Trends in sea-level trend analysis

Fedor Baart

May 8, 2012

Outline

Introduction

Fedor Baart

PhD thesis: Confidence in morpological forecasts

This research

http://citg.tudelft.nl http://www.deltares.nl
http://www.openearth.nl http://www.micore.eu

This research has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement 202798 and the Cornelis Lely foundation.

Articles

JCR-2009 Real-time forecasting of morphological storm impacts: a case study in the Netherlands

JCR-2011 Confidence in real-time forecasting of morphological storm impacts

NHESS-2011 Using 18th-century storm-surge data from the Dutch Coast to improve the confidence in flood-risk estimates

JCR-2012 **Baart, van Gelder, de Ronde, van Koningsveld, Wouters, The effect of the 18.6 year lunar nodal cycle on regional sea-level rise estimates**

JCR-2012 **Baart, van Koningsveld, Stive, Trends in sea-level trend analysis.**

TGIS-2012 A comparison between WCS and OPeNDAP for making model results available through the internet.

Study of the Dutch trend

Nourishment strategy

How much sea-level rise do we expect for the next 5 years?

Figure : Nourishment of the sand engine (src: zandmotor@flickr)

Improving the confidence of the 1/10000 storm surge estimate

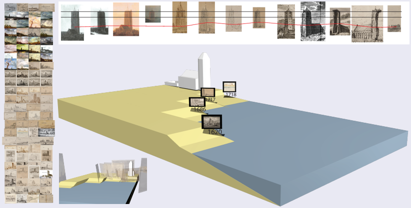
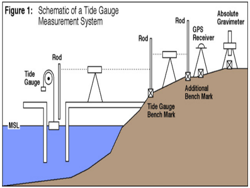
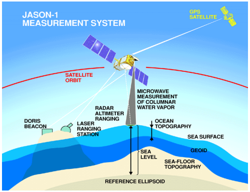


Figure : Using 18th century paintings to reconstruct the storm surge of 1717 at Egmond (NHESS-2011)

Sea level measurements



(a) Tide gauge



(b) Altimetry

(c) Tide gauge

(d) Altimetry

Sea level measurements

Relative

Absolute

(e) Tide gauge

(f) Altimetry

Sea level measurements

Figure : Satellite time series 1990-2010

Outline

Deceleration versus acceleration

Figure 3. Locations of 57 tide gauges.

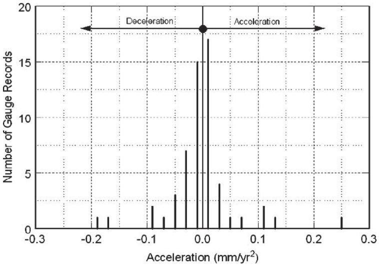


Figure 4. Number of gauge records in bins of acceleration, a_2, in mm/y ^{2}.

Figure : Significant deceleration in US and deceleration World tide gauges (1930-2010) (Houston & Dean JCR-2011)

Deceleration versus acceleration

Observations

Constant rise

Forecasts

Accelerated rise

Dutch forecasts

van Dantzig, 1956

Observed	20cm per century
Forecast	70cm per century

KNMI, 2006

Observed	20cm per century
Forecast	35 to 85 cm (1990–2100)

Forecasts

Are we structurally overestimating?

When should acceleration occur/have occured?

1700–1800

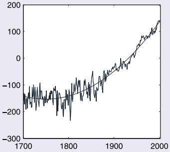


Figure 1. Sea level reconstruction since 1700, the shadow represents the errors of the reconstruction. The fitted curve is a second order polynomial fit.

Figure : Jevrejeva 2008

1993-2010

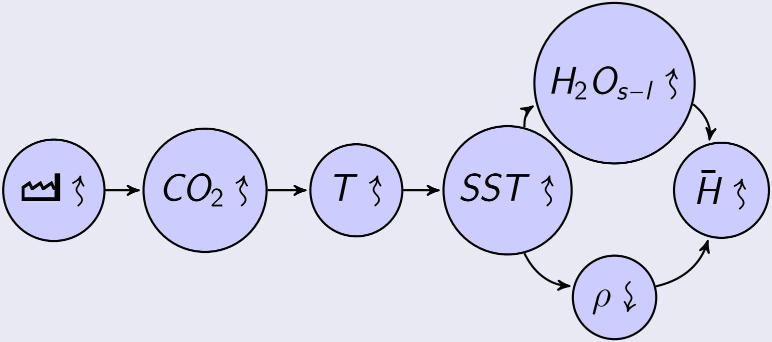
Donoghue (JCR-2011): 17 cm/century for past century versus 30 cm/century since 1993 (comparing tide gauges with altimetry satellites).

tomorrow

Rahmstorf (JCR-2011): Why would tide gauge data of the twentieth century show the acceleration expected in the twenty-first century?

