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EDITORIAL

Trends in Sea-Level Trend Analysis

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ABSTRACT

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Discussions on sea-level rise trend estimates as, for example, the one recently published in this *Journal of Coastal Research*, reveal different perspectives on proper methods of deriving sea-level trend estimates. This editorial discusses various methodological considerations and proposes a number of best practices for sea-level trend analysis.

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ADDITIONAL INDEX WORDS: *Sea level, subsidence, climate change, research methods.*

SEA-LEVEL DECELERATION

In their recent article in this journal, Houston and Dean (2011c) reported that the relative sea level along the U.S. coast and in a selection of global tide gauges is slightly decelerating. A relative sea-level deceleration was also reported recently by Watson (2011), based on tide gauges along the Australian coast. The conclusion that the sea-level rises, but that the rate of the rise is decreasing, does not conform to the general anticipation that the rate of sea-level rise should be accelerating, not decelerating, resulting in a fierce debate in the popular (Rintoul, 2011), as well as in the academic arena.

Donoghue and Parkinson (2011) concluded that the study had "little relevance to future sea-level change." Rahmstorf and Vermeer (2011) argued that "the five main arguments presented by Houston and Dean in support of a lack of acceleration in global sea-level rise are all unconvincing" and propose Rahmstorf's semi-empirical approach as a better alternative. Houston and Dean (2011a) replied to Donoghue and Parkinson by pointing out they had incorrectly assumed that only the U.S. tide gauges were studied. They rebutted Rahmstorf and Vermeer, indicating that the main point of their study was that projections of more than a meter per century sea-level rise are not in the same order of magnitude as the current observations (Houston and Dean, 2011b), referring to the global sea-level rise of between 0.5 and 1.4 m for the period 1990–2100 (Rahmstorf, 2007).

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Several interesting methodological topics were argued throughout the discussion. Should we use numerical models or rely on observations? Which is the correct independent variable, time or temperature? What are appropriate time periods for determining trends? Which corrections should be applied? A common element underlying all these questions relates to a fundamental question in the scientific method (Popper, 1934): Can we falsify a theory? The theory, in this case, is that sea level will rise at an accelerating rate. The evidence presented, the tide gauge observations, show a rise but no acceleration. This contradicts the quite fundamental theory that sea level will rise and do so at an increased rate or, at least, that it has done so in past decades.

The debate is important because the acceleration theory is widely used for coastal protection planning and climate change–related measures. For coastal protection, the relative sea level is important. The eustatic change is only one of the contributing factors. Especially for larger cities, subsidence can be more influential on the relative sea level than the change in absolute sea level (Camuffo and Sturaro, 2003; Waltham, 2002). For climate change–related studies, absolute sea level is the most used quantity. The discussion here relates to both relative sea level, as measured by tide gauges, and absolute sea level, as measured by altimetry satellites.

Rahmstorf and Vermeer, as well as Donoghue and Parkinson, argue that the methods used by Houston and Dean were not valid and *vice versa*. But then, what *are* valid methods? Is the theory of acceleration in the rate of sea-level rise falsifiable? By creating an overview of best practices, we aim to facilitate the ongoing scientific debate on sea-level trend estimates. It is our belief that the arguments used to underline opposing views can often be combined to achieve a more-robust and neutral approach.

FORECAST *VS.* TREND, PHYSICAL *VS.* EMPIRICAL

Would it be bad practice to use the observed sea-level trend as a forecast method? According to Donoghue and Parkinson (2011) it is: It "is inappropriate to relate sea-level history during the past century with projections for the next century." One could argue that recent sea-level rise can be used as an estimate for future sea-level rise. Using a regression model to predict future sea-level rise is not uncommon. For example, Church and White (2006) state, based on a regression model that included an acceleration term, that "[i]f this acceleration remained constant, then the 1990 to 2100 rise would range from 280 to 340 mm." This estimate was based on a reconstruction in which tide gauge measurements before 1900 were included.

Given the "near" linear trend of the sea-level rise throughout the 20th century (Church and White, 2006), it is easy to conclude that, for estimates on the order of a few decades, the recent sea-level rise has been shown to be a good indicator for future sea-level rise. It is also a very parsimonious approach. A regression line is determined by only two parameters, one for the level and one for slope. Using a regression with an acceleration term may be good as a method for detecting trends, but extrapolating future rise using this approach would have to be considered a bad practice. Perhaps the easiest way to see this is to extrapolate backward rather than forward. This results in trends that indicate that historically sea-level rise has dropped; where the general picture is that sea level has been rising since the last ice age.

