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Abstract

We analyse global temperature and sea-level data for the past few decades and compare them to projections published in the third and fourth assessment reports of the Intergovernmental Panel on Climate Change (IPCC). The results show that global temperature continues to increase in good agreement with the best estimates of the IPCC, especially if we account for the effects of short-term variability due to the El Niño/Southern Oscillation, volcanic activity and solar variability. The rate of sea-level rise of the past few decades, on the other hand, is greater than projected by the IPCC models. This suggests that IPCC sea-level projections for the future may also be biased low.

Keywords: global temperature, sea level, ocean, projections, ENSO, El Niño, volcanic eruptions, solar variability

1. Introduction

Climate projections like those of the Intergovernmental Panel on Climate Change (IPCC 2001, 2007) are increasingly used in decision-making. It is important to keep track of how well past projections match the accumulating observational data. Five years ago, it was found that CO_2 concentration and global temperature closely followed the central prediction of the third IPCC assessment report during 1990–2006, whilst sea level was tracking along the upper limit of the uncertainty range (Rahmstorf *et al* 2007). Here we present an update with five additional years of data and using advances in removing short-term noise from global temperature data.

Atmospheric carbon dioxide concentration continues to match the prediction: the mean value reached in 2011 was 390.5 ppm (NOAA 2012), only about 1.5 ppm higher than the central IPCC projections published in 2001. For historical perspective, in his article 'Are we on the brink of a pronounced global warming?', Broecker (1975) predicted an increase from 322 ppm observed in 1970 to 403 ppm in 2010. A more detailed analysis of anthropogenic climate forcing, which also includes other greenhouse gases, aerosols and surface albedo changes, is beyond the scope of this letter. Here we focus on two prime indicators of climate change: the evolution of global-mean temperature and sea level.

2. Global temperature evolution

To compare global temperature data to projections, we need to consider that IPCC projections do not attempt to predict the effect of solar variability, or specific sequences of either volcanic eruptions or El Niño events. Solar and volcanic forcing are routinely included only in 'historic' simulations for the past climate evolution but not for the future, while El Niño–Southern Oscillation (ENSO) is included as a stochastic process where the timing of specific warm or cool phases is random and averages out over the ensemble of projection models. Therefore, model-data comparisons either need to account for the short-term variability due to these natural factors as an added quasi-random uncertainty, or the

specific short-term variability needs to be removed from the observational data before comparison. Since the latter approach allows a more stringent comparison it is adopted here.

Global temperature data can be adjusted for solar variations, volcanic aerosols and ENSO using multivariate correlation analysis (Foster and Rahmstorf 2011, Lean and Rind 2008, 2009, Schönwiese *et al* 2010), since independent data series for these factors exist. We here use the data adjusted with the method exactly as described in Foster and Rahmstorf, but using data until the end of 2011. The contributions of all three factors to global temperature were estimated by linear correlation with the multivariate El Niño index for ENSO, aerosol optical thickness data for volcanic activity and total solar irradiance data for solar variability (optical thickness data for the year 2011 were not yet available, but since no major volcanic eruption occurred in 2011 we assumed zero volcanic forcing). These contributions were computed separately for each of the five available global (land and ocean) temperature data series (including both satellite and surface measurements) and subtracted. The five thus adjusted data sets were averaged in order to avoid any discussion of what is 'the best' data set; in any case the differences between the individual series are small (Foster and Rahmstorf 2011). We show this average as a 12-months running mean in figure 1, together with the unadjusted data (likewise as average over the five available data series). Comparing adjusted with unadjusted data shows how the adjustment largely removes e.g. the cold phase in 1992/1993 following the Pinatubo eruption, the exceptionally high 1998 temperature maximum related to the preceding extreme El Niño event, and La Niña-related cold in 2008 and 2011.

Note that recently a new version of one of those time series has become available: version of 4 the HadCRUT data (Morice *et al* 2012). Since the differences are small and affect only one of five series, the effect of this update on the average shown in figure 1 is negligible. We chose to include version 3 of the data in this graph since these data are available up to the end of 2011, while version 4 so far is available only up to the end of 2010.

