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Towards worldwide height system unification using ocean information

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Abstract

We describe the application of ocean levelling to worldwide height system unification. The study involves a comparison of 'geodetic' and 'ocean' approaches to determination of the mean dynamic topography (MDT) at the coast, from which confidence in the accuracy of state-of-the-art ocean and geoid models can be obtained. We conclude that models are consistent at the sub-decimetre level for the regions that we have studied (North Atlantic coastlines and islands, North American Pacific coast and Mediterranean). That level of consistency provides an estimate of the accuracy of using the ocean models to provide an MDT correction to the national datums of countries with coastlines, and thereby of achieving unification. It also provides a validation of geoid model accuracy for application to height system unification in general. We show how our methods can be applied worldwide, as long as the necessary data sets are available, and explain why such an extension of the present study is necessary if worldwide height system unification is to be realised.

1. Introduction

Worldwide height unification is a long-standing objective of modern geodesy for many practical as well as scientific reasons (Plag and Pearlman, 2009). The key factor in succeeding in that objective is the derivation of an accurate model of the geoid which is the global 'level' surface to which the many individual national and regional datums may be compared and thereby unified. The present paper, and others in this volume, will demonstrate that the success of recent space gravity missions in delivering considerably improved models of the geoid means that the objective of worldwide height system unification at the several-centimetre level is near to being achieved.

In the present paper, we describe the application of ‘ocean levelling’ to the study of height system unification. The investigation involves the use of measurements and modelling to estimate in different ways the Mean Dynamic Topography (MDT) of the ocean along a coastline. The MDT is the difference between the Mean Sea Level (MSL) in the case of tide gauges, or Mean Sea Surface (MSS) in the case of altimetry, and the geoid and has values of between -2 and +1 metres at different points in the ocean.

There are two general ‘approaches’ to determination of the MDT at the coast. In the ‘geodetic approach’, ellipsoidal heights of MSL at tide gauge stations, obtained with the use of Global Positioning System (GPS) receivers geodetically-connected to the tide gauge zeros of stations by means of conventional levelling, are compared to heights of the geoid above the ellipsoid from a geoid model. Alternatively, the ellipsoidal heights of sea level obtained from satellite radar altimetry are compared to geoid model heights. When tide gauge data are used, then clearly this exercise is conducted exactly at the coast, whereas when altimetry data are employed, then the comparison is necessarily performed some tens of km offshore.

The second approach is the ‘ocean’ one. In some early versions of the ‘ocean approach’ to the determination of an MDT, sets of oceanographic and meteorological measurements were made (coastal sea level, ocean currents, temperatures and salinities and air pressures and winds) and analysed in the context of the known equations of motion in the ocean, so as to provide sets of sea surface gradients (e.g. Cartwright and Crease, 1962). Nowadays, it is more convenient and rigorous to make use of ocean numerical models in which the oceanographic information may have been assimilated. The result is a two-dimensional field of the MDT which may be compared to those obtained from the geodetic approach. Figure 1(a) is an example of such a global field of the MDT from an ocean model.

Consistency between the MDT estimates obtained in the different approaches provides confidence in the ocean and geoid models that we use. Once confidence has been obtained in the use of particular models, then the aim is to apply them to height system unification. For example, a validated ocean model can be used to provide estimates of MDT-difference between sections of coastline where different national datums apply, thereby providing a reliable connection between datums. Similarly, a geoid model that has been validated using coastal ocean information is in a good position to be used with confidence in height unification generally, including between countries with no coastlines as there is no reason to believe that the geoid models are intrinsically more precise at the coast.

Section 2 below describes the various data sets and analysis methods that we have employed. The present work is largely restricted to study of MDT along the European and American coastlines of the North Atlantic and the North American Pacific coast, owing to these coastlines possessing many tide gauges with long time series of sea level information and equipped with GPS receivers so that their sea levels may be expressed as ellipsoidal heights within a geocentric reference frame. However, we also refer to two stations in the Mediterranean by way of demonstrating that our methods should be capable of being applied outside of our regions of immediate interest and to any coast equipped with at least one modern (or even historical) tide gauge installation for which the benchmarks have been surveyed by GPS.

Section 3 consists of a comparison of the MDT profiles along the American and European coastlines obtained using the ‘geodetic’ and ‘ocean’ approaches. The geodetic approach makes use of tide gauge and GPS data and of the recently available GOCO03S and higher spatial resolution ‘Extended GOCO03S’ geoid models The ocean approach is demonstrated with the use of one particular model. It will be seen that the consistency of the two approaches in deriving MDT profiles along the different coastlines is at the sub-decimetre level.

Section 4 extends the discussion to include several more ocean models for the ‘ocean approach’, pointing to the sections of coastline where differences in MDT between them are found. This leads to Section 5 wherein the geodetic approach is represented by altimeter rather than tide gauge sea level data. In this section, we make use of state-of-the-art altimetric MSS and geoid models to provide the coastal MDT, and we also refer to previously-published MDT estimates by other authors.

Section 6 returns to the examination of tide gauge data in the geodetic approach in an investigation of two stations in the Mediterranean, a region which was originally outside the scope of our project. However, the consistency of findings at the two stations with those of other coastlines demonstrates that our methods should be applicable worldwide. Section 7 presents a discussion of our results, leading to a summary of the main conclusions in Section 8.

2. Data Sets and Data Processing

This section describes the various data sets used in this paper. We have standardized primarily on the epoch 1993-2002 as that choice provides a good compromise between the availability of tide gauge and altimeter information. However, this choice is not a critical one with regard to demonstrating our methods.

All tide gauge data used are in the form of monthly and annual values of mean sea level (MSL) from the Permanent Service for Mean Sea Level (PSMSL, www.psmsl.org, Woodworth and Player, 2003). The Revised Local Reference (RLR) subset of the PSMSL provides MSL data measured relative to a known Tide Gauge Bench Mark (TGBM) at each site. The RLR stations selected for the present study have TGBMs for which heights are known with respect to the appropriate national datum, and which have been surveyed with GPS equipment or can be connected by local levelling to other marks which have been surveyed by GPS. As a result, the height of the TGBMs and of the MSL values of the tide gauge, can be expressed as geocentric heights above the WGS84 ellipsoid.

We have benefited considerably from collaboration with the Système d'Observation du Niveau des Eaux Littorales (SONEL, www.sonel.org) databank at the University of La Rochelle which has been able to provide us with many of the ellipsoidal heights as part of its GPS data reprocessing activities for the TIGA (TIde GAuge) project of the International GNSS Service and for the Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission. In these cases, we know that the ellipsoidal heights are determined rigorously within either the International Terrestrial Reference Frame (ITRF) 2005 or 2008 (Altamimi et al., 2011; Santamaria-Gomez et al., 2012).

However, for other stations we have had to rely on contacts with colleagues in various countries to provide us with the ellipsoidal heights computed by their agencies. As a consequence, heights in the USA were provided by the National Oceanic and Atmospheric Administration (NOAA) in the NAD83 (CORS96) reference frame and some European heights were provided in ETRS89 (or EUREF89). In these cases, there are web-based tools available to transform coordinates into ITRF-2005; these include www.ngs.noaa.gov/TOOLS/Htdp/Htdp_transform.html of the National Geodetic Survey of NOAA and www.epncb.oma.be/_productsservices/coord_trans/ of the Royal Observatory of Belgium. In some cases, our providers admitted that ellipsoidal heights could have been computed in several of the reference frames of the past decade, and that their documentation did not allow them to know which. In these cases, we have assumed that their heights are in ITRF-2005.

Whether heights are in ITRF-2005 or ITRF-2008 is not important for our studies of North Atlantic and North American stations. A test was undertaken using the NOAA Htdp tool in which coordinates on a global grid, nominally in ITRF-2005, were transformed to ITRF-2008 and the difference inspected. Any changes in the northern hemisphere were at the millimetre level.

GPS coordinates are usually expressed in ‘tide free’ form whereas other data types, such as radar altimeter data, are provided as ‘mean tide’ values (Ekman, 1989; Hughes and Bingham, 2008).

We decided to standardise throughout on ‘mean tide’ coordinates, which involved the use of a correction to the heights of the order of a decimetre. (Note that there is a minus sign error in the classic work of Ekman (1989) in referring to this conversion. This slip has recently been confirmed with the author.) Geoid model values discussed below were also employed in ‘mean tide’ form using the appropriate formulae to make any conversion.

All MSL values were adjusted for the inverse barometer (IB) effect using air pressure information from the National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalyses (Kistler et al., 2001). A reference air pressure of 1011.4 mbar was employed at each site, thereby ensuring that any MDT profiles computed along a coastline would not contain a contribution from air pressure gradients. A remaining possible correction would be for the nodal (18.6 year) long period tide, but that would be only ~1 cm given the restricted range of latitude of typically 20-65° N under study (Woodworth, 2011), and so for simplicity has not been applied in the present work.

A check for gross errors in the resulting geocentric MSL values was made by comparing them to the nearest possible height of the global MSS determined from satellite altimetry. The Technical University of Denmark (DTU) MSS model called DTU10 was used, that being a development of their earlier DNSC08 product (Andersen and Knudsen, 2008). The DTU10 values were used for quality control of the tide gauge data only in this step of the investigation; the use of altimeter rather than tide gauge data in the ‘geodetic approach’ is described in Section 5 below.

Two main geoid models were employed. The first is GOCO03S which, at the time of writing, is the state-of-the-art geoid model based on satellite information only including data from the Gravity Recovery and Climate Experiment (GRACE) and Gravity Field and Steady-State Ocean Circulation (GOCE) space gravity missions (Mayer-Gürr et al., 2012). It is a development of GOCO02S and previous models by the Gravity Observation COmbination (GOCO, www.goco.eu, Pail et al., 2011). Overviews of the GRACE and GOCE missions have been provided by Tapley et al. (2004) and Visser et al. (2002) respectively. GOCE has the greater relevance to the present study because of its ability to measure shorter spatial scale variations in the gravity field. Many papers concerned with aspects of the GOCE mission can be found in a special issue of the Journal of Geodesy (Volume 85, Number 11, 2011). GOCO03S includes 12 months of data from GOCE combined with information from the GRACE2010S model of the Institute of Theoretical Geodesy, Bonn and with satellite ranging data and is provided to degree 250. In the present study, we use the model to degree 180 only which is believed to be the useful limit of its accuracy based on knowledge of the cumulative error spectrum of this series of models (Mayer-Gürr et al., 2012; Gruber et al., 2013; Pail, 2013; Rummel, 2013).

The second geoid model is referred to as the 'Extended GOCO03S' model below. This model was constructed by making use of GOCO03S to degree 180, to which information from the Earth Gravitational Model 2008 (EGM08) (Pavlis et al., 2012) was added so as to provide a model to degree 2190. The Extended model gives an idea of the global product that one expects will be available at the completion of the GOCE mission when its data are combined with all available terrestrial, marine and airborne gravity information. It will be seen that the higher-degree contributions from EGM08 are important in compensating for the omission errors in GOCO03S, and result in greater consistency with the tide gauge information.

We have also made use of an extensive set of numerical ocean models from which we have computed MDT values along coastlines, and published and unpublished values of coastal MDT based on altimeter, geoid and oceanographic data, which we shall refer to below.

3. MDT Profiles using Tide Gauge Information

Figure 2(a,b) demonstrates the inadequacies of using national datums as if they were ‘level’ surfaces using values of mean sea level (MSL) for epoch 1993-2002 for stations on the Atlantic and Pacific coasts of North America. The blue points in Figure 2(a) show MSL values for Canadian stations, plotted as a function of latitude, and measured relative to the national levelling system called Canadian Geodetic Vertical Datum 1928 (CGVD28). The CGVD28 datum was defined in terms of historical MSL information from five tide gauges at Pointe-au-Père near Rimouski, Halifax and Yarmouth on the east coast of Canada and Vancouver and Prince Rupert on the west coast. Rimouski, located on the south bank of the St. Lawrence river in Québec, is particularly important, being used also as the reference for the North American Vertical Datum 1988 (NAVD88) used in the United States and the International Great Lakes Datum 1985 (Véronneau et al., 2006). (A list of MSL values in this and later figures may be obtained from the authors.)

It is not surprising that MSL at Rimouski for our chosen epoch in Figure 2(a) also has a value close to zero when measured relative to CGVD28 if one assumes that MSL has not changed significantly at that site in the intervening period. Similarly small values are obtained for neighbouring stations and for those in Newfoundland. However, MSL for stations in Nova Scotia and Prince Edward Island departs significantly from datum owing to the rise of MSL since 1928 (Forbes et al., 2009 and see the time series of MSL of each station on the PSMSL web site). The spatial pattern of these changes reflects relative sea level change due to the increase in volume of the ocean plus vertical land movements due to Glacial Isostatic Adjustment. The big differences in this area indicate the difficulty of using CGVD28 as a ‘level’ surface for science.

The red points in Figure 2(a) represent MSL values for stations in the USA from Key West in the south to Eastport near the Canadian border, each one measured relative to NAVD88. If CGVD28 and NAVD88 represented approximately the same datum, due to the Rimouski constraint, then one would have expected the red and blue points to have similar values near the border, as is the case for the St. Lawrence stations. However, if they were true ‘level’ surfaces one would also have expected MSL to fall going north, reflecting the MDT at the coast arising from the ocean circulation, and especially between Miami and Cape Canaveral (25.5-28.5° N) where there is a steeper gradient of sea level where the Gulf Stream is close to the coast (Higginson, 2012). Such a decrease of MSL with latitude is demonstrated in Figure 2(a) by the black points which are values of MDT from an ocean model sampled at the tide gauge locations, and in Figure 1(b) which shows a map of the MDT for the western part of the basin from the same model.

The black points in Figures 2-6 were obtained from the Liverpool University implementation of the Massachusetts Institute of Technology (MIT) ocean circulation model (Marshall et al., 1997a,b) in which hydrographic information derived by the scheme of Smith and Murphy (2007) at the UK Met Office has been assimilated. This model is available in two forms: one called the 'coarse grid' form has a global resolution of 1° (longitude and latitude), while the 'fine grid' version has higher resolution in the North Atlantic of 1/5 by 1/6° to provide a better simulation of sea level changes on the continental shelves. (Where we discuss Atlantic or Mediterranean stations below it can be assumed that we are referring to the 'fine grid' version.) We have found by comparing the model to tide gauge data that it does a reasonable job of representing interannual MSL variability over a range of latitude. Therefore, we have some confidence in using its time-averaged MSL values for our comparisons. We employ just the Liverpool-MIT model for the comparisons of this section to simplify the discussion, but in fact several other models are available as described in the next section.

If for the moment one assumes that the ocean model is correct, then one concludes that there must be spatially-dependent biases in the two national datums, most obviously the latitudinal bias in NAVD88. Such biases not only preclude the use of the datums as 'level' surfaces for scientific purposes, but the demonstrated decimetric errors mean that there is a limit to their use in practical applications.

Figure 2(b) presents a similar set of points for the Pacific coast of North America. In this case, the blue points indicating Canadian stations once again have MSL values close to zero, whereas the red points for US stations have values of approximately a metre and a northward gradient.

The main reason for the big difference between US and Canadian values stems from the way CGVD28 was constrained with the use of historical MSL information from Pacific tide gauges, whereas NAVD88 was constrained only at Rimouski, together with the large errors in transferring NAVD88 from Rimouski to the west coast. The consequences are that NAVD88 datum is clearly not an approximation of MSL on the west coast, and differs significantly from CGVD28 at the border. Moreover, the apparent northward slope shown by the red points is not what one expect from ocean modelling (black points), the MDT along the Pacific coast of North America having a much smaller gradient than along the Atlantic coast. Figure 2(b) demonstrates clearly that the two national datums cannot be used together as representing a 'level' surface for scientific purposes and that their significant offsets and internal biases will also present major difficulties for practical applications.

