ASCII grid file using the MBSystem tool 'mbm_grd2arc'. Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid with the combined coastline (to eliminate data interpolation into land areas). The pre-surface was converted to a shapefile and then exported as a xyz file for use in the final gridding process.

3.3.3 Building the Southern California CRM with MB-System

MB-System was used to create the 1 and 3 arc-second Southern California CRM. The MB-System tool 'mbgrid' applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 8. Greatest weight was given to the high-resolution DEM data. Least weight was given to the pre-surfaced bathymetric grid and bathymetry from the GEBCO 08 Global Relief Model.

A shell script was written to parse the CRM extents into 1° by 1° "tiles": 33 tiles to cover the 3 arc-second area, and 22 tiles to cover the 1 arc-second area. This schema made the map more manageable, as well as easier to view and edit. This script included a data buffer which built the tiles using extents slightly larger than the final "clipped" 1° by 1° tiles, in order to prevent warping and edge effects between adjacent tiles. Data were gridded in 1° by 1° tiles and were converted into an ESRI Arc ASCII grid file for viewing in *ArcGIS*.

Table 7: Data hierarchy used to assign gridding weight in MB System

Dataset	*Relative Gridding Weight*
NGDC DEMs	100
NOS hydrographic soundings	10
USGS NED topographic DEM	10
STRM/CGIAR topographic DEM	10
Multibeam swath sonar surveys	1
GEBCO 08 bathymetry	0.1
Pre-surfaced bathymetric grid	0.1

3.4 Quality Assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Southern California CRM is dependent upon the DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features have an estimated horizontal accuracy of about 30 meters, based on the cell size of the Southern California CRM. Bathymetric features in areas covered by multibeam swath sonar surveys are resolved within a few tens of meters in shallow water, and to a few hundred meters in deep-water areas; their positional accuracy is limited by the sparseness of surveys in offshore regions.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Southern California CRM is also dependent upon DEM cell size and the source datasets contributing to grid cell values. Topographic data have an estimated vertical accuracy between 7 meters for NED DEMs and 16 meters for SRTM DEMs. Bathymetric values have an estimated accuracy between 0.1 meters and 5% of water depth. Those values were derived from the wide range of sounding measurements from the early 20th century to recent, GPS-navigated multibeam swath sonar survey. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

4. SUMMARY

A revised, integrated bathymetric-topographic digital elevation model of the Southern California region, with cell spacing of 1 arc-second and 3 arc-seconds, was developed by NOAA's National Geophysical Data Center (NGDC). The best available digital data from U.S. federal agencies were obtained by NGDC, shifted to a common horizontal datum, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT, Quick Terrain Modeler, and MB-System software. The methodology used to build the revised model greatly improved upon the original Southern California CRM, and will enable updating of the U.S. CRM for other U.S. coastal regions.

Recommendations to improve the revised Southern California CRM, based on NGDC's research and analysis, are listed below:

- Conduct bathymetric coastal surveys between NGDC DEM extents.
- Conduct thorough, bathymetric deep-water multibeam surveys across EEZ boundaries.
- Obtain bathymetric data along the coast of western Baja California.

5. ACKNOWLEDGEMENTS

The authors would like to thank Kelly Carignan, Michael Sutherland, and Jesse Varner (NGDC) for their contributions to developing the Southern California CRM.

6. REFERENCES

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Carignan, K.S., L.A. Taylor, B.W. Eakins, R.J. Caldwell, D.Z. Friday, P.R. Grothe, and E. Lim, 2011. Digital Elevation Models of Central California and San Francisco Bay: Procedures, Data Sources and Analysis, NOAA Technical Memorandum NESDIS NGDC-52, U.S. Dept. of Commerce, Boulder, CO, 49 pp. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/665

Carignan, K.S., L.A. Taylor, B.W. Eakins, R.R. Warnken, E. Lim, P.R. Medley. Digital Elevation Models of Santa Barbara, California: Procedures, Data Sources and Analysis. 2009. NOAA Technical Memorandum NESDIS NGDC-29. U.S. Dept. of Commerce, Boulder, CO, 30 pp. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/603

