From Global to Regional:

Local Sea Level Rise Scenarios - Focus on the Mediterranean Sea and the Adriatic Sea

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Introduction

In the end of 2010 an international workshop was held on the topic of Climate Change Physical Knowledge and on the correlated Sea Level change in the northern Adriatic and the Venice Lagoon. The workshop was useful to discuss major controversial scientific issues on the topic and evidencing the scientific background. The Workshop was trying to identify multiple plausible sea level rise scenarios by 2100 for the northern Adriatic Sea, and is considered to be useful for the local authorities that are responsible for the implementation of major mitigation interventions.

The results of this workshop will be functional for an International Conference on “The Future of Venice and its Lagoon in the context of Global Change” to be held by UNESCO in 2011, which reflects its long tradition of scientific contribution to the world importance and relevance of Venice and its lagoon, recognizing it as a hot spot for issues connected with climate change. The results of the workshop are presented in this summary.

The global view

The last assessment report of IPCC (AR4) has given new estimates for the sea level rise that range between 18 and 59 cm until the end of the next century. This report corrected the previous one (AR3, 2001) that showed a higher uncertainty between 9 and 88 cm. An average between the different models and scenarios can be set at about 40 cm of global sea level rise (Fig. 1).

It is important to note that these estimates exclude the contribution of ice melting to the sea level rise. Basically, the estimates include only the steric component of the sea level rise due to the heating of the ocean waters and their consequent expansion. The numbers given by IPCC are therefore only a lower limit of the sea level rise that we should expect (Fig. 2).

The uncertainties of the results are due to two reasons. The first is the uncertainty of modeling the heat uptake of the oceans because the dynamics are not sufficiently understood. The second uncertainty is due to the different scenarios of CO2 emission and the consequent heating of the atmosphere.

If the dynamics of the ocean heat uptake is not yet fully understood, the problem of sea level rise due to ice melting is still less known. It is basically for this reason that IPCC has excluded this contribution from the global estimates, because these changes could not be modeled. This is seen, e.g., in the fact that observed sea level rise exceeded that predicted by models by 50% for the period 1961-2003 and by 80% for 1990-2008.

A possible solution for this problem is the inclusion of semi-empirical approaches to projecting sea level rise. These models are based on using an observable parameter that climate models can predict with confidence, namely global mean temperature, and establish with the help of observational data how this is linked to sea level.

New paleoclimatic data for the past two millennia show that 20^{th} Century sea level rise is unprecedented during this period.

Lately some papers have been published giving new estimates on global sea level rise since the AR4. All of these give much higher projections than those of the AR4 (Fig. 3). Rahmstorf (2007) gives an estimate of 50-140 cm, later corrected to 75-190 cm (Vermeer and Rahmstorf, 2009). Horton et al. (2008) estimates 54-89 cm (acknowledging that this could be a lower limit), Grinsted et al. (2009) 72-160 cm or 96-215 cm, and Jevrejeva et al. (2010) estimate the sea level rise to be between 60 and 160 cm. It can be seen that all estimates are substantially higher than the estimate of AR4. The Delta Committee (2006) estimated 55-110 cm (high end).

If one does not limit estimates to the end of this century, then there are two more estimates to be considered. The Delta Committee (2008) gives a range of 1.5-3.5 m for the year 2200, and WBGU (2006) estimates a sea level rise of 2.5-5.1 m for 2300. This means that sea level rise will be governed in the coming centuries by a delayed response to 21^{st} Century anthropogenic warming.

Even if short-term sea level response is dominated by thermal expansion and glacier melt, the long-term response is dominated by the ice-sheet volume reduction, which accounts for the largest rise of sea level. A realistic maximum rate of sea level rise can be inferred from the analysis of past data (Rohling et al., 2008; Andersen et al., 2010; Stanford et al., 2010). During the Last Interglacial, sea level rose above the present level at a rate of 1.6 ± 1.0 m/century, which is 2-3 times the rate reported in IPCC AR4 (Rohling et al., 2008). A probabilistic global summary confirms ‘jumps’ of last interglacial sea-level rise of the order of 1-2 m/century (Kopp et al., 2009). Maximum values of sea level rise (with 95% confidence) can reach 2.5 m/century, but mean sea level rise is probably closer to 1 m/century for the next century (Siddall et al., 2003; Rohling et al., 2004). The current understanding of the ice dynamics allows modern rates of 0.8-2.0 m/century to be estimated (Pfeffer et al., 2008). Antarctica alone may account for up to 1.5 m/century (SCAR report, 2009).