Figure 3(a) presents a similar plot to Figure 2(a) but this time the values of MSL have been determined as geocentric heights above the reference ellipsoid and are shown relative to values of the geoid from the GOCO03S model. A northward negative gradient can be seen in the data points, consistent with those of the ocean model (same black points as in Figure 2(a)), with an overall offset between data points and model values as shown in Table 1. We discuss the origin of this offset below. In addition, there is a scatter of the difference between data and model points with a standard deviation (stdev) of the order of several decimetres, consistent with expectations of geoid uncertainty due to omission errors beyond degree 180 in a model such as GOCO03S (Flury and Rummel, 2005). Figure 3(b) shows the corresponding information for the Pacific coast showing now alignment of the Canadian and US data points, and similar offset and stdev values. One concludes that values of MSL above the geoid computed this way represents the MDT along the coast more reliably than with the use of the ‘level’ surfaces of the national datums.

These data and model comparisons can be taken further with the use of the Extended GOCO03S model, which represents the type of geoid model one expects the community to be able to employ in future within height system unification studies. The Extended model makes use of EGM08 information at short spatial scales based on terrestrial, altimetry-derived and airborne gravity data that is available in varying proportions around the world (Pavlis et al., 2012). As most of our work in the present study is around North Atlantic and North American coasts, where *in situ* gravity data are relatively copious, then the use of the Extended model should be superior to that of GOCO03S itself.

Figure 4(a,b) shows equivalent information to Figure 3(a,b) but using the Extended geoid model. One can see that the scatter of data points is reduced with offsets similar to those before, and now, for Figure 4(a) in particular, one has a real sense of being able to observe genuine MDT signals along the coast.

To complete the US coastline, Figure 5 presents the corresponding information for the Gulf of Mexico plotted versus longitude: (a) MSL with respect to NAVD88, (b) geocentric MSL with respect to GOCO03S, and (c) geocentric MSL with respect to the Extended geoid model. One can see that the MDT profile along the Gulf coast as represented by the ocean model is fairly flat (black dots). However, although our comparisons would have benefitted from one or two additional stations between 88 and 95° W, Figure 5(a) shows that, if one used NAVD88 as a datum, then one would infer a westward slope of MSL. The comparisons of geocentric MSL minus geoid to model MDT (Figures 5b,c) show closer agreement in slope, while offset and stdev values (Table 1) are similar to those in Figures 3 and 4 indicating similar geoid accuracies in the different regions.

One can now turn to countries on the eastern boundary of the North Atlantic and to stations in mid-ocean. Almost all of these countries have national datums defined by MSL at a suitable coastal station with the datum transferred around the country by conventional levelling. In this way, all points could be expressed as 'heights above sea level'. The MSL used was usually an average value of sea level (relative to land) recorded over an extended period, traditionally chosen to be a lunar nodal period of 18.6 years, although in practice much shorter periods were employed. Occasionally, very short samples of sea level were used; for example only 10 days of measurements were used in March 1844 in the definition of Ordnance Datum Liverpool (ODL) in the UK (Close, 1922). This datum was replaced by Ordnance Datum Newlyn (ODN) defined in terms of MSL measured during May 1915-April 1921. Other examples of European national datums include Normaal Amsterdams Peil (NAP) in the Netherlands and Nivellement Général de la France (NGF) in France. All of these datums, when originally established approximately a century ago, were close approximations of the then MSL at Newlyn, Amsterdam and Marseille respectively.

We have produced tables of MSL expressed relative to the national datums in several European countries and compared them to values of MDT expected from ocean models, in a similar way to our study of US/Canadian MSL in Figure 2(a). Inconsistencies between MSL and model MDT were found to reflect the long-known relative biases in European datums (Rossiter, 1967; Adam et al., 1999; EVRF, 2007). The conclusion, as was already known from previous experience and was demonstrated for the case of US/Canada in Figures 2(a) and 3(a), is that combinations of national datums cannot be employed as a 'level' surfaces for scientific studies.

Figure 6(a) shows values of geocentric MSL relative to GOCO03S for stations in Iceland, along the Atlantic coast of Europe, and for Atlantic islands plotted as a function of latitude, the colours indicating the different countries. These can be compared to anticipated values of MSL from the same ocean model shown by the black dots. Scatter in the coloured points can be seen for stations on the NW continental shelf while data points for Bermuda and for the Azores, at 32.4 and 37.7° N respectively, fall outside the plot limits because of the considerable short-scale variability in the geoid around the islands. Figure 6(b) uses the Extended geoid model and shows much better agreement both for the European coastline and the Atlantic islands, indicating the importance of local gravity if comparisons are required at specific locations.

4. Other Ocean Models for the 'Ocean Approach'

As mentioned above, the black points in Figures 2-6 were obtained from the Liverpool-MIT ocean model which for present purposes can be described as a 'pure' ocean model i.e. one in which a set of oceanographic (e.g. temperatures, salinities, currents) and meteorological (i.e. air pressures and wind stresses) information will have been employed and in which the resulting MDT represents the ocean's dynamical response to these forcings using the three-dimensional equations of motion.

We have used the Liverpool-MIT 'pure' ocean model in its 'coarse' and 'fine' forms as described above. We have also considered one other 'pure' model, the 1/12 degree resolution OCCAM (Webb et al., 1997; Marsh et al., 2009) which, like the Liverpool model, is constrained only by observations of ocean density. In addition, we considered three models from the ECCO consortium, which assimilate a wide range of oceanographic and geodetic observations: the 18 km resolution ECCO-2 model (Menemenlis et al., 2005; http://ecco2.jpl.nasa.gov/), version 3 of the 1 degree resolution ECCO-GODAE model (Köhl et al., 2007), and the 1 degree GECCO model (Köhl and Stammer, 2008; http://icdc.zmaw.de/easy_init_ocean.html). The model data were regridded by nearest-point interpolation to a common ¼ degree grid, and averaged over the common 5-year epoch 1996-2000 (different from that used for tide gauge measurements because not all models had been run over that period). The spatial average has been removed from the ECCO2 result (one which is truly global), and the other models have had constant values added to ensure that the average difference from ECCO2 is zero over the common domain. (There are different methods for computing such an average difference but they result in values varying only by typically 1 cm).

Figure 7 demonstrates the consistency between the MDT spatial distributions of these models by plotting the standard deviation of the 6 MDT values at each point in the ocean. It can be seen that stdev values are less than 10 cm in most parts of the ocean, including the coastal oceans, apart from bands of higher stdev along the trajectories of the major currents and in Hudson Bay. There are significant, large regions where the stdev is less than 2.5 cm. This agreement between models provides a working estimate of the accuracy of models for use in height system unification.

Figure 8(b,d,f) shows profiles of MDT of each model around the East Pacific coastline and for the entire Atlantic coastline using the ¼ degree grid points adjacent to the coast. It can be seen that the MDT varies between -80 and +35 cm but that there is close agreement between models along many sections of coast. Places where there are differences include the east coast of Florida and the (non-coastal) section across the top of the Labrador Sea, where the stdev values (shown at the bottom of each figure) approach 20 cm. The representativeness of the Liverpool-MIT model used in the previous figures can be assessed by comparison to the other models.

5. MDT Estimation from Altimetry and Geoid Information for the 'Geodetic Approach'

Figure 8(b,d,f) also includes profiles of MDT obtained using the 'geodetic approach' of subtracting ellipsoidal heights of the geoid from those of MSL. However, this time the geocentric heights of sea level are not supplied by tide gauges, but are derived from mean sea surface models obtained from satellite altimetry measurements. Models include those of Maximenko et al. (2009) which uses data from altimetry, drifter information for currents and GRACE gravity, CLS-2009 (Rio et al., 2011) which uses similar input data sets as Maximenko et al. employed plus density information, CLS01-GOCE02 and CLS11-GOCE03 which use altimetry and GOCE geoid information only with 150 km smoothing. The MSS models CLS01 and CLS11 are available from the web site of Archivage, Validation et Interprétation de données des Satellites Océanographiques (AVISO, aviso.oceanobs.com and see also references in Bingham et al., 2008). The GOCE02 and GOCE03 geoid models are derived from 2nd and 3rd releases of GOCE gravity models, based on 6 and 12 months of observations spanning the periods beginning November 2009 and ending July 2010 and April 2011, respectively. The GOCE gravity models have been produced by the time-wise approach, which relies entirely on GOCE measurements to estimate the gravity field (Pail et al., 2011). An additional geodetic MDT, DTU10-GOCO03S, is determined from the DTU10 MSS (Andersen and Knudsen, 2009; available from www.space.dtu.dk), and the GOCO03S model, as employed in the tide gauge analysis above. GOCO03S uses GRACE and CHAMP space gravity and satellite laser ranging observations to improve the GOCE03 geoid model at long wavelengths (Pail et al., 2010, 2011). Time variations from version 3 of the AVISO gridded reference altimeter dataset have been used to ensure that the MDTs are representative of the same 1996-2000 epoch as that used for the model data. The MSS fields are converted to spherical harmonics before differencing, in order to ensure that properly-matched spectral filters are applied to both geoid and MSS. A Gaussian filter of radius (to half-maximum) 150 km is applied to all except the DTU10-GOCO03S product, for which it was found to be possible to use 125 km without introducing too much noise. An advantage in using altimetric information is that it is available for most of the global coastline, unlike at point locations from tide gauges, while a disadvantage is that altimeter data are obtained necessarily off-shore and not exactly at the coast where we wish to have information to relate to datums. Where data are unavailable in the coastal grid boxes, these have been filled by a simple extrapolation from nearby data (ocean grid points with no data are filled with the average of any neighbouring ocean points which have data, and this procedure iterated up to 10 times). The extrapolation distance can be quite variable, but is typically a few tens of kilometres.

Nevertheless, the level of agreement between altimetric MDT profiles and those of the models provides another estimate of consistency for use in height system unification, as described below. It can be seen that agreement with the models is very good in the eastern Atlantic, with stdev values of around 5 cm. Elsewhere, stdev values are typically between about 5 and 10 cm, with relatively large values in the western North Atlantic, where boundary currents are at their strongest.

Observations in the eastern Pacific appear relatively noisy, especially in comparison with the models which show rather similar profiles (except in the southern region where the coast is very convoluted, with many semi-enclosed inlets). There is also a systematic offset, with the geodetic MDTs being about 10-20 cm lower than the models. When we plot dynamic topographies following a line 2.5 degrees west of the coast (not shown) we find a significant decrease in both noise and offset, showing that this is a boundary effect. While there are boundary currents which vary between models (Figure 7), it seems most likely that this is mainly an effect of the very steep topography and associated geoid variations very close to the coast at this boundary. Omission error is particularly severe in this tectonically-active region where the plate boundary coincides with the ocean boundary.

6. Extensions to the Mediterranean

Our project was limited initially to a study of the North Atlantic coastlines, but a subsequent extension to the American Pacific coast was clearly beneficial as demonstrated above. Therefore, we decided to extend the study further to two sites in the Mediterranean, taking advantage of the fact that tide gauge, GPS and Liverpool-MIT model information is available for both locations. (A word of caution is that the performance of this model in the Mediterranean has not yet been studied by its authors in great detail. Altimetry-derived models suggest that the Mediterranean contains many short spatial scale variations in MDT, Rio et al., 2007).

The first site was Marseille on the south coast of France, historical sea level data from which was used for the definition of the French national datum (NGF). The various determinations of the NGF are known to have major systematic regional biases due to levelling errors, in common with experience in other countries (Thompson, 1980; Duquenne et al., 2007). Consequently, consistency between findings for Brest and Marseille in the present project is of some interest.

Our second site was Alexandria, Egypt which has the longest sea level time series in Africa with an unbroken record since 1944 obtained from a venerable harbour float gauge in the western harbour (Woodworth et al., 2007). The Tide Gauge Zero (TGZ) of this gauge is known with respect to the national Survey Department Datum that was defined by means of measurements of high and low waters during the years 1898 to 1906 (Cole, 1939; Frihy, 1992; Mohammed, 2005). It is not known if the high and low waters were recorded by an automatic tide gauge or by visual observations of a tide pole; the data themselves have not survived. The height of the TGZ of the harbour gauge has been related to that of a benchmark used for GPS measurements as described on the SONEL web site.

Alexandria is of interest for several reasons. One is that, because the continuity of sea level measurements there is of great importance, data from the western harbour float gauge have been complemented recently by measurements by a modern radar gauge in the eastern harbour. The National Oceanography Centre Liverpool (NOCL) was closely involved in that installation. More generally, Alexandria typifies a site in a highly-populated delta region which continues to be under threat from sea level rise (Nicholls, 2010) and even tsunamis (Hamouda, 2006). Any practical benefits of successful datum unification applied to such a country can, therefore, be taken as exemplifying those of unification worldwide.

Our findings for these two new sites are included in the discussion of the next section.

7. Discussion

7.1 Offsets between Geodetic and Ocean Approaches using Tide Gauge Data

Table 1 presents statistics for the offsets observed in Figures 2-6 between the MDTs of the ‘geodetic approach’ using tide gauge data (ellipsoidal height of MSL minus geoid height) and the MDT of the ‘ocean approach’ at the same positions using the Liverpool-MIT ocean model. It has one line for each coastline using either the GOCO03S or Extended geoid models. Each line lists the number of stations in each coastline, the mean offset and the stdev of the differences between MDT values from the two approaches at each station.

The offsets will contain several contributions. One will be geodetic and be related to the way that the C00 coefficient, the zero-order part of the gravity potential, is defined as described in section 4.4.3 of EGG-C (2010). This is a complicated subject but has no impact on our study of the spatial dependence of the MDT. A second contribution arises from the choice of reference air pressure for the IB corrections of tide gauge data. In addition, it is possible that there may be model offsets depending on the way that they calculate MDT. Therefore, the offsets may be systematically different when using different models.

A first observation is that stdev values are considerably smaller using the Extended model which reflects the importance of the shorter spatial scale (higher degree) gravity information provided by the EGM08 contribution to the model. The improvement with the Extended model is shown most dramatically for the two mid-Atlantic stations (Ponta Delgada, Azores and Bermuda) and for the northern Spanish stations of La Coruña and Santander which are major outliers using GOCO03S. (Note that there are two values for both of the Spanish stations and that their dots partially overlap in Figure 6(a,b)).

A second observation is that, using the more precise values for the Extended model, the offset for the US/Canada Atlantic coast is larger than for the other two North American coastlines. A reason for this could stem from ocean model error; it can be seen in Figure 8(d) that both the 'coarse grid' and 'fine grid' implementations of the Liverpool-MIT model tend to lie below those of the other models along the Atlantic coast, whereas they are more similar to the others for the Gulf and Pacific coasts. Offsets for the European Atlantic coast, including or excluding the two mid-Atlantic islands, are comparable to the American ones. However, those for the two

Mediterranean stations are smaller, especially so for Alexandria. The latter could also reflect ocean model error and/or geoid model error due to lack of local gravity. In addition, there could have been imprecision in levelling over the 3 km between the GPS and tide gauge stations, as shown in detail on the SONEL web site. Our colleagues at the University of La Rochelle plan to repeat this levelling in the near future.

The average offset for the four main groups is 654 mm with a half-range between them of 82 mm and the average stdev is 90 mm. One concludes that the various offsets are consistent with being the same at the sub-decimetre level.