Friday, D.Z., L.A. Taylor, B.W. Eakins, K.S. Carignan, P.R. Grothe, E. Lim. Digital Elevation Models of Port San Luis, California: Procedures, Data Sources and Analysis. 2011. NOAA National Geophysical Data Center technical report, Boulder, CO, 28 pp. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/3164

Grothe, P.G., L.A. Taylor, B.W. Eakins, K.S. Carignan, D.Z. Friday, and M. Love, 2012. Digital Elevation Models of Monterey, California: Procedures, Data Sources and Analysis, NOAA National Geophysical Data Center technical report, Boulder, CO, 15 pp. http://www.ngdc.noaa.gov/dem/squareCellGrid/download/3545

Lim, E., B.W. Eakins, R. Wigley. Coastal Relief Model of Southern Alaska: Procedures, Data Sources and Analysis. 2011. NOAA Technical Memorandum NESDIS NGDC-43, 22 pp. http://www.ngdc.noaa.gov/mgg/coastal/s_alaska.html

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7. DATA PROCESSING SOFTWARE

ArcGIS v. 10.1, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

GDAL v. 1.7.1 – Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://www.gdal.org/

GMT v. 4.5.9 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0, free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Quick Terrain Modeler v.8.0.0, developed by Johns Hopkins University Applied Physics Laboratory, licensed by Applied Imagery, Silver Spring, Maryland, http://www.appliedimagery.com/index.html

VDatum Transformation Tool v. 2.2.7 – California - San Francisco Bay Vicinity, v. 01 and Monterey Bay to Morro Bay, v. 01 – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/

8. APPENDICES

Appendix A

List of multibeam swath sonar surveys used in building the revised Southern California CRM

The following 173 multibeam swath sonar surveys were available in the Southern California region and fell into the 1 arc-second and 3 arc-second extents. Surveys highlighted in red were not used in the CRM development.

Survey ID	*Year*	*Ship Name*	*Collecting Institution*	*Data Source*
981107RR	1998	Roger Revelle	Scripps Institute of Oceanography (SIO)	NGDC
A125L19	1991	Atlantis II	Woods Hole Oceanographic Institute (WHOI)	NGDC
A-3-98-SC	1998	Ocean Alert	U.S. Geological Service (USGS)	NGDC
ACLV01RR	1999	Roger Revelle	SIO	NGDC
AMAT09RR	2006	Roger Revelle	Rolling Deck to Repository (R2R)	NGDC
AMLR92T	1992	Surveyor	NOAA	NGDC
AMLR94	1994	Surveyor	NOAA	NGDC
ARIA01WT	1982	Thomas Washington	SIO	NGDC
ARIA03WT	1982	Thomas Washington	SIO	NGDC
AT03L27	1998	Atlantis	WHOI	NGDC
AT03L42	1999	Atlantis	WHOI	NGDC
AT03L49	2000	Atlantis	WHOI	NGDC
AT07L09	2002	Atlantis	WHOI	NGDC
AT07L14	2002	Atlantis	WHOI	NGDC
AT11L19	2004	Atlantis	WHOI	NGDC
AT11L33	2005	Atlantis	WHOI	NGDC
AT15L20	2007	Atlantis	WHOI	NGDC
AT15L53	2009	Atlantis	WHOI	NGDC
AT15L07	2006	Atlantis	WHOI	NGDC
AT15L08	2006	Atlantis	WHOI	NGDC
AT15L11	2006	Atlantis	WHOI	NGDC
AT15L19	2007	Atlantis	WHOI	WHOI
AT15L24	2007	Atlantis	WHOI	WHOI
AT18L06	2011	Atlantis	WHOI	NGDC
AT18L11	2011	Atlantis	WHOI	NGDC
AT3L13	1998	Atlantis	WHOI	NGDC
AT3L14	1998	Atlantis	WHOI	NGDC
AT3L20	1998	Atlantis	WHOI	NGDC
AT3L6	1997	Atlantis	WHOI	NGDC
AVON01MV	1990	Melville	SIO	NGDC
AVON08MV	1999	Melville	SIO	NGDC