Overall, past data seem to suggest that sea-level rise for the next century is most likely to approach 1 m or more.

The Mediterranean

The sea level in the Mediterranean shows a strong variability in the last century. In any case, with a rate of approximately 1.2 mm/yr the observed rate of rise is significantly lower than the global average. Based on measurements of available tide-gauges the level increased until the 1960s and dropped a few cm between 1960 and 1993. Between 1993 and 2000, a quick sea level rise of 4-5 cm took place, after this there was no change.

One factor concerning regional sea level is atmospheric pressure forcing. A drop of 1 mbar is approximately equal to a rise of 1 cm in sea level. This forcing is responsible for the drop of sea level between 1960 and 1993 and can be linked to the North Atlantic Oscillation (NAO). The average change of sea level was a reduction of 0.6 mm/yr. Since climate models indicate that pressure could rise, a reduction of 2 cm (average -0.2 mm/yr) due to this forcing can be expected.

The other forcing that controls sea level change is the steric effect. Due to a change in temperature and salinity, the volume of the Mediterranean (and therefore sea level) is changed. Higher temperature increases sea level, while higher salinity will lower it.

It is estimated that the total steric effect has contributed to a lower sea level in the Mediterranean Sea. This means that due to a rise in temperature and salinity, the latter is dominating. However, results depend on the depth that these changes will propagate. If a depth of 300 m is used for integration, then a change of 0 to -2 ± 1 mm/yr can be computed.

Estimating trends for the future is even more complicated. The thermosteric increase (due to a temperature increase) in water level of about 50 cm in the next century is opposed by a halosteric reduction (due to increasing salinity) of about equal size, making the estimates highly uncertain and problematic. This results in a sea level change that can be positive or negative, with a low confidence in the overall result.

Moreover, the Mediterranean is not a stand-alone basin, but is linked to the Atlantic Ocean. The resulting sea level will be therefore only partially governed by the regional change. One of the crucial uncertainties concerns the fact, how exchanges through the Strait of Gibraltar will influence sea level in the Mediterranean.

These results are confirmed by the application of a global and regional model framework (CMCC-MED) that allows, for the first time, accurate assessment of the role and feedbacks of the Mediterranean Sea in the global climate system, coupling a general circulation model with a high-resolution model of the Mediterranean Sea. Results obtained indicate at the end of this century an increase in temperature of 2.5-3 °C with respect to the past (1961-1990). Evaporation increase and reduced precipitation is reduced and all of this has an important impact on the density of the

Mediterranean Sea. At the end of the century the sea level rise due to the steric effect of the Mediterranean appears to be around 22 cm.

Similar results have been obtained by another regional model consisting of the RegCM and the MITgcm. In these simulations the maximum steric sea level difference in the South Adriatic Sea ranges between 16 and 26 cm at the year 2050, depending on the applied scenario.

All models indicate the importance of the Gibraltar Strait in controlling the changes between the Mediterranean and the Atlantic Sea. With increasing salinity difference across the strait, it becomes more and more hydraulically controlled and transport through the strait tends to saturate. Depending on the degree of isolation of the Mediterranean basin, the scenarios discussed range from a possible sea level drop of -14 cm (Mediterranean completely isolated with halosteric effects dominating) to a sea level rise completely governed by the Atlantic and global ocean and changes propagating undisturbed into the Mediterranean basin. In this cases the sea level rise (as explained above) may vary between 20 and 200 cm.

In a recent study (Jorda et al., 2011), a conceptual model was developed for the mass exchange through the Gibraltar Strait. In this work the message is clear: sea level in the Mediterranean will basically follow the Atlantic Ocean. The time scales for the exchange will be in the order of months. There might be a sea level difference between the Mediterranean and the Atlantic, but it should be not more than 5-10 cm over the next 100 years.