We referred to Brest and Marseille above. If one computes the difference between (MSL minus geoid) at the two sites and subtracts the difference between model MDT, one obtains -71 and 157 mm using the GOCO03S and Extended model respectively. This suggests agreement at the decimetre level but, as mentioned above, the accuracy of this calculation may be limited by the adequacy of the ocean model in the Mediterranean. We shall investigate this further using other models in collaboration with our University of La Rochelle colleagues.

7.2 Deficiencies of Ocean Modelling

Section 4 has discussed how a number of global ocean models exist which can be applied to the present research. However, it is important to keep in mind that these models were designed primarily for study of the deep ocean circulation, rather than sea level changes at the coast. As a consequence, there are deficiencies common to many of them with regard to spatial and temporal resolutions and forcing factors. For example, inadequate spatial resolution clearly limits the ability of a model to simulate shelf processes. Then, regarding temporal resolution, the main forcing in all ocean models is wind stress, but some models are forced by monthly-averaged wind stresses only, rather than the hourly wind stress values used as main forcing in coastal tide+surge models (Woodworth and Horsburgh, 2011). Therefore, as far as the time-averaged contribution of storm surges to an MDT at coastal locations is concerned, a global ocean model might in fact do a reasonable job (questions of spatial resolution aside) but that component would be computed more rigorously using barotropic models and hourly forcing. A further example relates to forcing factors which are not usually included in ocean models such as river runoff, which adds water (mass) to the ocean as well as moderating its salinity; only the latter will have been considered in the model if it makes use of coastal hydrographic information. The importance of this forcing is shown in the estuaries of major rivers such as the Ganges–Brahmaputra delta, where it is strong enough to moderate sea level at nearby coastal gauges, primarily on seasonal timescales (Tsimplis and Woodworth, 1994). Whether these gauges should then be regarded as sea level stations or river level gauges is a moot point, but it matters for us if those stations are used to define national datums and if we cannot model MDT at those locations adequately.

As an example of the discussion of the previous paragraph, Figure 9 presents three sea level surfaces for the NW European continental shelf. Figure 9(a) shows MDT from the Liverpool-MIT ocean model as used above. Figure 9(b) shows the same quantity for the same epoch but from the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) coastal model (Holt and James, 2001). This model is used in the study of a wide range of shelf processes, including research into changes in water quality and ecosystems, and so needs to consider forcings such as river runoff for the proper simulation of environmental parameters as well as physical ones such as sea level. The two models indicate broadly similar patterns of MDT, with higher values on the shelf and more negative ones in the north. However, short spatial scale differences are evident, especially in the central North Sea and along the Atlantic coasts of France and Spain.

Figure 9(c) shows the mean sea surface for the same epoch using a barotropic (two-dimensional or depth-averaged) tide+surge model (Flather et al., 1998). The model has a relatively coarse spatial resolution of 1/2 by 1/3° (longitude by latitude). However, it has been demonstrated to provide a good representation of tides and surges on the shelf and was formerly the model used for operational flood forecasting and warning in the UK (Flather, 2000). The sea level in this figure has not been corrected for the IB-effect unlike the MDT values of Figure 9(a,b), so there may be some long-wavelength inconsistencies between them. However, our reason for showing it is to point to the decimetric topographic signal generated by wind setup off the west coast of Denmark and in the German Bight. This signal was first identified by Rossiter (1967) in a regression analysis of the MSL response to winds and air pressures in European waters. It is reassuring that this feature is also indicated in Figure 9(a,b) at some levels, but perhaps not as sharply and, to be very conservative, one can take the magnitude of this feature as the accuracy of the different models in shelf seas.

Another example of wind setup in the North Atlantic is shown in Figure 10(a) which shows the time-averaged MSL for four separate decades for the US and Canadian stations in Figure 10(b) obtained from the model of Bernier and Thompson (2006). Once again, this figure shows sea level uncorrected for the IB but the main reason for the decimetric variation in MSL will be due to the wind. The conclusion from Figures 9 and 10 is that wind stress in coastal areas tends to lead to time-averaged signals in the MDT which can be decimetric and may be better described in some models than in others.

Finally, there are processes such as wave setup to be kept in mind. The physics of wave setup is understood well enough to know that it could contribute several decimetres to MSL at times on sloping beaches and in bays and harbours. Brown et al. (2011) in a modelling study describe how wave setup of the order of half a metre can occur at times in Liverpool Bay, while Dean and Dalton (2009) provide a comprehensive overview of experiments and theory. However, these large signals occur only during storms and one suspects that when averaged over a decade that the wave setup contribution to observed mean sea level will be only centimetric. So far as we know, wave setup is not included in any operational or reanalysis modelling scheme that would provide a long time series for investigation, so it is difficult to arrive at a more quantitative conclusion on its potential importance to the present study.

A step forward in modelling could be to envisage the merger of deep ocean and regional coastal models. While global models are optimised to determine the large scale MDT, it is best where possible to supplement this information with fine scales taken from regional models, in order to extrapolate the global information to actual coastal locations. A natural place to begin merging global and regional models is at the continental shelf edge, where the steep topography acts to limit the coupling between deep and shallow dynamics, and tends to reduce the occurrence of short wavelength alongshore gradients in MDT. NOCL has such a project called POLGCOMS (a Global version of POLCOMS) which has an objective of constructing a worldwide set of regional coastal models coupled to a global deep ocean model (Holt et al., 2009).

7.3 Height System Unification

We have explained how our study involves a complementary validation of geoid and ocean models within the 'geodetic' and 'ocean' approaches to determination of MDT profiles along coastlines. Were we to be able to settle upon a 'best' ocean model (or more likely an average of suitably performing ocean models) then its resulting MDT profile could be used to provide an MDT correction to MSL measurements made at tide gauges along the coast. Therefore, given that MSL can be expressed relative to a national datum, then datums in different countries along a coastline can be unified and consistency of a datum within each country can be verified. In other words, the MSL can be used as a 'level' surface once a suitable correction derived from a model can be decided upon.

As a side remark, we can point out that our use of tide gauge (exactly coastal) and altimeter (near coastal) data in the geodetic approach provides a validation of regional ellipsoidal heights of sea level (after consideration of the near-coastal effects mentioned above), and links the present study to those of larger-scale use of altimetry minus geoid for determination of the MDT and ocean circulation in the deep ocean. These large scale studies will provide their own assessment of available ocean models.

We have not in the present work selected our preferred model(s). It is likely that certain models will perform better in some areas than others, and a full quality assessment requires more detailed study than we have made so far. However, we have been able to estimate the uncertainty in our approach by making use of a set of models. This uncertainty depends upon location but is typically of the order of a decimetre.

As mentioned above, it is possible that all the ocean models we have employed could misrepresent the coastal MDT owing to limitations in the way that they are constructed (e.g. limitations of spatial and temporal resolution) or omission of certain ocean processes. In our opinion, the systematic errors in modelled MDT averaged over a decade are unlikely to exceed a decimetre, although processes such as wave setup are difficult to estimate rigorously for all the coastline. Ultimately, it might be possible to identify areas prone to larger uncertainty and exclude them from height system unification exercises.

The other half of our comparison has involved validation of the newly-available geoid models GOCO03S and Extended GOCO03S. As time progresses, one expects there to be progressively more accurate and more complete geoid models for use within the 'geodetic approach', but we can say already that the Extended model performs well in explaining the ellipsoidal heights of MSL along our coastlines. 'Extended' models containing shorter spatial scale information than that available from GOCE alone are always likely to be required to provide the most complete representation of the geoid.

We have pointed to the need to extend our work to other regions. The reason is that, while our studies of the North Atlantic and North American Pacific coastlines have been instructive, it will be desirable to undertake comparisons along all the world coastlines if one wishes to work towards worldwide height system unification. Such an extension will provide further confidence in the consistency of the two ‘approaches’ by using data sets from different oceanographic régimes.

8. Conclusions

This paper has demonstrated that the new models of the geoid arising from the recent space gravity missions, and especially from the GOCE mission, are now accurate enough that one can derive the MDT along a coastline in terms of the ellipsoidal heights of MSL (measured at tide gauges or obtained from altimetry) minus geoid height. Moreover, the resulting values of MDT are similar to those suggested by a number of ocean models. This exercise thereby provides a validation of both sets of models.

Our work has some similarity to recent studies of MSL variations and datums along the North American Atlantic coast (Higginson, 2012) and around the coast of Australia (Featherstone and Filmer, 2012). In particular, it has resolved one of the longest-standing discussions in oceanography concerning the direction of the tilt of sea level along the American coast (Sturges, 1974). It is certain that, now that the geoid models are so good and will improve further, much more science will flow.

However, to return to the main reason for the present study, to assess the contribution of 'ocean levelling' to worldwide height system unification, we believe that this is now possible with a typical uncertainty of better than a decimetre. However, this statement is subject to reservations concerning the limitations in the ocean models available for analysis, and to the fact that a global study remains to be made. Our use of data from North Atlantic coastlines and islands, the North American Pacific coast and the Mediterranean has demonstrated that our methods should be capable of being applied to any countries with at least one operational or historical tide gauge for which at least one of the benchmarks has been surveyed by GPS.

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Figure captions

1(a) The global Mean Dynamic Topography (MDT) for the period 1993-2002 from the 'coarse grid' Liverpool-MIT ocean model. Contours every 200 mm, (b) the MDT from the 'fine grid' version of the same model focussing on the western North Atlantic. Contours every 100 mm.

2(a). MSL values for the Atlantic coast of the USA and Canada for the period 1993-2002 shown by red and blue dots and measured relative to NAVD88 and CGVD28 respectively. Note that at Rimouski (48.48° N) the MSL is approximately zero with respect to CGVD28, whereas the five Canadian values with large MSL are in Nova Scotia. Black dots show MDT from the Liverpool-MIT ocean circulation model. (b) A similar set of points for the Pacific coast of North America.

3(a). As Figure 2(a) but with values of MSL determined as geocentric heights above the reference ellipsoid and are shown relative to values of the geoid from the GOCO03S model. (b) A similar set of points for the Pacific coast of North America.

4(a,b). Equivalent information to Figure 3(a,b) but using the Extended GOCO03S geoid model.

5. Corresponding information for the Gulf coastline. (a) MSL with respect to NAVD88, (b) geocentric MSL with respect to GOCO03S, and (c) geocentric MSL with respect to the Extended GOCO03S geoid model. Note that Key West has been included in Figures 2(a), 3(a), 4(a) and the present figure so as to provide a link between the Atlantic and Gulf coastlines.

6(a). Geocentric MSL relative to GOCO03S for stations in Iceland, along the Atlantic coast of Europe, and for Atlantic islands plotted as a function of latitude. Black dots from the same ocean model as in Figure 2. Coloured data points for Bermuda and Azores are outside the plot area. (b) Geocentric MSL relative to the Extended GOCO03S geoid model.

7. Standard deviations at each point in the ocean between the MDT values for a set of ocean models described in the text.

8. Profiles of MDT for the common 5-year epoch 1996-2000 from the ‘geodetic’ approach (red-orange), from ‘pure’ ocean models in the ‘ocean’ approach(blue) and ocean models which assimilate geodetic information (green-cyan) along (b) the East Pacific, (d) the West Atlantic and (f) the East Atlantic coastlines with model grid values extrapolated to the coast. Stdev values between all MDTs are shown in black at the bottom of each figure, with a -100 cm offset applied. Panels (a), (c) and (e) illustrate the geography of the respective coastlines, with a red/black colour code to help identify particular stretches in the adjacent plots. G of C stands for Gulf of California, and Fla-Nflnd is the coastal stretch from the tip of Florida to Newfoundland.

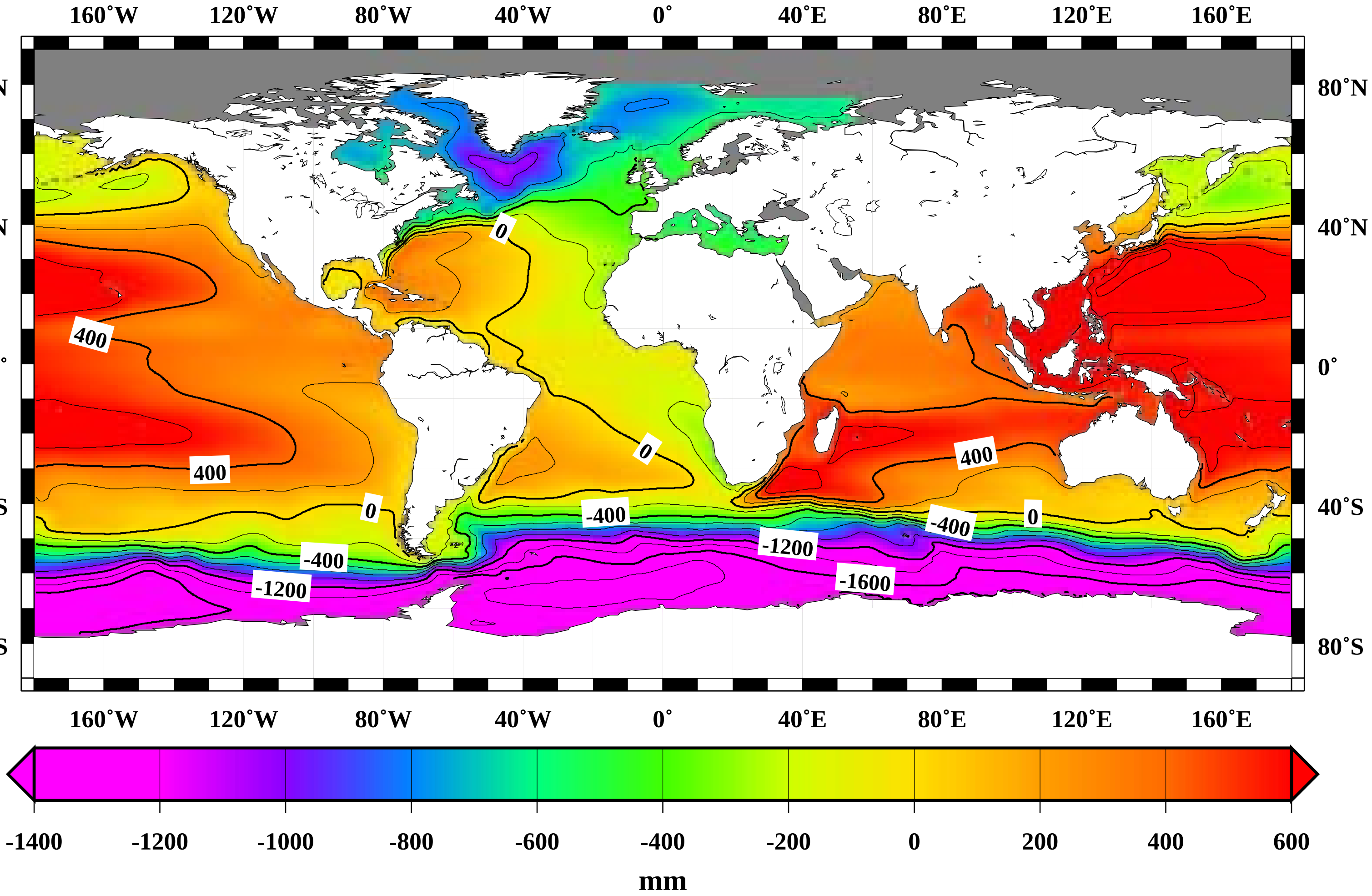
9(a). MDT from the ‘fine grid’ Liverpool-MIT ocean model for the NW European Continental Shelf, (b) MDT from the POLCOMS regional model, and (c) variations in MSL from a tide+surge barotropic model. Each plot is for the decade 1993-2002. Units mm.

