The north-south tilt in the Australian Height Datum is explained by the ocean's mean dynamic topography

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[1] Using geodetic and oceanographic data, we show that the apparent north-south slope between the Australian Height Datum (AHD) and the geoid is caused almost completely by the ocean's time-mean dynamic topography (MDT). This is because the AHD was constrained to zero height at local mean sea level at multiple tide gauges around the Australian continent. Using MDT models and corrected leveling data, almost all of the apparent north-south slope can be removed from the AHD. An auxiliary observation is that a satellite-only MDT model based on only around one year of GOCE data generates results commensurate with geodetic, oceanographic and combined MDT models.

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1. Introduction

[2] Apparent sea level slope is the disparity between geodetically leveled and oceanographically derived height differences along a coastline. It was first recognized by *Bowie* [1929] and has been discussed and debated since [e.g., *Fischer*, 1975, 1976, 1977; *Arur and Mueller*, 1975; *Castle and Elliott*, 1982]. A component of this disparity is due to the different reference surfaces and terminologies used by geodesists and oceanographers [e.g., *Fischer*, 1977; *Hamon and Godfrey*, 1980], as well as the propagation of different error sources [e.g., *Entin*, 1959; *Vaníček et al.*, 1980; *Bingham and Haines*, 2006]. Nevertheless, apparent sea level slopes have been reported for many countries and continents [e.g., *Sturges*, 1967, 1974; *Iida*, 1972; *Balazs and Douglas*, 1979; *Dixon*, 1979; *Thompson*, 1980; *Kumar and Soler*, 1981; *Blaha and Sturges*, 1987; *Zilkoski and Kumar*, 1988]. Indeed, apparent sea level slope in Australia has been quite an intense topic of investigation [*Hamon and Greig*, 1972; *Mitchell*, 1973a, 1973b, 1975; *Angus-Leppan*, 1975; *Leppert et al.*, 1975; *Coleman et al.*, 1979; *Macleod et al.*, 1988; *Macleod*, 1990]. However, studies conducted prior to 1976 were contaminated by an erroneous leveling traverse along the northeast Australian coast [*Holloway*, 1988; *Morgan*, 1992]. The data used in this study have been corrected for this leveling error.

[3] The Australian Height Datum (AHD) provides the official vertical geodetic reference frame for physically meaningful heights in Australia [*Granger*, 1972; *Roelse et al.*, 1975; *National Mapping Council of Australia*, 1979]. The AHD on the Australian mainland is technically a separate vertical datum to the AHD on Tasmania [*Rizos et al.*, 1991; *Filmer and Featherstone*, 2012]. Only the AHD on the mainland will be considered in this study and the abbreviation AHD used in the remainder of this paper. The AHD was realized in 1971 from a staged least squares adjustment of ∼170,000 km of differential leveling observations (Figure 1). The types and precisions of leveling used in the AHD are classified in *Filmer and Featherstone* [2009]. The AHD uses the *Rapp* [1961] version of the normal-orthometric height system that only partly corrects for non-parallelism of equipotential surfaces, does not deliver heights exactly relative to the geoid [*Filmer et al.*, 2010], and which will be discussed later in the context of the north-south tilt in the AHD.

[4] This 1971 realization of the AHD involved the least squares adjustment of a sparse subset of the leveling network (called the basic leveling; black lines in Figure 1) fixed to zero AHD height for local mean sea level (MSL) measured at 30 tide gauges around the Australian mainland (black circles in Figure 1). This fixing strategy is at odds with most other vertical datums, where MSL at only one tide gauge is held fixed to zero height [e.g., *Vaníček*, 1991]. The choice to use multiple tide gauges was deliberate for the AHD so as to avoid users encountering negative heights on dry land [*Roelse et al.*, 1975; *National Mapping Council of Australia*, 1986]. The remainder of the leveling network (called the supplementary leveling; gray lines in Figure 1) was then least squares adjusted on to the (fixed) basic network to provide AHD heights in more regions. This two-stage adjustment strategy was also driven by the computing power available at that time.

[5] Using GPS and gravimetric geoid models, it has become quite well established that a north-south-oriented tilt and regional distortions of ∼0.5–1.0 m in magnitude exist in the AHD [e.g., *Johnston and Luton*, 2001; *Featherstone et al.*, 2001, 2011; *Featherstone*, 2004, 2006; *Featherstone and Filmer*, 2008]. The tilt was often attributed to fixing the adjustment to MSL at multiple tide gauges, thus making

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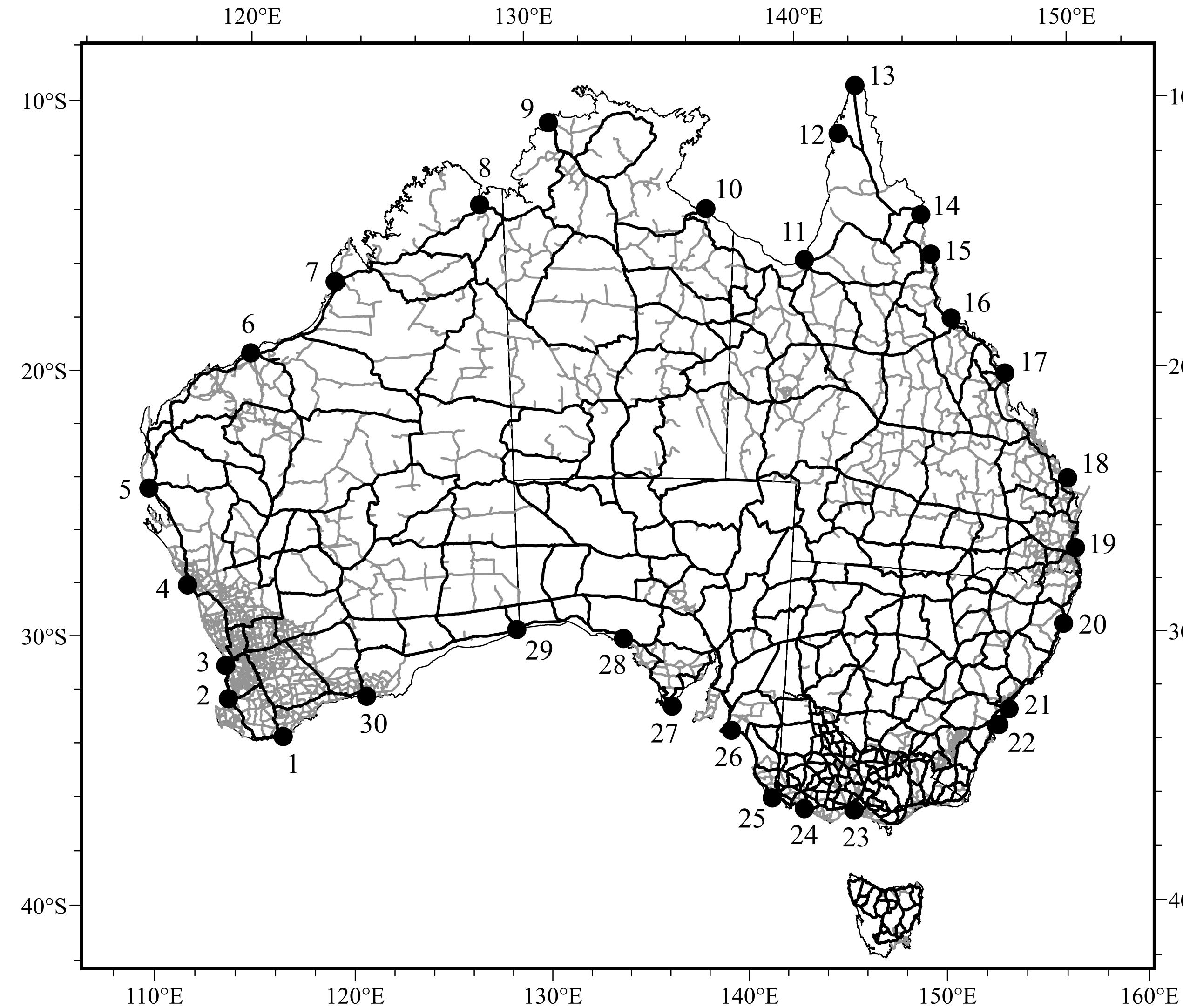

Figure 1. The 30 tide gauges used as zero height points for the AHD (numbered black circles); leveling traverses forming the "basic leveling" (black lines); leveling traverses forming the "supplementary leveling" (gray lines).

it subject to the effects of the ocean's time-mean dynamic topography (MDT). This attribution was not conclusive however, because of errors in the gravimetric geoid models, Australian tide gauge observations of MSL [*Mitchell*, 1973a, 1973b, 1975; *Coleman et al.*, 1979; *Morgan*, 1992], leveling observations [e.g., *Filmer and Featherstone*, 2009] and their reductions [e.g., *Leppert*, 1967; *Roelse et al.*, 1975; *Angus-Leppan*, 1975; *National Mapping Council of Australia*, 1979; *Morgan*, 1992; *Bretreger*, 1986; *Kearsley et al.*, 1988]. The study reported here will now prove that MDT is the principal cause for the north-south-oriented tilt in the AHD.

[6] Any tilt in the AHD is undesirable because it provides an incorrect zero reference surface with regards to the geoid as the classical figure of the Earth. While the tilt may not necessarily impact on localized height transfer on land (e.g., surveying for small-scale engineering projects), it becomes more prominent for large scale studies that rely on heights or for unification of the AHD in a global vertical datum. The north-south tilt in the AHD has also necessitated the distortion of the AUSGeoid09 model to make it coincide with the AHD [*Featherstone et al.*, 2011], but this remains unsatisfactory because the AHD is not coincident with the geoid and is generally inadequate as a modern vertical datum. Finally, Australia is investing in the acquisition of high-resolution digital elevation models (DEMs), but which are being distorted to fit the AHD, thus effectively adding error to this spatial data infrastructure and rendering it incompatible with global DEMs.