The removal of the known short-term variability components reduces the variance of the data without noticeably altering the overall warming trend: it is 0.15 °C/decade in the unadjusted and 0.16 °C/decade in the adjusted data. From 1990–2011 the trends are 0.16 and 0.18 °C/decade and for 1990–2006 they are 0.22 and 0.20 °C/decade respectively. The relatively high trends for the latter period are thus simply due to short-term variability, as discussed in our previous publication (Rahmstorf *et al* 2007). During the last ten years, warming in the unadjusted data is less, due to recent La Niña conditions (ENSO causes a linear cooling trend of −0.09 °C over the past ten years in the surface data) and the transition from solar maximum to the recent prolonged solar minimum (responsible for a −0.05 °C cooling trend) (Foster and Rahmstorf 2011). Nevertheless, unadjusted observations lie within the spread of individual model projections, which is a different way of showing the consistency of data and projections (Schmidt 2012).
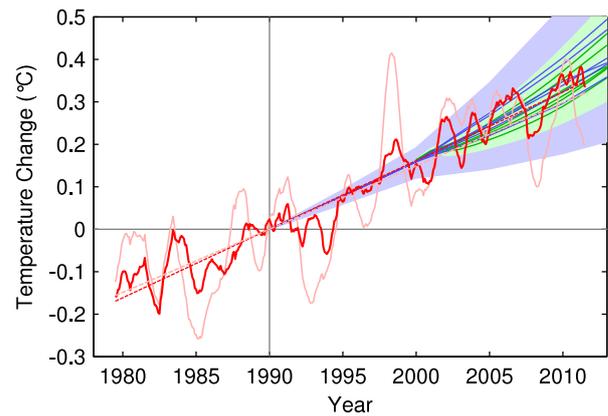

Figure 1. Observed annual global temperature, unadjusted (pink) and adjusted for short-term variations due to solar variability, volcanoes and ENSO (red) as in Foster and Rahmstorf (2011). 12-months running averages are shown as well as linear trend lines, and compared to the scenarios of the IPCC (blue range and lines from the third assessment, green from the fourth assessment report). Projections are aligned in the graph so that they start (in 1990 and 2000, respectively) on the linear trend line of the (adjusted) observational data.

Figure 1 shows that the adjusted observed global temperature evolution closely follows the central IPCC projections, while this is harder to judge for the unadjusted data due to their greater short-term variability. The IPCC temperature projections shown as solid lines here are produced using the six standard, illustrative SRES emissions scenarios discussed in the third and fourth IPCC reports, and do not use any observed forcing. The temperature evolution for each, including the uncertainty range, is computed with a simple emulation model, hence the temperature curves are smooth. The temperature ranges for these scenarios are provided in the summary for policy makers of each report, in figure 5 in case of the third assessment and in table SPM.3 in case of the fourth assessment (where the full time evolution is shown in figure 10.26 of the report; Meehl *et al* 2007).

For historic perspective, Broecker in 1975 predicted a global warming from 1980–2010 by 0.68 °C, as compared to 0.48 °C according to the linear trend shown in figure 1, an overestimate mostly due to his neglect of ocean thermal inertia (Rahmstorf 2010). A few years later, Hansen *et al* (1981) analysed and included the effect of ocean thermal inertia, resulting in lower projections ranging between 0.28 and 0.45 °C warming from 1980–2010. Their upper limit thus corresponds to the observed warming trend. They further correctly predicted that the global warming signal would emerge from the noise of natural variability before the end of the 20th century.