AVON10MV	1999	Melville	SIO	NGDC
AVON11MV	1999	Melville	SIO	NGDC
AVON12MV	1999	Melville	SIO	NGDC
BMRG01MV	1995	Melville	SIO	NGDC
BMRG09MV	1996	Melville	SIO	NGDC
BOLT02MV	2008	Melville	SIO	NGDC
BONZ02WT	1982	Thomas Washington	SIO	NGDC
BONZ03WT	1982	Thomas Washington	SIO	NGDC
C-1-96-SC	1996	Coastal Surveyor	USGS	NGDC
C-1-99-SC	1998	Coastal Surveyor	USGS	NGDC
CALF01RR	1996	Roger Revelle	SIO	NGDC
CALF03RR	1996	Roger Revelle	SIO	NGDC
CERE02WT	1982	Thomas Washington	SIO	NGDC
CERE04WT	1982	Thomas Washington	SIO	NGDC
Channel	1998	Ocean Alert	Monterey Bay Aquarium Research Institute (MBARI)	NGDC
CHIL19VG	1992	AGOR Vidal Gormaz	SIO	NGDC
CNTL01RR	2002	Roger Revelle	SIO	NGDC
CNTL02RR	2002	Roger Revelle	SIO	NGDC
CNTL03RR	2003	Roger Revelle	SIO	NGDC
CNTL04RR	2003	Roger Revelle	SIO	NGDC
CNTL06RR	2003	Roger Revelle	SIO	NGDC
CNTL07RR	2003	Roger Revelle	SIO	SIO
CNTL08RR	2003	Roger Revelle	SIO	NGDC
CNTL09RR	2003	Roger Revelle	SIO	NGDC
COOK25MV	2002	Melville	SIO	NGDC
CORE01MV	1999	Melville	SIO	NGDC
CRGN01WT	1987	Thomas Washington	SIO	NGDC
DANA01RR	2003	Roger Revelle	SIO	NGDC
DANA07RR	2004	Roger Revelle	SIO	MGDS
DANA08RR	2004	Roger Revelle	SIO	MGDS
DELV02RR	1996	Roger Revelle	SIO	NGDC
DRFT01RR	2001	Roger Revelle	SIO	NGDC
DRFT16RR	2002	Roger Revelle	SIO	NGDC
E-1-04-SC	2004	Maurice Ewing	Lamont-Doherty Earth Observatory (LDEO)	NGDC
ENCR01WT	1992	Thomas Washington	SIO	NGDC
ENCR02WT	1992	Thomas Washington	SIO	NGDC
EW0209	2002	Maurice Ewing	LDEO	NGDC
EW0210	2002	Maurice Ewing	LDEO	NGDC
EW0406	2004	Maurice Ewing	LDEO	NGDC
EW0407	2004	Maurice Ewing	USGS	NGDC

