Contemporary Sea Level Rise

Anny Cazenave and William Llovel

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Abstract

Measuring sea level change and understanding its causes has considerably improved in the recent years, essentially because new in situ and remote sensing observations have become available. Here we report on most recent results on contemporary sea level rise. We first present sea level observations from tide gauges over the 20th century and from satellite altimetry since the early 1990s. We next discuss most recent progress made in quantifying the processes causing sea level change on time scales ranging from years to decades, i.e., thermal expansion of the oceans, land ice mass loss and land water storage change. We show that for the 1993-2007 time span, the sum of climate-related contributions (2.85 +/- 0.35 mm/yr) is only slightly less than altimetry-based sea level rise (of 3.3 +/- 0.3 mm/yr) : ~ 30% of the observed rate of rise is due to ocean thermal expansion and ~ 55% results from land ice melt. Recent acceleration in glacier melting and ice mass loss from the ice sheets increases this contribution to sea level rise up to 80% over the past five years.

Key words: Sea level rise, climate change, land ice melt, ocean warming

1. Introduction

Sea level is a very sensitive index of climate change and variability. In effect sea level responds to change of several components of the climate system. For example, as ocean warms in response to global warming, sea waters expand, thus sea level rises. Coupled atmosphere-ocean perturbations, like El Nino-Southern Oscillation, affect sea level in a rather complex manner. As mountain glaciers melt because of increasing air temperature, sea level rises because of fresh water mass input to the oceans. Modification of the land hydrological cycle due to climate variability and anthropogenic forcing leads to increased or decreased runoff, hence ultimately to sea level change. Change in the mass balance of the ice sheets has also direct effect on sea level. Even the solid Earth affects sea level, e.g. through small changes of the shape of ocean basins (such an example is post-glacial rebound, the visco-elastic Earth mantle and crust response to last deglaciation).

While sea level had remained almost stable during the 2-3 last millennia (e.g., Lambeck et al., 2004) subsequently to last deglaciation that started ~ 15 000 years ago, tide gauge measurements available since the late 19th century have indicated significant sea level rise during the 20th century (e.g., Douglas, 2001). For now >15 years, the global mean sea level is routinely measured at 10-day interval over the whole oceanic domain with high-precision satellite altimetry. These observations have shown clear evidence of global mean sea level rise. However, important regional variability is also reported. Quasi global in situ ocean temperature data made available in the recent years have allowed quantifying the contribution of ocean warming to sea level rise. Mountain glaciers surveys and satellite measurements of the mass balance of the ice sheets available since the early 1990s have also provided new information on the land ice contribution. Finally, space based gravity data from the recently launched GRACE mission now allow determination of the land water storage component, while providing also important constraints on the mass balance of the ice sheets. The 4th Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) published in 2007 summarized current knowledge on sea level observations and on contributing climate factors (Bindoff et al., 2007). In this review, we present most recent findings on these topics, including new results published since the IPCC AR4. Most of the discussion concerns the last 50 years, with focus on the satellite altimetry era (since 1993).

2. Sea level observations

2.1. Past century sea level rise

Our knowledge of past century sea level change comes from tide gauge measurements located along continental coastlines and islands. The largest tide gauge data base of monthly and annual mean sea level records is the Permanent Service for Mean Sea Level (PSMSL, Woodworth and Player, 2003) (www.pol.ac.uk/psmsl/) which contains data for the 20th century from ~2000 sites maintained by about 200 nations. The records are somewhat inhomogeneous in terms of data length and quality. For long term sea level studies, only ~10% of this data set is useable. Indeed, while today's tide gauge network is rather dense, the number and distribution of tide gauges degrade in the past. Moreover some tide gauge have not functioned continuously through time (for a significant number of them, large data gaps are observed). Others have functioned only for limited time span. Another well known difficulty relates to the fact that tide gauges measure sea level relatively to the ground, hence monitor also crustal motions. In active tectonic and volcanic regions, or in areas subject to strong ground subsidence due to natural causes (e.g., sediment loading in river deltas) or human activities (ground water pumping and oil/gas extraction), tide gauge data are directly affected by the corresponding ground motions. Post glacial rebound (also called Glacial Isostatic Adjustment, GIA) is another process that gives rise to vertical land movement. Thus correction is needed to interpret tide gauge measurements in terms of 'absolute' sea level change. In recent years, precise positioning systems like GPS (Global Positioning System) have been installed at a few tide gauge sites to monitor land motions. But the equipped sites are few and the GPS records still short (Woppelmann et al., 2007). Geodynamic models of GIA have been developed (e.g., Peltier, 2004, Paulson et al., 2007) so that this effect can be corrected from tide gauge records.

Several studies have been devoted to estimate past century sea level rise from historical tide gauges. Some conducted careful selection of the tide gauges, considering only those located in stable continental regions and displaying nearly continuous measurements over several decades. This led the authors to only keep a small number of good quality records of limited spatial coverage (e.g., Douglas, 2001, Holgate and Woodworth, 2004, Holgate, 2007). Other studies considered larger sets of tide gauges, up to several hundreds, and developed either regional grouping or reconstruction methods (see 2.4) to provide an historical sea level curve (e.g., Jevrejeva et al., 2006; Church et al., 2004, Church and White, 2006). Fig.1 compares two estimates of the global mean sea level since 1900 (yearly averages from Church et al., 2004 and Jevrejeva et al., 2006). We note that between 1900 and 1930 the rate of rise was modest. Since then the rate increased and amounted 1.8 +/- 0.3 mm/yr over the past 50 years. Also clearly apparent in Fig. 1 are large decadal fluctuations superimposed to the linear trend. Spectral analysis of global mean sea level rates displays high energy in the 4-8 year waveband, likely linked to ENSO (El Nino-Southern Oscillation) frequency (e.g., Chambers et al., 2002, Hebrard et al., 2008). Lower frequency oscillations (>20 years) in global mean sea level rate have been reported (e.g., Church and White, 2006, Holgate, 2007, Jevrejeva et al., 2007). Church et al. (2005) and Grinsted et al. (2007) showed that major volcanic eruptions induce temporary cooling of the oceans, able to produce small negative signature in the global mean sea level curve.

From an analysis based on tide gauges records from 1870 through 2004, Church and White (2006) detected acceleration in the rate of sea level rise, of 0.013 +/- 0.006 mm/yr^2. Another global mean sea level reconstruction since 1700 (Jevrejeva et al., 2007) reported a sea level acceleration up to the present of about 0.01 mm/yr^2. In a recent compilation of regional and global sea level studies for the 20th century, Woodworth et al. (2009) conclude to significant accelerations (either positive or negative) at particular epochs, but often these accelerations have a regional signature, consistent with regional-scale natural climate variability (see below).

2.2 Altimetry era (last 2 decades)

Since the early 1990s, satellite altimetry has become the main tool for precisely and continuously measuring sea level with quasi global coverage and short revisit time. The concept of the satellite altimetry measurement is simple: the onboard radar altimeter transmits microwave radiation towards the sea surface which partly reflects back to the satellite. Measurement of the round-trip travel time provides the height of the satellite above the instantaneous sea surface (called ‘range’). The quantity of interest in oceanography is the sea surface height above a reference fixed surface (typically a conventional reference ellipsoid). It is obtained by the difference between the altitude of the satellite above the reference (deduced from precise orbitography) and the range measurement. The estimated sea surface height needs be corrected for various factors due to atmospheric delay and biases between the mean electromagnetic scattering surface and sea at the air-sea interface. Other corrections due geophysical effects, such as solid Earth, pole and ocean tides are also applied. Since the mid-1970s, several altimetry missions have been launched. However it is only two decades later, with the launch of the Topex/Poseidon mission in 1992, that errors affecting altimetry-derived sea surface height dropped below the 10-cm level, allowing for the first time precise detection of ocean dynamics processes. It is worth mentioning that global sea level change monitoring was not initially included in the Topex/Poseidon mission goals. In effect, to measure global mean sea level rise with <5% uncertainty, a precision of ~ 0.1 mm/yr in the rate of rise is needed, implying a precision of 1-2 cm on individual sea surface height measurements. This requirement implies thorough control of all possible errors affecting the altimetry system (in particular instrumental drifts) and data processing. It has pushed altimetric systems towards their ultimate performance limit. While early Topex/Poseidon precision was > 5 cm for a single sea surface height measurement (Chelton, 2001), further progress in the various data processing steps has decreased this error level to ~1-2 cm (e.g., Leuliette et al., 2004, Nerem et al., 2006), a performance also valid for the successors of Topex/Poseidon, Jason-1 and Jason-2 (launched in 2001 and 2008 respectively). Fig.2 shows the temporal evolution of the global mean sea level from satellite altimetry between January 1993 and December 2008. This curve is based on Topex-Poseidon until 2001, on combined Topex/Poseidon and Jason-1 data between 2002 and 2005 and Jason-1 data since then. In Fig.2 the annual cycle has been removed and a 90-day smoothing applied. The global mean sea level increases almost linearly over this 16 years time span. The positive anomaly seen between 1997 and 1999 is related to the 1997-1998 ENSO event (see section 3.3). Similarly, the negative anomaly occurring by the end of 2007 is likely related to the recent La Nina (the cold phase of ENSO). The rate of rise estimated over 1993-2008 amounts 3.1 mm/yr (with a formal uncertainty of 0.1 mm/yr).

Precision/accuracy of altimetry-derived rate of sea level rise has been assessed through error budget analyses and comparisons with high-quality tide gauges data (e.g., Mitchum, 2000, Nerem and Mitchum, 2001, Leuliette et al., 2004, Ablain et al, 2009), leading to more likely uncertainty of ~0.4 mm/yr. We adopt it further. Accounting for the small correction of -0.3 mm/yr due to global deformation of ocean basins in response to GIA (Peltier, 2004), we thus get a rate of global mean sea level rise of 3.4 +/- 0.4 mm/yr over 1993-2008. Differences in estimates of altimetry-derived rate of sea level rise for the past 15-16 years by different investigators fall within the 0.4 mm/yr range (e.g., Nerem et al., 2006, Beckley et al, 2007, Ablain et al., 2009, C.K. Shum, personal communication), suggesting that the 0.4 mm/yr uncertainty is realistic.