10(a). Variation in MSL for the stations on the Atlantic coast of the USA and Canada shown in (b) using the tide+surge model of Bernier and Thompson (2006). The four lines correspond to the decades 1960-69, 1970-79, 1980-89 and 1990-99.

Table 1: Statistics of the differences between the MDT of the 'geodetic approach' using tide gauge data (ellipsoidal height of MSL minus geoid height) and the MDT of the 'ocean approach' at the same positions (using the Liverpool-MIT ocean model).Units are millimetres.

Region	Number of Stations	Geoid Model	Mean Offset	Stdev
Atlantic US/Canada	38	GOCO03S	775	334
Pacific US/Canada	26		575	633
Gulf Coast USA	13		544	240
European Atlantic and Atlantic Islands	29		807	1001
European Atlantic only	27		579	375
Ponta Delgada, Azores	1		2446	
Bermuda	1		5315	
Marseille	1		717	
Alexandria	1		379	
Atlantic US/Canada	38	GOCO03S Extended Model	745	95
Pacific US/Canada	26		632	137
Gulf Coast USA	13		580	61
European Atlantic and Atlantic Islands	29		659	65
European Atlantic only	27		657	64
Ponta Delgada, Azores	1		753	
Bermuda	1		616	
Marseille	1		506	
Alexandria	1		403	

Figure 1(a,b) Next pages


160°W
120°W
80°W
40°W
0°
40°E
80°E
120°E
160°E
80°N
40°N
0°
40°S
80°S
400
0
-400
-1200
-1600
-1400
-1200
-1000
-800
-600
-400
-200
0
200
400
600
mm

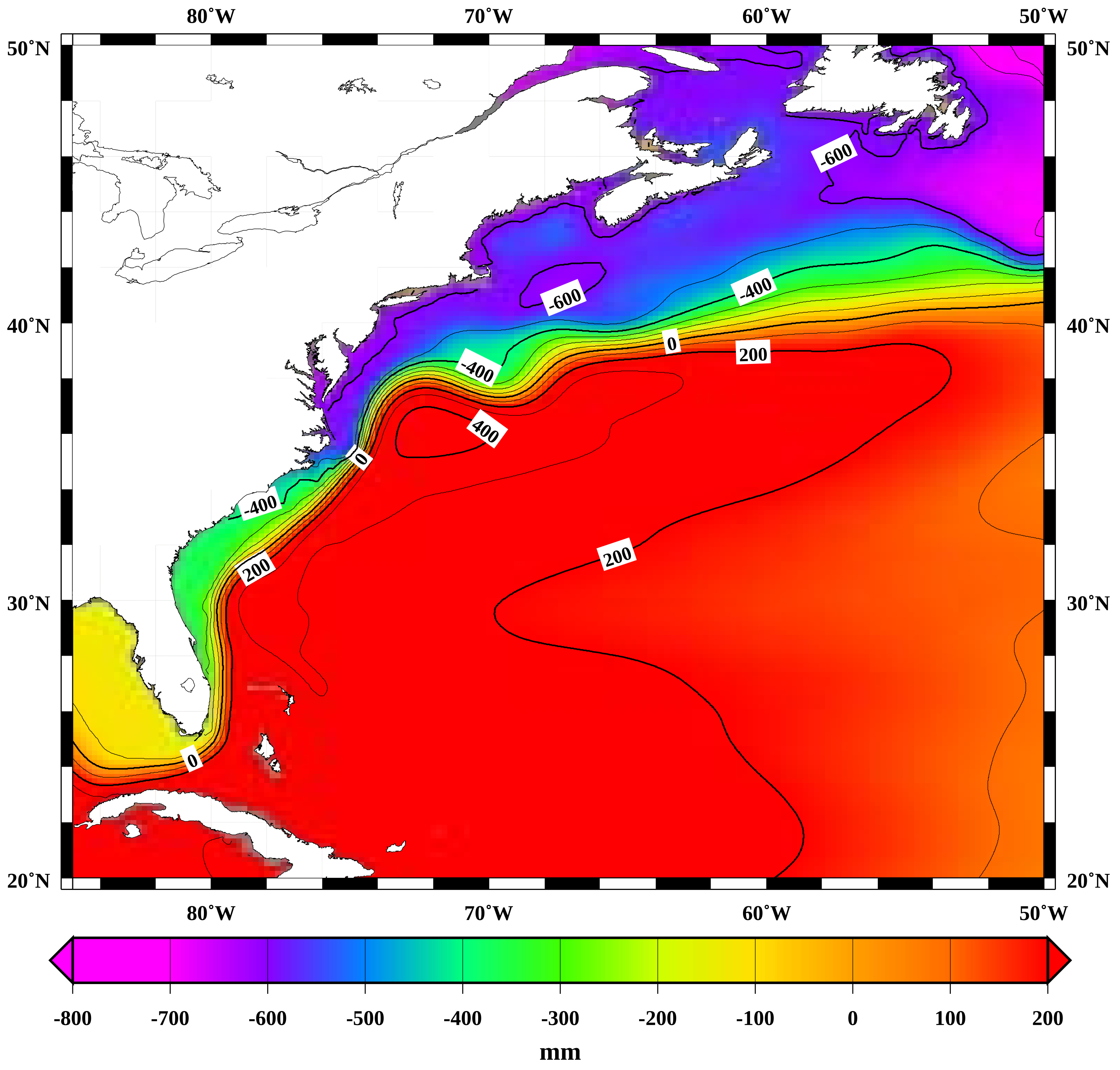
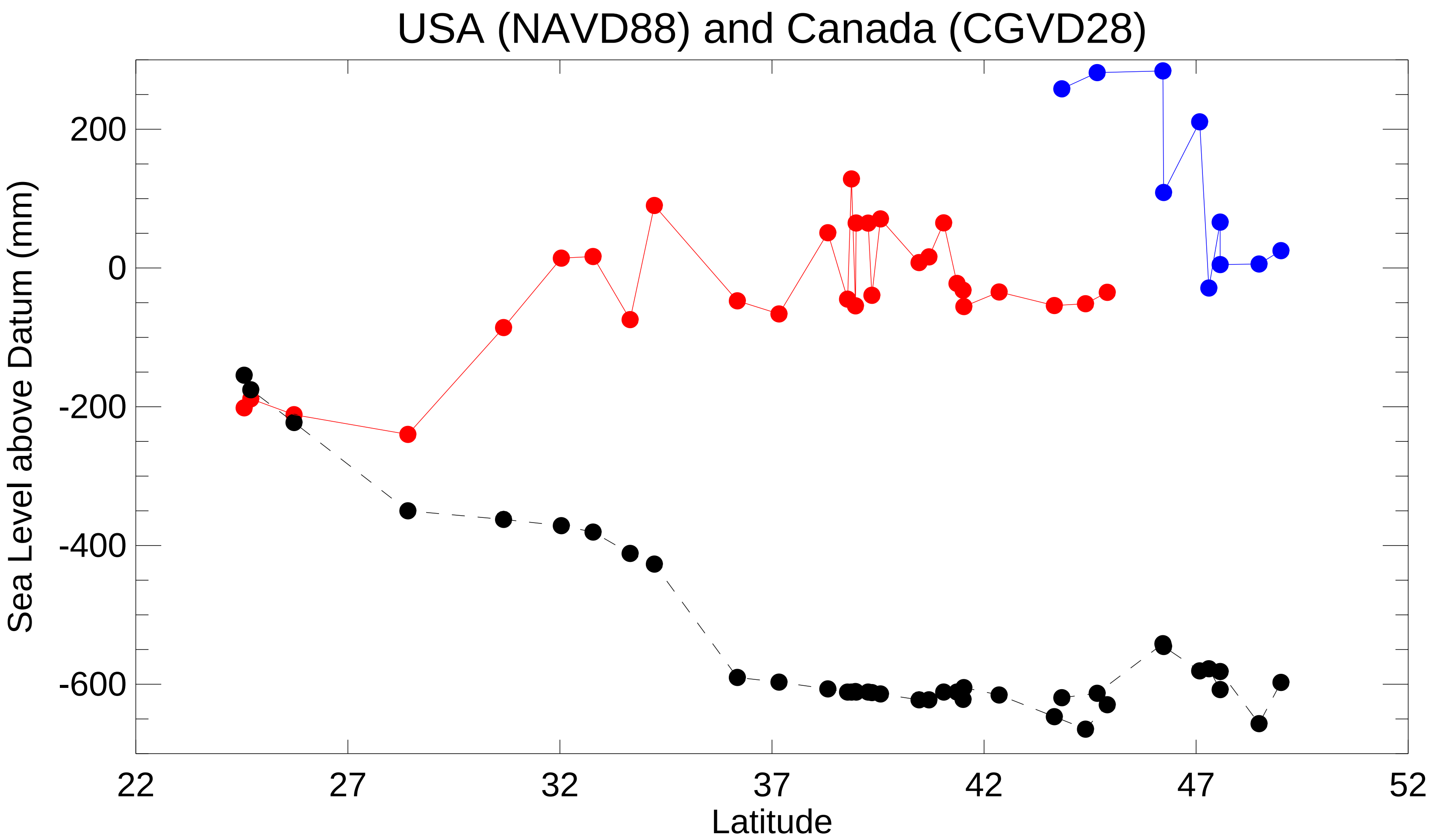
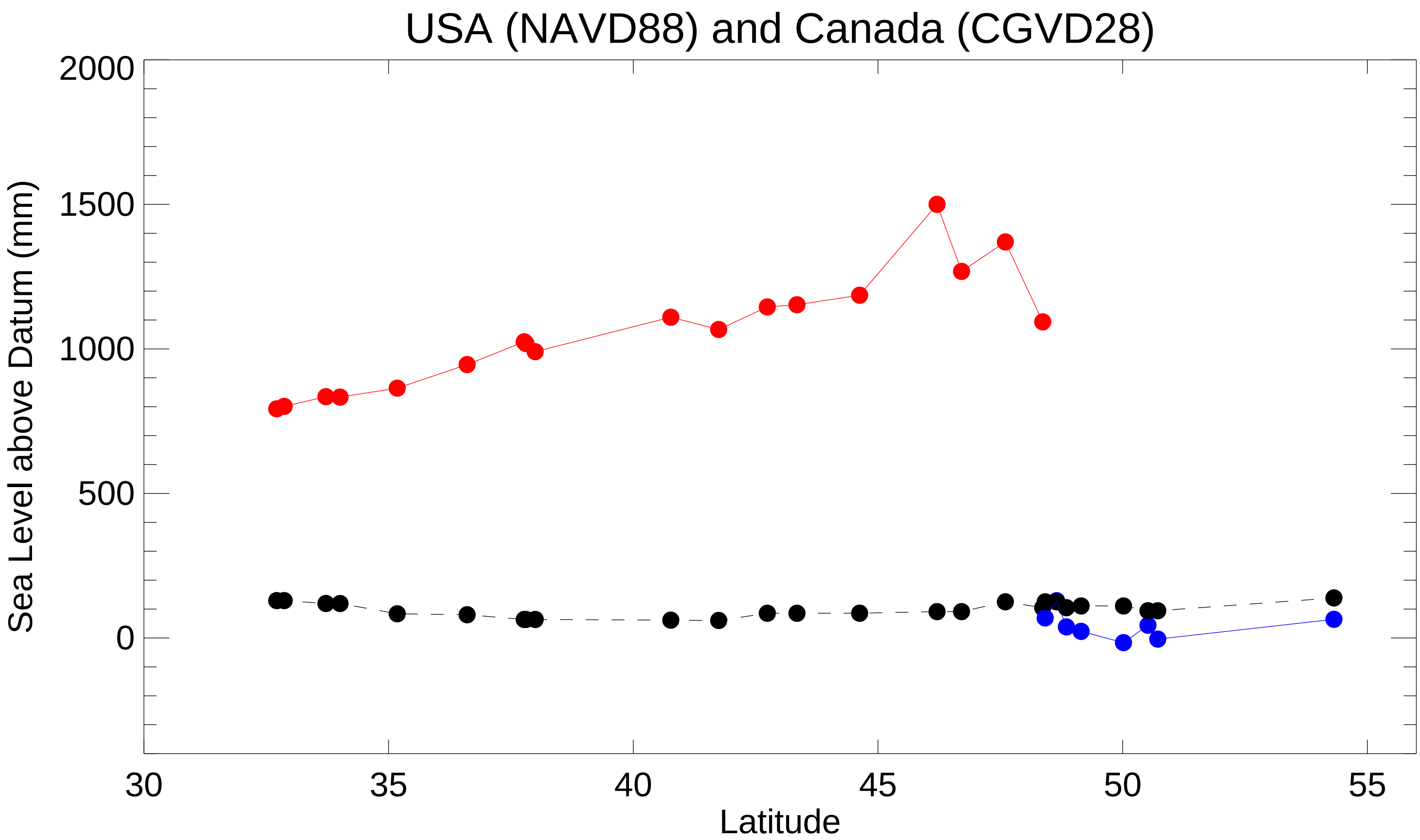

80°W
70°W
60°W
50°W
50°N
40°N
30°N
20°N
-600
-400
0
200
400
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
mm

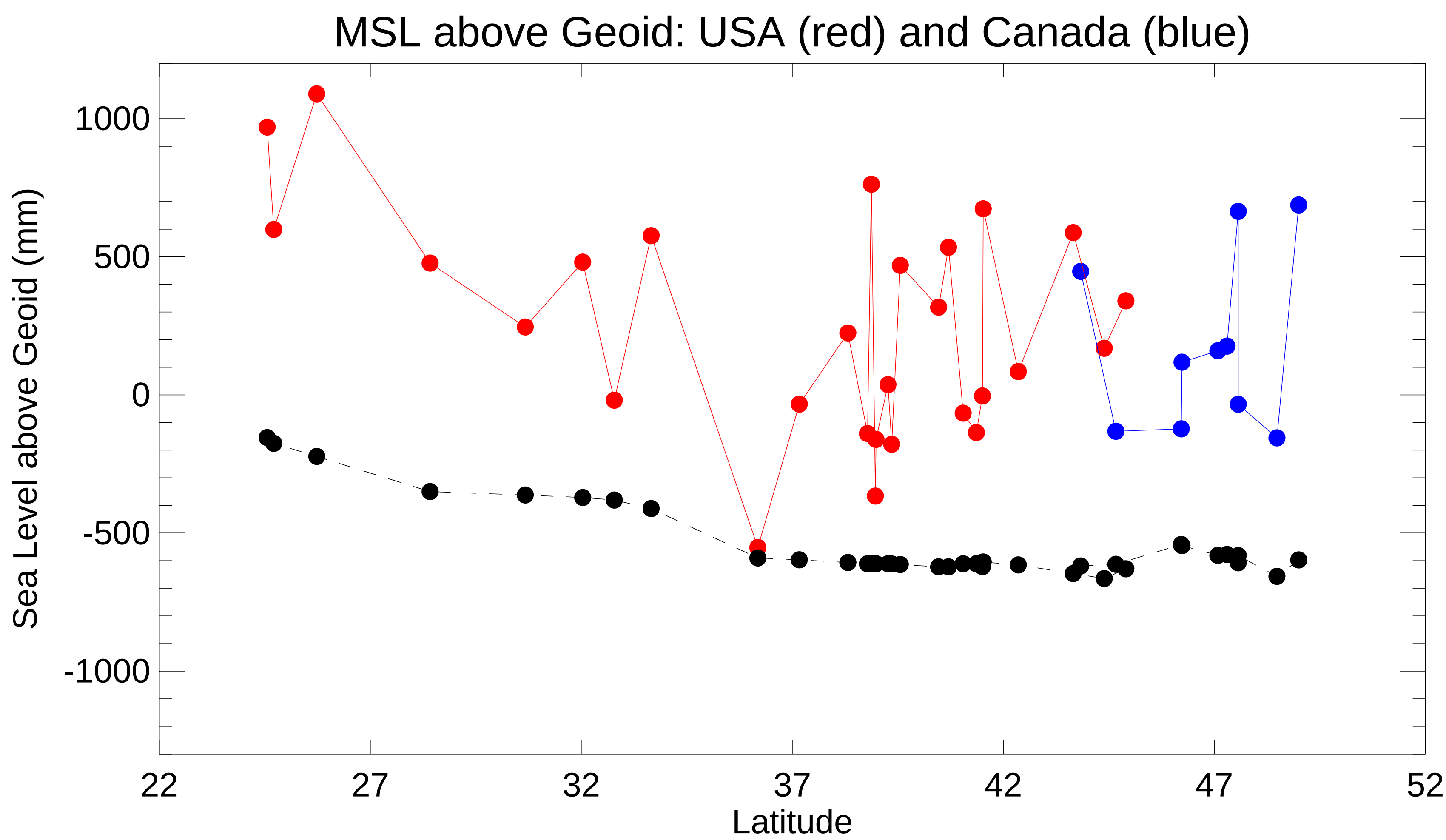
Figure 2(a,b) Next pages


USA (NAVD88) and Canada (CGVD28)
Sea Level above Datum (mm)
200
0
-200
-400
-600
22
27
32
37
42
47
52
Latitude