EW0410	2004	Maurice Ewing	LDEO	NGDC
EW9414	1994	Maurice Ewing	LDEO	NGDC
EW9415	1994	Maurice Ewing	LDEO	NGDC
EW9504	1995	Maurice Ewing	LDEO	NGDC
EW9506	1995	Maurice Ewing	LDEO	NGDC
EW9708	1997	Maurice Ewing	LDEO	NGDC
EW9709	1997	Maurice Ewing	LDEO	NGDC
EW9903	1999	Maurice Ewing	LDEO	NGDC
EW9904	1999	Maurice Ewing	LDEO	NGDC
EX0908	2009	Okeanos Explorer	NOAA	NGDC
GENE04RR	1997	Roger Revelle	SIO	NGDC
GLOR00MV	1992	Melville	SIO	NGDC
GLOR01MV	1992	Melville	SIO	NGDC
HLY03TA	2003	USCGC Healy	R2R	NGDC
HLY05TI	2005	USCGC Healy	R2R	NGDC
HNRO18RR	2000	Roger Revelle	SIO	NGDC
INSV01WT	1990	Thomas Washington	SIO	NGDC
JNUS01WT	1992	Thomas Washington	SIO	NGDC
KIWI01RR	1997	Roger Revelle	SIO	NGDC
KIWI02RR	1997	Roger Revelle	SIO	NGDC
KM0819	2008	Kilo Moana	SIO	NGDC
KN195-08	2009	Knorr	WHOI	NGDC
KN195-09	2009	Knorr	WHOI	NGDC
KNOX01RR	2006	Roger Revelle	SIO	NGDC
KRUS06RR	2004	Roger Revelle	SIO	NGDC
LFEX01MV	2004	Melville	SIO	NGDC
LFEX02MV	2004	Melville	SIO	NGDC
LPRS02RR	2002	Roger Revelle	SIO	NGDC
LWAD99MV	1999	Melville	SIO	NGDC
MCD0212	2002	USNS McDonnell 51	U.S. Navy	NGDC
MGL0810	2008	Marcus G. Langseth	LDEO	NGDC
MGL1102	2011	Marcus G. Langseth	LDEO	NGDC
MGL1104	2011	Marcus G. Langseth	LDEO	NGDC
MGL1108	2011	Marcus G. Langseth	LDEO	NGDC
MGLN01MV	2006	Melville	SIO	NGDC
MR05-04	2005	Mirai	JAMSTEC	JAMSTEC
MR05-05	2005	Mirai	JAMSTEC	JAMSTEC
MOCE05MV	1999	Melville	SIO	NGDC
Monterey	1998	Ocean Alert	MBARI	NGDC
MRTN01WT	1984	Thomas Washington	SIO	NGDC
MRTN15WT	1985	Thomas Washington	SIO	NGDC

MV1009	2010	Melville	SIO	NGDC
MV1011	2010	Melville	SIO	NGDC
MV1105	2011	Melville	SIO	NGDC
MV1106	2011	Melville	SIO	NGDC
NALU01RR	2000	Roger Revelle	SIO	NGDC
NBP0206	2002	Nathaniel B. Palmer	LDEO	NGDC
NBP0207	2002	Nathaniel B. Palmer	LDEO	NGDC
NECR01RR	2000	Roger Revelle	SIO	NGDC
NEMO04MV	2000	Melville	SIO	NGDC
NPAL98MV	1998	Melville	SIO	NGDC
NV9704MV	1997	Melville	SIO	NGDC
OXMZ01MV	1999	Melville	SIO	NGDC
PACS03MV	1998	Melville	SIO	NGDC
PANR01MV	1997	Melville	SIO	NGDC
PANR08MV	1998	Melville	SIO	NGDC
PASC01WT	1983	Thomas Washington	SIO	NGDC
PASC05WT	1983	Thomas Washington	SIO	NGDC
PHNX03MV	1992	Melville	SIO	NGDC
PHNX04MV	1992	Melville	SIO	NGDC
Pioneer	1998	Ocean Alert	MBARI	NGDC
PLUM01WT	1990	Thomas Washington	SIO	NGDC
PLUM09WT	1990	Thomas Washington	SIO	NGDC
PPTU01WT	1985	Thomas Washington	SIO	NGDC
PPTU11WT	1986	Thomas Washington	SIO	NGDC
RAIT01WT	1988	Thomas Washington	SIO	NGDC
RAIT03WT	1988	Thomas Washington	SIO	NGDC
RAPA00WT	1990	Thomas Washington	SIO	NGDC
RAPA01WT	1990	Thomas Washington	SIO	NGDC
REM-01MV	1993	Melville	SIO	NGDC
REM-02MV	1993	Melville	SIO	NGDC
REVT01RR	1996	Roger Revelle	SIO	NGDC
REVT02RR	1996	Roger Revelle	SIO	NGDC
REVT03RR	1996	Roger Revelle	SIO	NGDC
RNDB01WT	1988	Thomas Washington	SIO	NGDC
RNDB03WT	1988	Thomas Washington	SIO	NGDC
RNDB18WT	1989	Thomas Washington	SIO	NGDC
Rodrigue	1998	Ocean Alert	MBARI	NGDC
RSCN01MV	1997	Melville	SIO	NGDC
S-10-09-MB	2009	Parke Snavely	USGS	NGDC
S-7-09-MB	2009	Parke Snavely	USGS	NGDC
SANQ01RR	2005	Roger Revelle	SIO	SIO