The Adriatic Sea

The Adriatic Sea is better connected to the rest of the Mediterranean than the Mediterranean to the Atlantic Ocean. It is therefore expected that variations in sea level will be much stronger related to the rest of the basin.

The most important feature of the sea level rise is a slowing down that was recorded since 1960s (Orlić and Pasarić, 2000; Tsimplis and Baker, 2000) and that now appears to be over. As mentioned before, this deceleration is partially due to a change in air pressure and wind forcing (Tsimplis et al., 2005), with the steric component the other factor.

Long-term trends in the Adriatic Sea are available for the Italian and Croatian coast. During the last century the mean sea level rise was approximately 1-2 mm/yr. During winter these values are quite coherent through the whole basin, but during summer, the behavior is more heterogeneous. The fluctuations of sea level during winter can mostly be ascribed to atmospheric pressure variations, particularly in the northern basin.

Analysis of tide gauge data between 1993 and 2005 shows a general rise in the Adriatic Sea that ranges from 2.9 to 5.7 cm during the 13-year period (only highly significant data has been used). When compared to satellite measurements of the Mediterranean mean (2.17 cm), the global mean (3.3 cm) and IPCC data (3.1 cm), this data indicates that the Adriatic Sea shows a higher rate of sea level rise in the period 1993 to 2005.

What concerns the storminess and the storm surges in the North Adriatic Sea, data show large inter-annual variability and very little overall tendencies on a multidecadal time scale (e.g., 11-year solar cycle). This suggests progressively milder storms during the second half of the 20th century (Lionello et al., 2010). There is a trend of higher storm surge frequency, but it can be explained by the increase of relative sea level. In the future, scenario simulations (Lionello et al., 2003) suggest higher frequency of intense storms for the B2 scenario, but not for the A2. Likely, these differences are not the effect of climate change, but of climate multidecadal variability. Therefore, there is no convincing evidence for more stormy conditions in future scenarios and the Northern Adriatic storminess is not very sensitive to climate change. There is substantial agreement between present trends and the available climate change scenarios for storm surges and waves, suggesting that marine storm extremes will not change or become slightly milder in future climate conditions

The Venice lagoon

Measured data (ISPRA, the Italian Environmental Protection Agency, and French SONEL) indicate that mean sea level has risen during summer months about 10 cm in the last 3 years. This rise is strongly correlated with anomalies in atmospheric pressure observed in recent years. However, during winter months this rise (observable in most of the stations around Italy) shows a relative rise of around 20 cm. This is again correlated with a drop in atmospheric pressure from 2020 to 2013 in the last 3 years. It is doubtful that these trends will continue, but extreme variability of mean sea level in the Adriatic Sea and close to the Venice lagoon is likely.

The inlets have a strong hydraulic control on the water entering the Venice lagoon from the Adriatic Sea. Water masses entering the lagoon are slowed down by bottom friction. This effect has been controlled and altered by human interaction, especially around the year 1970, when the industrial channel that leads from the central inlet to the industrial port was built. During the period 1940-1965 3128 events with fast rising water levels (defined as a growth of higher than 20 cm/h) occurred in the Venice lagoon, compared to 13293 in Trieste, where sea level is not damped by strong hydraulic controls. But during the period 1970-1995, there where 6912 events in Venice and 13122 in Trieste. Therefore, in the two 25 year periods, the fraction of these cases between Venice and Trieste has risen from 0.235 to 0.527, increasing by more than a factor of 2.

Even with this strong hydraulic control exerted by the inlets, the mean sea level is basically the same between the Adriatic Sea and the lagoon. This means that the slow water level variations happening in the Adriatic Sea will propagate inside the lagoon with no reduction. It is generally acknowledged that a water level of 110 cm is the height where the city starts to be flooded. During the last century the lagoon was gradually sinking due to natural (subsidence and sea level rise) and men made (ground water extraction) activities. Therefore, during the 1980's and 1990's the average water level was about 23 cm above the zero datum. Newer data shows that the average water level is now closer to 30 cm above datum. This indicates that a sea level rise of 80 cm would bring the mean water level to the critical threshold of 110 cm. In this case, Venice, due to the tidal oscillation (tidal amplitude 40 cm during spring tide), would experience regular flooding twice a day.