Using the current, linear trend in sea-level rise to predict future sea level implicitly assumes that the trend we have seen in the past is representative of the trend we will see in the near future. Of course, like Donoghue and Parkinson (2011) point out, if one anticipates conditions that have not been experienced for many millennia, using the existing trend makes little sense. The current trend-forecast method, if not assumed to be the best approach, could at least be used as a reference approach. Thus, when making a forecast about sea-level rise, the forecast skill (SS) can be computed with the current sea-level rise trend as a reference forecast.

The advantage of models that are based on physical-process knowledge over trend extrapolations is that the effects of changing conditions can be included in forecasts, assuming of course, that sufficient knowledge on the relevant acting processes and boundary conditions is available. Rahmstorf and Vermeer (2011) argued that "sea level as a simple function of time, $H(t)$, is not physical." Houston and Dean (2011b) pointed out that the same argument was used by Stocker *et al.* (2010) to disqualify the suggested alternative, semiempirical model by Rahmstorf (2007).

The methods available to forecast sea level cover a broad spectrum. On one end of the spectrum, we find the full physical approach, like that used to estimate the scenarios for the Intergovernmental Panel on Climate Change (IPCC). This approach is based on a chain of different numerical models (Meehl *et al.,* 2007). On the other end of the spectrum, there are the empirical models that are based on the observed relation between measured quantities. The most common approach is to estimate sea level as a function of time, where time is a proxy for other monotonic varying conditions, such as temperature, gravitation effects, ice melting, and subsidence. The aforementioned estimates of Church and White (2006) and Rahmstorf (2007) are examples of this method. Whichever approach is used, there are assumptions, weak and strong, about the representativeness of the formulas and the processes used to describe the parameters of interest.

The above discussion shows strong similarities to the recurring debate in geoscientific modeling, on whether to use a statistical (empirical) or a numerical (process-based) model. When choosing one model over another, there is a wide variety of arguments to choose from. Some of the arguments relate to the expected validity. Will the model predict future situations? Is the model representing the processes that it should describe? Was the model tested for this purpose? How many free parameters does the model have? Other arguments relate to practical aspects, such as run time and software quality. Is there enough time to run the model 1000 times to get a probabilistic answer? Is the source available? What is the test coverage of the model? See Merali (2010) for a relevant discussion on the quality of scientific software.

A challenge for any modeler is to find an appropriate balance between the relevant processes and proxies to include, on the one hand, and keeping the model as simple as possible, on the other. Examples of such discussions can be found in various scientific disciplines, such as river modeling (Booij, 2002).

This challenge is further complicated by the tension between pursuit of scientific interest, often driving scientists toward including ever more detail, and the need for practical spin-off, requiring scientists to provide answers to practical questions with imperfect tools (van Koningsveld *et al.,* 2003). Best practice for both the cautious and the opportunistic researcher is to ensure complete transparency in the methods used and to facilitate, as much as possible, detailed scrutiny by peers. Where possible, it is wise to make use of approaches from opposing schools of thought at the same time. Approaching the problem from different perspectives will help to keep an open mind to the strengths and limitations that are inevitably involved in any approach.

THE FORBIDDEN YEARS AND WHERE DID THE WATER GO?

What is the best time window to compute a trend in sea-level rise? This question lingers after Rahmstorf and Vermeer (2011) noted that Houston picked "a unique and specially selected start date (1930)." In reaction, Houston and Dean point out that Rahmstorf and Vermeer "do not continue the plot when accelerations become negative." Because of the decadal variations in tide gauges records (because of the nodal cycle and ocean oscillations) trend estimates are indeed quite sensitive to the start and end period of the time window. By including the decadal variation by known decadal cycles, such as the 18.6-year nodal cycle, some of these sensitivities can be avoided (Baart *et al.,* 2012).

The origin of the sensitivity of the trend, however, is not only in the start and end period. The sensitivity to the starting period is extra large because both Rahmstorf and Vermeer (2011) as well as Houston and Dean (2011c) focus on only one of the three parameters of the regression equation, *viz.* acceleration, while leaving their assumptions on rate and level implicit. Equation (1) provides the complete description of the ordinary least-square equation, with a denoting sea-level rise rate, b denoting sea-level acceleration, c denoting sea level at $t = 0$, and t denoting the time in years (often since 1970).

$$H(t) = at + bt^2 + c \quad (1)$$

Part of the sensitivity is in the free c parameter. Comparing models over different periods with a free intercept can easily result in an artificial gain or loss of cubic kilometers of ocean volume: $\Delta_c \times \mathit{oceansurface}$. Such discontinuities in water volume can be avoided by using a volume-conserving regression approach. This can be achieved by fixating the constant parameter at the start of a subsequent regression window to the final value of the trend of the preceding period. Equation (2) provides the ordinary least-squares equation with a fixed constant, based on the assumption of volume conservation at t_0.

$$H(t - t_0) = at + bt^2 + h(t_0) \quad (2)$$

There are also other statistical problems in applying ordinary linear regression to estimate an autocorrelated time series (see Granger and Newbold [1974] and the comments from Schmith, Johansen, and Thejll [2007]), but these points are left for future discussion.