SEAB0BWT	1981	Thomas Washington	SIO	NGDC
SEAW02RR	2001	Roger Revelle	SIO	NGDC
SERA02WT	1991	Thomas Washington	SIO	NGDC
SMNT01WT	1983	Thomas Washington	SIO	NGDC
SOJN01MV	1996	Melville	SIO	NGDC
SPNT02WT	1984	Thomas Washington	SIO	NGDC
Sur	1998	Ocean Alert	MBARI	NGDC
Taney	1998	Ocean Alert	MBARI	NGDC
TERA01WT	1991	Thomas Washington	SIO	NGDC
TN245	2009	Thomas G. Thomson	SIO	NGDC
TN279	2012	Thomas G. Thomson	SIO	NGDC
TN281	2012	Thomas G. Thomson	SIO	NGDC
TO9001WT	1990	Thomas Washington	SIO	NGDC
TO9002WT	1990	Thomas Washington	SIO	NGDC
Tran2mon	1998	Ocean Alert	MBARI	NGDC
Tran2tan	1998	Ocean Alert	MBARI	NGDC
TUGA01WT	1987	Thomas Washington	SIO	NGDC
TUIM01MV	2005	Melville	SIO	NGDC
TUNE01WT	1991	Thomas Washington	SIO	NGDC
TUNE09WT	1992	Thomas Washington	SIO	NGDC
VANC33MV	2004	Melville	SIO	NGDC
VNTR01WT	1989	Thomas Washington	SIO	NGDC
VNTR03WT	1989	Thomas Washington	SIO	NGDC
WEST00MV	1993	Melville	SIO	NGDC
WEST01MV	1993	Melville	SIO	NGDC
WEST15MV	1995	Melville	SIO	NGDC
WSFL01WT	1990	Thomas Washington	SIO	NGDC

Appendix B

List of NOS hydrographic soundings used in building the revised Southern California CRM

The following 47 NOS hydrographic soundings were available in the Southern California region and fell into the 1 arc-second and 3 arc-second extents. Surveys highlighted in red were not used in the CRM development.

Survey ID	*Year*	*Ship Name*
B00085	Davidson	1986
B00117	Davidson	1987
B00134	Surveyor	1988
B00135	Surveyor	1988
B00157	Davidson	1988
B00210	Discoverer	1990
B00212	Discoverer	1990
B00216	Discoverer	1990
H05332	Virginia I	1933
H05500	Guide	1933
H05508	Pioneer	1933
H05509	Pioneer	1933
H05567	Guide	1934
H05603	Pioneer	1934
H05604	Pioneer	1934
H05611	Guide	1933
H05641	Guide	1934
H05642	Guide	1934
H05646	Pioneer	1933
H05651	Guide	1934
H05671	Guide	1934
H05746	Pioneer	1934
H05775	Pioneer	1933
H05776	Pioneer	1934
H05777	Pioneer	1933
H06116	Pioneer	1935
H06118	Pioneer	1935
H06120	Pioneer	1935
H06121	Pioneer	1935
H06209	Pioneer	1936
H06211	Pioneer	1936
H06258	Pioneer	1937
H06259	Pioneer	1937
H06260	Pioneer	1937
H09065	Pathfinder	1969

H09067	Pathfinder	1969
H09068	Pathfinder	1969
H09112	McArthur	1970
H09113	McArthur	1970
H09253	Rainier	1971
H09254	Rainier	1971
H09274	Rainier	1972
H09276	Rainier	1972
H09467	Fairweather	1974
H09468	Fairweather	1974
H11880	Quicksilver	2008
H11953	Pacific Star	2008