[7] MDT is the difference between the time-mean sea surface (corrected for the inverse barometer (IB) response [e.g., *Wunsch and Stammer*, 1997]) and the geoid. It is the surface manifestation of ocean dynamics [e.g., *Pugh*, 1987] and depends on the time period over which it is calculated. In much of the geodetic literature, it is referred to as sea surface topography. MDT is notoriously difficult to model geodetically in the coastal zone [e.g., *Metzner et al.*, 1995; *Hipkin*, 2000; *Bingham et al.*, 2008]. In addition, the tide gauges used as zero points for vertical datums are often located in harbors and estuaries for reasons of convenience and maritime navigation, so the measured MSL can include

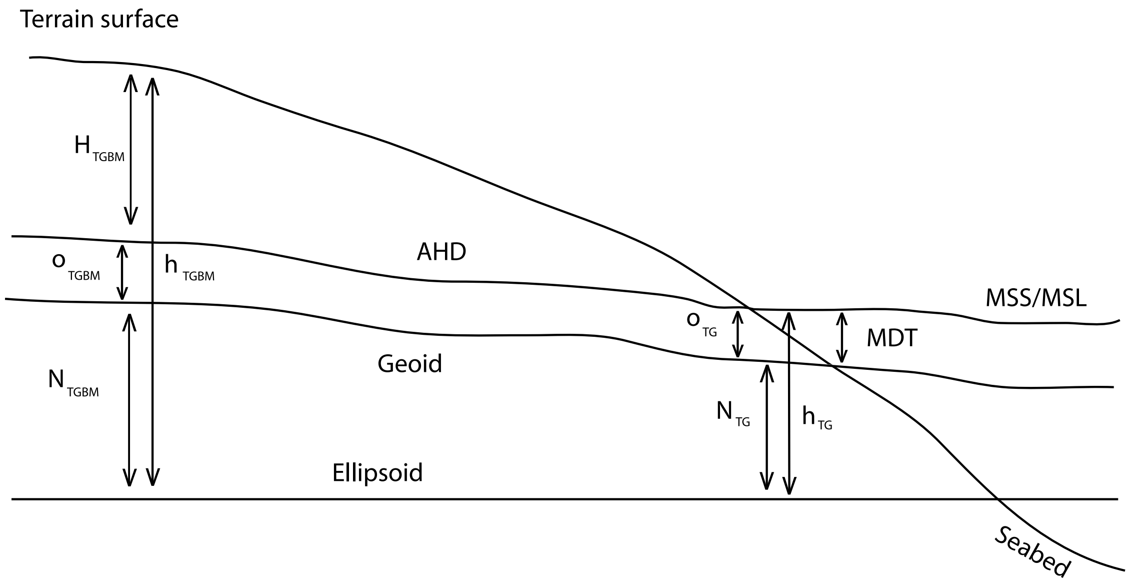

Figure 2. Relationship among MSS/MSL, AHD (*H*), MDT, geoid (*N*) and ellipsoid (*h*). The offset (o) between the vertical datum (AHD) and the geoid at the tide gauge, o_{TG} and inland at the TGBM (tide gauge benchmark) o_{TGBM} is assumed to be constant within a few km of the coastline.

a steric contribution from freshwater outflow [e.g., *Meade and Emery*, 1971] and nearshore oceanic processes [e.g., *Merry and Vaníček*, 1983]. Land subsidence or uplift [e.g., *Belperio*, 1993; *Aubrey and Emery*, 1986], spatial variability of sea level change [e.g., *Church et al.*, 2010; *Aubrey and Emery*, 1986], the IB response and other processes also affect the determination of MSL from tide gauges. While these latter factors could cloud the issue as to how much MDT has caused the north-south slope in the AHD, it will be shown that they are less significant when all 30 tide gauges are considered together.

[8] We will use combinations and permutations of GPS-derived ellipsoidal heights, leveled heights, geoid-model and [geodetic, oceanographic and combined geodetic-oceanographic] MDT-model estimates at AHD tide gauges to show that MDT almost fully accounts for the north-south slope in the AHD. Thus, the relation

$$h - H - N - MDT = \text{constant} \tag{1}$$

will be satisfied at the tide gauges, where H is the height relative to the AHD, h is the ellipsoidal height, and N is the geoid-ellipsoid separation (cf. Figure 2). All these quantities vary with location. The constant in equation (1) is to account for an offset between the AHD and the geoid, the inexactly known zero-degree term in the geoid, and the different reference levels for the MDT. The latter is exemplified in Figure 5. However, this constant term vanishes in our relative analyses. Linear regression of the residuals of equation (1) as a function of latitude will be used to quantify the north-south tilt attributable to fixing the AHD to MSL, and thus the contamination from unaccounted-for MDT.

[9] In section 2, we shall describe the peculiarities of the heterogeneous data types used, focusing on their limitations, expected errors, and different observation epochs. We will then demonstrate that recent geodetic, oceanographic and combined geodetic-oceanographic MDT models are reasonably similar around the Australian coast, but this conclusion is subject to deficiencies in gravimetric geoid models in the coastal zone, deficiencies in the leveling, and the determination of MSL at the tide gauges (section 3.1). Finally, we demonstrate that the north-south slope in the AHD is almost fully attributable to MDT; if MDT models are used in a readjustment of the leveling, the apparent sea level slope in Australia will largely vanish (section 3.2).

2. Data

2.1. AHD Tide Gauges

2.1.1. The 3-D Locations

[10] The horizontal locations (latitude and longitude) of the 30 AHD tide gauges on the mainland were taken from the Permanent Service for Mean Sea Level (PSMSL) [*Woodworth and Player*, 2003] at http://www.psmsl.org. Where there was a disparity between the coordinates, the National Tide Centre http://www.bom.gov.au/oceanography/projects/ntc/ntc.shtml value was used, but only if it was closer to the location given in the Australian National Levelling Network (ANLN) database provided by Geoscience Australia (GA) (G. M. Johnston, personal communication, 2007). However, there is a one arc-minute (~1.8 km), or greater, uncertainty in the horizontal locations of the tide gauges, which causes some additional uncertainty when interpolating and extrapolating data. This situation could be avoided if more significant figures were included in the above databases. For instance, a handheld GPS configured for the WGS84 datum could be used during routine inspections of the tide gauges and this horizontal location passed to the PSMSL, together with any other appropriate metadata.

[11] GPS-derived ellipsoidal heights (h_{TGBM}) at 30 tide gauge benchmarks (TGBMs) used in the 1971 realization of the AHD were also provided by GA (N. J. Brown, personal communication, 2009). These are referred to the GRS80 ellipsoid [*Moritz*, 1980] and the International Terrestrial

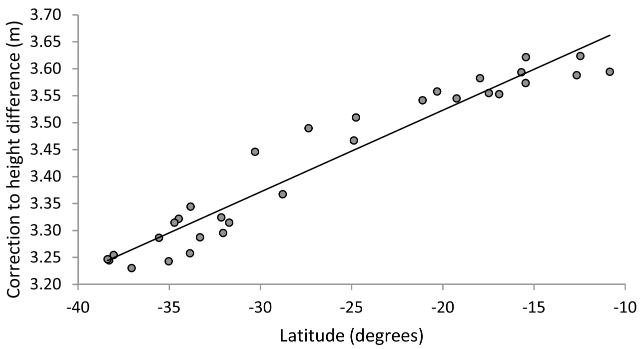

Figure 3. Height differences between normal-orthometric-corrected heights and the observed leveled heights with no height correction applied at the 30 TGBMs. The north-south slope is 15 mm per degree with a coefficient of determination of 0.93.

Reference Frame 2005 (ITRF2005) epoch 2000.0 datum [*Altamimi et al.*, 2007]. The dual-frequency GPS data were observed in circa 2000 by State/Territory geodetic agencies for at least five continuous days and re-processed by *Hu* [2009] using IERS conventions [*McCarthy and Petit*, 2004]. The ellipsoidal heights are claimed to be precise to a few mm, but internally propagated error estimates from GPS processing software are typically overoptimistic by a factor of 5–10 [e.g., *Rothacher*, 2002]. Therefore, a more realistic error estimate for the GPS-derived ellipsoidal heights is, say, ~10–20 mm, but this is not significant because of the larger errors likely in the other data sources.

[12] Since the GPS ellipsoidal height of the tide gauge (h_{TG}) is required for this analysis (equation (1)), it was necessary to transfer it from the TGBMs to the zero of the tide gauges using leveled height differences. This approach assumes that the offset between the AHD and the geoid is the same at the tide gauge and its corresponding TGBM (Figure 2) [cf. *Hipkin et al.*, 2004]. The AHD TGBMs are mostly within ~2 km of the tide gauges, but some are ~10 km away. We calculated the GPS-geoid MDT by first subtracting a geoid model referenced to GRS80 from the GPS ellipsoidal height of the TGBM, then subtracting the height of the TGBM above local MSL at the tide gauge. The weak link in this process is the imprecision of geoid models in the coastal zone, which will be discussed in section 3.1.

2.1.2. MSL Estimates

[13] The 30 MSL estimates used for the AHD and this study come from tide gauge observations made between January 1 1966 and December 31 1968, except at Karumba January 1 1957–December 31 1960 (tide gauge 11 in Figure 1) [*Roelse et al.*, 1975]. These define zero points of the AHD, but may be biased for a variety of reasons as follows. Since the three to four year time span omits long-period tides, we determined whether there was any influential north-south contribution from the nodal tide using *Woodworth* [2012, equation (1) and Table 1], scaled by the cosine of the mean longitude of the Moon's ascending node over this time period [*Pugh*, 1987]. The mean nodal tide ranges from ~2.5 mm to ~−12 mm with north-south variation of 0.05 mm per degree, which is insignificant compared to the slope in the AHD (section 3.2).

[14] Other effects on the tide gauge estimation of MSL are more difficult to quantify, but should also be much less than the north-south slope in the AHD. *Easton* [1968] visited some of the AHD tide gauges, finding that the conditions and operating methods left much to be desired, and with many gaps in the records. The placement of many AHD tide gauges at river mouths means that the steric effect from freshwater outflow can bias the MSL estimate [*Meade and Emery*, 1971]. For instance, *Morgan* [1992] estimated the effect of river discharge at Bundaberg (tide gauge 18 in Figure 1) could be as much as a few dm. Nearshore oceanic processes [e.g., *Merry and Vaníček*, 1983; *Pugh*, 1987], sea level variability [e.g., *Church et al.*, 2010; *Aubrey and Emery*, 1986], and land subsidence or uplift [e.g., *Belperio*, 1993; *Aubrey and Emery*, 1986] will also bias the tide gauge estimates of MSL. Other errors can result from the support structure subsiding/uplifting, or shocks passing from shipping or vehicles.

[15] Finally, no correction for the IB response was applied to the estimates of MSL used in the realization of the AHD. Since mean atmospheric pressure generally increases toward the poles, this will generate some proportion of the north-south slope in the AHD. We therefore computed the IB response over the epochs of the MSL measurements using monthly mean sea level air pressure values extracted from the NCEP reanalysis [*Kalnay et al.*, 1996] with respect to 1013.3 mbar and the formula in *Wunsch and Stammer* [1997]. The corresponding IB correction varies between −36 mm and +38 mm with a north-south influence of −2.8 mm/degree, which is much less than the slope in the AHD. Since MSL alone was used in the definition of the AHD, the IB correction is not included in the analyses in sections 3.1 and 3.2.

2.2. Leveling

[16] The quality of the Australian leveling data has been discussed and debated by many authors [cited in the Introduction]. A digital version of the ANLN in a format that can be least squares adjusted was provided by GA (G. M. Johnston, personal communication, 2007). The spirit-leveled height differences held in this file comprise mostly pre-1971 data that was used in the original realization of the AHD. Some additional leveling has been added to this file since, including corrections for errors found in the 1975–1976 re-leveling of the northeast coast between Coffs Harbor and Cairns (tide gauges 20 and 15 in Figure 1) [*Holloway*, 1988; *Morgan*, 1992] and a part of southwest Australia [*Wellman and Tracey*, 1987].