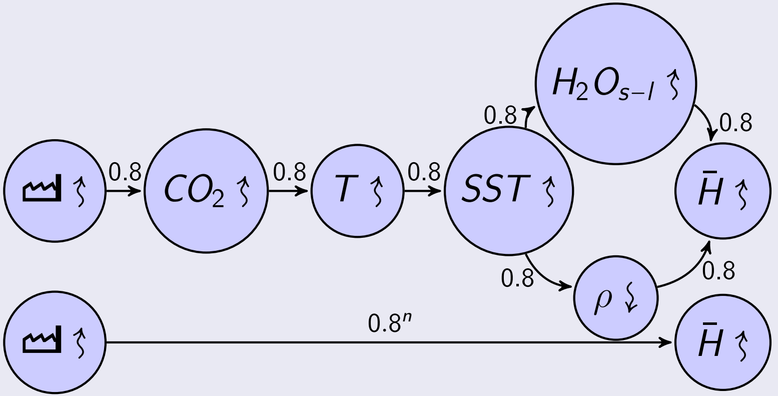
Predictability of sea level rise from climate scenarios

Model chain used for sea level rise forecasts



Predictability of sea level rise from climate scenarios

Model chain used for sea level rise forecasts



Physicalness

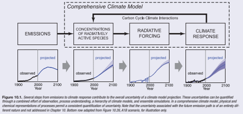
Empirical

$h(t) = \beta_0 t + \beta_1 t^2 + c$

Semi-empirical

$h(t) =$
$\beta_n(T_t - T_{t-n}) + h(t-1)$

Numerical



Independent variables?

Time versus temperature versus emission.

Outline

R sealevel rise package

Loading data

```r
library(sealevel)
data(dutch)
# data is a list of stations
llply(dutch, function(x){x$name})
## $`1`
## [1] "BROUWERSHAVENSCHE GAT"
## $`2`
## [1] "CADZAND"
```

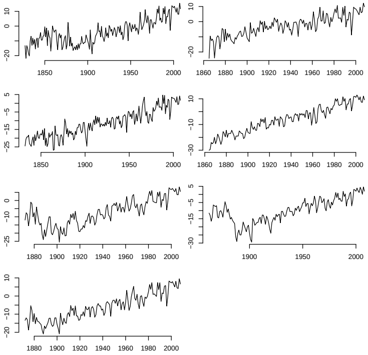
Selecting

```r
denhelder <- dutch[[6]]
denhelder$data
##      year waterlevel
## 1    1832      -24.5
## 2    1833      -20.6
## 3    1834      -19.3
```

Trends

Dutch coast

Based on tide gauges.



? - 1960 0.15 á 0.20 cm/year(land subsidence) [?]

1990 - 2005 0.27 cm/year [?][?]

R sealevel rise package

Loading data

```
library(ggplot2)
ggplot(denhelder$data, aes(year,
     waterlevel)) + geom_point()
# Selection
dh <- denhelder$data[denhelder$data$year 4
      >= 1890, ]
```

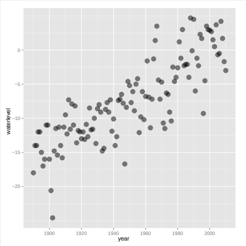


Figure : Water level at Den Helder

Linear regression

Fitting a model

```
> fit <- lm(waterlevel ~ year, dh)
> fit
## (Intercept)          year
##   -286.9476        0.1433
```

Summary

```
> summary(fit)
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) -2.869e+02  1.730e+01  -16.59   <2e-16 ***
## year         1.433e-01  8.871e-03   16.16   <2e-16 ***
## ---
## Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 . 0.1 ' ' 1
##
## Residual standard error: 3.408 on 119 degrees of freedom
## Multiple R-squared: 0.6869, Adjusted R-squared: 0.6842
## F-statistic:   261 on 1 and 119 DF,  p-value: < 2.2e-16
```