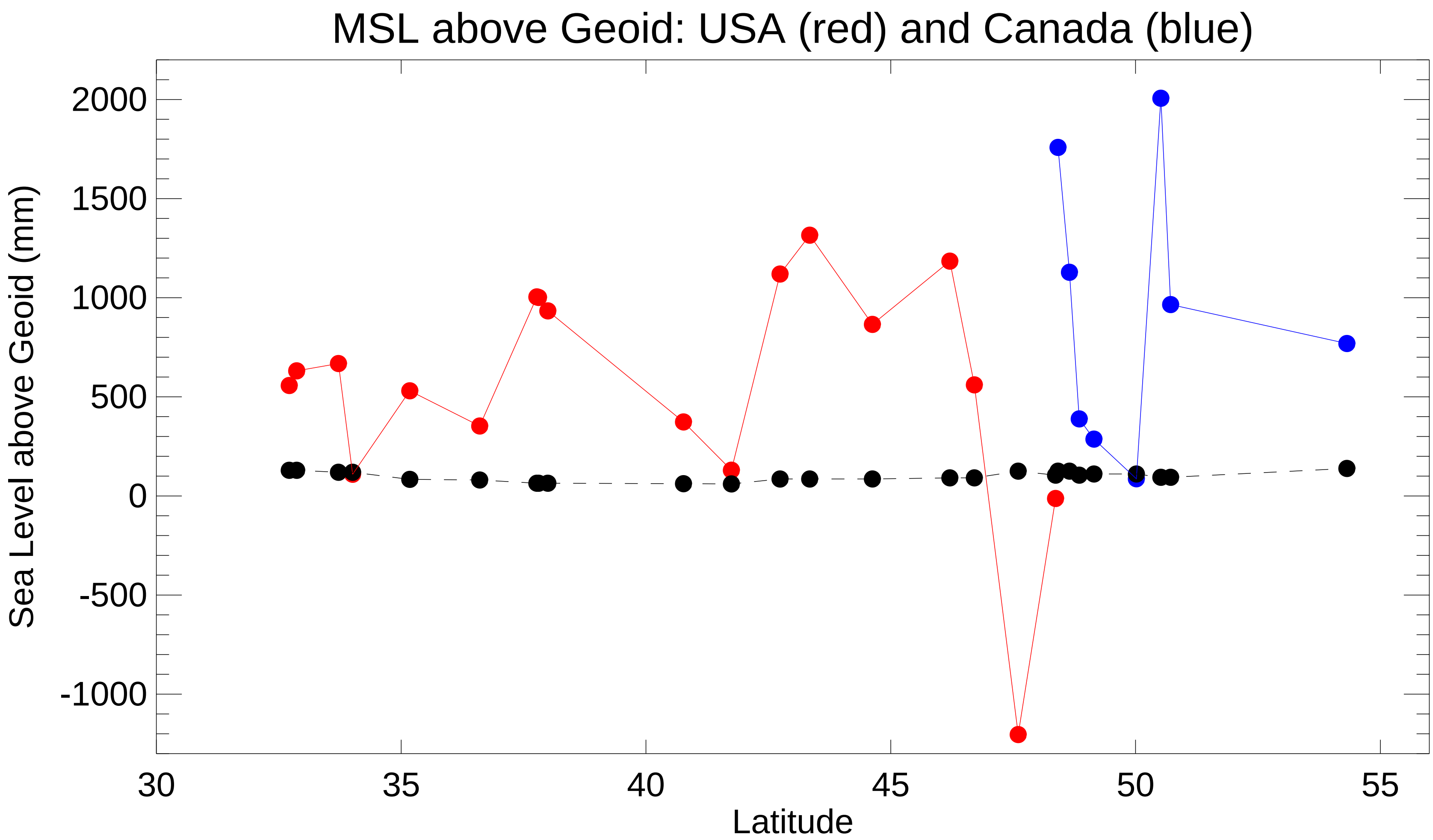


USA (NAVD88) and Canada (CGVD28)
Sea Level above Datum (mm)
2000
1500
1000
500
0
30
35
40
45
50
55
Latitude

Figure 3(a,b) Next pages

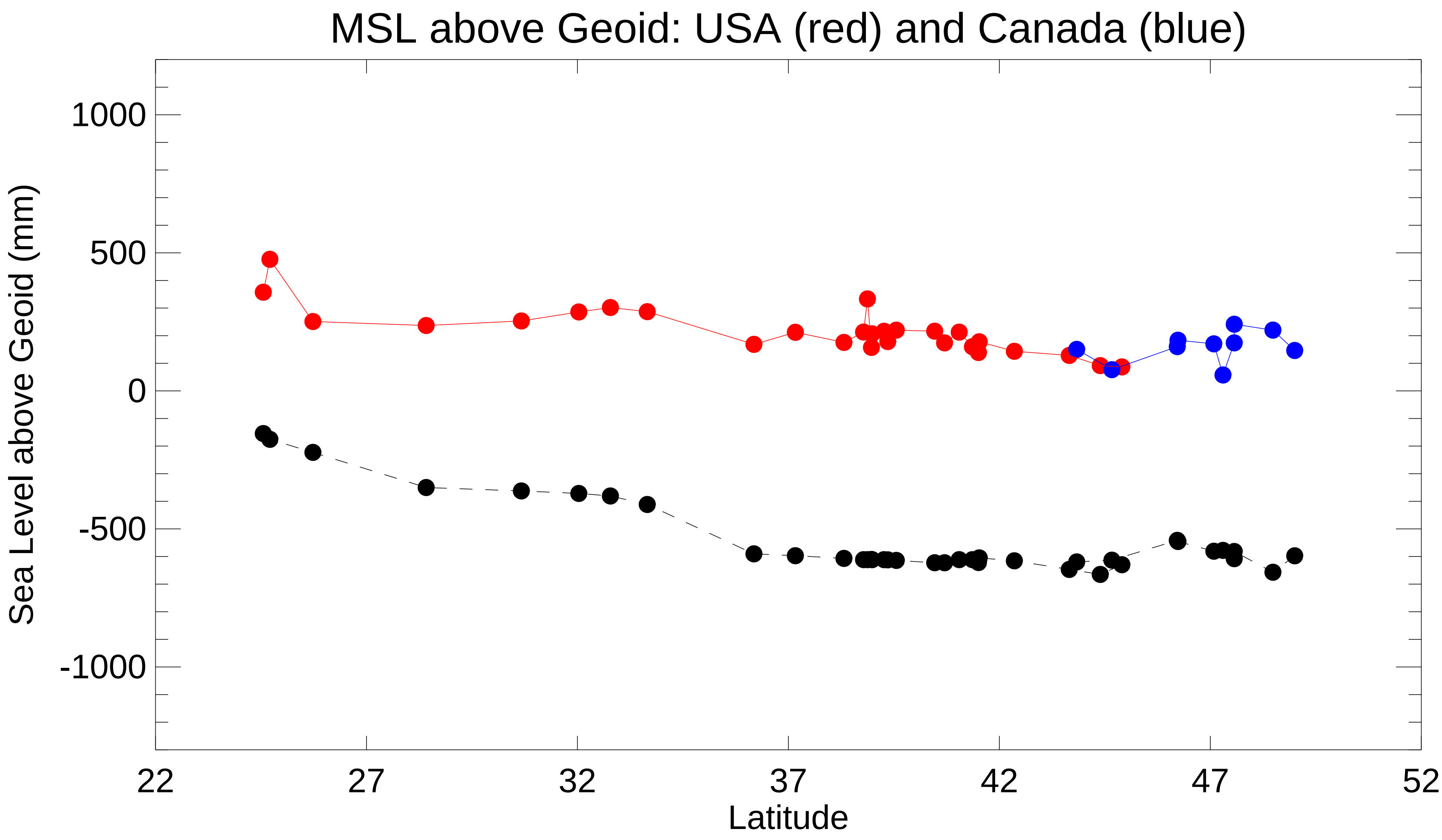


MSL above Geoid: USA (red) and Canada (blue)
Sea Level above Geoid (mm)
1000
500
0
-500
-1000
22
27
32
37
42
47
52
Latitude



MSL above Geoid: USA (red) and Canada (blue)
Sea Level above Geoid (mm)
2000
1500
1000
500
0
-500
-1000
30
35
40
45
50
55
Latitude

Figure 4(a,b) Next pages



MSL above Geoid: USA (red) and Canada (blue)
Sea Level above Geoid (mm)
1000
500
0
-500
-1000
22
27
32
37
42
47
52
Latitude