2.3. Regional sea level variability

Tide gauge records had previously suggested that sea level rise is not spatially uniform (e.g., last century rate is twice as large at New York than at Buenos Aires). However until the advent of satellite altimetry and its almost global coverage of the oceanic domain, mapping the regional variability was not possible. Satellite altimetry has revealed considerable regional variability in the rates of sea level change (Fig.3a). To highlight this regional variability in the rates of sea level rise, a uniform (global mean) trend of 3.4 mm/yr has been removed from Fig.3a. Fig.3b shows the spatial trend patterns with respect to the global mean. In some regions, such as the western Pacific, north Atlantic around Greenland, southeast Indian Ocean and Austral Ocean, sea level rates are up to three times faster than the global mean (in these regions, sea level is higher by ~ 15 cm than 16 years ago), while eastern Pacific and west Indian oceans exhibit a lower rate. In section 5 we discuss causes of non uniform sea level change and will see that ocean thermal expansion is the dominant factor at the origin of the observed spatial trend patterns (Cabanes et al., 2001, Lombard et al., 2005).

2.4 Two- dimensional past sea level reconstructions

It has been established that during the past few decades, trend patterns in thermal expansion were not stationary but fluctuated both in space and time in response to ENSO, NAO (North Atlantic Oscillation) and PDO (Pacific Decadal Oscillation) (e.g., Levitus et al. 2005, Lombard et al., 2005). This suggests that present-day sea level trend patterns, as seen in Fig.3a,b are not steady features and are not necessarily representative of the distant past (e.g., last century). Yet, it is important to know past regional sea level variability, in particular to validate climate models used to predict future sea level change at regional and global scales (important uncertainties affect sea level projections for a wide range of spatio-temporal scales, Meehl et al., 2007). Unfortunately, for the last century, information on regional sea level variability is lacking. For that reason, a number of studies have attempted to reconstruct past decades sea level in two dimensions (2-D), combining sparse but long tide gauge records with global gridded (i.e., 2-D) sea level (or sea level proxies) time series of limited temporal coverage (either from satellite altimetry or OGCMs -Ocean general Circulation Models- reanalyzes) (Chambers et al., 2002, Church et al., 2004, Berge-Nguyen et al., 2008, Llovel et al., 2009). In this approach, the dominant modes of regional variability are extracted from the statistical information contained in altimetry data or OGCMs reanalyzes. Fig.4 shows spatial trend patterns (with respect to a uniform global mean trend), for the 1950-2003 time span, based on Llovel et al. (2009' study. We clearly see significant difference with the 1993-2008 patterns (Fig.3b), confirming that regional variability observed for the recent years are not steady. The above studies have shown that the dominant mode of temporal variability of the spatial trend patterns is related to the decadal modulation of ENSO (Chambers et al., 2002, Church et al., 2004) but lower frequency oscillations are also present (Llovel et al., 2009).

3. Causes of global mean sea level change

The two main causes of global mean sea level change are fresh water addition to ocean basins as a result of land ice loss and water exchange with terrestrial reservoirs (soil and underground reservoirs, lakes, snowpack, etc.), and thermal expansion of the sea waters in response to ocean warming. We examine below each of these contributions.

3.1 Ice sheets

The mass balance of the ice sheets is a topic of considerable interest in the context of global warming and sea level rise. If totally melted, Greenland and West Antarctica would raise sea level by about 7 m and 5 m respectively. Thus even a small amount of ice mass loss from the ice sheets would produce substantial sea level rise, with adverse societal and economical impacts on vulnerable low-lying coastal regions. Observations over the past two decades show rapid acceleration of outlet glaciers in Greenland and Antarctica (Howat et al., 2007, Witze, 2007). For example marine terminated Jakobshavn Isbrae glacier on west coast of Greenland has experienced rapid thinning and accelerated flow velocity since the early 1990s (reaching about 13 km in 2003, Holland et al., 2008, Joughin et al., 2008). Glaciers draining into the Amundsen Sea, West Antarctica, have also rapidly retreated (e.g., Shepherd and Wingham, 2007, Rignot et al., 2008). These observations have been attributed to a dynamical response of the ice sheets to recent warming, with most of the ice sheet mass loss resulting from coastal glacier flow (Alley et al., 2007, 2008). Two main processes have been invoked to explain these observations: (1) lubrification of the ice-bedrock interface resulting from summer meltwater drainage through crevasses, and (2) weakening and break-up of the floating ice tongue or ice shelf that buttressed the ice stream. While the first mechanism may play some role in Greenland where substantial surface melting occurs in summer, glaciologists now favour the second mechanism as the main cause able to explain the recent dynamical changes affecting the ice sheets (e.g., Alley et al., 2008, Holland et al., 2008). Because the ice shelf are in contact with the sea, warming of sea water (e.g., Gille, 2008, Holland et al., 2008) and change in ocean circulation may trigger basal melting and further break up, allowing ice-flow speed-up (Alley et al., 2008).

Since the early 1990s, different remote sensing techniques have offered new insight on contemporary mass change of the ice sheets. Radar altimetry (e.g., ERS-1/2 and Envisat satellites) as well as airborne and satellite laser altimetry (IceSat satellite since 2003) allow monitoring ice sheet elevation change, a quantity further expressed in terms of ice volume change. The InSar (Synthetic Aperture Radar Interferometry) technique provides measurements of glacier surface flow, hence ice discharge into the oceans if glacier thickness is known. When combined with other parameters of surface mass balance (mainly snow accumulation), the net ice sheet mass balance can then be derived. Space gravimetry from the GRACE space mission (since 2002) is another tool for measuring the mass balance of the ice sheets, with nearly complete coverage of the high-latitude regions, up to 89°N/S. The basic quantity measured by GRACE is spatio-temporal change of the Earth's gravity field, which can be converted, over the ice sheets, into ice mass change.

Comparing results from different techniques is not easy because each technique has its own bias and limitations: e.g., differences in spatial and temporal sampling, measurement errors, contamination from unrelated signals and lack of direct information on ice mass (except for GRACE). For example, radar altimetry misses narrow coastal glaciers because of the large radar foot print and measured elevations are much less reliable over steep undulated surfaces than over flat high-elevation surfaces. Ice elevation change needs to be corrected for ice compaction: uncertainty in surface density (snow or ice) when converting elevation change into mass change is an important source of error. To be helpful for mass balance estimates, InSAR needs information on ice thickness, a quantity difficult to estimate. GRACE space gravimetry is sensitive to solid Earth mass change, in particular that associated with GIA. Over Antarctica where the GIA effect is of the same order of magnitude as the ice mass change, the poorly known GIA correction is a source of significant uncertainty. In spite of these problems, satellite-based sensors clearly show accelerated ice mass loss from the ice sheets over the recent years.

Greenland mass balance (last 2 decades)

Comparison of elevation changes from successive airborne laser altimetry surveys indicated significant ice mass loss in near coastal regions of Greenland (Krabill et al., 2004). In contrast, satellite radar altimetry suggested elevation increase in Greenland interior for the 1992-2003 period (Johannessen et al., 2005). Using InSAR observations, Rignot and Kanagaratnam (2006) detected widespread glacier ice flow acceleration since 1996.

Recent results from GRACE (Velicogna and Wahr, 2005, 2006b; Ramillien et al., 2006, Chen et al., 2006b; Luthcke et al., 2006, Cazenave et al., 2009, Wouters et al, 2008) and ICEsat (Slobbe et al. 2008) confirm other remote sensing results, i.e., ice mass loss from coastal regions of southern Greenland, although quite large dispersion between the different investigations is noticed. GRACE results indicate accelerated ice mass loss from coastal regions of the Greenland ice sheet since 2002-2003.

Many more references about Greenland mass balance can be found in IPCC AR4 (Lemke et al., 2007).

Antarctica mass balance (last 2 decades)

Laser airborne, laser and radar satellite altimetry, as well as InSAR (Synthetic Aperture Radar Interferometry) surveys over West Antarctica reported accelerated ice mass loss in the Amundsen Sea sector during the past decade (Rignot and Thomas, 2002, Thomas et al., 2004). Davis et al. (2005) analysed satellite radar altimetry measurements over 1992-2003 and found significant elevation decrease, especially in the Admunsen Sea sector.

GRACE observations over west Antarctica also show important mass loss over the past few years (Velicogna and Wahr, 2006a, Ramillien et al., 2006, Chen et al., 2006a, Cazenave et al. 2009). However, because of GIA contamination, GRACE results over Antarctica are more uncertain than over Greenland. Over Antarctica, the GIA effect is of the same order of magnitude as present-day ice mass change (Ivins and James, 2005; Peltier, 2004). However the GIA correction depends on still poorly known parameters such as Earth’s mantle viscosity structure and deglaciation history. It is available from modelling only, with important differences between models.

A recent analysis over 85% of the Antarctica's coastlines by Rignot et al. (2008) combining InSAR data with regional climate modelling over 1992-2006 confirms earlier results, i.e., widespread ice mass loss in West Antarctica (Amundsen and Bellingshausen seas and Antarctica Peninsula), with loss concentrated in narrow outlet glaciers. In comparison, East Antarctica was found in near balance.

Remote sensing-based estimates of the mass balance of the two ice sheets are summarized in Fig. 5a,b. (updated from Cazenave et al., 2006). We note a clear acceleration since about 2003 of ice mass loss from the Greenland ice sheet. For 1993-2003, IPCC AR4 (Lemke et al., 2007) estimated to 0.21 +/- 0.035 mm/yr the Greenland contribution to sea level. For 2003-2007, the mean contribution of Greenland to sea level has increased to ~ 0.5 mm/yr (average of values shown in Fig.5a). In West Antarctica, acceleration is also visible but less than for Greenland. Total Antarctica contribution to sea level was estimated by IPCC AR4 to 0.21 +/- 0.17 mm/yr for 1993-2003.