3. Global sea-level rise

Turning to sea level, the quasi linear trend measured by satellite altimeters since 1993 has continued essentially unchanged when extending the time series by five additional years. It continues to run near the upper limit of the
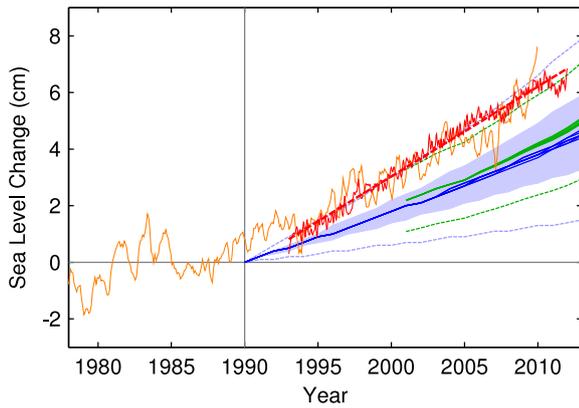
Figure 2. Sea level measured by satellite altimeter (red with linear trend line; AVISO data from (Centre National d'Etudes Spatiales) and reconstructed from tide gauges (orange, monthly data from Church and White (2011)). Tide gauge data were aligned to give the same mean during 1993–2010 as the altimeter data. The scenarios of the IPCC are again shown in blue (third assessment) and green (fourth assessment); the former have been published starting in the year 1990 and the latter from 2000.
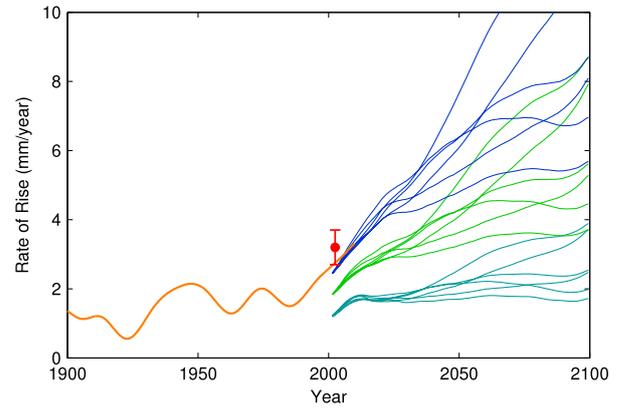

Figure 3. Rate of sea-level rise in past and future. Orange line, based on monthly tide gauge data from Church and White (2011). The red symbol with error bars shows the satellite altimeter trend of 3.2 ± 0.5 mm yr^{-1} during 1993–2011; this period is too short to determine meaningful changes in the rate of rise. Blue/green line groups show the low, mid and high projections of the IPCC fourth assessment report, each for six emissions scenarios. Curves are smoothed with a singular spectrum filter (ssatrend; Moore *et al* 2005) of 10 years half-width.

projected uncertainty range given in the third and fourth IPCC assessment reports (figure 2). Here, the sea-level projections provided in figure 5 of the summary for policy makers of the third assessment and in table SPM.3 of the fourth assessment are shown. The satellite-based linear trend 1993–2011 is 3.2 ± 0.5 mm yr^{-1}, which is 60% faster than the best IPCC estimate of 2.0 mm yr^{-1} for the same interval (blue lines). The two temporary sea-level minima in 2007/2008 and 2010/2011 may be linked to strong La Niña events (Llovel *et al* 2011). The tide gauges show much greater variability, most likely since their number is too limited to properly sample the global average (Rahmstorf *et al* 2012). For sea level the fourth IPCC report did not publish the model-based time series (green lines), but these were made available online in 2012 (CSIRO 2012). They do not differ significantly from the projections of the third IPCC report and thus continue to underestimate the observed upward trend.

Could this underestimation appear because the high observed rates since 1993 are due to internal multi-decadal variability, perhaps a temporary episode of ice discharge from one of the ice sheets, rather than a systematic effect of global warming? Two pieces of evidence make this very unlikely. First, the IPCC fourth assessment report (IPCC 2007) found a similar underestimation also for the time period 1961–2003: the models on average give a rise of 1.2 mm yr^{-1}, while the best data-based estimate is 50% larger at 1.8 mm yr^{-1} (table 9.2 of the report; Hegerl *et al* 2007). This is despite using an observed value for ice sheet mass loss (0.19 mm yr^{-1}) in the 'modelled' number in this comparison. Second, the observed rate of sea-level rise on multi-decadal timescales over the past 130 years shows a highly significant correlation with global temperature (Vermeer and Rahmstorf 2009) by which the increase in rate over the past three decades is linked to the warming since 1980, which is very unlikely to be a chance coincidence.

Another issue is whether non-climatic components of sea-level rise, not considered in the IPCC model projections, should be accounted for before making a comparison to data, namely water storage in artificial reservoirs on land (Chao *et al* 2008) and the extraction of fossil groundwater for irrigation purposes (Konikow 2011). During the last two decades, both contributions approximately cancel (at -0.3 and $+0.3$ mm yr^{-1}) so would not change our comparison in figure 2, see figure 11 of Rahmstorf *et al* (2012) based on the data of Chao *et al* (2008) and Konikow (2011). This is consistent with the lack of recent trend in net land-water storage according to the GRACE satellite data (Lettenmaier and Milly 2009). For the period 1961–2003, however, the effect of dam building (which peaked in the 1970s at around -0.9 mm yr^{-1}) very likely outstripped groundwater extraction, thus widening the gap between modelled and observed climatically-forced sea-level rise.