[17] Because the separation between equipotential surfaces of the Earth's gravity field increases toward the equator, it is necessary to apply gravimetric corrections to leveled height differences [e.g., *Heiskanen and Moritz*, 1967, chapter 4]. *Roelse et al.* [1975] used the normal-orthometric correction of *Rapp* [1961] as an approximation because observed gravity values were unavailable along the leveling traverses. Figure 3 shows the difference between the normal-orthometric-corrected heights and the observed leveled heights at the 30 TGBMs. The height of the Albany TGBM (tide gauge 1 in Figure 1) has been set to its AHD value of 3.243 m. Figure 3 shows that if the normal-orthometric correction had not been applied, a north-south slope in the

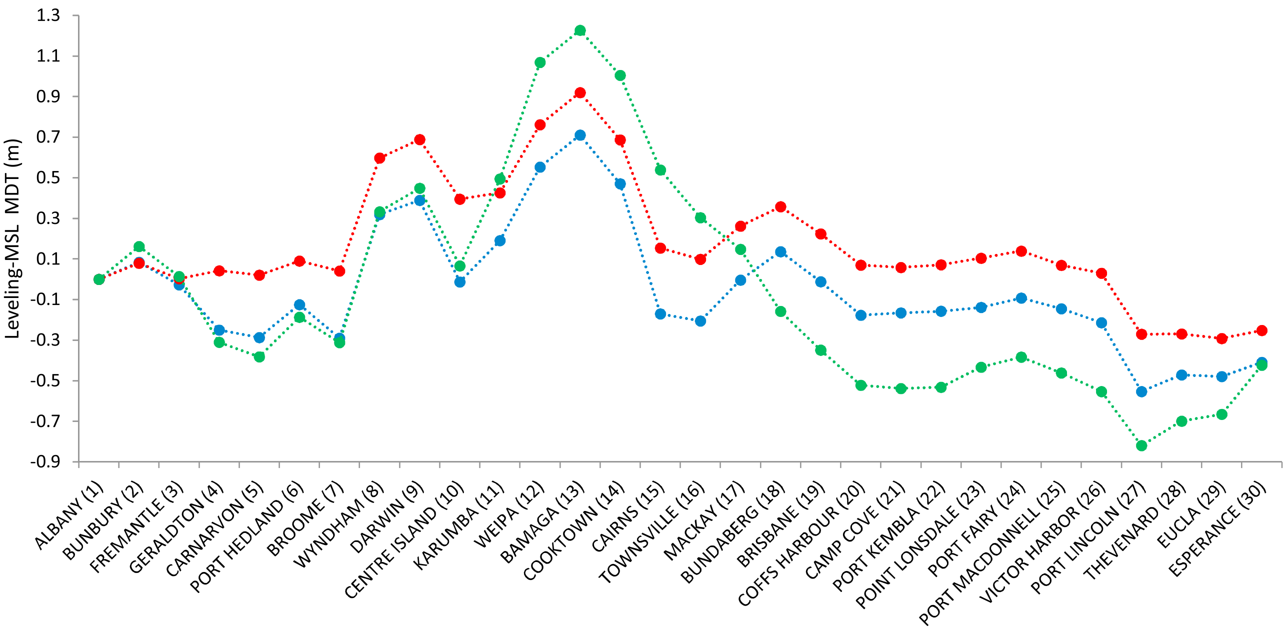

Figure 4. Leveling-MSL relative MDT at 30 AHD tide gauges from MCAs of the original 1971 basic network (green), the corrected basic leveling network (blue), and the corrected entire ANLN (red). Values relative to Albany tide gauge fixed at local MSL = zero. See Figure 1 for locations.

AHD of ~15 mm per degree would have come from the leveling alone, amounting to ~0.4 m.

[18] In order to determine whether the ~600 mm north-south slope in the AHD is influenced by the accuracy of the leveling, we conducted a minimally constrained least squares adjustment (MCA) of the normal-orthometric-corrected ANLN, this time holding the Johnston geodetic station in central Australia fixed to an arbitrary height [cf. *Roelse et al.*, 1975]. This avoids any 'preference' being given to any particular tide gauges because leveling errors propagate as the square root of distance. The standard deviations (STDs) of the adjusted heights of the TGBMs are generally between ~100 mm and ~150 mm, but this increases to ~200 mm for Weipa and Bamaga (tide gauges 12 and 13 in Figure 1). This is due to the geometric weakness of the leveling network in this region (black and gray lines in Figure 1), coupled with several traverses of lower accuracy [cf. *Filmer and Featherstone*, 2009]. Despite this, the magnitude of the leveling error from the MCA makes the apparent north-south slope between the AHD and the geoid difficult to explain without considering the MDT.

[19] The 1971 least squares adjustments of the AHD included a MCA of the basic leveling network [*Roelse et al.*, 1975], which showed differences from MSL at the 30 tide gauges that were sometimes larger than could be expected from leveling tolerances alone. However, this original adjustment was contaminated by the leveling error along the northeast coast. The corrected ANLN file is in a format that can be least squares adjusted in a single continent-wide adjustment, rather than the 1971 staged adjustments of the basic then supplementary leveling. We have arbitrarily held Albany (tide gauge 1 in Figure 1) fixed to MSL = zero in the new MCAs described below, and vertically translated the differences given in *Roelse et al.* [1975] so as to allow for easier visual comparison.

[20] Figure 4 shows the differences between the leveled height of the tide gauges and the MSL values used in the AHD based on three different MCAs: (1) the 1971 MCA of the basic network by *Roelse et al.* [1975] (green); (2) a new MCA of the basic network with the corrected leveling (blue); and (3) a new MCA of the entire corrected ANLN basic and supplementary networks in one adjustment (red). *Rapp*'s [1961] normal-orthometric correction was applied to all leveling sections used in these MCAs. This gives what is effectively the leveling-MSL MDT at the AHD tide gauges, all relative to Albany (1). Thus we are only looking at relative—not absolute—MDT in order to ascertain the source of the north-south tilt in the AHD.

[21] Three principal observations can be made from Figure 4. (1) The two large leveling blunders between Bundaberg (18) and Townsville (16) exaggerate the relative MDT implied by the original MCA (green line versus blue line). (2) A leveling error is apparent in the basic network between Fremantle (3) and Geraldton (4) (cf. red line versus blue and green lines), showing the advantage of being able to use the entire network (basic and supplementary leveling) in a single MCA, and thus profit from the additional redundancy of observations. (3) There are higher frequency oscillations in the leveling-MSL MDT (e.g., centered at Darwin (9), Bamaga (13), Bundaberg (18) and Port Lincoln (27)), which are due to regional distortions and undetectable blunders in the leveling network [*Featherstone and Filmer*, 2008; *Filmer and Featherstone*, 2009], but ~100–200 mm of these comes from the internal error estimate from the MCA.

2.3. MDT Models

[22] MDT can be modeled geodetically, oceanographically or from a combination of geodetic and oceanographic data (Table 1). Geodetic MDT models take the difference between an (IB-corrected) time-mean sea surface (MSS)

Table 1. Summary of the MDT Models Used to Assess the North-South Slope in the AHD

MDT Model	Classification	Brief Description
JPL08	Satellite-terrestrial geodetic	An update of *Tapley et al.* [2003]. Difference between DNSC08MSS [*Andersen and Knudsen*, 2009] and EGM2008 [*Pavlis et al.*, 2012]. A 111 km half-width Gaussian filter was used to smooth the MDT. Epoch: 1993–2004; Tide system: Mean tide; Grid spacing: $30' \times 30'$; URL: http://grace.jpl.nasa.gov
DTU10MDT	Satellite-terrestrial geodetic	An update of DNSC2008MDT [*Andersen and Knudsen*, 2009]. Difference between DTU10MSS from re-tracked altimetry and EGM2008 [*Pavlis et al.*, 2012]. A 75-km half-width Gaussian filter was used to smooth the MDT. Epoch: 1993–2009; Tide system: Mean tide; Grid spacing: $2' \times 2'$; URL: http://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Mean_Dynamic_topography.aspx
RJB2012 (R. J. Bingham, personal communication, 2012)	Satellite-only	CLS01 mean sea surface from 1993 to 1999 multimission altimetry [*Hernandez and Schaeffer*, 2001], converted to spherical harmonics and truncated at degree 220. GO_CONS_GCF_2_TIM_R3 geoid to degree 220 from ~12 months of GOCE data between 11/01/2009 and 04/17/2011 [*Pail et al.*, 2011]. A 150 km half-width Gaussian filter was used to smooth the MDT. Epoch: 1993–1999; Tide system: Mean tide; Grid spacings: $2' \times 2'$ and $15' \times 15'$
CNES-CLS09, v 1.1 [*Rio et al.*, 2011]	Combined geodetic-oceanographic	An update of Rio05 [*Rio and Hernandez*, 2004]. Geodetic data: CLS01 mean sea surface from 1993 to 1999 multimission altimetry [*Hernandez and Schaeffer*, 2001]; EIGEN-GRGS.RL02 geoid to degree 160 from 2003.2 to 2007.7 GRACE and LAGEOS data, excluding 2002 [*Bruinsma et al.*, 2010]. Satellite-only MDT filtered in several stages as described in *Rio et al.* [2011, sect 3]. Oceanographic in situ data: Drifting buoy data from 1993 to 2008; Argo temperature and salinity profiles from 2002 to 2008; Conductivity-temperature-depth (CTD) casts from 1993 to 2008. Tide system: Mean tide; Epoch: 1993–1999; Grid spacing: $15' \times 15'$; URL: http://www.aviso.oceanobs.com/en/data/products/auxiliary-products/mdt/index.html
CARS2009 [*Ridgway et al.*, 2002; *Dunn*, 2009]	Oceanographic-only	See the main text (section 2.3). Tide system: not applicable; Epoch: ~1950–2009 with bias to more recent times; Grid spacing: $15' \times 15'$; URL: http://www.marine.csiro.au/~dunn/cars2009/

derived from satellite altimetry and a gravimetric geoid model [e.g., *Mather*, 1975; *Tapley et al.*, 2003; *Andersen and Knudsen*, 2009]. Several global geodetic MDT models have been produced over the decades as more altimeter data have been collected and global geoid models have been refined. The gravimetric geoid model used can come from satellite observations alone or from a combination of a satellite model and terrestrial data. We therefore further classify these geodetic MDTs as: satellite-only and satellite-terrestrial. The oceanographic MDT model used here makes use of in situ data on temperature, pressure, salinity and ocean currents to derive the MDT [e.g., *Ridgway et al.*, 2002; *Dunn*, 2009]. Combined geodetic-oceanographic MDT models merge both data sets [e.g., *Rio and Hernandez*, 2004; *Rio et al.*, 2011].