3.2 Glaciers

Glaciers and ice caps (GIC) are very sensitive to global warming. Observations indicate that since the 1970s most worlds' glaciers are retreating and thinning, with noticeable acceleration since the early 1990s. GIC represent about 35 cm sea level equivalent, thus represent another important source of fresh water mass susceptible to be added to the oceans and raise sea level. Mass balance estimates of GIC are based either on in situ measurements (monitoring of the annual mean snow accumulation and ice loss from melt) or geodetic techniques (measurements of surface elevation and area change from airborne altimetry or digital elevation models). The data are collected by the World Glacier Monitoring Service (WGMS, available at http://www.geo.unizh.ch/wgms/) and concern about 300 hundred glaciers worldwide tracked over the past decades, with information for about 30 reference glaciers in nine mountain ranges since 1980.

On the basis of published results, the IPCC AR4 estimated the GIC contribution to sea level rise to 0.77 +/- 0.22 mm/yr over 1993-2003 (Lemke et al., 2007). Since the IPCC AR4 publication, a few updated estimates of GIC loss have been proposed from traditional mass balance measurements (Kaser et al., 2006, Meier et al., 2007, Cogley, 2009). A number of space-based (from GRACE and satellite imagery) glacier mass changes have also been published for particular ice fields and confirm enhanced GIC mass loss (e.g., Patagonia: Chen et al., 2007; Alaska: Chen et al., 20006a, Lutchke et al., 2008; Himalaya: Berthier et al., 2007). Kaser et al. (2006) reported a contribution to sea level rise of 0.98 +/- 0.19 mm/yr for 2001-2004, slightly larger than during the previous decade. Using the same data as Kaser et al. (2006) and assuming that ice losses by GIC increased linearly with time since year 2000, Meier et al. (2007) found the GIC contribution to be 1.1 +/- 0.24 mm/yr for year 2006. Recently, Cogley (2009) provided an updated compilation of global average GIC mass balance up to 2005. Cogley's results indicate a contribution to sea level of 1.4 +/- 0.2 mm/yr for 2001-2005, a value larger than earlier estimates due to better representation of tidewaters glaciers.

3.3 Land waters

Excluding ice sheets and glaciers, fresh water on land is stored in various reservoirs: snow pack, rivers, lakes, man-made reservoirs, wetlands and inundated areas, root zone (upper few meters of the soil) and aquifers (ground water reservoirs). Terrestrial waters are continuously exchanged with atmosphere and oceans through vertical and horizontal mass fluxes (evaporation, transpiration of the vegetation, surface and underground runoff) and are an integral part of the global climate system, with important links and feedbacks generated through its influence on surface energy and moisture fluxes between continental water, atmosphere and oceans. Thus climate change and variability modify land water storage. Some human activities also directly affect water storage: for example, removal of ground water from aquifers by pumping (particularly in arid regions), building of artificial water reservoirs by construction of dams on rivers and wetland drainage. Other anthropogenic effects on land waters result from change of physical characteristics of the land surface by urbanization and land use associated with agriculture and deforestation. All these effects which either increase or decrease runoff, have an impact on sea level.

Climatic and anthropogenic contributions of land waters to sea level (past few decades)

Past decades variations in land water storage caused by climate change and variability cannot be directly estimated from observations because these are almost inexistent at a global scale. However global hydrological models (or land surface models) developed for atmospheric and climatic studies can be used for that purpose. The models compute the water and energy balance at the earth surface, providing water storage change in response to prescribed variations of near-surface atmospheric data (precipitation, temperature, humidity and wind) and radiation. Using atmospheric re-analyses over 1950-2000 and the Orchidee land surface model, Ngo-Duc et al. (2005a) found no climatic long-term trend in sea level but large interannual/decadal fluctuations of several millimetres amplitude, a result also found by Milly et al. (2003) based on the Land Dynamics model over 1980-2000. In another model-based study, Ngo-Duc et al. (2005b) showed that the positive anomaly visible in sea level in 1997-1998 (see Fig.2) was associated with land water storage change in the tropics in response to the 1997-1998 ENSO event.

Direct human intervention on land water storage and induced sea level changes have been estimated in several studies (e.g., Chao, 1995, Sahagian, 2000, Gornitz, 2001). These results have been recently reviewed by Huntington (2008) and Milly et al. (2009). The largest contributions come from ground water pumping (either for agriculture, industrial and domestic use) and reservoir filling. Surface water depletion has a non negligible contribution.

Although detailed information is lacking, and estimates vary significantly between authors, ground water depletion may have contributed to past decades sea level rise by 0.55-0.64 mm/yr (Huntington, 2008).

During the past 50 years, several tens of thousands dams have been constructed over world rivers, leading to water impoundment into artificial reservoirs, hence negative contribution to sea level. Several attempts have been made to estimate the total volume of water stored in artificial reservoirs over the past half century (e.g., Chao, 1995, Gornitz, 2001, Vorosmarty et al., 2003). The recent study by Chao et al. (2008) which reconstructs water impoundment history of nearly 30 000 thousands reservoirs constructed during the 20th century, estimates to -0.55 mm/yr the contribution to sea level of dams and artificial reservoirs during past half century. Hence, over the last few decades, effects on sea level from ground water depletion and water impoundment behind dams almost cancelled each other

Estimates of surface and total water storage contribution from satellite altimetry and space gravimetry (recent years)

While satellite altimetry has been developed and optimized for open oceans, numerous studies used this technique to monitor lake and river water levels. Water level time series for >15 years based on Topex/Poseidon, Jason-1 and Envisat altimetry missions are now available for several hundreds continental lakes. Using water level time series over lakes from the HYDROWEB data base http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb, we can estimate the water volume change of the largest surface water bodies since the early 1990s. For the period 1993-2008, water storage of the Caspian and Aral seas, East African lakes and North American lakes decreased on average. Considering the 15 largest lakes, we estimate to about + 0.1 mm/yr lakes contribution to sea-level rise for the period 1993-2008 (the largest contributions coming from the Caspian and Aral seas, and Huron lake, the latter two been strongly affected by non-climatic, anthropogenic forcing). However, lake water storage is dominated by interannual variability, so that the contribution estimated for the past ~15 years does not reflect long-term trend.

GRACE measures temporal changes of the vertically integrated water column (surface waters, soil moisture, underground waters). Thus GRACE cannot separate the contribution of individual reservoirs. In addition GRACE does not discriminate climate and direct anthropogenic components. Ramillien et al. (2008) estimated the water volume trend in the 27 largest river basins worldwide using GRACE data over 2003-2006 and found either positive or negative water volume change over that period depending on the location of the river basins. The net water volume change was slightly negative (i.e., water loss), corresponding to <0.2 mm/yr sea level rise. An update of this study using a longer GRACE data set (2002-2008) over the 32 largest river basins of the world gives a negative contribution to sea level, of ~ – 0.2 mm/yr (Cazenave et al., 2009b), suggesting that over a few years time span, the land water signal is dominated by interannual variability.

To conclude, climate-driven change in land water storage mainly produces interannual to decadal fluctuations but (so far) no long-term trend. This is in contrast with direct human-induced change in land hydrology which clearly has led to 'secular' –either positive or negative- change in sea level over the past half-century. However, the two major contributions –ground water depletion and reservoir filling- more or less canceled each other. But this may not be true anymore in the future: while dam building is clearly decelerating (e.g., Chao et al., 2008); ground water pumping will likely continue at a sustained rate in the future, with a positive contribution to sea level.

3.4 Temperature and salinity change of the oceans

Anomalies in temperature and salinity in the ocean water column change density which further gives rise to sea level variations (classically called 'steric', or 'thermosteric' or 'halosteric' if associated only to temperature or salinity variations). We first discuss the contribution of temperature variations.

In situ hydrographic measurements collected mainly by ships since the middle of the 20th century have suggested that in terms of global mean, the oceans have warmed. Since the late 1960s, ocean temperature has been essentially measured with expandable bathythermographs (XBT) along ship tracks, complemented by mechanical bathythermographs (MBT) and Conductivity-Temperature-Depth (CTD) systems. Since a few years, an international program of profiling floats, Argo (Roemmich and Owens, 2000; www.argo.ucsd.edu), has been set up, providing temperature and salinity measurements globally down to 2000m with a revisit time of ~ 40 days. The Argo network was almost complete by the end of 2003. Historical as well as modern in situ hydrographic measurements are stored in the World Ocean Database (WOD) with regular updates (Boyer et al., 2006). Two major problems affect XBT historical measurements: (1) systematic bias due to uncertainty in assigning a correct depth value to each temperature measurement and (2) sparse data coverage –both geographical and in the deep ocean- in the past. XBT instruments do not directly measure depth as they fall within the water column. Traditionally, depth is deduced from a 'fall-rate' equation and time elapsed since the probe entered the sea surface. Even with calibrated fall-rate equations (Hanawa et al., 1995), systematic depth errors are supposed to remain (Gouretski and Kolternann, 2007). The problem of sparse data coverage in the past can hardly be overcome unless using OGMs with data assimilation (see section 5). Thus estimates of ocean heat content and thermal expansion for the past are biased by lack of data in certain regions, in particular in the southern hemisphere (Levitus et al., 2005). In spite of these limitations, several analyses of global ocean temperature have been conducted in recent years (Domingues et al., 2008, Guinehut et al., 2004, Ishii et al., 2006; Ishii and Kimoto, 2009, Levitus et al., 2005, 2009, Willis et al., 2004). Most recent analyses take special care of systematic depth bias corrections affecting XBT and MBT measurements, and here we only report the latest results (Domingues et al., 2008, Ishii and Kimoto, 2009, Levitus et al., 2009). Compared to earlier analyses, the new analyses show substantial reduction of spurious large interannual anomalies in ocean heat content, in particular around the mid-1970s. Fig.6 shows the evolution of the ocean thermal expansion since 1955 from Levitus et al. (2009) and Ishii and Kimoto (2009) (temperature data down to 700 m). The mean trend over the 1955-2001 period is estimated to 0.4 +/- 0.01 mm/yr and 0.3 +/- 0.01 mm/yr for the Levitus et al. and Ishii and Kimoto data respectively. Based on a reconstruction of ocean temperatures, Domingues et al. (2008) estimate to 0.5 +/- 0.08 mm/yr the thermal expansion trend over 1961-2003.