Linear regression

Loading data

```
> ggplot(dh, aes(year, waterlevel)) +
    geom_point(size=5, alpha=0.5) +
    stat_smooth(method="lm")
```

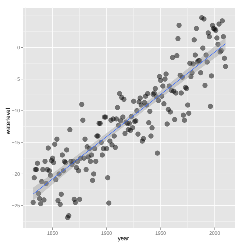


Figure : Water level at Den Helder

Linear regression

Fitting a model

```
> fit <- lm(waterlevel ~ year + I(year*year), dh)
> fit
##     (Intercept)            year   I(year * year)
##       1.162e+03      -1.343e+00       3.812e-04        4
```

Summary

```
> summary(fit)                                                   1
## Coefficients:
##                   Estimate Std. Error t value Pr(>|t|)
## (Intercept)      1.162e+03  1.076e+03   1.080    0.282
## year            -1.343e+00  1.104e+00  -1.217    0.226
## I(year * year)   3.812e-04  2.830e-04   1.347    0.181       6
##
## Residual standard error: 3.397 on 118 degrees of freedom
## Multiple R-squared: 0.6916, Adjusted R-squared: 0.6864
## F-statistic: 132.3 on 2 and 118 DF,  p-value: < 2.2e-16
```

Linear regression

Fitting a model

```
> fit1 <- lm(waterlevel ~ year, dh)
> fit2 <- lm(waterlevel ~ year + I(year*year), dh)
```

Summary

```
> anova(fit1, fit2)
## Analysis of Variance Table
##
## Model 1: waterlevel ~ year
## Model 2: waterlevel ~ year + I(year * year)
##   Res.Df    RSS Df Sum of Sq      F Pr(>F)
## 1    119 1382.5
## 2    118 1361.5  1    20.931 1.8141 0.1806
```

Fitting methods

Regression (OLS)

Assumes uncorrelated errors.

Generalizable?

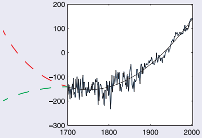


Figure 1. Sea level reconstruction since 1700, the shadow represents the errors of the reconstruction. The fitted curve is a second order polynomial fit.

Figure : Fitted trend from Jevrejeva 2008 extrapolated to < 1700

Water level

Correlated errors

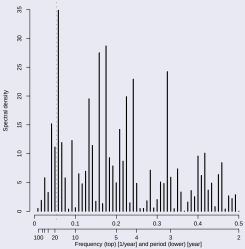


Figure : Multiy year spectrum of relative sea level along Dutch coast

Linear regression

Loading data

```
> spectrum(residuals(lm(waterlevel ~
    year, dh)))
```

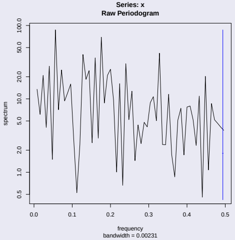


Figure : Spectrum of residuals for water level at Den Helder

Harmonic fit

Fitting a model

```
> Nsin <- sin(2*pi*(dh$year-1970)/18.613)
> Ncos <- cos(2*pi*(dh$year-1970)/18.613)
> fit <- lm(waterlevel ~ year + Nsin + Ncos , dh)
## Coefficients:                                                          4
## (Intercept)        year        Nsin        Ncos
##   -287.2717      0.1435     -1.5318      0.6417
```

Summary

```
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) -2.873e+02  1.637e+01 -17.554  < 2e-16 ***
## year         1.435e-01  8.391e-03  17.097  < 2e-16 ***
## Nsin        -1.532e+00  4.147e-01  -3.694 0.000337 ***                 4
## Ncos         6.417e-01  4.153e-01   1.545 0.124999
## ---
## Residual standard error: 3.224 on 117 degrees of freedom
## Multiple R-squared: 0.7246, Adjusted R-squared: 0.7175
## F-statistic: 102.6 on 3 and 117 DF,  p-value: < 2.2e-16                9
```

Current observed trend (tide gauges)

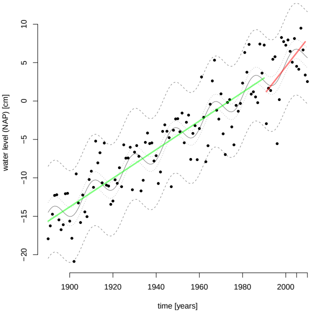


Figure : Relative sea-level at the Dutch coast 19 cm/century (± 1.5), no acceleration (JCR-2012)