[23] In coastal zones, geodetic-only and—to a lesser extent—combined MDT models are limited by three principal factors. (1) Poorer altimeter waveform tracking in the coastal zone [e.g., *Deng and Featherstone*, 2006; *Andersen and Knudsen*, 2000, 2009] and imprecise tidal models over continental shelves [e.g., *Shum et al.*, 1997] render the altimeter-derived MSS less reliable near the coast. (2) The quality of gravimetric geoid models is restricted by the dearth of detailed gravity data in the coastal zone: ship track gravimetry cannot approach the coast because of navigation restrictions, and altimeter-derived marine gravity anomalies are degraded in the coastal zone [e.g., *Hwang et al.*, 2006; *Andersen et al.*, 2010]. (3) Spatial filtering, which is required to remove noise from geodetic MDTs, can blur coastal changes associated with finer scale features of the ocean's circulation, such as narrow boundary currents [e.g., *Bingham et al.*, 2008; *Rio et al.*, 2011; *Bingham et al.*, 2011].

[24] In the open oceans, geodetic and combined MDT models, while better than in the coastal zones, are still limited by the accuracy of the geoid models over the oceans [e.g., *Wunsch and Gaposchkin*, 1980; *Tapley et al.*, 1994; *Losch and Schröter*, 2004]. This is where ESA's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission [*Drinkwater et al.*, 2003; *Rummel et al.*, 2009] is starting to make some substantial contributions to MDT determination [e.g., *Vossepoel*, 2007; *Knudsen et al.*, 2011]. During the review cycle of this article, R. J. Bingham (personal communication, 2012) provided us with a GOCE-based MDT model using a third-generation GOCE geoid (abbreviated as RJB2012 in Table 1). This is the only MDT model used in this study that is based purely on satellite data. It was provided at $2' \times 2'$ and $15' \times 15'$ grid spacings, allowing us to test the effect of interpolation/extrapolation error, as well as the better definition of the land-ocean boundary in the MDT model.

[25] Also during the review cycle of this article, O. B. Andersen (personal communication, 2012) provided us with some information on the differences between DTU10MDT (Table 1) and DNSC2008MDT [*Andersen and Knudsen*, 2009]. Most notably, more re-tracked satellite altimeter data closer to the coastline were included in the DTU10MSS, and a corrected 75-km Gaussian filter was used. As such, it can be expected that DTU10MDT is an improvement upon DNSC2008MDT in the coastal zones.

[26] The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atlas of Regional Seas 2009 (CARS2009) is a high-resolution seasonal climatology that covers the global oceans on a $0.25° \times 0.25°$ grid (http://www.marine.csiro.au/~dunn/cars2009/). It is an update of CARS2006 [*Ridgway et al.*, 2002]. Six water properties are charted: temperature, salinity, oxygen, nitrate, silicate and phosphate, based on the BLUElink Ocean Archive (BOA) of high-quality buoy and hydrographic cast data [*Dunn*, 2008]. More than 500,000 profiles of ocean in situ data, mostly from between 1950 and 2009, have also been used in CARS2009.

[27] A space-time locally weighted least squares method based on LOESS mapping [e.g., *Cleveland and Devlin*, 1988] was developed by *Ridgway et al.* [2002] to interpolate the irregularly spaced BOA data. This also takes into account the influence of land barriers and bathymetry: data on the continental shelves is strongly down-weighted for deep ocean mapping; deep ocean data is moderately down-weighted for shelf mapping; and both deep water and shelf data are moderately down-weighted for mapping mid-water regions [*Dunn and Ridgway*, 2002]. The LOESS scheme allows for sea bottom topography (topographic adjusted relief), land barriers (barrier adjusted relief) and fitting seasonal components in a single step [*Ridgway et al.*, 2002].

[28] The CARS2009 MDT is modeled by integration of the temperature, pressure and salinity fields on a water depth of 2 km. Where the depth is <2 km, interpolation (ocean ridges), vertical regression procedures (depths > 400 m) and locally weighted extrapolation (continental slope and shelf areas) methods have been used [*Ridgway and Dunn*, 2003]. The incorporation of this spatial and temporal complexity is expected to improve the coastal representation of mean MDT in Australian waters [e.g., *Deng et al.*, 2008]. The epoch over which CARS2009 applies is more difficult to define, but the CARS website claims that it is over the past 50 years, stating "the CARS mean values are inevitably biased towards the recent ocean state."

[29] Figure 5 shows charts of the MDTs from the five models in Table 1, as well as the error chart for the CNES-CLS09 MDT [cf. *Rio et al.*, 2011, Figure 3]. Although the MDT models in Figure 5 show different absolute values, this study is only concerned with the relative MDT. Values are only plotted where there are data points using GMT [*Wessel and Smith*, 1998], so the different levels of pixilation reflect the grid-spacing (not the spatial resolution) of each MDT model. CARS2009 does not provide MDT values over large areas to the north of Australia and does not adjoin the coastline around most of Australia. Therefore, it will have to be extrapolated to the locations of the tide gauges in later analyses. The geodetic and combined MDT models all adjoin the coast, and extend inland in some cases. The shorelines used in Figure 5 are from *Wessel and Smith* [1996].

[30] Figure 6 charts the differences around Australia between CNES-CLS09 and the remaining MDT models listed in Table 1. The GMT surface routine [*Smith and Wessel*, 1990] was used to interpolate the MDT models to common sized grids for comparison, with MDT models that do not adjoin the coast (e.g., CARS2009; Figure 5a) being extrapolated into the coastal zone in this process. Large differences are evident in several coastal zones, particularly along the eastern coastline. This is due to the lack of data in some MDT models, but is compounded by ocean dynamics and western boundary currents to the east of Australia [e.g., *Ridgway and Godfrey*, 1997; *Ridgway and Dunn*, 2003], and

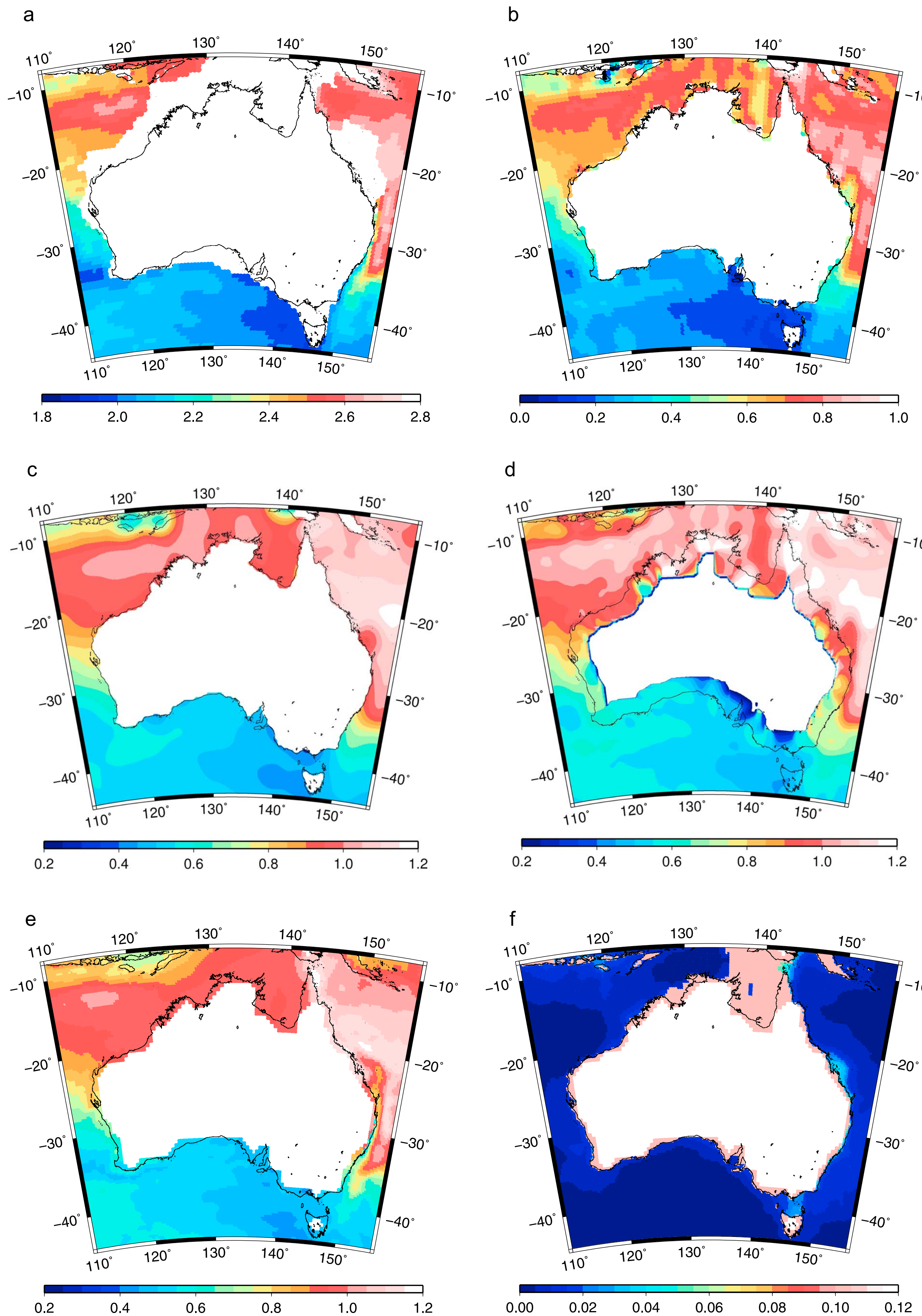
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Figure 5