According to Levitus et al. (2001, 2009), heat stored in the oceans during the last 4 decades (~16 x 10^{22} J) is about 15 and 20 times larger than heat stored on continents and inside the atmosphere, indicating that ~85% of heat excess of the climate system over that period has accumulated in the oceans. Hansen et al. (2005) discuss the Earth radiative budget based on climate modeling of the different forcing agents (greenhouse gases, aerosols, albedo, solar irradiance and land use) and suggest that the Earth is currently in a state of energy imbalance, amounting 0.85 +/- 15 W/m^2 (i.e., excess of energy absorbed from the sun versus reemitted to space). This value is in agreement with satellite-based observations at the top of the atmosphere for 2001-2004 (Trenberth et al., 2009). Levitus' value for the ocean heat storage over the last 40 years corresponds to ~0.3 Wm^{-2} (after scaling by the ocean surface), i.e., ~ 1/3 of the Earth's total energy imbalance. However if one considers ocean heat storage over the altimetry era (in the range 0.6-0.7 Wm^{-2}), the ocean component becomes dominant.

Fig.7 shows thermosteric sea level curves since 1993 based on Ishii and Kimoto (2009) and Levitus et al (2009) temperature data (down to 700m). On the altimetry time span, trends amount to 1.1 +/- 0.25 mm/yr and 0.9 +/- 0.2 mm/yr respectively, hence a mean of ~1 +/- 0.3 mm/yr since 1993. This thermosteric trend is lower than that reported by IPCC AR4 over 1993-2003 (1.6 +/- 0.3 mm/yr; Bindoff et al., 2007), likely a result from the plateau seen in ocean heat content beyond 2003 (see section below). On Fig.7 is also shown altimetry-based sea level (annual averages) and residual curves (observed minus thermosteric sea level). The mean residual trend amounts to 2.3 mm/yr.

Recent results based on Argo show that since about 2003, thermal expansion is following a plateau (after correcting for instrumental drifts of some Argo probes: early estimates of Argo-based thermal expansion, Lyman et al, 2006, showed a negative trend as of 2003; however, instrumental problems were subsequently reported on some probes, leading to cold bias, hence artificial ocean cooling). For the recent years, thermal expansion rates range from -0.5 +/- 0.5 mm/yr over 2003-2007 (Willis et al., 2008) to +0.4 +/- 0.1 mm/yr over 2004-2007 (Cazenave et al., 2009) and +0.8 +/- 0.8 mm/yr over 2004-2007 (Leuliette and Miller, 2009). The 2003 data coverage is very sparse and it is likely that the Willis et al. (2008) value is biased low for that reason. The recent flattening of the thermal expansion curve likely reflects natural short term variability. Similar short term plateaus are also well visible in the past (see Fig.6).

Assuming constant total salt content, density changes arising from redistribution of salinity by the ocean circulation (halosteric effect) has no effect on the global mean sea level (although it does at local/regional scales; Wunsch et al., 2007). On the other hand, fresh water addition to the oceans due to increased river runoff and precipitation as well as ice melting modifies ocean salinity. If global measurements of salinity were available, it would be possible to estimate the global mean change of salinity and deduce the amount of fresh water added to the oceans. Ultimately this would provide an estimate of ocean mass change and its contribution to sea level. Unfortunately, the coverage of salinity measurements is very sparse for the past decades, preventing reliable estimates of global mean ocean mass change by this method (because of sufficient coverage of salinity profiles over the north Atlantic, Boyer et al., 2007, were able to determine regional changes in fresh water content over 1955-2006). However, with space gravimetry data from GRACE, it is now possible to directly estimate the change in global mean mass of the oceans (section 4).

4. Sea level budget

The IPCC AR4 summarized the sea level budget for two periods (1961-2003 and 1993-2003; Bindoff et al., 2007). For 1961-2003, the contribution of thermal expansion, glaciers and ice sheets were estimated to 0.4 +/- 0.006 mm/yr, 0.5 +/- 0.1 mm/yr and 0.2 +/- 0.2 mm/yr respectively (quoted error bars are one standard deviation). Their sum, of 1.1 +/- 0.25 mm/yr, was compared to the 1.8 mm/yr rate of sea level rise observed over that period. The IPCC AR4 concluded that the sea level budget of the past four decades was not closed. For the 1993-2003 decade, the contribution of thermal expansion, glaciers and ice sheets was estimated to 1.6 +/- 0.25 mm/yr, 0.8 +/- 0.11 mm/yr and 0.4 +/- 0.2 mm/yr respectively, with a sum of 2.8 +/- 0.35 mm/yr, in rather good agreement with the altimetry-based rate of rise (3.1 +/- 0.4 mm/yr).

Since the IPCC AR4 publication, new results have appeared in the literature, in particular for thermal expansion as discussed above. Recently reprocessed ocean temperature data (Domingues et al., 2008 Levitus et al., 2009; Ishii and Kimoto, 2009) do not lead to any important revision for the thermal expansion rate of the past 4-5 decades (see discussion in section 3.4), although the interannual variability has been greatly reduced. As there are no new estimates for the land ice contribution for the past few decades, we do not discuss this period any further. We concentrate rather on the altimetry period (since 1993) for which several new results are available. Table 1 presents sea level budget since 1993. Two time spans are considered: 1993-2007 and 2003-2007.

1993-2007

Over 1993-2007, the altimetry-based rate of sea level rise is 3.3 +/- 0.4 mm/yr. Mean thermal expansion rate (average of Levitus et al. and Ishii and Kimoto values over their common time span) is 1. +/- 0.3 mm/yr. The rate difference between observed sea level rise and mean thermal expansion is 2.3 mm/yr. This represents the ocean mass increase (plus eventually a deep ocean thermal contribution). For the glaciers contribution since 1993, we use Kaser et al. (2006) and Meier et al. (2007) updates, leading to a value of 1.1 +/- 0.25 mm/yr. Although ice sheet mass loss is clearly not linear (see Fig.5a,b), we deduce from a compilation of published results a mean contribution to sea level of ~0.7 mm/yr for the two ice sheets (~0.4 mm/yr for Greenland and ~0.3 for Antarctica). This leads to a total ice component of ~ 1.8 mm/yr, lower than the 2.3 mm/yr residual rate. As in IPCC AR4 for 1993-2003, the sea level budget is not totally closed. But over 1993-2007, the mass component dominates the thermal component (unlike over 1993-2003).

2003-2008; Recent developments

As indicated above, Argo-based ocean thermal expansion has increased less rapidly since 2003 than during the previous decade, although sea level has continued to rise, although at a reduced rate, of 2.5 +/- 0.4 mm/yr (Ablain et al., 2009). GRACE data averaged over the oceans provide a measure of the ocean mass change. However GRACE is also sensitive to GIA and the latter effect averaged over the oceanic domain is still uncertain, ranging from 1 mm/yr (Paulson et al., 2007) to 2 mm/yr (Peltier, 2009). Depending on the assumed GIA correction, estimated ocean mass change over 2003-2007 ranges from 1.1 mm/yr (Leuliette and Miller, 2009) to 2.1 mm/yr (Cazenave et al., 2009a). Independent estimates of glaciers and ice sheet contributions to sea level over the same time span can help discriminating between the two values. Meier et al. (2007) as well as Cogley (2009) report accelerated glacier melting since 2003, leading to 1.4 +/- 0.25 mm/yr equivalent sea level rise in year 2006. The mass balance of the ice sheets has been recently re-evaluated using GRACE and other remote sensing techniques. For example, Rignot et al. (2008) find an Antarctica contribution to sea level of 0.56 mm/yr for year 2006, in good agreement with GRACE-based Antarctica mass balance estimate (0.55 +/- 0.06 mm/yr, Cazenave et al., 2009a). GRACE data also suggest an increased contribution of Greenland (0.4 +/- 0.05 mm/yr, Wouters et al., 2009). Using ICEsat laser altimetry, Slobbe et al. (2008) estimated to 0.39 +/- 0.2 the Greenland contribution over 2003-2008. Summing all land ice components leads to 2.1 +/- 0.25 mm/yr equivalent sea level rise over 2003-2007, in agreement with the GRACE-based ocean mass increase if the largest GIA correction is considered. These new observations report accelerated land ice loss which may have contributed to ~80% of the recent years sea level rise (compared to 50% during the 1993-2003 decade; IPCC AR4).

Chambers et al. (2004) and Lombard et al. (2007) showed that combining satellite altimetry and GRACE data provides an estimate of the steric component. In effect, satellite altimetry represents the sum of thermal expansion and ocean mass change, while GRACE averaged over the oceans measures the ocean mass change component only. The 'altimetry minus land ice contribution' (using values presented in Table 1) shows a slightly positive trend of 0.3 mm/yr over 2003-2007, in agreement with the Argo-based reduced thermosteric rate over that same period.