In the last years large changes have occurred in the Venice inlets. One of these is the construction of the mobile gates for Venice flood protection (MOSE). One question that needs to be answered concerns how long these mobile gates will be able to protect Venice from flooding. During the planning phase, three scenarios for sea level rise for the next century have been considered. The most probable one (Corila, 1999) was 16.4 cm, the prudent one (the one recommended for the MOSE project) was 22 cm and the pessimistic one was 31.4 cm. These estimates were clearly given at a time when climate change and sea level rise were still highly debated. However, it turns out that these numbers (even the pessimistic one) are now on the lower end of what is believed to be a realistic sea level rise scenario for the next century.

In assessing potential economic damages sea level rise could bring to Venice, two main aspects have to be considered. The first deals with damages to the historic center's buildings used for dwellings and economic activities. The estimates consider the increase of maintenance costs for building structures due to the periodic contact with salt water during inundations. It is estimated that the increase in damages (and subsequent annual maintenance costs) is about 50 %, confronted with the damages experienced in the actual situation.

The second point deals with the tourism sector. In 2030 the climatic attractiveness of the four Venetian local tourism systems (Jesolo-Eraclea, Chioggia, Bibione-Caorle and Venice) is expected to worsen as a result of compounded effects of an increase in the number of Italian tourists and a decrease in foreign tourists. Venice in particular might lose, according to simulations, 19 % of visitors in the trend scenario. However, losses are smaller when specific vulnerability is accounted for. Its cultural and artistic appeal can partially compensate the lower climatic attractiveness and losses drop to an average of 6 %. In 2030, in absolute terms, Venice could lose between 105 and 415 million Euros annually because of a decline of tourism arrivals due to a decrease in climate-attractiveness.

Conclusions

The future of Venice is uncertain. In this report the potential impact of the sea level rise in this century has been investigated. Data and modeling have been used to come to an understanding of the changes in sea level that can be expected for the Venice lagoon.

The highest uncertainty we have to deal with is the global sea level rise. Estimates of the increase until the end of this century range from 18-59 cm (IPCC, 2007) to 215 cm (Grinsted et al., 2009). Results from IPCC only consider steric changes and do not consider ice melting. Models that give higher numbers are based on an empirical approach. However, data from satellites seem to indicate that sea level rise is already at its maximum with respect to the IPCC estimates. This evidence should point us to the possibility of a sea level rise higher than 60 cm. A rise of 100 cm should not be excluded.

It will still take some time to settle the question of how much sea level in the Mediterranean and in the Atlantic can differ. However, latest findings indicate that the difference between both basins should not be higher than 10 cm, with an adjustment process that should not take longer than a few months. With these findings the sea level rise in the Mediterranean will be dominated by the global signal, even if some local differences might continue to exist. The fact that the steric change of the Mediterranean Sea could be much less (or even negative) simply indicates that the contribution of the Mediterranean to the global sea level rise will be much smaller than that of the other oceans. However, in the long run, the Mediterranean will follow the global ocean.

The same problem of how independently the single sub-basins react to sea level rise turns up when dealing with the Adriatic Sea. However, in this case the connection with the rest of the Mediterranean is much less restricted as it is between the Mediterranean and the Atlantic Ocean. It is therefore conceivable that the Adriatic Sea should follow very closely the trends in the Mediterranean.

Finally, the exchanges between the Adriatic Sea and the Venice lagoon will not allow any mean water level difference between both basins. Even if it has been shown (Umgiesser, 1999 and 2004) that most of the storm surge peaks could be lowered by 20 cm if the section of the inlets would be (sometimes drastically) reduced, these interventions will not be able to change the mean water level between the interior and the exterior of the lagoon.

In conclusion, with the projections given in this report there should be no doubt that the sea level will eventually rise to a value that will not be sustainable for the lagoon and its old city. The planned mobile barriers (MOSE) might be able to avoid flooding for the next decades, but the sea will eventually rise to a level where even continuous closures will not be able to protect the city from flooding. The question is not if this will happen, but only when it will happen.