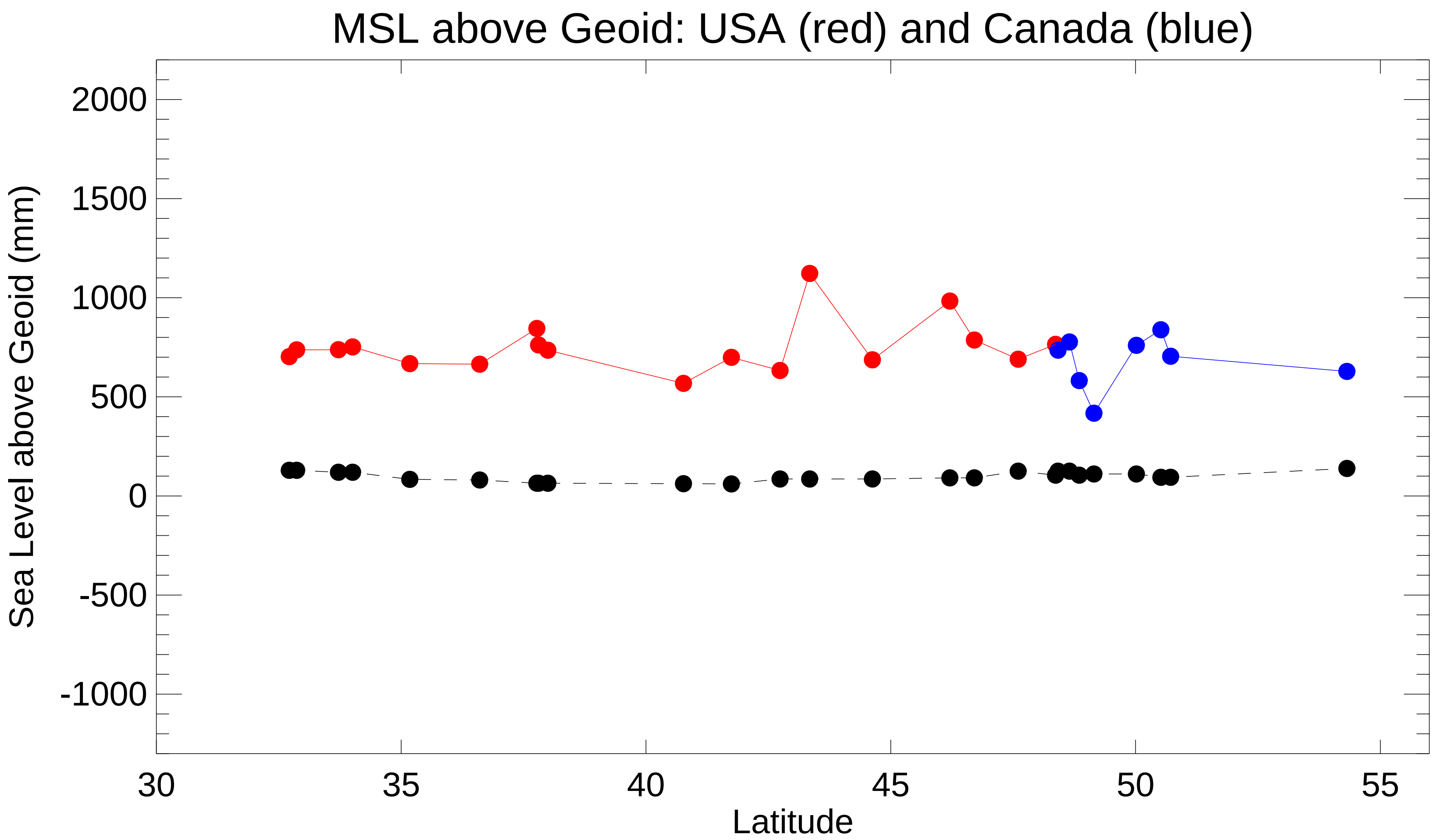
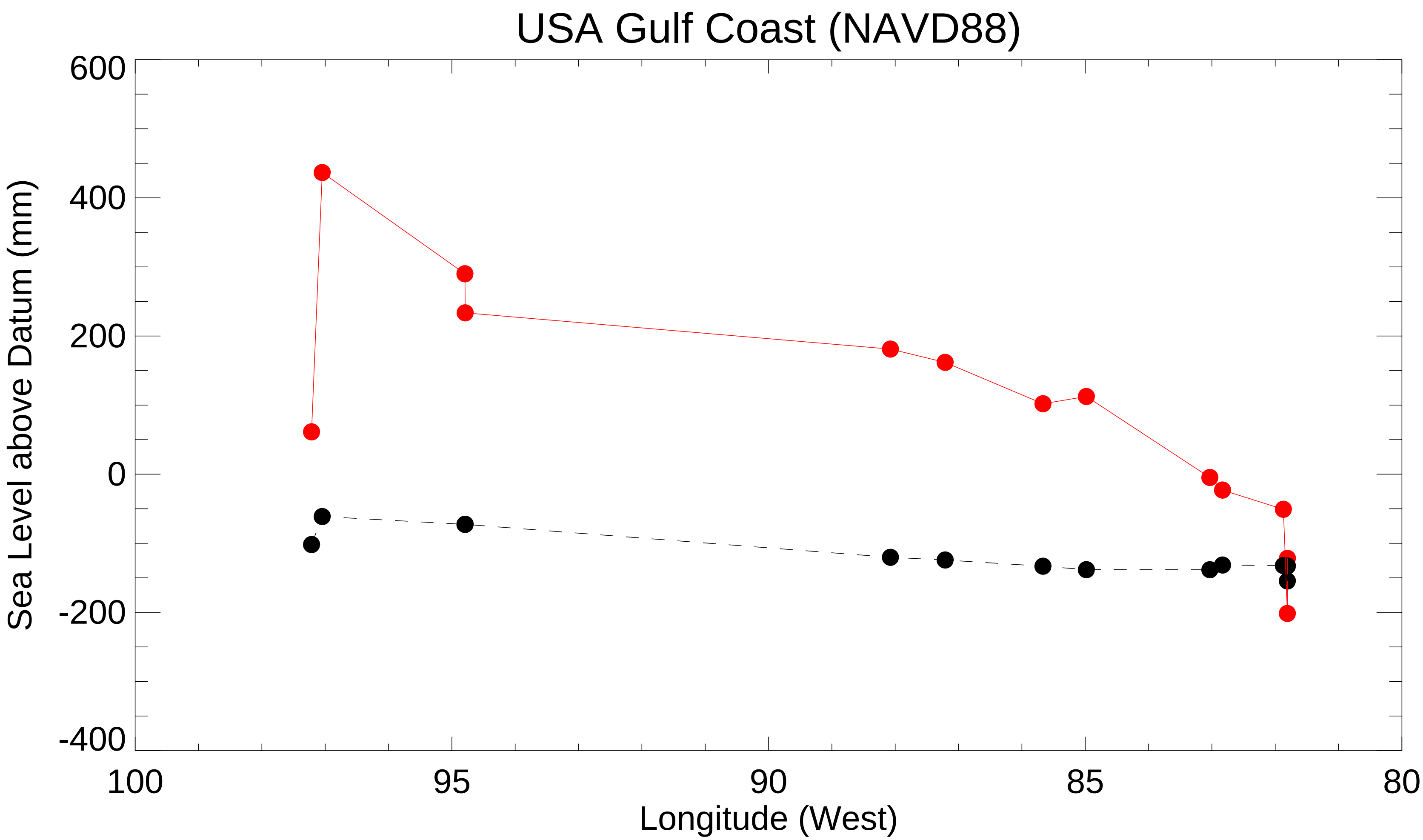
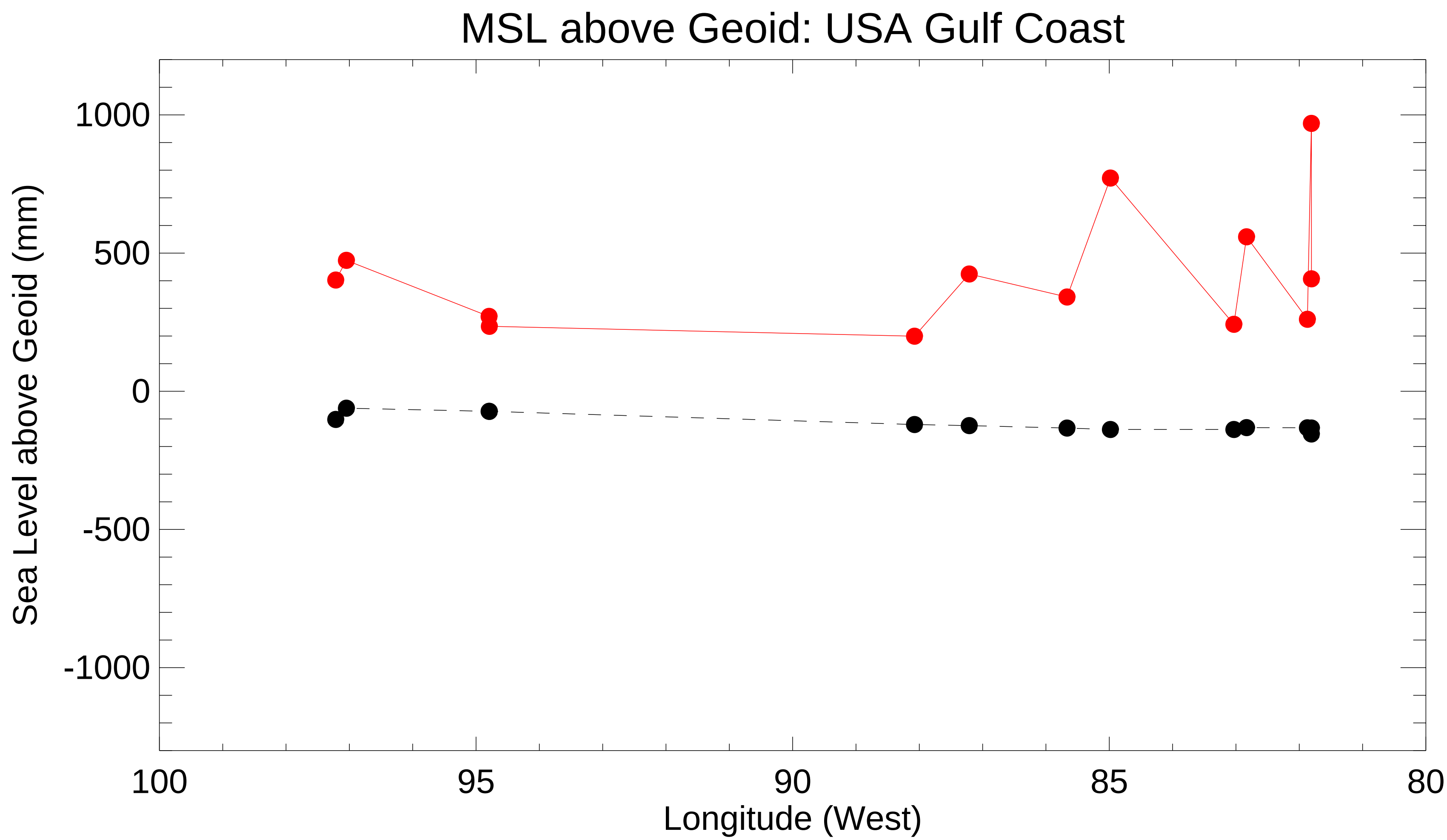
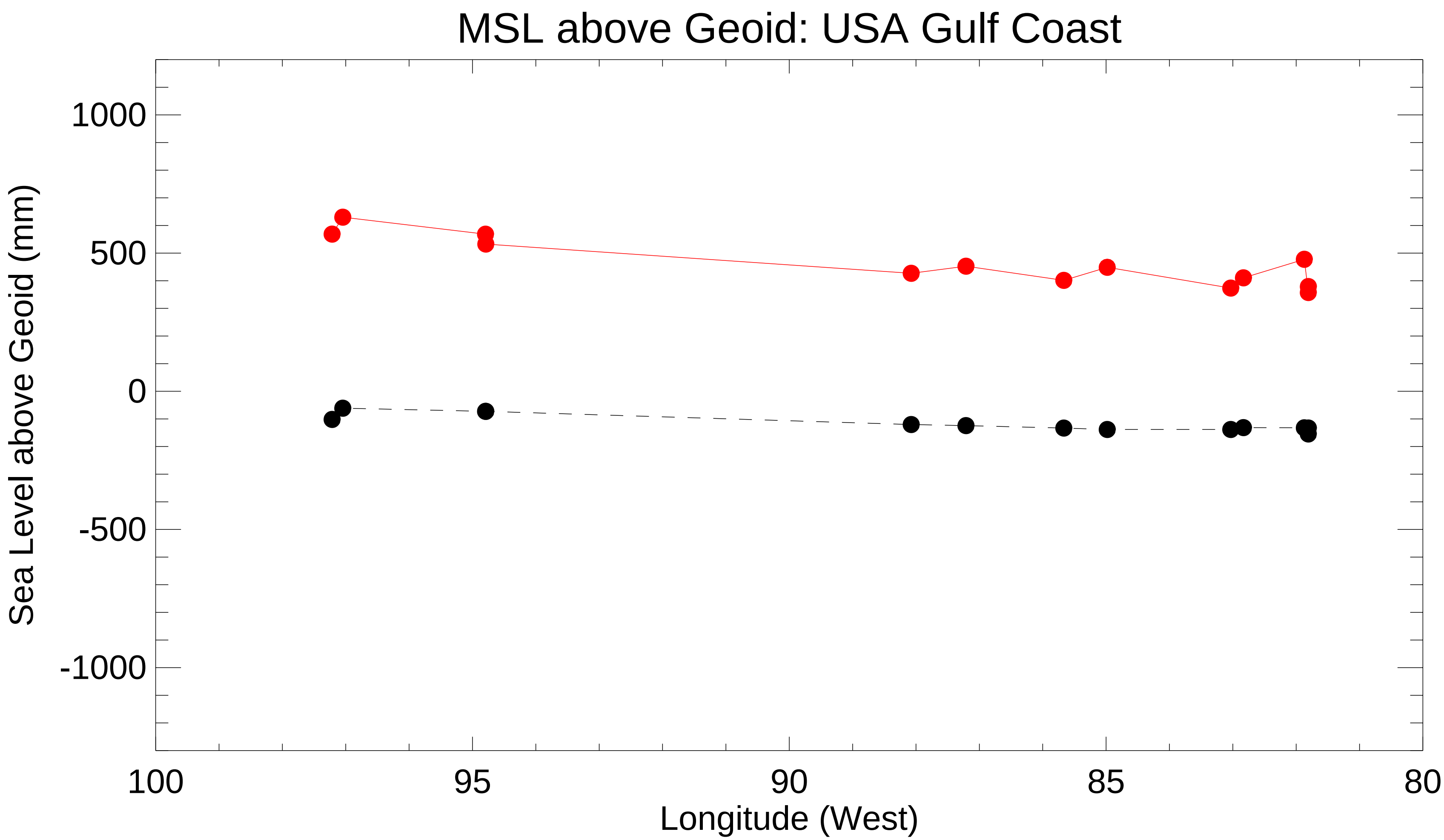

MSL above Geoid: USA (red) and Canada (blue)
Sea Level above Geoid (mm)
2000
1500
1000
500
0
-500
-1000
30
35
40
45
50
55
Latitude

Figure 5(a,b,c) Next pages

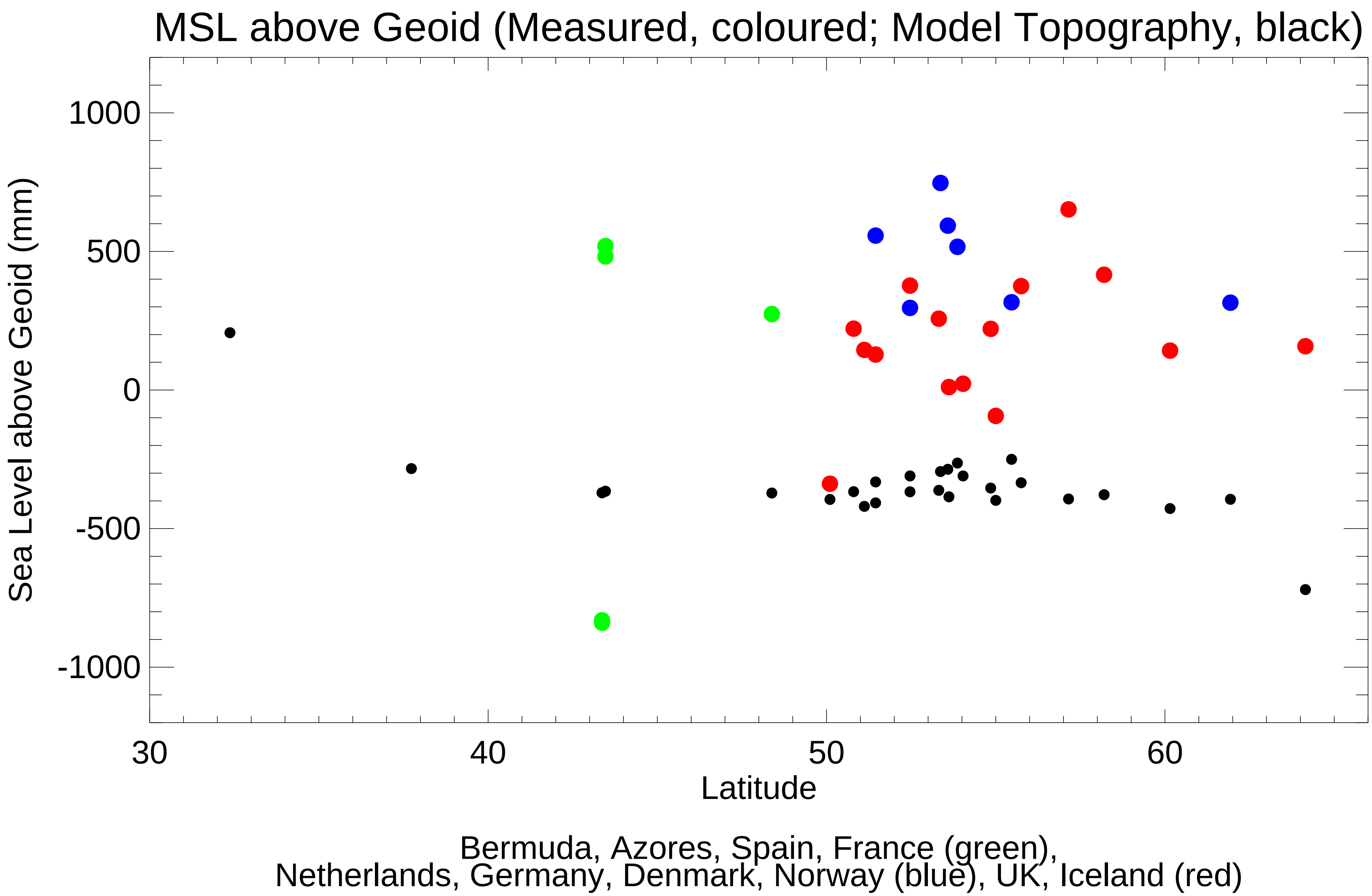

USA Gulf Coast (NAVD88)
Sea Level above Datum (mm)
600
400
200
0
-200
-400
100
95
90
85
80
Longitude (West)