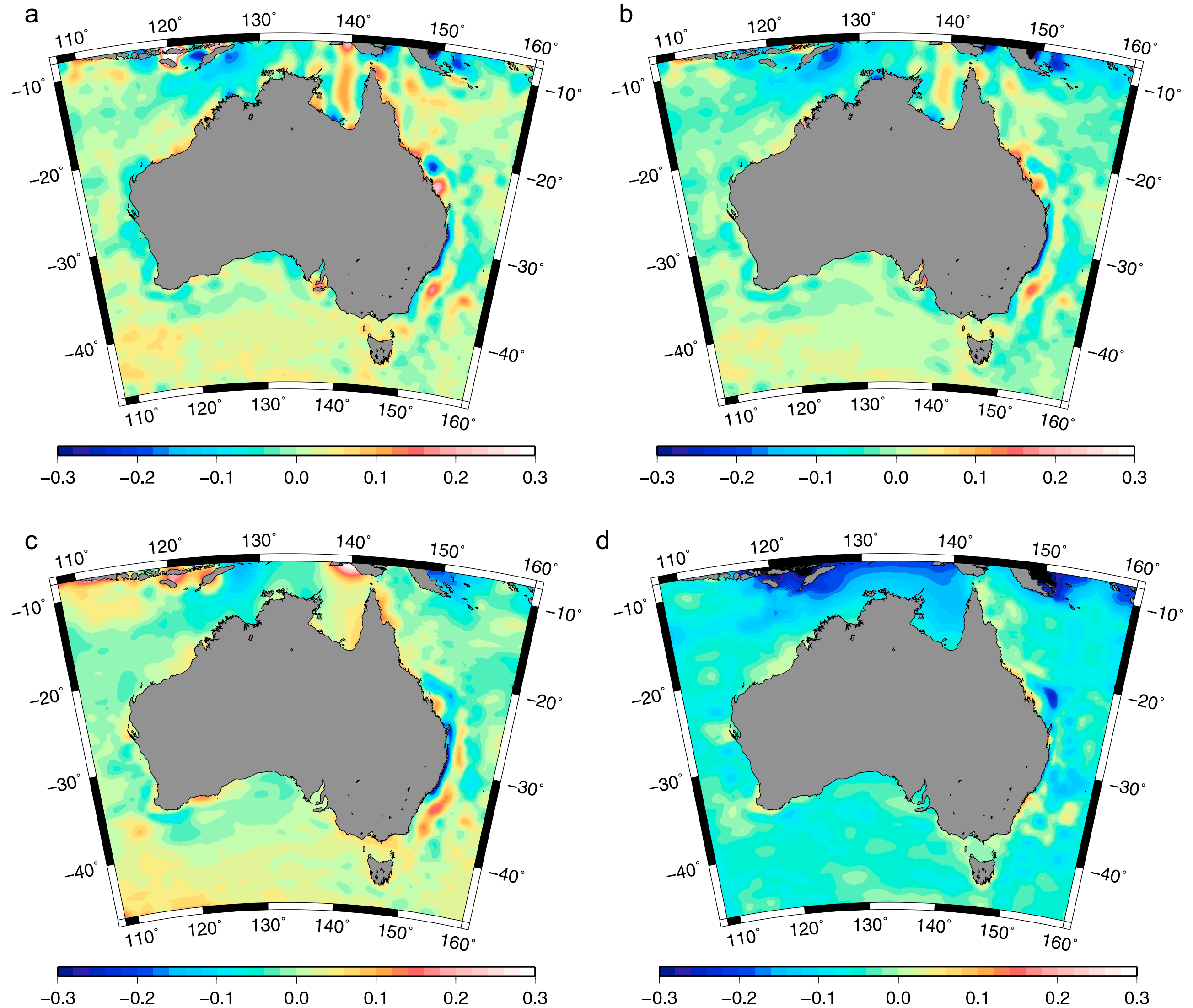

Figure 6. MDT models subtracted from CNES-CLS09: (a) JPL08, (b) DTU10MDT, (c) RJB2012, and (d) CARS2009. Units in meters. Lambert conical projection.

the Great Barrier Reef may allow freshwater outflow to back up [cf. *Meade and Emery*, 1971]. There are also larger differences for some of the MDT models in and around the Gulf of Carpentaria (centered at ~140°E, ~15°S). For the MDT models that include oceanographic data, this is due to the lack of observations in this gulf sea that is <200 m deep (i.e., the areas mapped with 100 mm errors in Figure 5f). For the geodetic and combined MDT models, this is likely to be associated with the sea surface height anomaly in this region [*Forbes and Church*, 1983].

[31] All MDT models in Table 1 were interpolated/extrapolated from their respective grids to the locations of the tide gauges. The effect of the positional uncertainty of the tide gauges was investigated by shifting the location by 1 arc-minute in each direction and examining the discrepancies among interpolated values. The differences were only a few cm, reflecting the smoothness of the MDT models. Figure 7 shows the modeled MDT extrapolated/interpolated to the locations of the 30 AHD tide gauges in Figure 1. All values have been translated vertically to be zero at Albany (1), thus giving relative MDT. There is broad similarity among the profiles in Figures 4 and 7, which will be examined numerically in section 3.

2.4. Epochs and Tides

[32] There are problems when trying to reconcile data collected over different time periods, especially when the quantities being measured are time-varying. For instance, 29 of the tide gauges observed MSL between 1966 and 1968; the GPS data were collected over different five-day periods

Figure 5. Charts of the MDT from the five models in Table 1: (a) CARS2009, (b) JPL08, (c) RJB2012, (d) DTU10MDT, (e) CNES-CLS09, as well as (f) the error field for CNES-CLS09. Pixels are only plotted where there are data. The formal error for CNES-CLS09 is 100 mm close to the coasts or in areas where no in situ oceanographic data are available, notably in the Gulf of Carpentaria. Units in meters. Lambert conical projection.

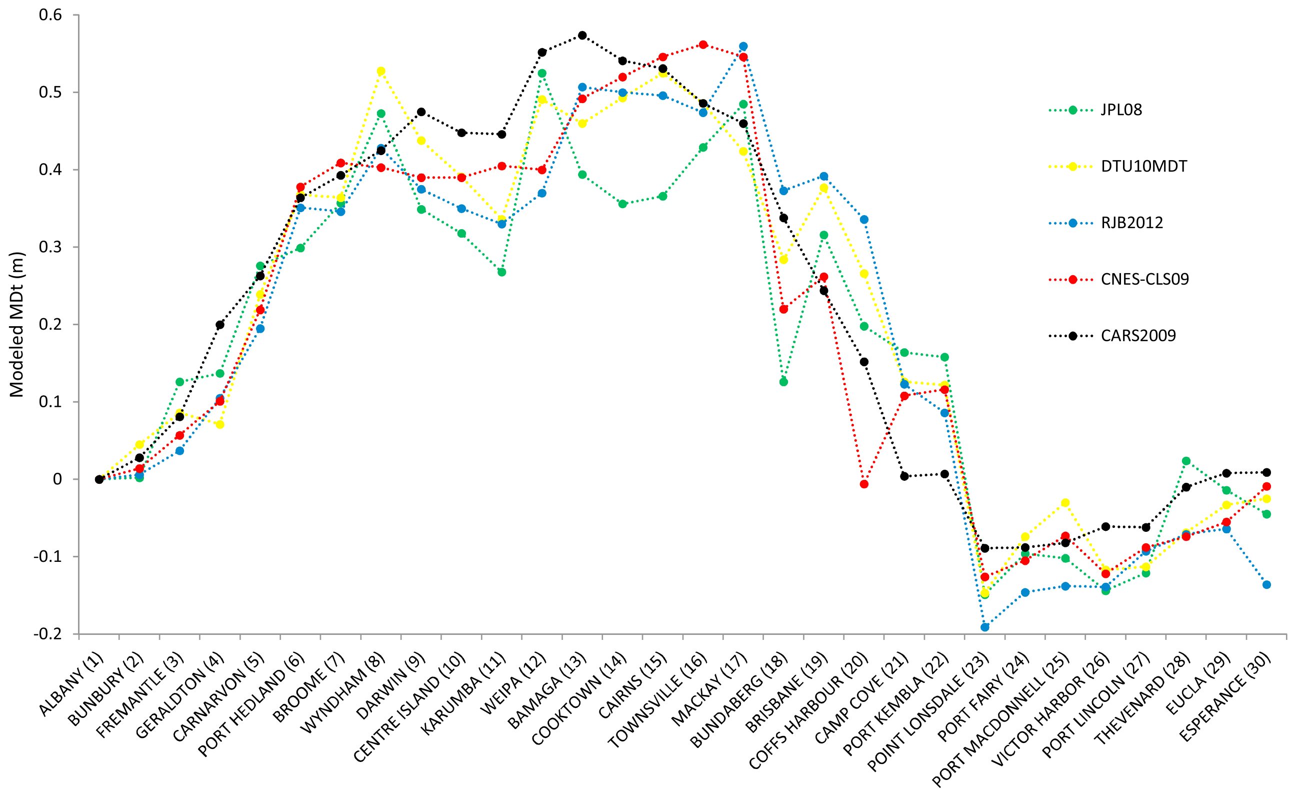

Figure 7. Modeled MDT at 30 AHD tide gauges from JPL08 (green), DTU10MDT (yellow), RJB2012 $2' \times 2'$ (blue), CNES-CLS09 (red), and CARS2009 (black). Albany fixed at modeled MDT = zero. See Figure 1 for locations.

in circa 2000; the satellite-only geoid models use data spanning between one and four years (Table 1), whereas the combined satellite-terrestrial and regional geoid models include gravity observations collected over the past 60 years; the altimeter-derived MSS varies from about 6 to 16 years (Table 1); the leveling data were collected in traverses over about 20 years [*Lines*, 1992]. The epochs over which the MDT models apply coincide with the epochs of the MSS used in their construction (Table 1) because temporal variations in the geoid are assumed small in comparison to temporal variations in the sea surface. As such, we will have to assume all quantities are representative of their true mean value during the overall epoch considered.

[33] Another consideration is the treatment of the permanent tides, which ideally should be consistent among all the data sets [e.g., *Ekman*, 1989; *Rapp*, 1989; *Poutanen et al.*, 1996; *Makinen and Ihde*, 2009]. The nodal tide was shown to be insignificant in section 2.1.2. Most of the MDT models are in the mean tide system (cf. Table 1). The GPS ellipsoidal heights are in the tide-free (non-tidal) system (G. R. Hu, personal communication, 2012). The EGM2008 and AGQG2009 geoid models are in the zero-tide system, but there is some ambiguity about the tide system used for the terrestrial gravity data used in the latter [*Featherstone et al.*, 2011]. Nothing is known about the tide system used for the Australian leveling [cf. *Makinen and Ihde*, 2009]. In addition, some of the conversions between tide systems are in relative form and depend on the choice of Love and Shida numbers for the Earth's elastic response to the permanent tides.

[34] Therefore, we estimated the slope that may be induced relative to the mean tide system from the northernmost and southernmost AHD tide gauges using the formulas of *Ekman* [1989] after accounting for being in the Southern Hemisphere. P. L. Woodworth (personal communication, 2012) pointed out that equation (20) of *Ekman* [1989] omits a minus sign, which we confirmed by re-derivation. For the ellipsoidal heights the tide-system conversion is ~ -64 mm, and for the geoid heights it is ~ -104 mm. When applied via equation (1), these effects cumulate to deliver a north-south slope of 6.1 mm per degree, but which is still less than the slope in the AHD (section 3.2). As such, they will be neglected throughout the remainder of this paper.