5. Regional variability in sea level trends

Satellite altimetry has revealed strong regional variability in sea level trends (Fig.2a,b). Several studies have shown that non uniform ocean warming, hence non uniform thermal expansion is mostly responsible for the observed spatial trend patterns in sea level (e.g., Lombard et al., 2005). Recent studies based on ocean general circulations models, either in with data assimilation (e.g., Carton and Giese, 2008, Wunsch et al., 2007) or without (Lombard et al., 2009) confirm that regional sea level trend patterns reported by satellite altimetry are mainly due to regional variability in thermal expansion. However, salinity changes are not negligible at regional scale. For example, using the ECCO (Estimating the Circulation and Climate Experiment of the Ocean) ocean circulation model with atmospheric data forcing and assimilation of a large number of ocean data (in situ temperature and salinity, altimetry-based sea level sea surface temperature, satellite-based surface winds, etc.), Wunsch et al. (2007) reproduced local sea level trend patterns observed by satellite altimetry over 1993-2004. They showed that thermal expansion change in the upper ocean is the dominant contribution to observed spatial trend patterns but also that about 25% of the temperature contribution is locally compensated by salinity. Lombard et al. (2009) were also able to reproduce spatial trend patterns using the high-resolution (0.25°) OPA/NEMO ocean circulation model without data assimilation over 1993-2001. As in Wunsch et al. (2007), thermosteric trend patterns closely resemble observed trend patterns (although not everywhere; e.g., in the southwest Atlantic ocean)

Wunsch et al. (2007) discuss the issue of attribution of the observed local/regional trend patterns : (1) warming and cooling of the ocean, (2) exchange of fresh water with the atmosphere and land through change of evaporation, precipitation and runoff, (3) redistribution of water mass by advection within the ocean. To these processes should also be added solid Earth processes due to gravity and ocean volume changes (discussed below). Concerning factors (1) through (3), Wunsch et al. showed that observed trend patterns result from a complex dynamical response of the ocean, involving not only the forcing terms but also water movements associated with wind stress. These authors also stressed that given the long memory time of the ocean, observed patterns only partly reflect forcing patterns over the period considered but also forcing and internal changes that occurred earlier in the past.

This suggests that sea level trends distribution observed by satellite altimetry over the last 16 years may not be steady but will eventually adjust over much longer time spans towards different geographical patterns than currently observed.

Concerning the response of the ocean circulation to fresh water forcing associated with Greenland and Antarctic ice melting, using ECCO simulations, Stammer (2008) showed that significant sea level rise would be expected along the western coast of North Atlantic in response to Greenland melting.

We have seen above that steric sea level change is the dominant contributor to the observed spatial trend patterns in sea level. However other processes are expected to also give rise to regional sea level variations. This is the case for the response of the solid Earth to last deglaciation (GIA) and to ongoing melting of land ice in response to global warming. These processes give rise to secular change of the geoid (an equipotential surface of the Earth gravity field that coincides with the mean surface of the oceans at rest) and gravitational deformations of ocean basins and of the sea surface (Peltier, 2004, Mitrovica et al., 2001). Recently, Mitrovica et al. (2009) showed that rapid melting of the ice sheets and glaciers will lead to non uniform sea level rise because of the changing mutual gravitational attraction between the ice sheet and the nearby ocean as well as the elastic deformation of the solid Earth to the load redistribution. Such regional sea level changes are broad-scale but different for each melting source (Greenland, Antarctica, glaciers). To give an order of magnitude, they can reach up to 30% of the melt contribution to sea level rise.

Now that high-quality in situ temperature and salinity measurements with global coverage are available from the Argo observing system, it may become possible to detect the fingerprint of land ice melt (due to both gravitational and dynamical effects) using satellite altimetry data corrected for steric sea level.

6. Sea level projections

IPCC AR4 projections indicated that sea level should be higher than today's value by ~ 35 cm by 2100 (within a range of +/- 15 cm due to model results dispersion and uncertainty on future greenhouse gases emissions) (Meehl et al., 2007). However this value is likely a lower bound because physically realistic behavior of the ice sheets was not taken into account. As discussed in section 3.4, a large proportion of ice sheet mass loss results from coastal glacier flow into the ocean through dynamical instabilities. Such processes only begin to be understood. They were not taken into account in the IPCC AR4 sea level projections. Recently some studies (e.g., Rahmstorf, 2007) have provided empirical sea level projections based on simple relationship established for the 20th century between global mean sea level rate and global mean Earth's temperature. Using mean temperature projections from climate models, Rahmstorf (2007) extrapolated future global mean sea level. His range of sea level rise in 2100 (between 40 cm and 120 cm) directly reflects the temperature projections range. The middle value (~80 cm) is about twice the IPCC AR4 value. While future sea level rates may not necessarily follow past century dependence on global mean Earth's temperature (in particular if ice sheet dynamics plays larger role in the future), such an approach offers independent insight on plausible ranges of future sea level rise. This is an interesting alternative to still uncertain coupled climate model projections.

We have seen that observed sea level rates present high regional variability around the global mean (Fig.3b). Regional variability in sea level trends is thus expected in the future. The mean regional sea level map for 2090-2100 provided by IPCC AR4 (Meehl et al., 2007) shows higher than average sea level rise in the Arctic Ocean in response to increasing ocean temperature and decreasing salinity. On the other hand, lower sea level is projected in the Austral Ocean. These model-based projections essentially reflect that part of the regional variability due to long-term climate signals but do not account for decadal/multidecadal natural variability. On decadal time scale, spatial trend patterns may differ by a factor 2-3 from the global mean sea level rise (section 2.3). Regional sea level projections at 10-20 years interval should be proposed by climate models. To evaluate future regional impacts, this information is of crucial importance.

7. Coastal Impacts

Main physical impacts of sea level rise are rather well known (e.g., Nicholls, 2002, 2007). These include: (1) inundation and recurrent flooding in association with storm surges, (2) wetland loss, (3) shoreline erosion, (4) saltwater intrusion in surface water bodies and aquifers, and (5) rising water tables. In many coastal regions of the world, the effects of rising sea level act in combination of other natural and/or anthropogenic factors, such as decreased rate of fluvial sediment deposition in deltaic areas, ground subsidence due to tectonic activity or ground water pumping and hydrocarbon extraction. Change in dominant wind, wave and coastal current patterns in response to local or regional climate change and variability may also impact shoreline equilibrium.

Deltas are dynamical systems linking fluvial and coastal ocean processes (Ericson et al., 2006). Over the last 2 millenia, agriculture has accelerated the growth of many world deltas (MacManus, 2002). But in the recent decades dam and reservoir construction as well as river diversion for irrigation had considerably decreased sediment supply along numerous world rivers, destroying natural equilibrium of many deltas.

Accelerated ground subsidence due to local groundwater withdrawal and hydrocarbon extraction is another problem that affects numerous coastal megacities. For example over the 20^{th} century, Tokyo subsided by 5 m, Shangai by 3 m and Bangkok by 2 m (Nicholls, 2007). Hydrocarbon extraction in the Gulf of Mexico causes ground subsidence along the Gulf coast in the range 5-10 mm/yr (Ericson et al., 2006). Whatever the causes, ground subsidence produces effective (relative) sea level rise that directly interacts with and amplifies climate-related sea level rise (long-term trend plus regional variability).

In terms of impacts, what is important is relative sea level rise, i.e., the combination of the climate-related sea level rise and ground subsidence. In many coastal regions of the world, these two factors are currently of the same order of magnitude (and of opposite sign), hence interfer positively. If sea level continues to rise at current rates and more likely accelerates, then the climate change impacts (sea level rise) may become dominant. As mentioned in section 6, future sea level projections are likely underestimated. In addition climate models are not yet able to provide reliable regional variability (that superimposes positively or negatively on the global mean rise) for the next 20, 30 and 50 years. Hence, it is very difficult to quantify future sea level rise in specific regions. However this should be among the priorities for the climate modelling community. In parallel, multi-disciplinary studies of sea level rise impacts that take an integrated approach involving all factors (climate change, anthropogenic forcing, solid earth processes, etc.) need to be developed.

8. Conclusions

Most recent developments indicate that sea level is currently rising, slightly faster since the early 1990s than during the previous decades. Owing to the progress realized in the recent years in understanding the causes of present-day sea level rise, we can nearly close the sea level budget for the period 1993-2007: about 30 % of the rate of sea level rise is due to ocean thermal expansion in response to ocean warming. Mountain glaciers and ice sheets mass loss explains about 55%. Since 2003 ocean thermal expansion rate has slightly reduced while sea level has continued to rise. Direct and indirect estimates of land ice contribution indicate that ocean mass increase explains ~80 % of the past 5-year observed sea level rate. If, as most likely, recent thermal expansion pause is temporary, and if land ice shrinking continues to accelerate, sea level may cause some surprise in the near future. Recently launched Jason-2 satellite, the successor of Jason-1, will provide continuity in the monitoring of sea level variations from space, at least for the coming years. Besides, ocean temperature and salinity measurements from Argo, mass balance of the ice sheets from GRACE and other remote sensing techniques, GRACE-based land water storage change and in situ and remote observations of mountain glaciers are absolutely crucial for understanding sea level evolution with time and its response to climate change and variability. These observations also offer invaluable constraints to the climate models developed for future sea level projections: sea level is a climate parameter difficult to determine by climate models because it involves interactions of all components of the climate system (ocean, ice sheets and glaciers, atmosphere, land water reservoirs) on a wide range of spatial and temporal scales. Even the solid Earth through its elastic response to changing crust and mantle as well as water mass redistribution affects sea level. Systematic monitoring of oceans, cryosphere and land waters from in situ and space observing systems are thus crucially important to validate climate models, hence improve future sea level projections.

Considering the highly negative impact of future sea level rise for society, the multidisciplinary aspects of sea level rise (observations, modeling, study of coastal impacts) should remain a major area of future climate research.