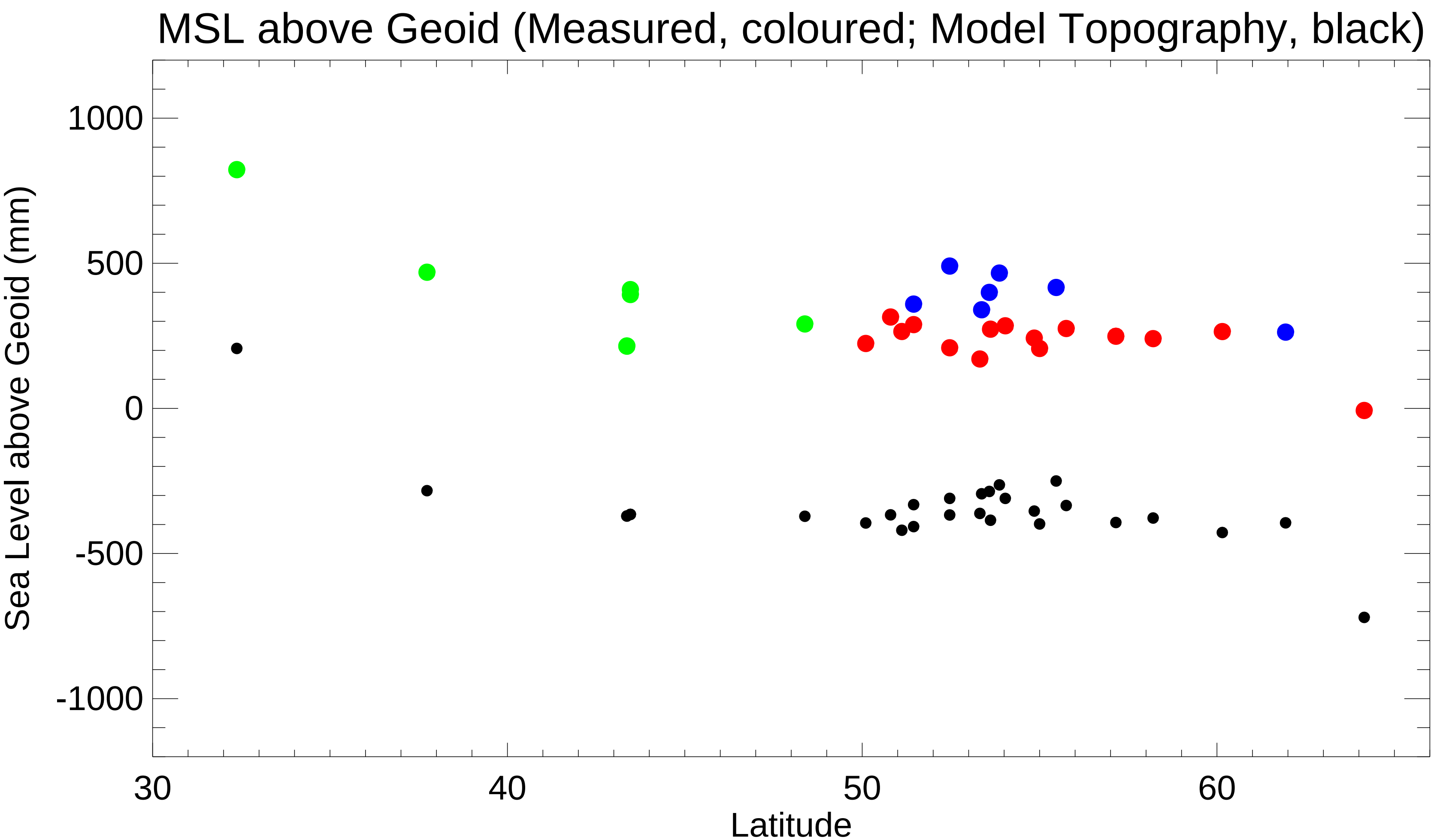

MSL above Geoid: USA Gulf Coast
1000
500
0
-500
-1000
Sea Level above Geoid (mm)
100
95
90
85
80
Longitude (West)



MSL above Geoid: USA Gulf Coast
1000
500
0
-500
-1000
Sea Level above Geoid (mm)
100
95
90
85
80
Longitude (West)

Figure 6(a,b) Next pages


MSL above Geoid (Measured, coloured; Model Topography, black)
1000
500
0
-500
-1000
Sea Level above Geoid (mm)
30
40
50
60
Latitude
Bermuda, Azores, Spain, France (green),
Netherlands, Germany, Denmark, Norway (blue), UK, Iceland (red)



Bermuda, Azores, Spain, France (green),
Netherlands, Germany, Denmark, Norway (blue), UK, Iceland (red)

Figure 7 Next page

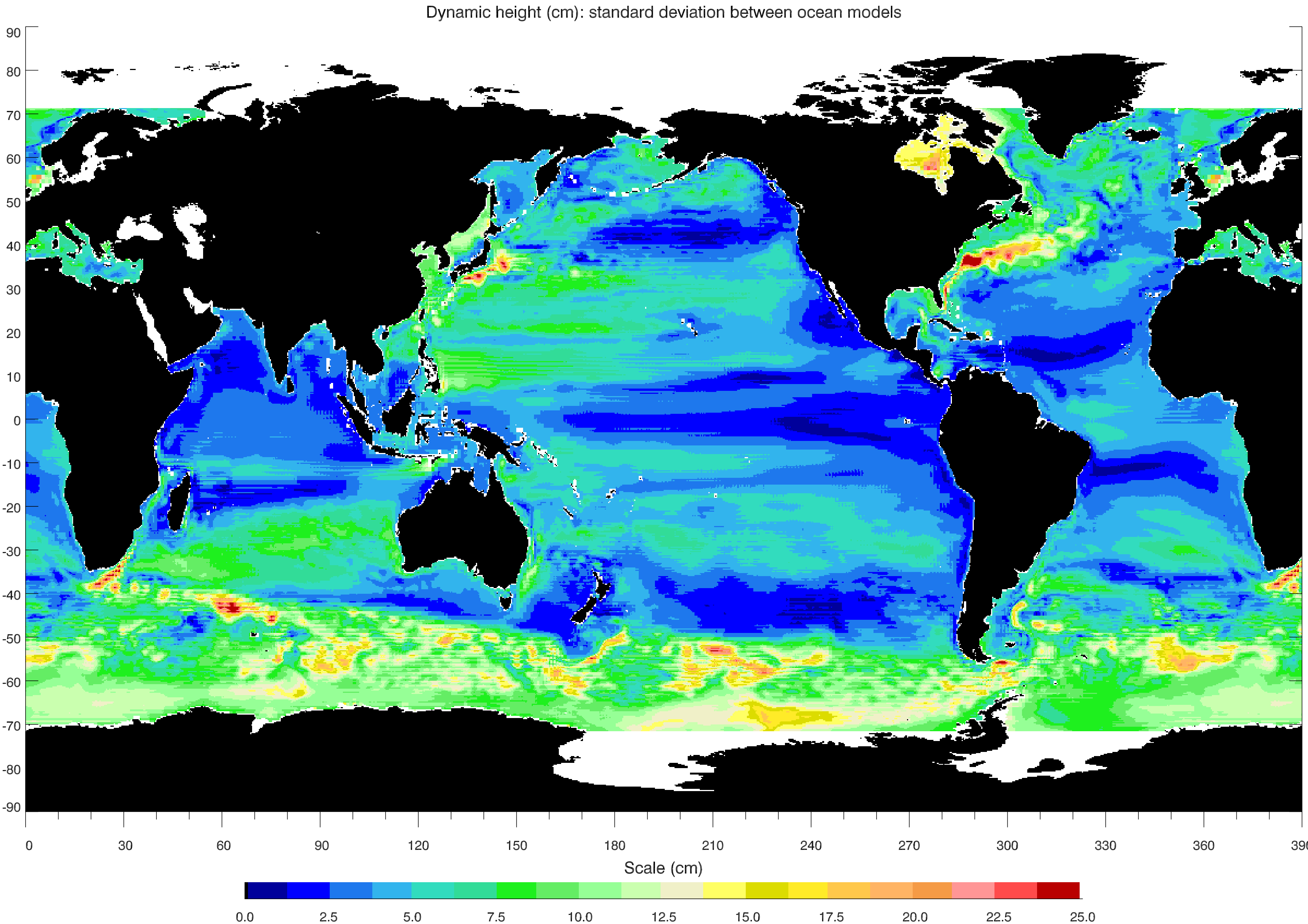
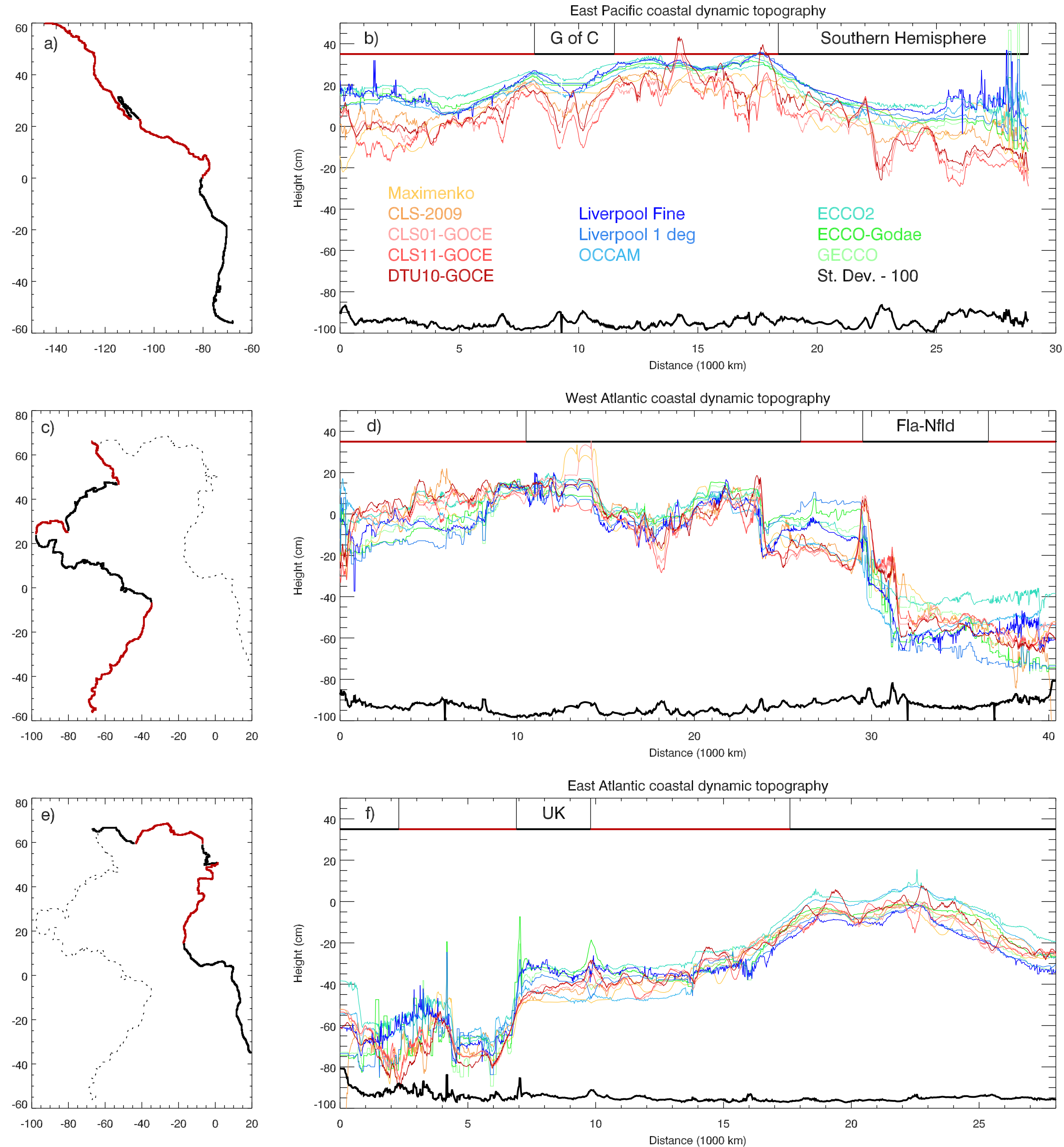
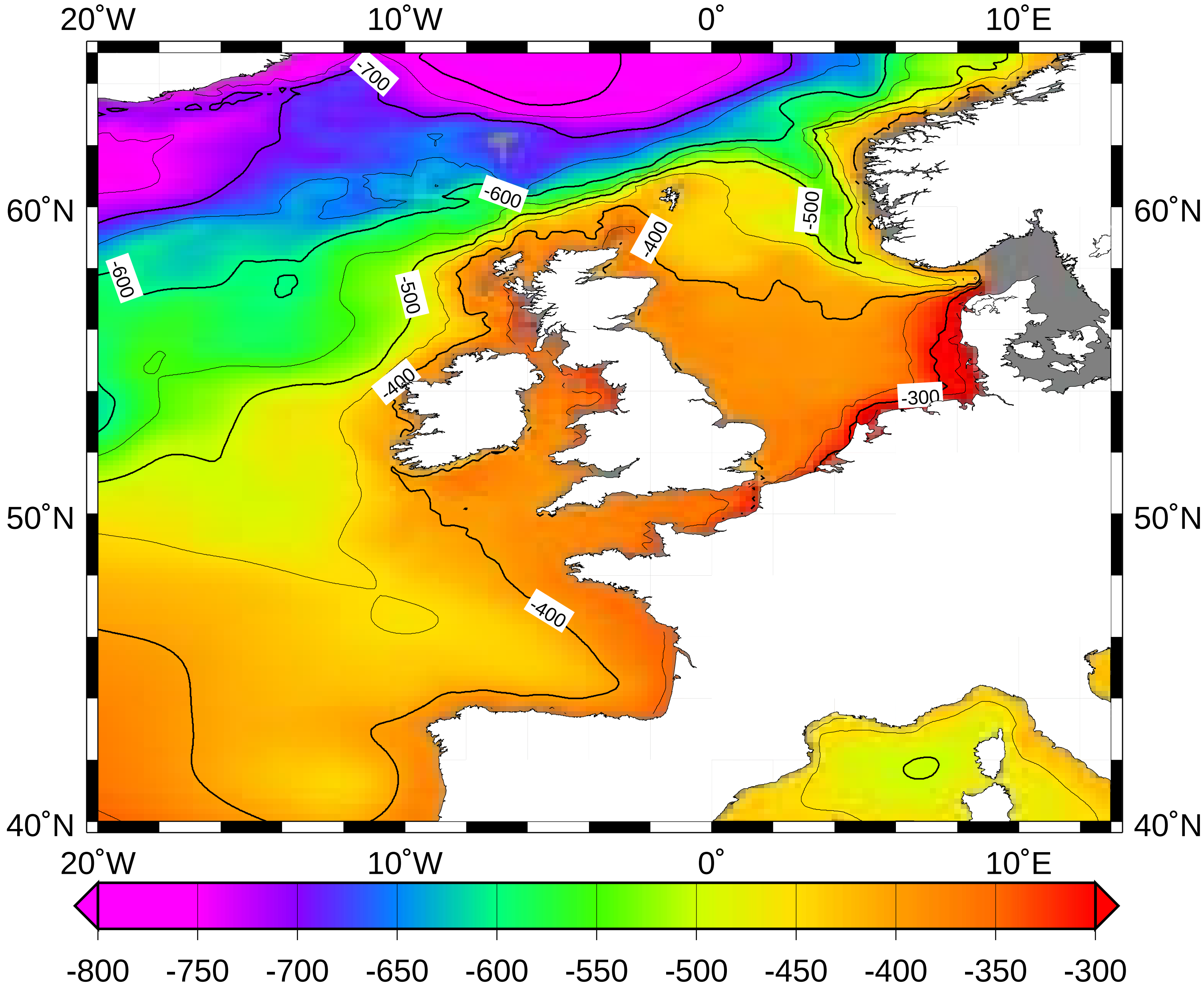

Dynamic height (cm): standard deviation between ocean models
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0 30 60 90 120 150 180 210 240 270 300 330 360 390
Scale (cm)
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5 25.0