3. Results and Discussions

3.1. Assessment of MDT Models at Tide Gauges

[35] From the disagreements among MDT models in Figures 6 and 7, it is useful to try to determine which is most suitable in the Australian coastal zone for assessing the cause of the north-south tilt in the AHD. Yet another way to determine the MDT at a tide gauge is to rearrange equation (1), where a gravimetric geoid model is subtracted from the GPS-derived height of local MSL at the tide gauge. We term this the GPS-geoid MDT. Importantly, it is independent from the leveling-MSL MDT (section 2.2). The latter should not be interpreted as an absolute quantity because the AHD is a local vertical datum that is offset from the true geoid. Also, the GPS-geoid MDT is adversely affected by the

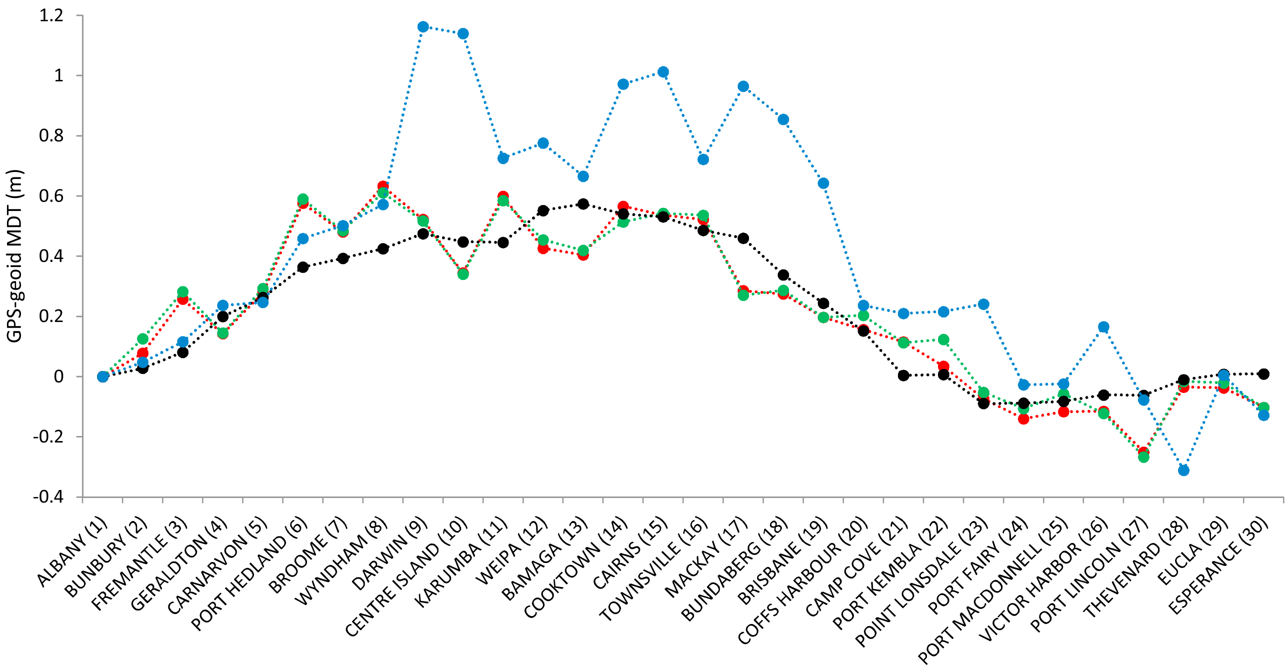

Figure 8. GPS-geoid MDT at 30 AHD tide gauges using EGM2008 (red), AGQG2009 (green), and AUSGeoid98 (blue). MDT from CARS2009 (black) is shown for comparison. Albany fixed at MDT = zero.

generally lower accuracy of satellite-terrestrial and regional geoid models in the coastal zone.

[36] Figure 8 shows the GPS-geoid MDT at the 30 AHD tide gauges derived from the GPS, short-range leveling between the TGBM and tide gauge (cf. Figure 2), and geoid heights from the EGM2008 satellite-terrestrial model [*Pavlis et al.*, 2012] and the AUSGeoid98 and AGQG2009 regional gravimetric quasigeoid models [*Featherstone et al.*, 2001, 2011]. The GO_CONS_GCF_2_TIM_R3 geoid to degree 220 [*Pail et al.*, 2011] that was used in RJB2012 (Table 1) is not included because its omission error is large in comparison with the above geoid models. The geoid and quasigeoid are separate surfaces beneath the land, and which depart as a function of the Bouguer gravity anomaly and topographic height. As the TGBMs are usually at a low elevation and the tide gauges are close to the geoid (e.g., <4 m at Albany; cf. Figure 3), then the conceptual difference is negligible in comparison to geoid model errors in the coastal zone. Figure 8 also shows the MDT modeled from CARS2009 for comparison. As done earlier, all relative MDT values have been translated vertically to give zero at Albany (1).

[37] From Figure 8, there is reasonable agreement among the GPS-geoid MDT and the totally independent but extrapolated CARS2009 MDT. The very close agreement between the GPS-EGM2008 MDT and GPS-AGQG2009 MDT is because AGQG2009 is a regional augmentation of EGM2008 [*Featherstone et al.*, 2011]. Both geoid models also use the same DNSC20008GRA altimeter-derived marine gravity anomalies [*Andersen et al.*, 2010] in coastal zones. The small remaining differences are due to the different computational approaches [cf. *Pavlis et al.*, 2012; *Featherstone et al.*, 2011]. Regardless, both geoid models are inevitably restricted by the dearth of gravity data in the coastal zone. As such, the GPS-geoid MDT is quite noisy relative to the smoother CARS2009 (cf. Figure 5).

[38] Figure 8 also includes AUSGeoid98 [*Featherstone et al.*, 2001], the predecessor of AGQG2009. This gives an indication of the improvements made in gravimetric geoid computation, both data- and algorithm-driven, over the past decade. Taking, for the moment, CARS2009 as error-free ground truth, the root mean square (RMS) of the difference for GPS-AGQG2009 MDT is ±111 mm and for GPS-AUSGeoid98 MDT is ±308 mm. This indicates a threefold improvement in Australian coastal geoid model accuracy over a decade, but most of this can be attributed the use of erroneous ship track gravity data in AUSGeoid98 [cf. *Featherstone et al.*, 2011].

Table 2. Descriptive Statistics of the Differences Between GPS-AGQG2009 MDT and Model MDT at 29 AHD Tide Gauges, Albany Excluded (m)

	JPL08	DTU10MDT	RJB2012	CNES-CLS09	CARS2009
Maximum	0.317	0.249	0.255	0.226	0.226
Minimum	−0.214	−0.180	−0.289	−0.275	−0.205
Mean	0.049	0.020	0.039	0.035	0.009
Standard deviation	0.123	0.102	0.130	0.115	0.111
Root-mean-square	0.132	0.104	0.136	0.120	0.111

Table 3. Descriptive Statistics of the Differences Between ANLN-Leveling-MSL MDT and Model MDT at 29 AHD Tide Gauges, Albany Excluded (m)

	JPL08	DTU10MDT	RJB2012	CNES-CLS09	CARS2009
Maximum	0.526	0.460	0.413	0.428	0.346
Minimum	−0.330	−0.387	−0.375	−0.463	−0.387
Mean	−0.006	−0.035	−0.016	−0.020	−0.046
Standard deviation	0.235	0.217	0.233	0.235	0.209
Root-mean-square	0.235	0.219	0.233	0.236	0.215

[39] In order to determine the consistency of the various MDT estimates at the AHD tide gauges (leveling-MSL, GPS-geoid and modeled MDT), Tables 2 and 3 present descriptive statistics of their differences. The expectation is that the best MDT model will show the smallest RMS difference, though some of the data are correlated (e.g., geoid models and MSS models; cf. Table 1). Table 2 shows descriptive statistics of the differences between GPS-AGQG2009 and modeled MDT, assuming AGQG2009 to be the currently best-available geoid model in this region [cf. *Featherstone et al.*, 2011]. However, the limitations on poor geoid modeling in the coastal zone remain, so such an analysis cannot be definitive. Table 3 shows the statistics for the leveling-MSL versus modeled MDT. The latter is subject to both errors in the leveling and the determination of MSL at the AHD tide gauges. The RMSs in Table 3 are roughly 100 mm larger than those in Table 2, which is commensurate with the MSL error estimates made by *Coleman et al.* [1979] and the precision of the leveling deduced from the least squares adjustment (section 2.2).

[40] From Tables 2 and 3, the geodetic (JPL08, DTU10MDT and RJB2012), combined CNES-CLS09 and oceanographic-only CARS2009 MDTs are all very similar, with the relative differences among their RMSs not exceeding 30 mm. This is encouraging because they have assimilated data from different sources, notably with CARS2009 being totally independent of geodetic data. DTU10MDT shows the closest agreement with the GPS-geoid MDT (Table 2), whereas CARS2009 shows the closest agreement with the GPS-leveling MDT. However, some qualification is needed regarding Table 2 because JPL08, DTU10MDT and AGQG2009 all use EGM2008. As such, Table 3 is a more independent, but less powerful, test of the MDT models because of the precision of the Australian leveling and AHD MSL estimates. With the above in mind, and coupled with the results in section 3.2, CARS2009 provides the slightly better MDT model at the AHD tide gauges, even though it has been extrapolated from offshore (cf. Figure 5a).

[41] Another observation from Tables 2 and 3 concerns RJB2012. The GOCE mission is still in operation, so geoid models derived from it are improving over time as more data are collected and improved data processing strategies are devised [e.g., *Pail et al.*, 2011; *Hirt et al.*, 2012]. RJB2012 uses only ~12 months of GOCE data and is a satellite-only MDT, whereas the other geodetic MDT models incorporate satellite-terrestrial geoid models based on many years of data. The RJB2012 $2' \times 2'$ grid performed better than the $15' \times 15'$ grid (not shown), chiefly because the land-ocean boundary is better defined by this fine grid, and to a lesser extent from reduced interpolation/extrapolation errors.

[42] The differences among the geodetic MDTs in Tables 2 and 3 (JPL08, DTU10MDT and RJB2012) is due to the different data sources, but also the different filter widths used to smooth them (cf. Table 1). The 150-km filter used in RJB2012 is conservative compared with the 75-km filter used in DTU10MDT, but there is scope to use GPS-geoid and leveling-MSL MDTs to tune the filters for this particular application. DTU10MDT also performs relatively well because effort was spent on retracking the altimeter-derived

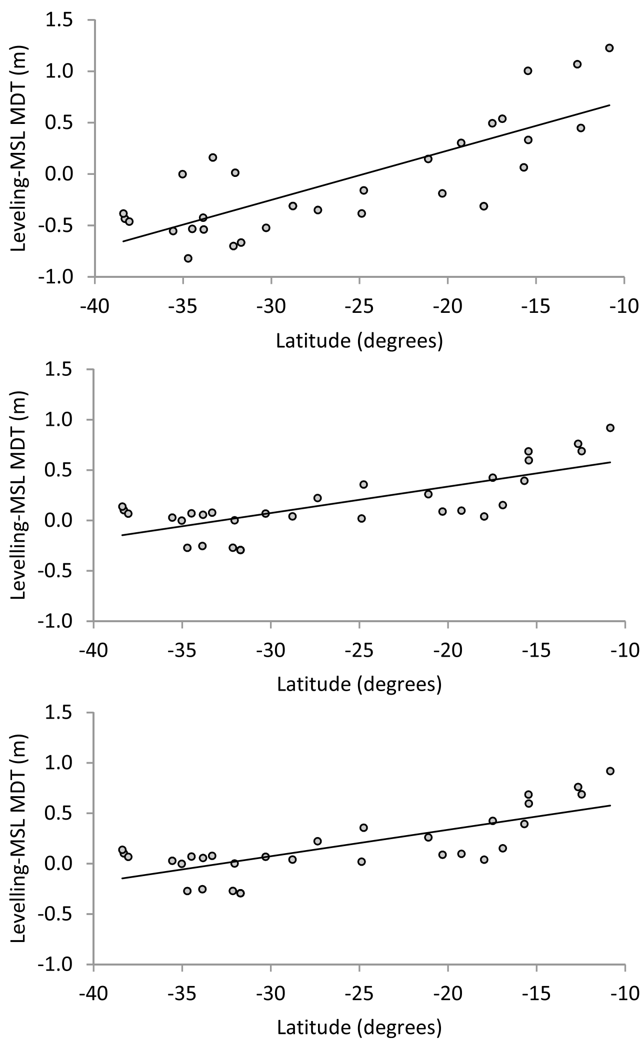

Figure 9. Linear regression of leveling-MSL MDT as a function of latitude, showing the north-south slope in the AHD. (top) MCA of basic leveling from *Roelse et al.* [1975]; (middle) MCA of corrected basic leveling network; (bottom) MCA of corrected ANLN (basic and supplementary leveling). Slopes and R^2 are shown in the leveling-MSL MDT row of Table 4. Units in meters.