Table 1: Sea level budget for two time spans (1993-2007; 2003-2007); Quoted errors are one standard deviation. The observed sea level rate is GIA corrected (-0.3 mm/yr removed)

Sea level rise (mm/yr)	**1993-2007**	**2003-2007**
1. Observed	3.3 +/- 0.4	2.5 +/- 0.4 (Ablain et al., 2009)
2. Thermal expansion	1.0 +/- 0.3 mean of Levitus et al (2009) and Ishii and Kimoto (2009) values	0.25 +/- 0.8 (Argo) mean of Willis et al. (2008), Cazenave et al. (2009a) and Leuliette and Miller (2009) values
3. Ocean mass	2.3 +/- 0.1 (observed rate minus thermal expansion)	1.9 +/-0.1 (GRACE with a 2 mm/yr GIA correction; Cazenave et al., 2009a)
4. Glaciers	1.1 +/- 0.25 based on Kaser et al. (2006) and Meier et al. (2007)	1.4 +/- 0.25 (Cogley, 2009)
5. Ice sheets (total) • Greenland • Antarctica	0.7+/- 0.2 0.4 +/- 0.15 0.3 +/- 0.15 (compilation of published results)	1. +/- 0.2 0.5 +/-0.15 0.5 +/- 0.15 (compilation of published results)
6. Land waters	N/A	-0.2 +/- 0.1 (Cazenave et al., 2009b)
7. Sum of (2+4+5+6)	2.85 +/- 0.35	2.45 +/- 0.85
8. Observed rate minus sum	0.45	-0.05

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Figure Captions

Fig.1: Observed global mean sea level (from tide gauges) between 1900 and 2001. Red dots are from Church et al. (2004); Blue dots are from Jevrejeva et al. (2006). Unit : mm.

Fig.2: Global mean sea level from satellite altimetry between January 1993 and December 2008. Annual cycle has been removed. Blue dots are raw 10-day data. Red curve corresponds to a 90-day smoothing of the raw data. The -0.3 mm/yr GIA correction has been removed. Unit : mm.

Fig.3: (a) Map of spatial trend patterns of observed sea level between January 1993 and December 2008.
(b) Same as (a) but a uniform global mean trend of 3.4 mm/yr has been removed.
Unit: mm/yr

Fig.4: Map of spatial trend patterns of reconstructed sea level between 1950 and 2003 (from Llovel et al., 2009). Unit: mm/yr.

Fig.5 : (a) Compilation of Greenland ice sheet mass loss based on remote sensing observations between 1992 and 2008. (b) Same as (a) but for the Antarctica ice sheet. (figure updated from Cazenave et al., 2006). Unit: Gt/yr.

Fig.6: Blue curves : thermosteric sea level (or thermal expansion) between 1955 and 2001 from Ishii and Kimoto (2009) (solid curve) and Levitus et al. (2009) (dashed curve). Red curves: residual sea level, i.e., observed global mean sea level from Church et al. (2004) minus thermal expansion (solid and dashed curves refer to Levitus et al. and Ishii and Kimoto thermal expansion data respectively). Unit: mm.

Fig.7 : Blue curves : thermosteric sea level (or thermal expansion) since 1993 from Ishii and Kimoto (2009) (solid curve; up to 2006) and Levitus et al. (2009) (dashed curve up to 2007). Black curve: altimetry-based global mean sea level (annual averages). Red curves: residual sea level, i.e., observed global mean sea level minus thermal expansion (solid and dashed curves refer to Ishii and Kimoto and Levitus et al. thermal expansion data respectively). Unit: mm.

Figure 1

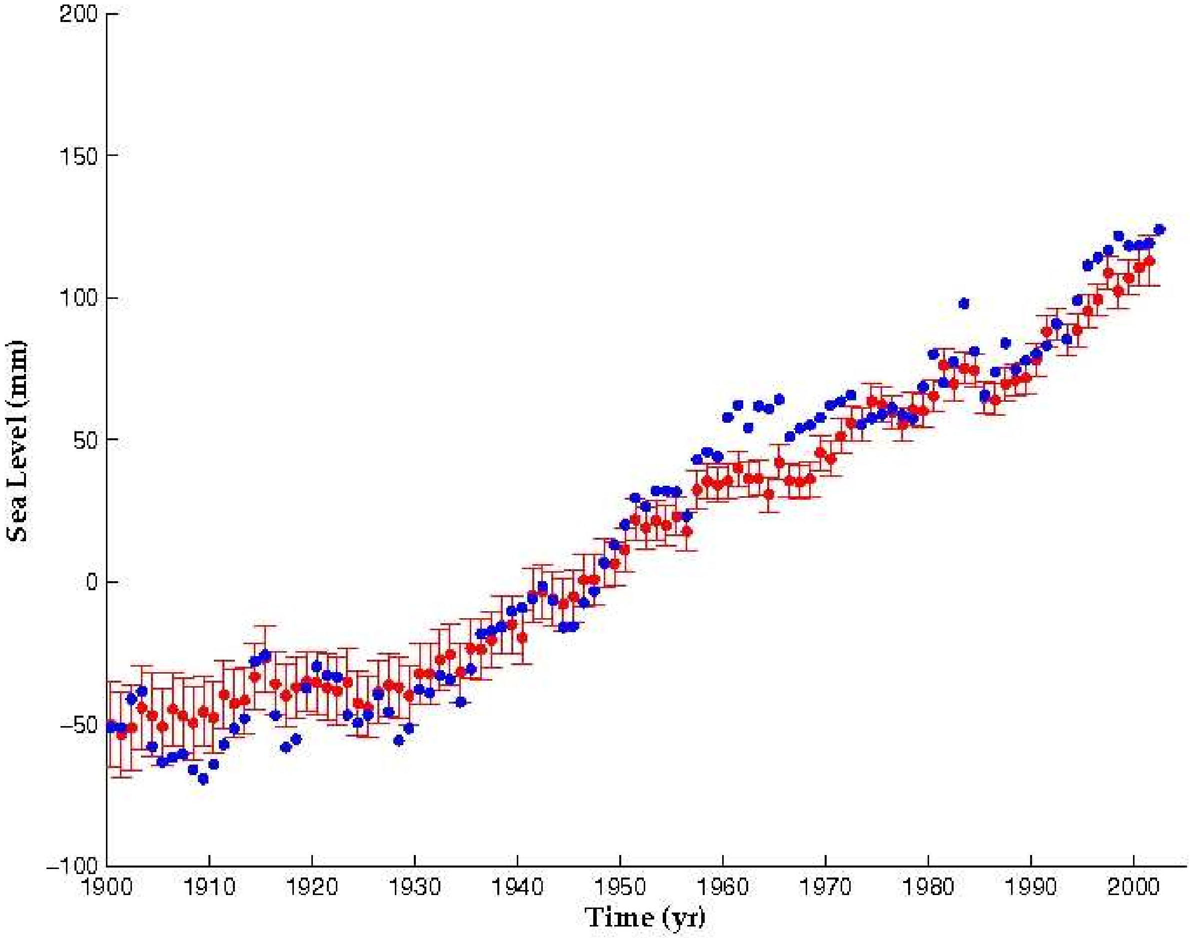

200
150
100
50
0
−50
−100
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Sea Level (mm)
Time (yr)

Figure 2

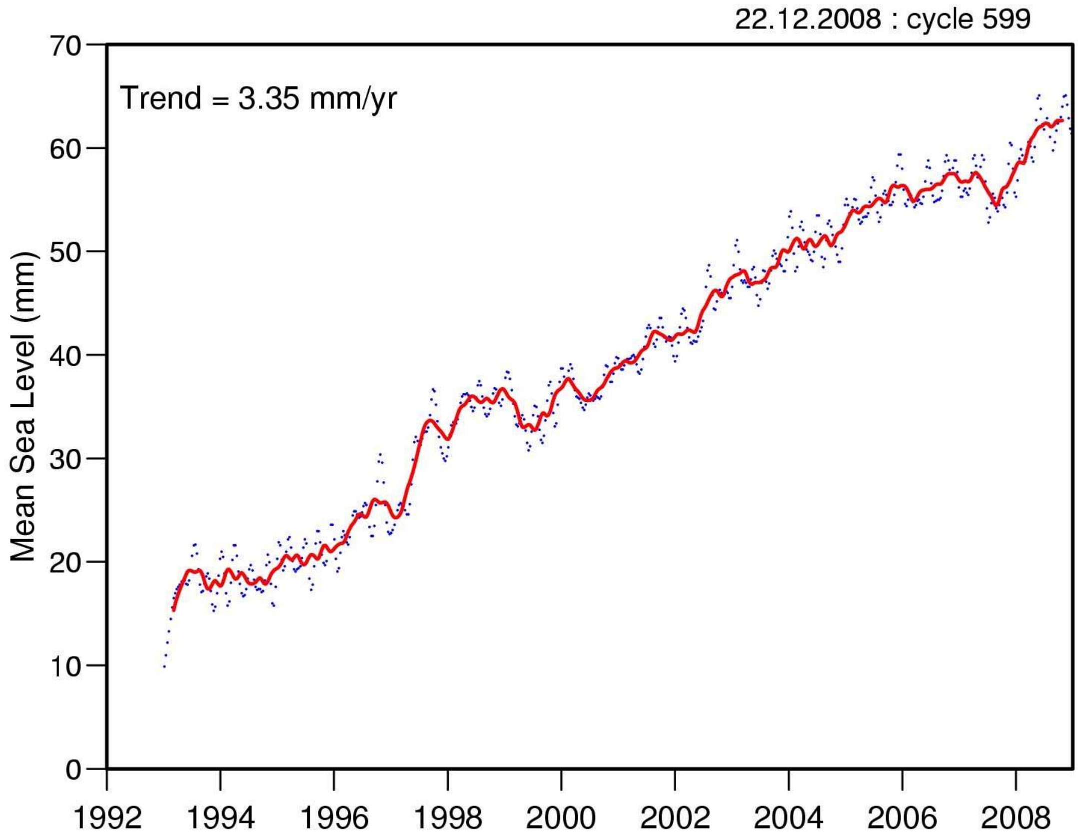

22.12.2008 : cycle 599
Trend = 3.35 mm/yr
Mean Sea Level (mm)
70
60
50
40
30
20
10
0
1992
1994
1996
1998
2000
2002
2004
2006
2008