Figures

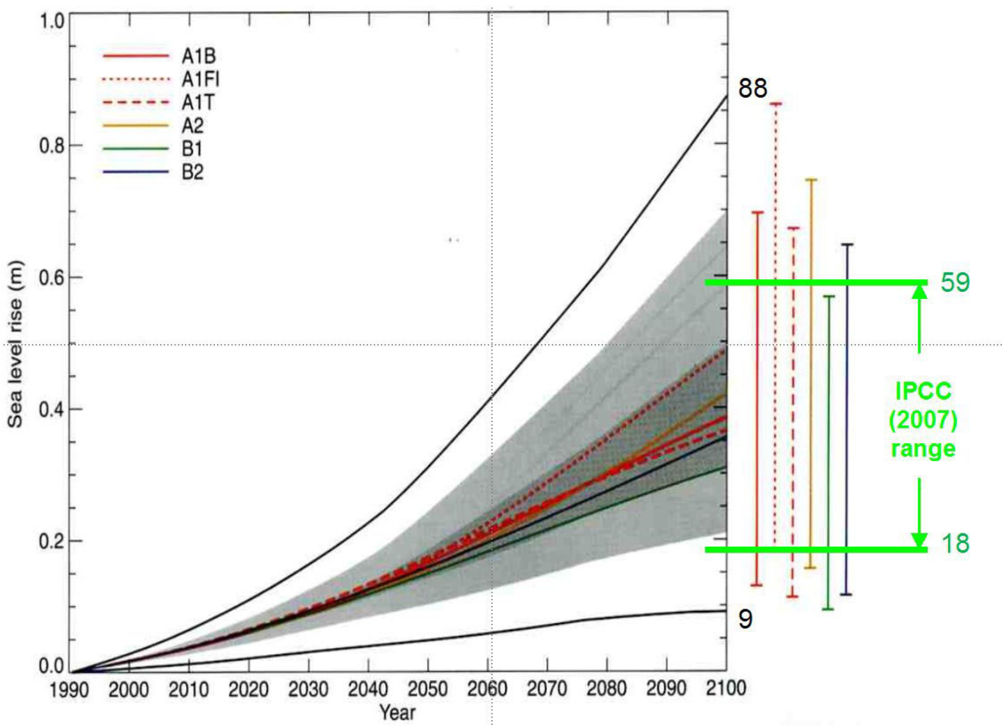

Fig. 1: Projections of sea level rise by IPCC (IPCC 2001 and 2007).