THE FALSIFIABILITY OF SEA-LEVEL FORECASTS AND STATISTICAL POWER

The most fundamental scientific point touched by the recent discussions relates to the falsifiability of the theory of accelerating sea-level rise. The essence is summarized by Houston and Dean (2011b): "To reach the multimeter levels projected for 2100 by Rahmstorf requires large positive accelerations that are one to two orders of magnitude greater than those yet observed in sea-level data." Both Rahmstorf and Vermeer and Houston and Dean appear to agree that a recent acceleration is what would be expected from the theory that global warming causes recent and future sea-level rise. The definitions of *recent* vary a bit. Rahmstorf and Vermeer (2011) argue that there is, in fact, a recent acceleration, referring to the changes after the period 1700–1800, and do not expect an increased sea-level rise for the 20th century, in hindsight. Houston and Dean (2011c) were expecting an increased sea-level rise in the past few decades. Donoghue and Parkinson (2011) point to the rate of the absolute sea level as measured by altimetry satellites as the already-increased rate.

An obvious way to test the theory of acceleration is to look at the old forecasts. Although describing relative sea-level states has been a common activity over the past centuries, forecasting the change in sea level on a decadal scale is an activity that became popular in the past decades.

An early publication of a forecast was provided by van Dantzig (1956), who made a rough estimate of 70 cm, local, relative sea-level rise in the coming century because of, among other reasons, the melting of ice on Greenland. This relation between ice melting and sea level is a theory that was examined by, for example, Thorarinsson (1940). Van Dantzig chose a high estimate of expected sea-level rise. This was mainly due to the coastal engineering considerations that were needed by the first Deltacommissie to reconsider the safety of the Dutch coast after the devastating 1953 flood. For engineering purposes, one often takes into account a high, but not totally unlikely, scenario (see Kabat *et al.* [2009] for a similar approach applied by the second Deltacommissie). A series of forecasts were made from the 1980s onward, when the ice cap melting theory got a new impulse through the study of the anthropogenic origin. Since then, new sea-level measurements have become available, enabling many of these forecasts to be subjected to falsification.

Two issues that make the falsification of sea-level forecasts difficult. Sea-level forecasts generally cover periods of several decades, which means one has to be patient before new measurements for model testing become available. This issue can partially be handled by starting the forecast before the current date. For example, when a forecast is made in this year (2011), the forecasting period should start in 1981 at the latest, allowing the last 30 years of measurements to be used as a verification period. Douglas (1992) even suggests using 50 years of data as a good practice, but, for the higher estimates, a shorter verification period of 20 years may be enough (Baart *et al.,* 2012). If the proper verification data are not yet available, one has to wait to enable the falsification of the forecast with enough statistical power. Because many sea-level forecasts were made in the 1980s, sufficient observation data are now available to compare the forecasts made at that time with the trends observed now. For example, the first forecast presented by the IPCC (Warrick and Oerlemans, 1990) expected a sea-level rise of 18 cm in the period 1990–2030. We could now state that was an overestimate if we could assume that the rise over the period was constant.

This brings us to the second issue in the falsifiability of sea-level forecasts: Sea-level rates during the forecast period are not always well defined. In the first IPCC forecast (Warrick and Oerlemans, 1990) and in the forecast made by van Dantzig (1956), only the total rise was given. No details were provided about how that rise was expected to take shape during the forecast period. This makes the falsification of the forecast almost impossible before its final due date. This issue can partly be handled by assuming a trend, *e.g.,* a linear one. However, the forecaster may claim a nonlinear trend should be used. Omitting this kind of detailed information from sea-level forecasts allows the intermediate falsification of the hypothesis to be deferred with the claim that "the acceleration may start tomorrow."

An alternative, empirical result that could falsify the theory of *global warming–induced* acceleration in the rate of sea-level, as Rahmstorf and Vermeer propose, could be made by using historical tide gauge data. If it could be shown that current sea-level rise started before the onset of temperature change, the temporal ordering required for a causal relation would not exist, enabling falsification of the theory.

There are a wide variety of studies on how the sea level varied over the past millennia. Thanks to the collection of tide-gauge data sets by PSMSL (Woodworth and Player, 2003), we have a good overview of how the sea level changed near the coast during the past century. With the help of altimetry satellites, we know how the sea level varied in the past two decades across the globe (Beckley *et al.,* 2007). How the sea level varied in the centuries before 1900 is less known. Tide gauges before 1900, at least the Dutch ones, are not well suited for estimating trends, as discussed already by Van Veen (1945). Therefore, estimates of trends before 1900, such as by Jevrejeva *et al.* (2008), should be confirmed before used. Confirmation can be provided by using other sources, such as historic records, paintings (Camuffo and Sturaro, 2003), and vegetation (Woodworth, Menéndez, and Gehrels, 2011).