Figure 3 a

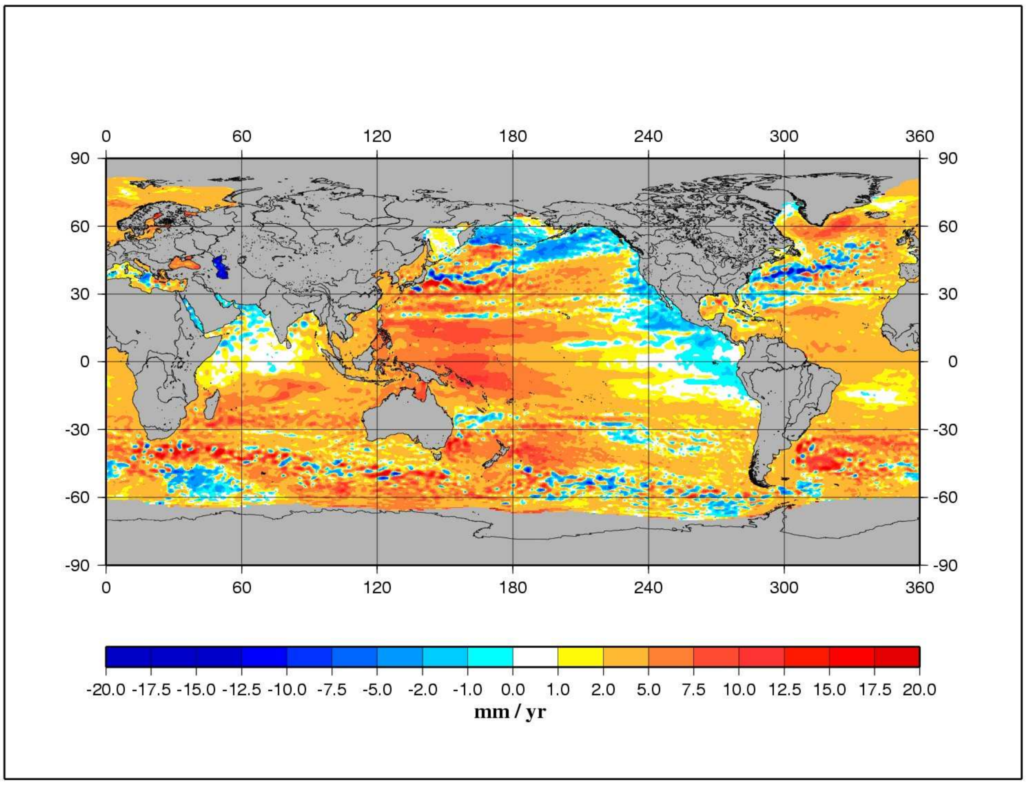


Figure 3b

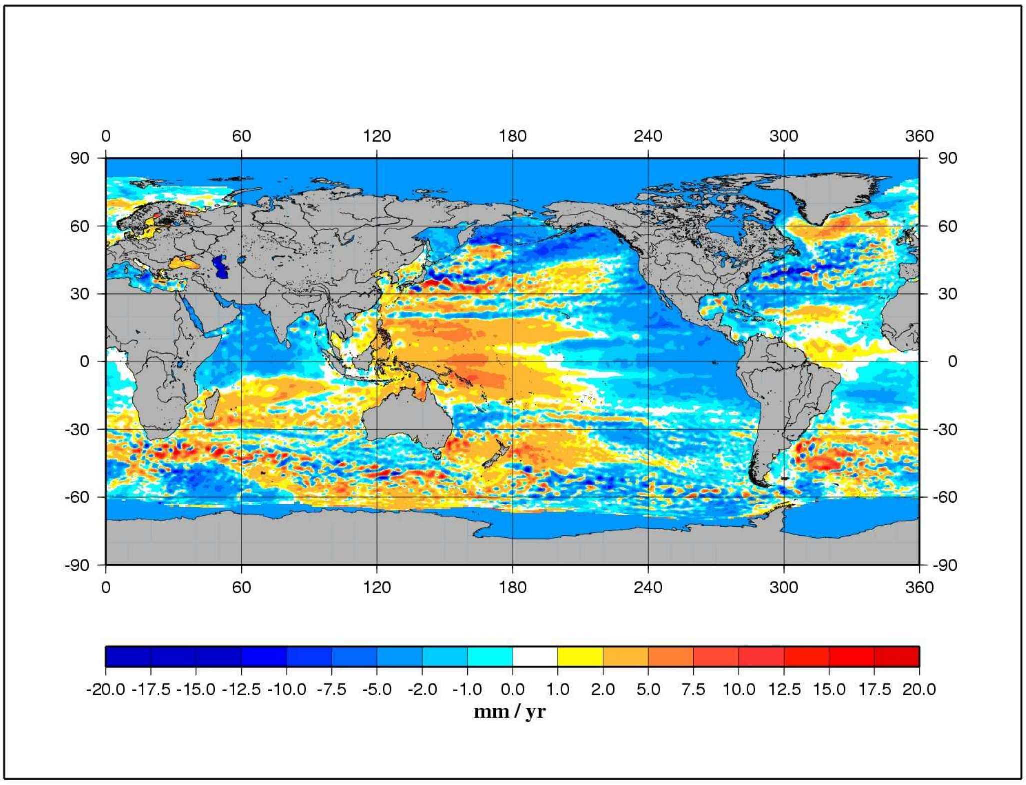


Figure 4

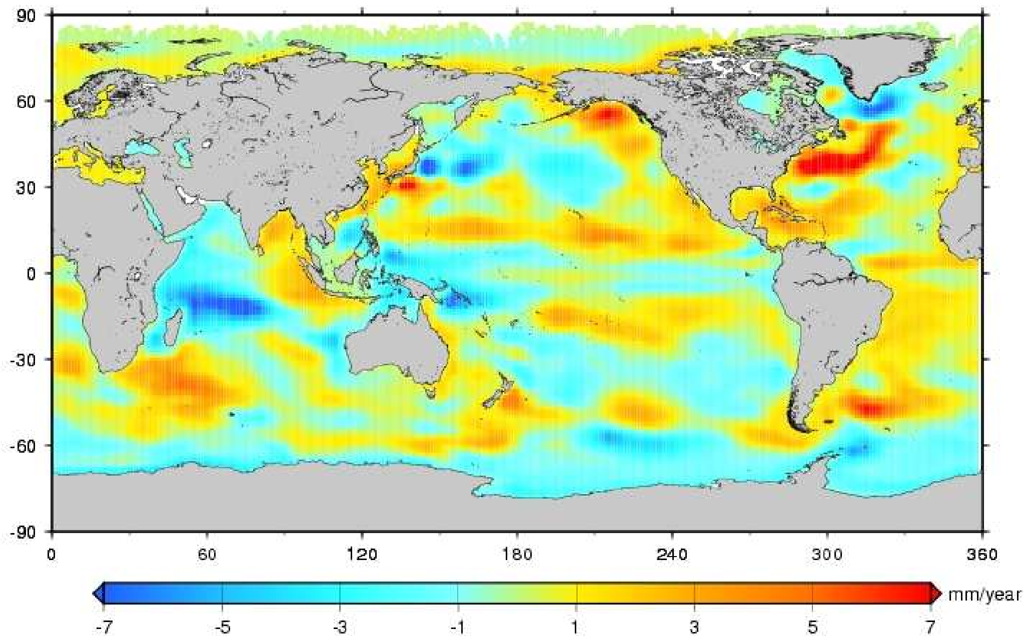


Figure 5a

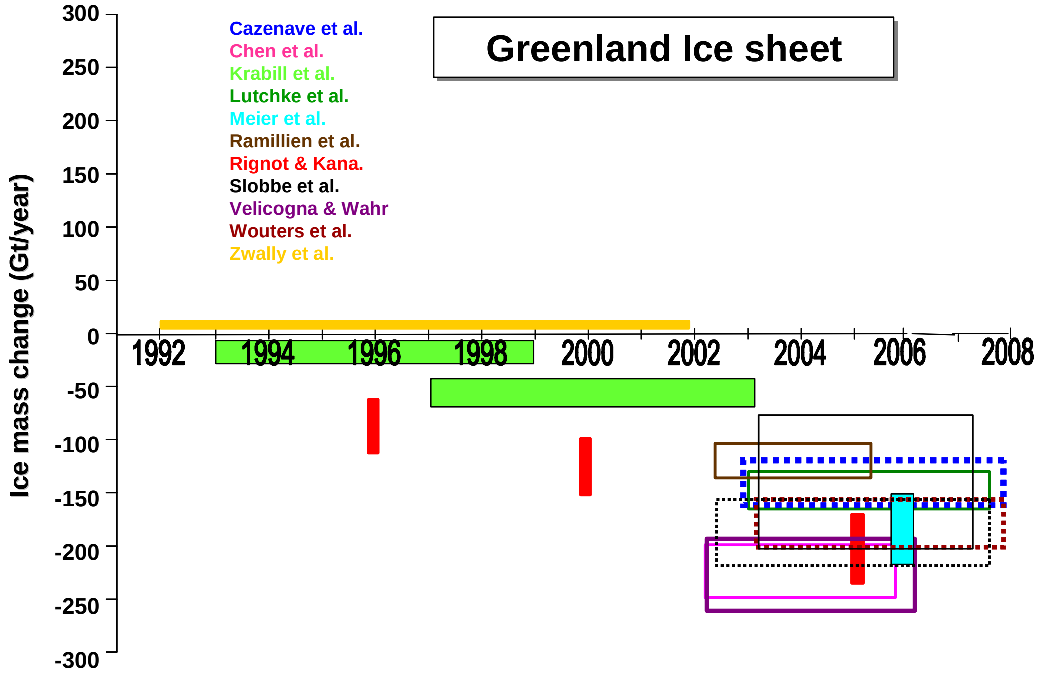


Figure 5b

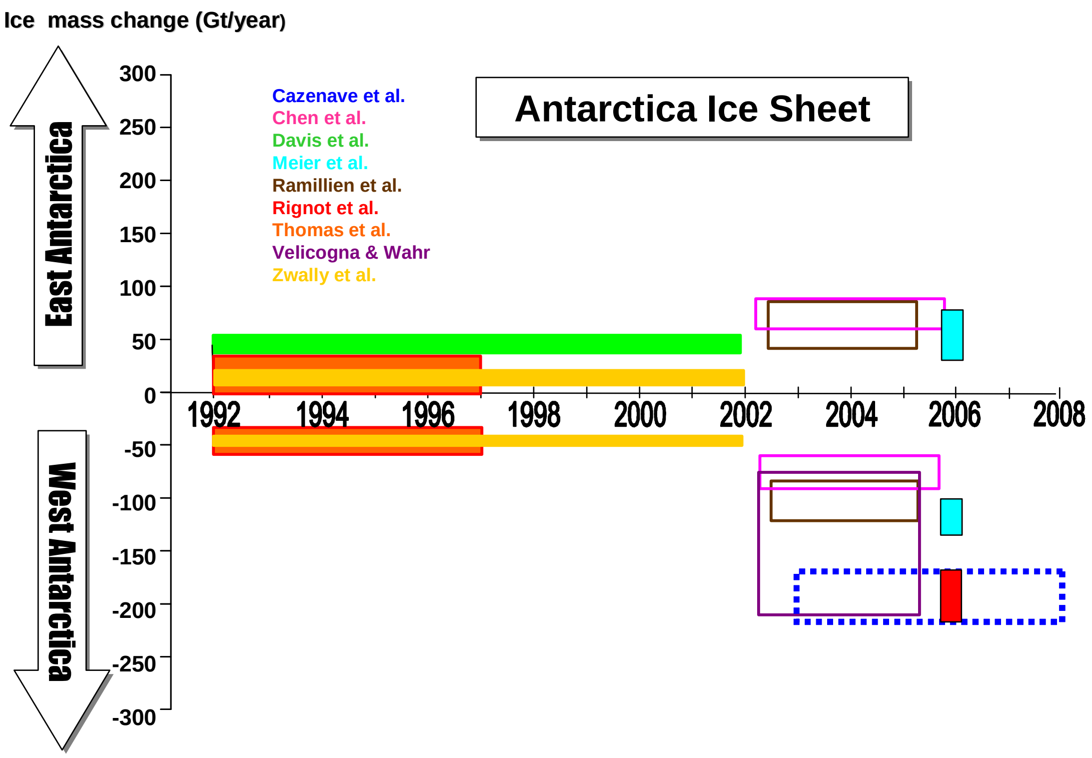


Figure 6