Table 4. North–South Slope (mm per degree of latitude) of Leveling-MSL MDT as a Function of Latitude, Showing the North–South Slope in the AHD and Its Reduction After Removal of Modeled MDT[a]

	Original 1971 MCA			MCA of Corrected Basic			MCA of All ANLN		
	Slope	R^2	Slope Removed (%)	Slope	R^2	Slope Removed (%)	Slope	R^2	Slope Removed (%)
Leveling-MSL MDT (cf. Figure 9)	48.0	0.6293	–	21.9	0.4139	–	26.2	0.5782	–
Leveling-MSL minus JPL08	27.4	0.3286	43	1.2	0.0018	95	5.6	0.0465	79
Leveling-MSL minus DTU10MDT	24.5	0.2939	49	−1.7	0.0039	108	2.7	0.0128	90
Leveling-MSL minus RJB2012 (2′x2′)	24.0	0.2662	50	−2.2	0.0058	110	2.2	0.0072	92
Leveling-MSL minus CNES-CLS09	23.6	0.2853	51	−2.6	0.0078	112	1.8	0.0048	93
Leveling-MSL minus CARS2009	22.2	0.2757	54	−3.9	0.0214	118	0.5	0.0004	98
Leveling-MSL minus GPS-AGQG2009 MDT	22.5	0.2546	53	−3.6	0.0160	116	0.7	0.0008	97

[a]Original MCA from *Roelse et al.* [1975], MCA of corrected basic leveling network, and MCA of corrected ANLN (basic and supplementary leveling networks in one adjustment) are shown. Coefficients of determination (R^2) and percentage of slope removed by the MDT models (slope removed) are also shown.

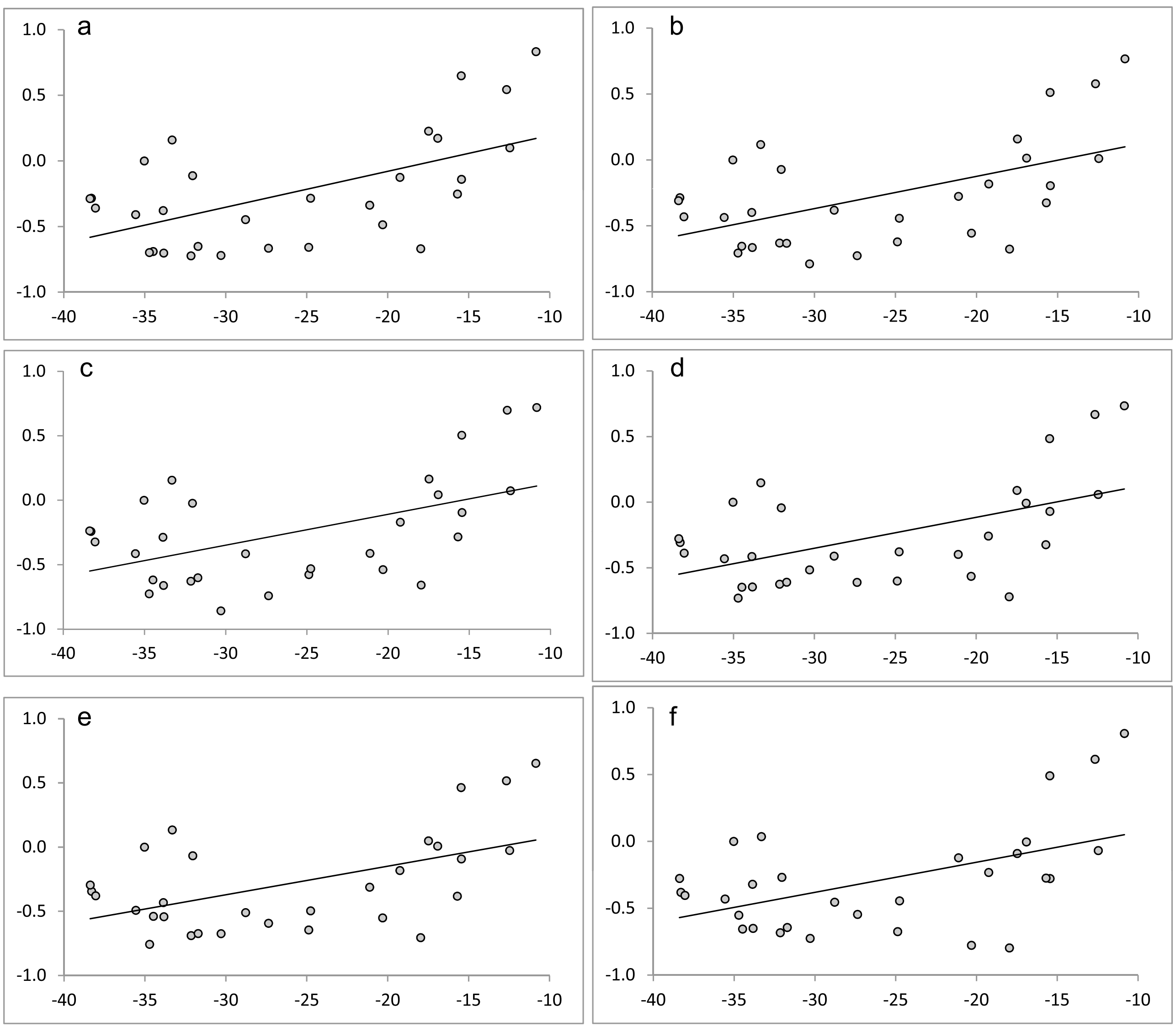

Figure 10. Linear regressions of MDT-corrected leveling from the original MCA from *Roelse et al.* [1975] as a function of latitude, showing the north-south slope in the AHD is reduced (cf. Figure 9): leveling minus (a) JPL08, (b) DTU10MDT, (c) RJB2012, (d) CNES-CLS09, (e) CARS2009, and (f) GPSAGQG2009. Slopes and R^2 are shown in Table 4. Units in meters.

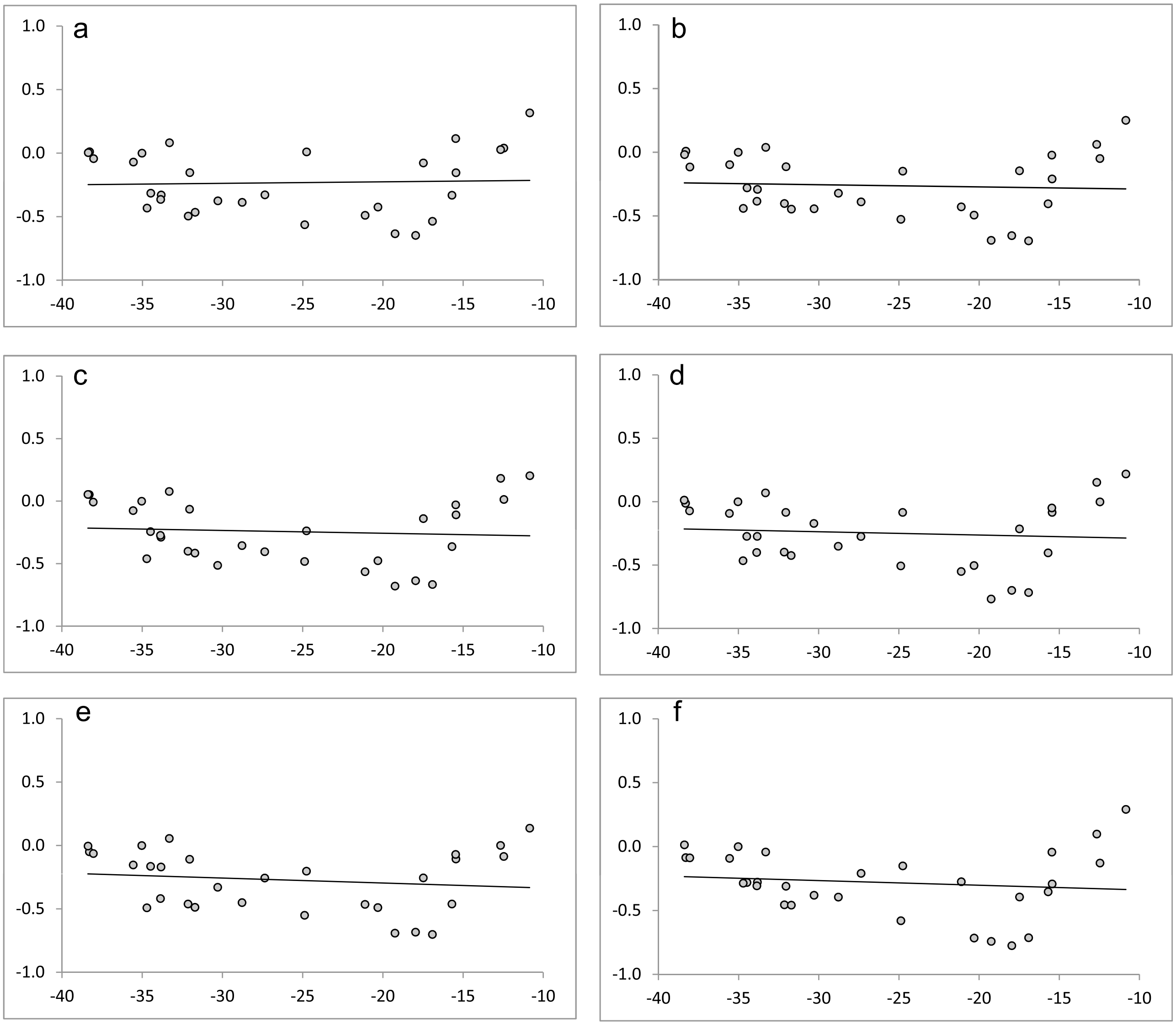

Figure 11. Linear regressions of MDT-corrected leveling from an MCA of the corrected basic leveling network as a function of latitude, showing the north-south slope in the AHD is reduced (cf. Figure 9): leveling minus (a) JPL08, (b) DTU10MDT, (c) RJB2012, (d) CNES-CLS09, (e) CARS2009, and (f) GPSAGQG2009. Slopes and R^2 are shown in Table 4. Units in meters.