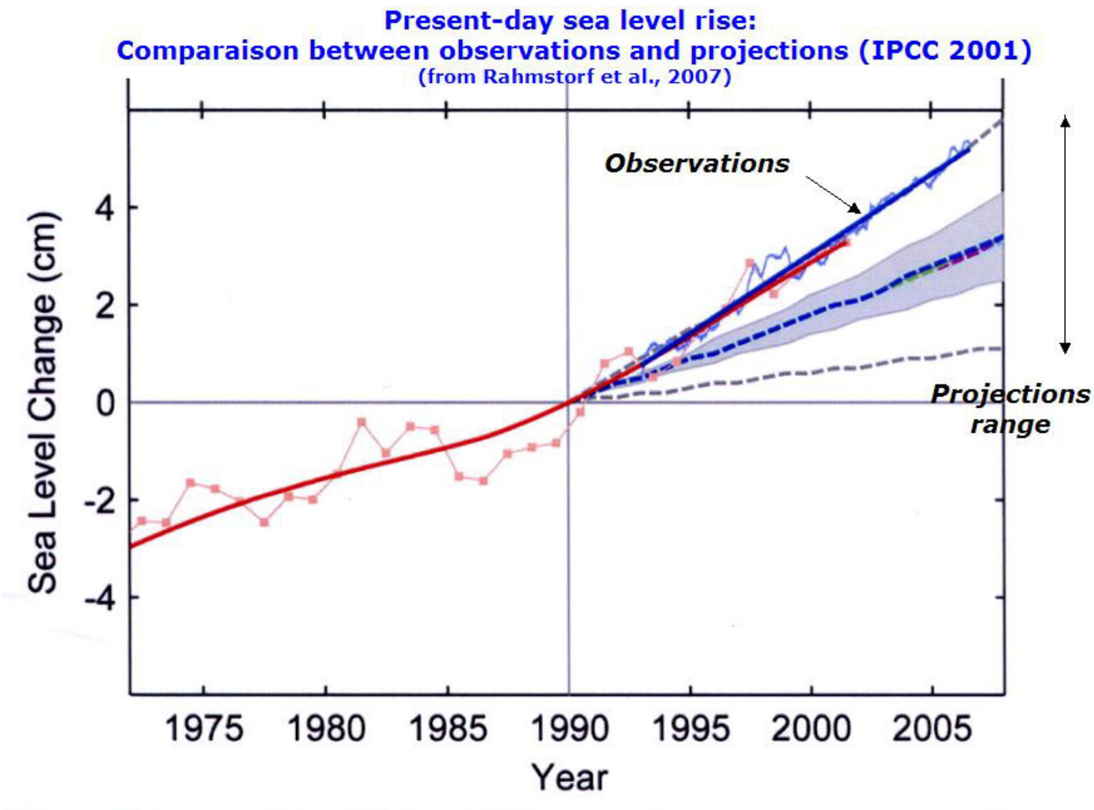

Fig. 2: Short term projections (IPCC, 2001) of sea level rise and observations.

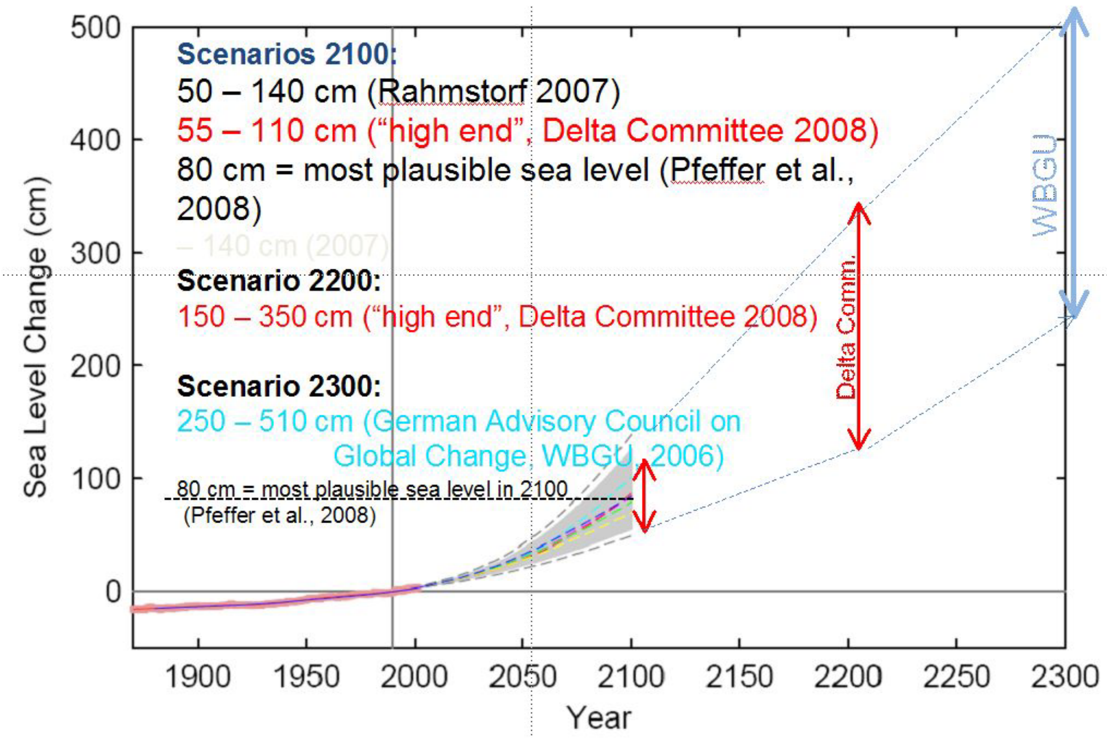

Fig. 3: Long term projections of sea level rise by various authors and committees.