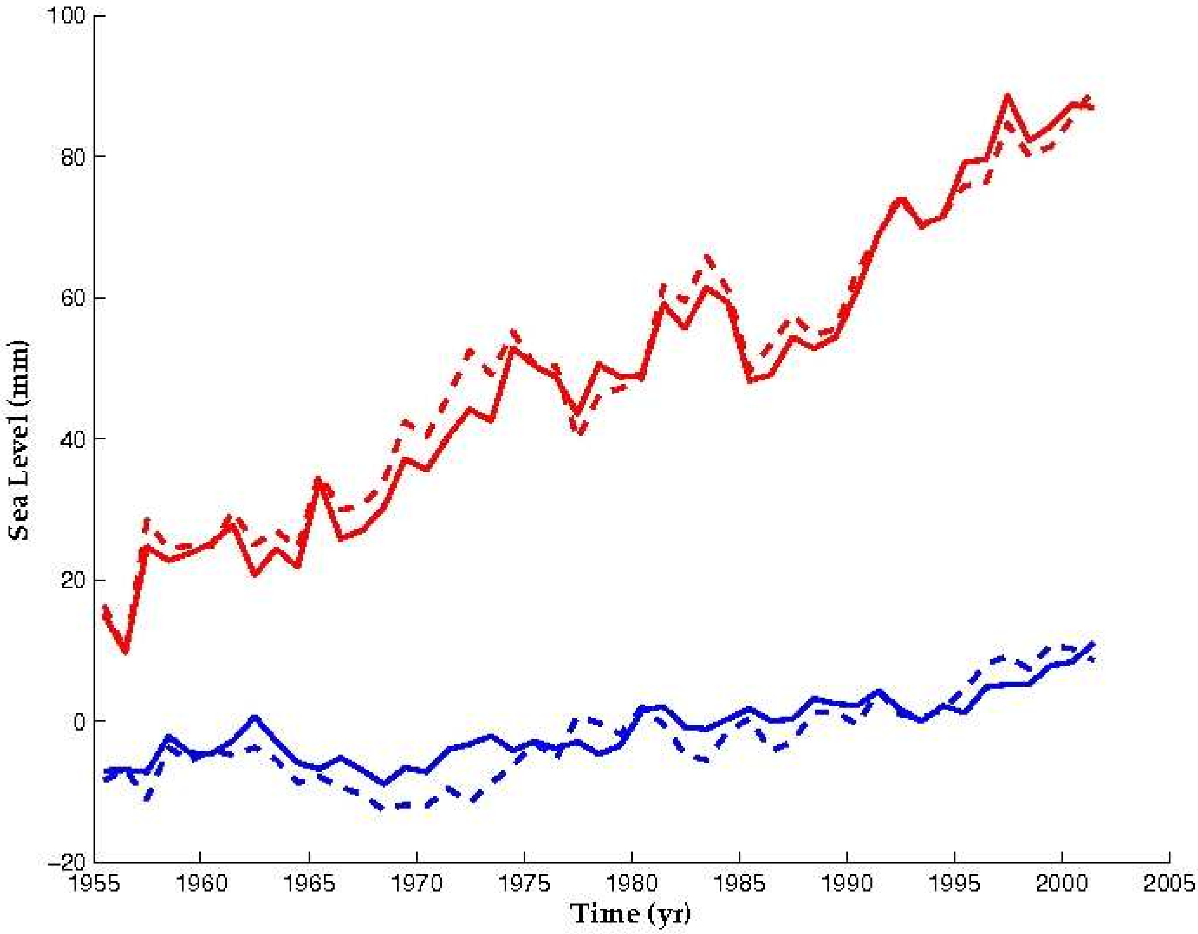
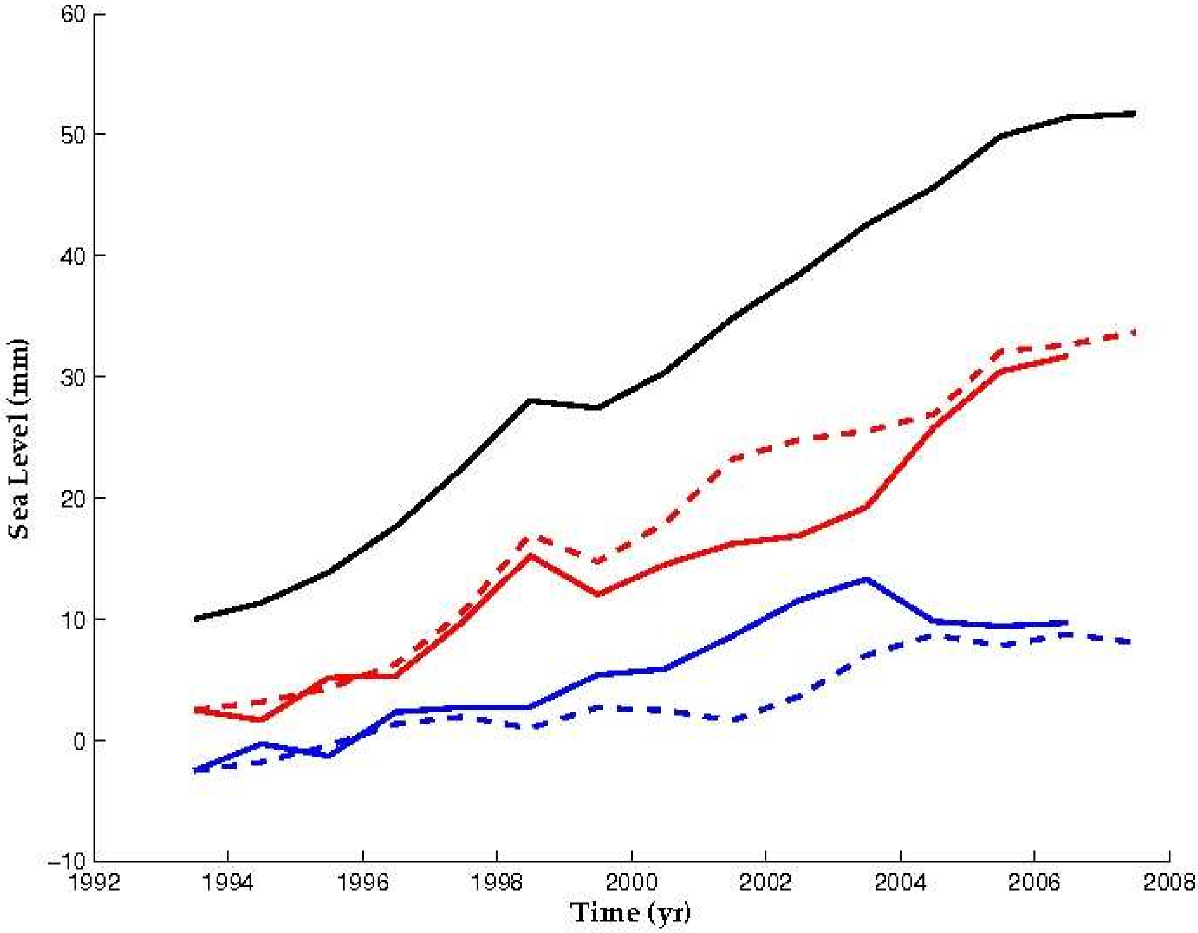

100
80
60
40
20
0
−20
Sea Level (mm)
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
Time (yr)

Figure 7


60
50
40
30
20
10
0
−10
Sea Level (mm)
1992
1994
1996
1998
2000
2002
2004
2006
2008
Time (yr)