MSS in the coastal zones (O.B. Andersen, personal communication, 2012), whereas the CLS01 MSS (used in both RJB2012 and CNES-CLS09) did not use coastal retracking [*Hernandez and Schaeffer*, 2001]. As such, retracking altimetry in the coastal zone, among other things, seems to confer benefits to coastal geodetic MDT modeling [cf. *Deng and Featherstone*, 2006; *Andersen and Knudsen*, 2009].

3.2. Residual Slope After Removal of Modeled MDT

[43] We now turn to the main motivation behind this study: seeking the primary cause of the north-south tilt in the AHD. Previous studies have implied apparent sea level slopes (see the citations in the Introduction), sometimes with geodesists 'blaming' oceanographers and vice versa. Performing linear regression as a function of latitude with and without the various MDT models applied to the 30 AHD tide gauges shows that the 1971 strategy of holding MSL fixed to zero height has indeed caused a north-south tilt in the AHD with respect to the geoid. Other effects such as tide systems, determination of MSL and the IB response are much smaller than the MDT contribution, so are less plausible candidates.

[44] Figure 9 shows linear regressions of the differences between heights from three MCAs of the leveling network and MSL at the 30 AHD tide gauges (the leveling-MSL MDT; cf. Figure 4), and the top row of Table 4 gives the slopes (in mm per degree of latitude) and coefficients of determination (R^2). The larger north-south slope for the *Roelse et al.* [1975] MCA (Figure 9, top) is due to the erroneous traverse along the northeast coast (cf. Figure 4). This has been corrected for the two new MCAs (Figures 9, middle and 9, bottom), and the north-south slope is reduced by about 50% (Table 4) after this correction. This confirms that all the apparent sea-slope studies in Australia conducted

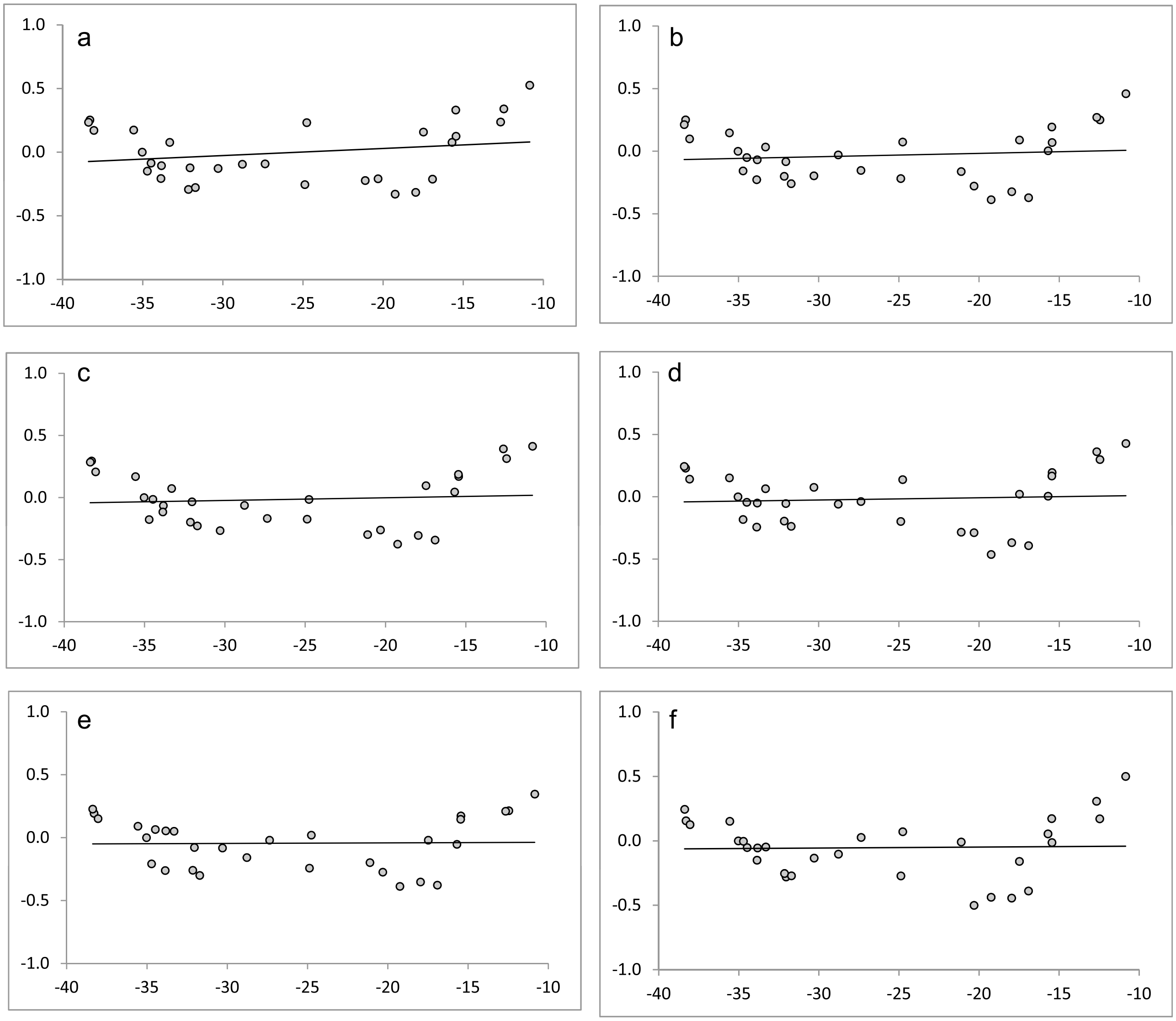

Figure 12. Linear regressions of MDT-corrected leveling from an MCA of the corrected ANLN (basic and supplementary leveling networks in one adjustment) as a function of latitude, showing the north-south slope in the AHD is reduced (cf. Figure 9): leveling minus (a) JPL08, (b) DTU10MDT, (c) RJB2012, (d) CNES-CLS09, (e) CARS2009, and (f) GPSAGQG2009. Slopes and R^2 are shown in Table 4. Units in meters.

prior to 1976 should be treated with skepticism. Nevertheless, there is a demonstrable north-south slope in the AHD from all the MCAs used to generate the leveling-MSL MDT.

[45] Next, the various modeled MDT values were subtracted from the three leveling-MSL MDTs (cf. equation (1)), with the expectation that the AHD slopes will be lessened substantially or even removed completely if MDT is the sole cause for the north-south slope in the AHD. All MDT models tested were applied at the 30 AHD tide gauges. Figures 10–12 show the linear regression lines and scatter of residuals; Table 4 details the north-south slopes (in mm per degree) and R^2.

[46] All results for the *Roelse et al.* [1975] MCA should be given less credence because of the leveling error along the northeastern Australian coast, but are included for reference (first broad column in Table 4 and Figure 10). The new MCAs (Figures 11 and 12) both show slightly contradictory results. However, from Figure 4 and knowledge that an MCA of the whole leveling network provides much more redundancy, more credence can be placed on the MCA of the whole ANLN (third broad column in Table 4 and Figure 12). However, this still needs tempering because erroneous leveling sections and uncertainty surrounding the MSL estimates can distort the residuals.

[47] Figure 12 and Table 4 show that the MDT models remove almost the entire north-south slope in the AHD when all the corrected leveling data are used in a MCA, but can only remove around half of the slope from the original AHD adjustment (Figure 10). From Tables 2–4 and Figure 12, CARS2009 is the best MDT model for removing the north-south slope in the AHD. However, the scatter of residuals around the trend-line in Figures 10–12 is similar

for each MDT model, which is significant because they are from sometimes-independent sources. Because of the independence, this points strongly to the presence of regional distortions in the leveling data [cf. *Filmer and Featherstone*, 2009]. For instance, the high points on the right hand side of each regression plot coincide with the Weipa (12) and Bamaga (13) tide gauges, which have a larger error from the least squares adjustment (section 2.2). The AHD uses leveling that is less precise than that used in other counties and continents (e.g., North America or Europe). Nevertheless, equation (1) is now satisfied within expected error (particularly for the leveling), showing that MDT is the cause of the north-south slope in the AHD.

[48] In terms of removing the tilt in the AHD, it is noteworthy that an MDT model based solely on in situ oceanographic data outperforms all the geodetic MDTs, especially as it has been extrapolated (cf. Figure 5a). It is thus likely that the LOESS scheme and consideration of bathymetry in its construction (section 2.3) make it more reliable toward the coastal zones. It is also unaffected by the filtering that has to be applied to geodetic MDTs. JPL08 is less effective at removing the tilt than would be expected from the statistics in Tables 2 and 3. This may be due to its use of the DNSC08MSS and coarser grid spacing (Table 1). The relatively good performance of the GPS-AGQG2009 MDT adds credence to the earlier studies that used GPS and geoid models to detect the north-south slope in the AHD (section 1). The performance of RJB2012 is quite impressive in that it is a pure satellite-only MDT model using around one year of GOCE data and is conservatively filtered, yet it performs equally with DTU10MDT and CNES-CLS09 (Tables 2 and 3).

4. Conclusions

[49] Using combinations and permutations of geodetic and oceanographic data, we have shown that the apparent north-south tilt between the AHD on the Australian mainland and the geoid is caused almost completely by unaccounted-for MDT. It is desirable for Australia to have a vertical datum that is more coincident with the geoid so as to be compatible with global height data sets, and also avoids the need to distort regional geoid models to fit the AHD. The fixing of 30 tide gauges to MSL as zero height in the 1971 realization of the AHD, while designed to be pragmatic and avoid users having to deal with negative heights near the Australian coastline [*Roelse et al.*, 1975], has rendered it subject to the effects of MDT at the tide gauges. If there is to be a future readjustment of the AHD that fixes multiple tide gauges, then MDT must be considered in order to remove the apparent north-south tilt.

[50] As part of this investigation, we trialed several MDT models and compared them with GPS-geoid and leveling-MSL estimates of the MDT at 30 AHD tide gauges. All models compare quite well, which is encouraging because they have used some quite different data sources (Table 1). A pure satellite-only MDT derived from one year of GOCE geoid model data agrees well with other geodetic-only MDTs that are based on geoid models that use many more years of data. Finally, the oceanographic-only CARS2009 MDT is the most effective for our application, accounting for 98% of the north-south slope in the AHD.

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