It is instructive to analyse how the rate of sea-level rise changes over longer time periods (figure 3). The tide gauge data (though noisy, see above) show that the rate of sea-level rise was around 1 mm yr^{-1} in the early 20th century, around 1.5–2 mm yr^{-1} in mid-20th-century and increased to around 3 mm yr^{-1} since 1980 (orange curve). The satellite series is too short to meaningfully compute higher order terms beyond the linear trend, which is shown in red (including uncertainty range). Finally, the AR4 projections are shown in three bundles of six emissions scenarios: the 'mid' estimates in green, the 'low' estimates (5-percentile) in cyan and the 'high' estimates (95-percentile) in blue. These are the scenarios that comprise the often-cited AR4-range from 18 to 59 cm sea-level rise for the period 2090–99 relative to 1980–99 (IPCC 2007). For the period 2000–2100, this corresponds to a range of 17–60 cm sea-level rise.

Figure 3 shows that in all 'low' estimates, the rate of rise stays well below 3 mm yr^{-1} until the second half of the 21st

century, in four of the six even throughout the 21st century. The six 'mid' estimates on average give a rise of 34 cm, very close to what would occur if the satellite-observed trend of the last two decades continued unchanged for the whole century. However, figure 3 shows that the reason for this relatively small projected rise is not an absence of acceleration. Rather, all these scenarios show an acceleration of sea-level rise in the 21st century, but from an initial value that is much lower than the observed recent rise.

Figure 3 further shows that only the 'high' models represented in the range of AR4 models validate when compared to the observational data and can in this regard be considered valid projection models for the future. These 'high' model scenarios represent a range of 21st century rise of 37–60 cm. Nevertheless, this range cannot be assumed to represent the full range of uncertainty of future sea-level rise, since the 95-percentile can only represent a very small number of models, given that 23 climate models were used in the AR4. The model(s) defining the upper 95-percentile might not get the right answer for the right reasons, but possibly by overestimating past temperature rise.

Note that the IPCC pointed out that its projections exclude 'future rapid dynamical changes in ice flow'. The projections now published online (CSIRO 2012) include an alternative version that includes 'scaled-up ice sheet discharge'. These projections validate equally well (or poorly) with the observed data, since they only differ substantially in the future, not in the past, from the standard projections. The sea-level rise over 2000–2100 of the 'high' bundle of these scenarios is 46–78 cm.

Alternative scalings of sea-level rise have been developed, which in essence postulate that the rate of sea-level rise increases in proportion to global warming (e.g. Grinsted *et al* 2009, Rahmstorf 2007). This approach can be calibrated with past sea-level data (Kemp *et al* 2011, Vermeer and Rahmstorf 2009) and leads to higher projections of future sea-level rise as compared to those of the IPCC. The latter is immediately plausible: if we consider the recently observed 3 mm yr^{-1} rise to be a result of $0.8\,°C$ global warming since preindustrial times (Rahmstorf *et al* 2012), then a linear continuation of the observed warming of the past three decades (leading to a 21st century warming by $1.6\,°C$, or $2.4\,°C$ relative to preindustrial times) would linearly raise the rate of sea-level rise to 9 mm yr^{-1}, as in the highest scenario in figure 3—but already for a rather moderate warming scenario, not the 'worst case' emissions scenario.

4. Conclusions

In conclusion, the rise in CO_2 concentration and global temperature has continued to closely match the projections over the past five years, while sea level continues to rise faster than anticipated. The latter suggests that the 21st Century sea-level projections of the last two IPCC reports may be systematically biased low. Further support for this concern is provided by the fact that the ice sheets in Greenland and Antarctica are increasingly losing mass (Rignot *et al* 2011, Van den Broeke *et al* 2011), while those IPCC projections assumed that Antarctica will gain enough mass in future to largely compensate mass losses from Greenland (see figure 10.33 in Meehl *et al* (2007)). For this reason, an additional contribution ('scaled-up ice sheet discharge') was suggested in the IPCC fourth assessment. Our results highlight the need to thoroughly validate models with data of past climate changes before applying them to projections.

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