BEST PRACTICES

The recent discussions on trend estimates and forecasts in sea-level rise have revealed that this research field could benefit from a constructive debate on appropriate research methods and reporting approaches. The fact that we are entering an era where decades worth of verification data are now available exacerbates the crucial need for a clear framework to facilitate the imminent scientific progress on this topic.

Although we realize its incompleteness, this article has attempted to take a first step toward that framework by discussing, in as neutral a manner as possible, various methodological considerations raised in the contemporary literature, and to derive from them a number of best practices for sea-level trend analysis. The most important ones are reiterated briefly in this final section:

(1) **Aim for falsifiability.**—A crucial ingredient of the scientific method is the proposition of clear hypotheses that may be subjected to falsification by peers. Previous publications in the field of sea-level research have involved obstacles that make it hard, and in some cases, nearly impossible to test the hypotheses proposed. Examples include a lack of information on the methods, the corrections and assumptions applied, the trend periods used, the trend evolution predicted, *etc*. Good practice would be to aim for falsifiable claims as much as possible, *e.g.,* by providing so-called crucial tests that any peer could perform to refute the proposed theory when sufficient data are available. *Nota bene:* It is important to realize that the falsification of a single hypothesis does not inevitably prove that an entire theory is false, merely, that the theory needs to be reformulated to accommodate the new evidence.

(2) **Take care of transparency and reproducibility.**—Another crucial element of the scientific method is that results should be reproducible by peers. In some publications, authors have not made all data, models, and tools available, thus making it difficult for peers to establish exactly what analytic methods were used, to reproduce the results based on the same data, and to apply the same approach to new or other data. Good practice would make all data, models, and tools available, as much as possible, with the report or article in which a particular claim is made.

(3) **Include perspectives from opposing schools of thought.**—A recurring element in the current debate on sea-level trends is the discrediting of one method while placing full belief in another, *e.g.,* relying on models *vs.* relying on data. Although an important function of the scientific debate is to identify and point out flaws and errors in the methods applied, different approaches can have merit in specific cases, and approaching one problem from different points of view can be a powerful way to gain a better understanding. Good practice would be to use a broad range of methods rather than to rely on a single method only.

(4) **Avoid unnecessary controversy related to jargon.**—The field of sea-level research is complex and involves researchers from various disciplines. This means that unnecessary conceptual confusion is a realistic threat to the already-emotional debate. Someone with a background in statistics may have a different association with the term *linear model*, for example, than someone with a background in hydraulic engineering. Furthermore, short formulations intended to facilitate the reader's comprehension may, in fact, turn out to promote confusion. An example would be the use of a term like *sea-level rise*, leaving the reader unclear about whether absolute or relative sea-level rise is intended. Another example would be to speak of "x m" of sea-level rise without indicating the interval over which that rise is supposed to materialize. Good practice would be to formulate carefully, using clear terminology consistently throughout a publication, while avoiding as much as practicably possible the use of jargon.

(5) **Make appropriate use of statistical methods.**—When using linear regression or any other generalized linear model, assumptions like independence of errors should be verified, and the full, fitted model should be reported. The linear trend estimated by the linear regression is a good reference model for forecasts. If a model does not provide a forecast significantly better than that reference forecast, the simple line is probably the best choice. Most estimation methods are quite sensitive to the selections made in time and space. At least one aspect that can reduce those sensitivities is to make sure that the trend estimates for connecting periods also have a connecting sea level.

(6) **Use available data to test old as well as new predictions.**—The time is ripe to compare old forecasts to current, observed trends. Several forecasts from the 1980s can already be tested to acquire a first indication of our skill in forecasting sea-level rise. For new forecasts, longer verification periods should be allowed for than is the current practice. Forecasts should be reported with well-defined time windows and rates over the forecast period.

As mentioned before, the best practices listed above are by no means complete. Inevitably, readers of this article may feel that important items have been overlooked. In fact, some of the best practices suggested here, although logical to the authors, may trigger fierce debate in their own right. Adding to these and the other ongoing debates, a reflective component that promotes productive discussion would be a big step forward in sea-level research.

It is the hope of the authors that the current article delivers a constructive contribution to the ongoing debates. With the best practices suggested in this article and the development and subsequent application of other best practices, we hope that the scientific debate may again focus on delivering the best estimates, rather than on providing the best counterarguments.

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