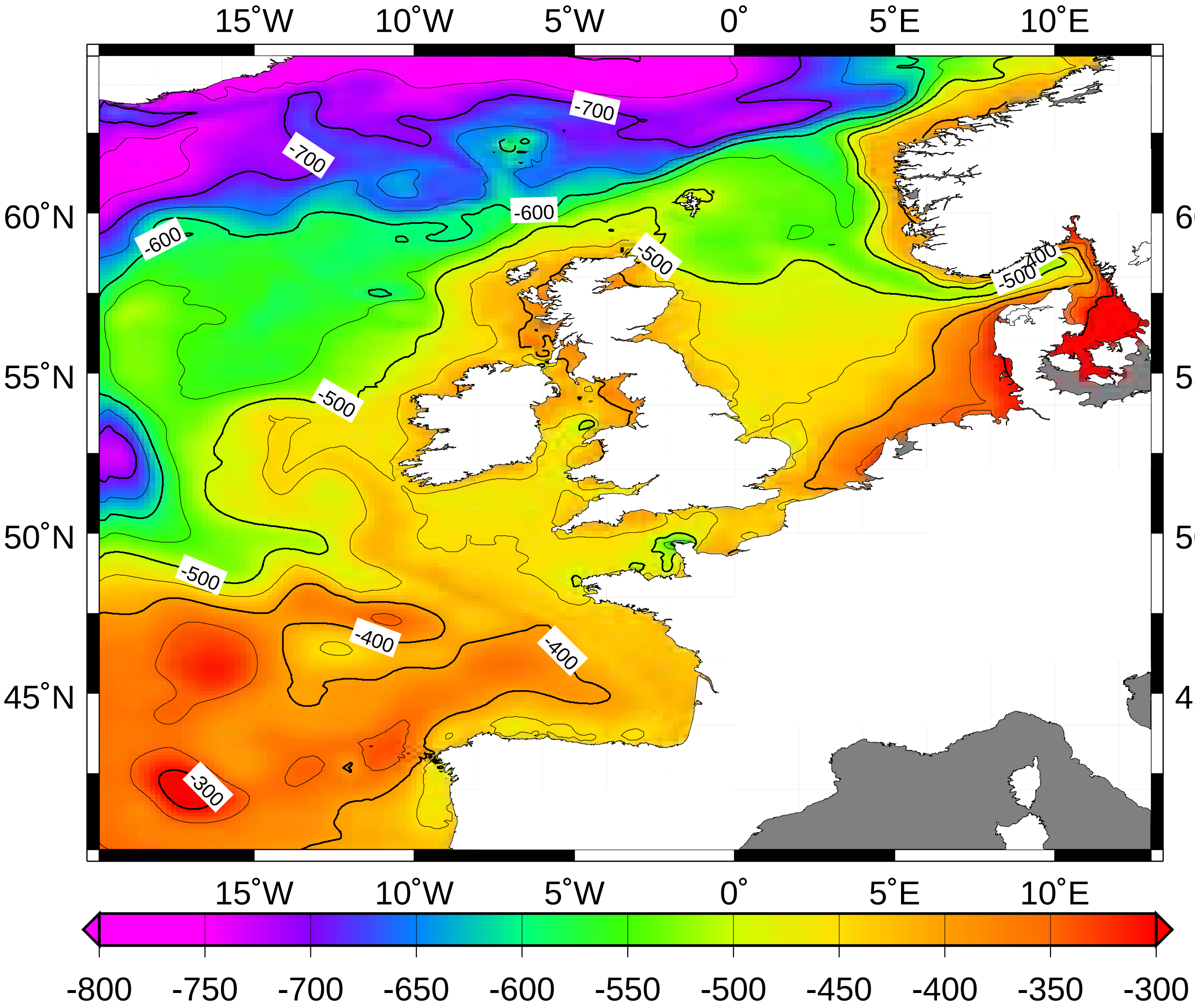
Figure 8 Next page



East Pacific coastal dynamic topography
a)
b)
G of C
Southern Hemisphere
Height (cm)
Distance (1000 km)
Maximenko
CLS-2009
CLS01-GOCE
CLS11-GOCE
DTU10-GOCE
Liverpool Fine
Liverpool 1 deg
OCCAM
ECCO2
ECCO-Godae
GECCO
St. Dev. - 100
West Atlantic coastal dynamic topography
c)
d)
Fla-Nfld
Height (cm)
Distance (1000 km)
East Atlantic coastal dynamic topography
e)
f)
UK
Height (cm)
Distance (1000 km)

Figure 9(a,b,c) Next pages


20°W
10°W
0°
10°E
60°N
50°N
40°N
-700
-600
-500
-400
-300
-800
-750
-650
-550
-450
-350



15°W
10°W
5°W
0°
5°E
10°E
60°N
55°N
50°N
45°N
-700
-600
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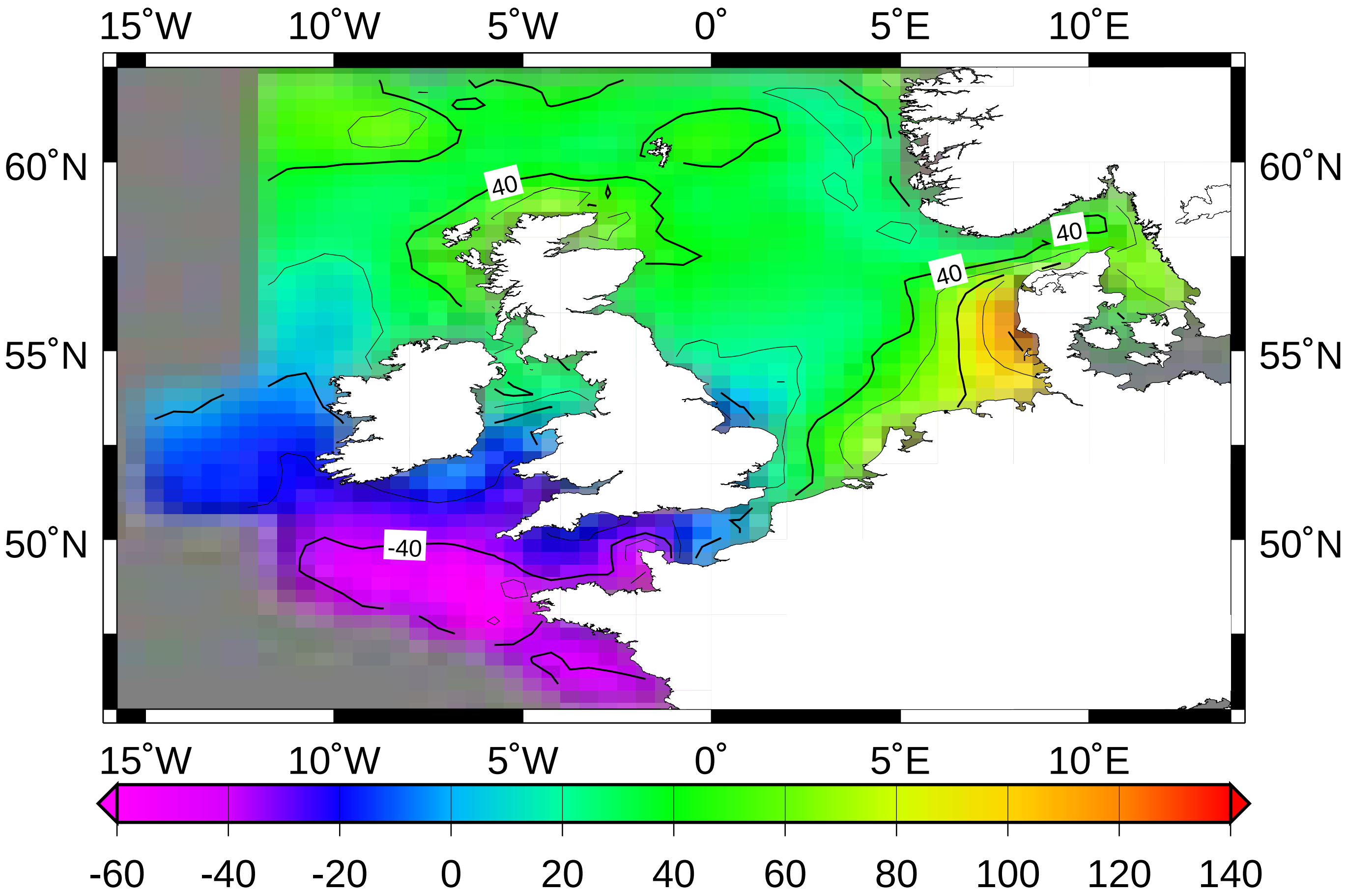
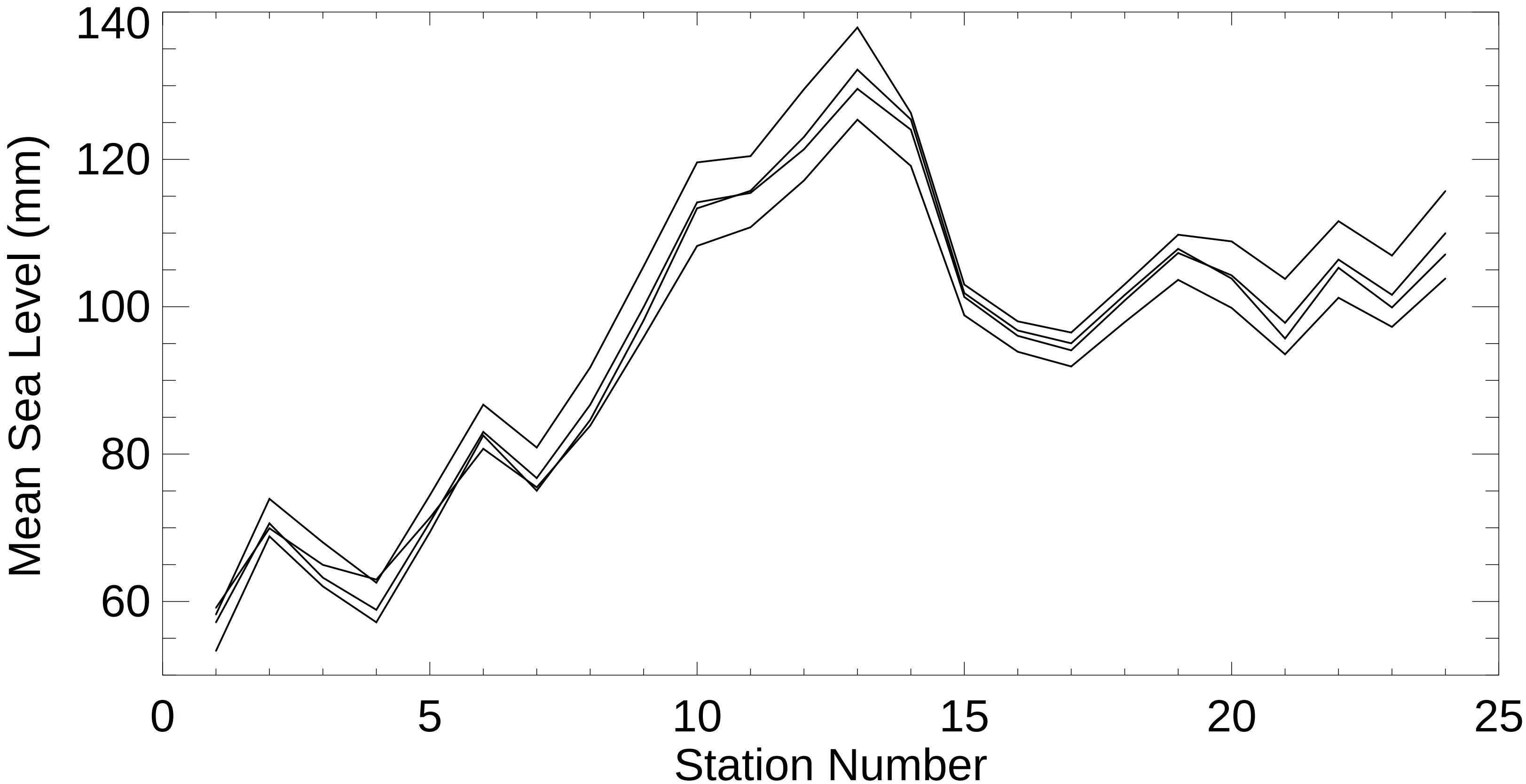
-400
-300
-800
-750
-650
-550
-450
-350

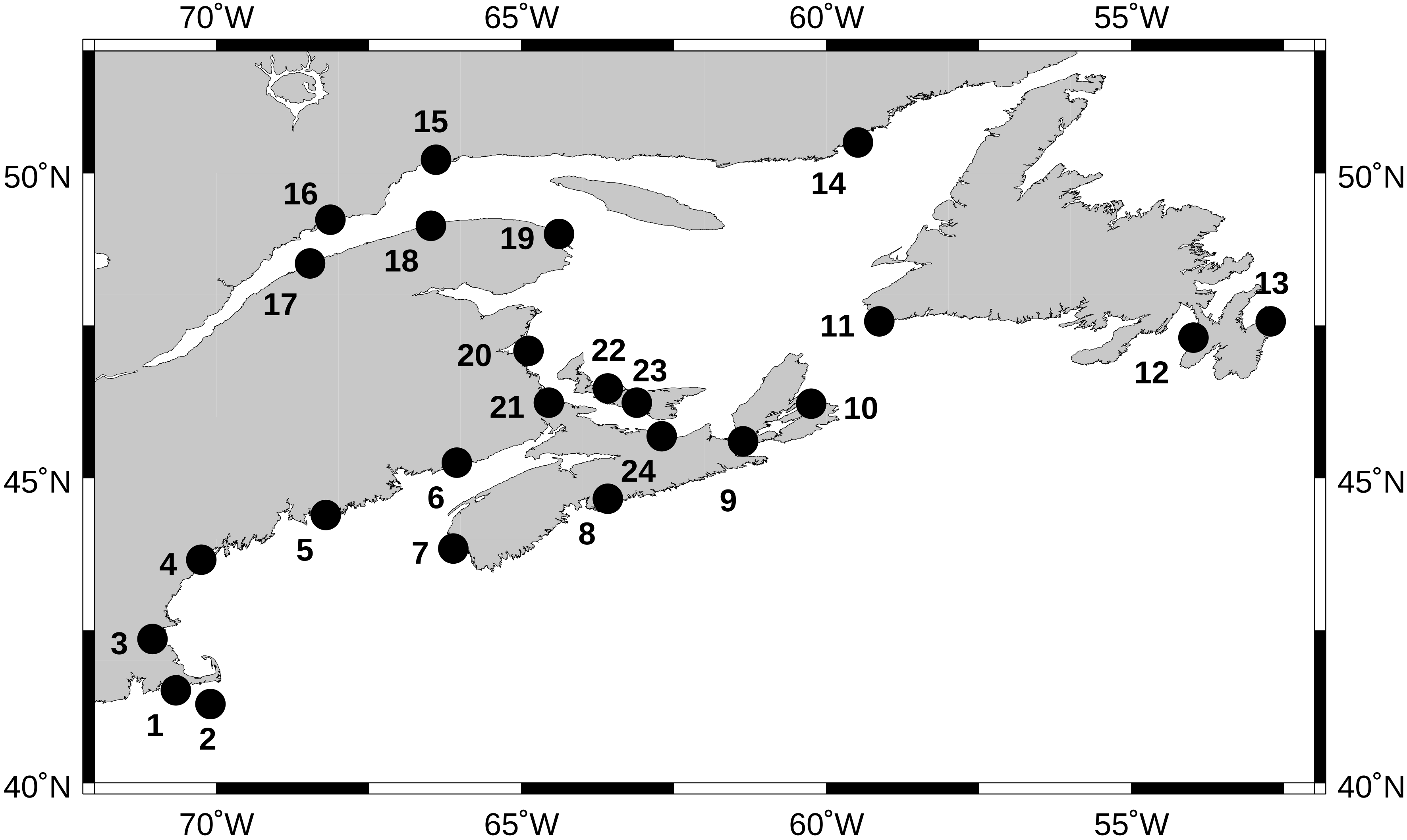


15°W
10°W
5°W
0°
5°E
10°E
60°N
55°N
50°N
40
40
40
-40
-60
-40
-20
0
20
40
60
80
100
120
140

Figure 10(a,b) Next pages



Mean Sea Level (mm)
140
120
100
80
60
0
5
10
15
20
25
Station Number


70°W
65°W
60°W
55°W
50°N
45°N
40°N
15
16
17
18
19
14
11
12
13
20
21
22
23
24
10
9
6
5
8
7
4
3
1
2