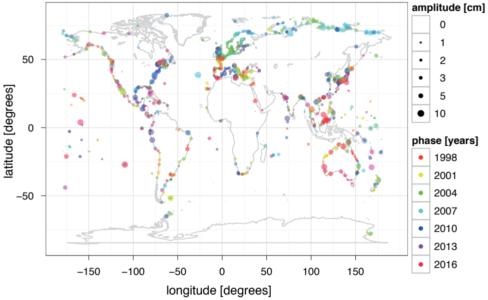


Figure : Nodal cycle variation in tidal gauges (JCR-2012)

Outline

Start low

Regression

Sensitive to starting period.

Start low

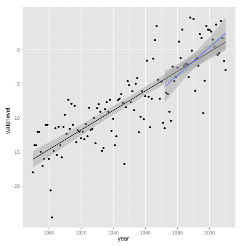


Figure : Start in 1972 for Den Helder to raise sea level from 14 to 21cm/century

disclaimer: this part is intended to explain some bad practices, not to encourage them.

End high

Regression

Sensitive to end period.

Start low

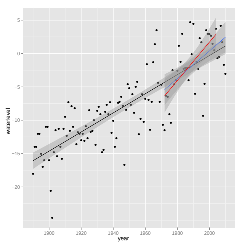


Figure : End in 2005 for Den Helder to raise sea level from 21 to 28cm/century

Use nodal cycle

Use the nodal cycle

Start in low of the cycle, end in peak.

Dutch case

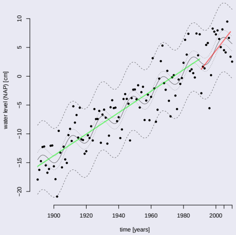


Figure : Ignoring the nodal cycle resulted in an overestimation of the sea level rise by 50%

Ignore the intercept

Don't match up trends

Use a split linear regression to allow for a broken intercept. Common method is to only report the slope and not the intercept.

Dutch case

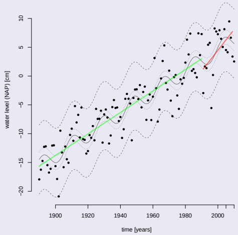


Figure : The red curve starts below the old sea level

Use specific datasets

Tide gauges

15 - 20 cm / century

Altimetry satellites

30 - 35 cm / century

Formulation

The rate over the period 19xx to 20xx *was* 18 cm/century and the *current rate* of sea level rise *is* 32 cm/century.

Include corrections

Common corrections

GIA Glacial Isostatic Adjustment: accounts for the fact that the ocean basins are getting slightly larger since the end of the last glacial cycle. 0==3 cm/century.

IB Inverse Barometer correction: some of the sea level variation correlates with the average pressure (+- 7% explained variance at Dutch coast).

seasonal Variation in seasons results in sea level variation that can be filtered out.

rlr Revised local reference system. Corrected vertical reference level (vertical levels change, for example in the Netherlands 2005).

Include corrections

J1 no GIA, no IB

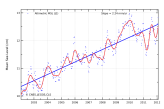


Figure : SLR = 2.2

Jason 1 with GIA and IB

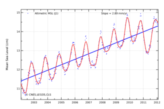


Figure : SLR = 2.9

Combined J1 + J2 + T/P + GIA + IB

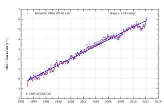


Figure : SLR = 3.2

src:www.aviso.oceanobs.com

Wait for corrected data

- 1993 - 2001 0.25 cm/year Cazenave2003a
- 1993 - 2003 0.28 cm/year Cazenave2004
- 1993 - 2003 0.31 cm/year Bindoff2007 (based on Cazenave2004)

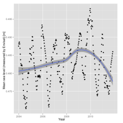


Figure : Envisat March 2012: Sea level decline

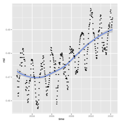


Figure : Envisat May 2012: Sea level rise

Include historical data

Data from Venice 1700–1800

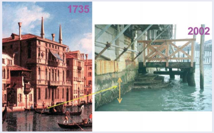


Figure 3. A view of Palace Giustinian-Lolin painted by Bellotto in 1735 (left), and a detail of the main entrance today (right). The algae shift is 66 ± 10 cm. The main staircase is now submersed and a new wooden wharf was necessary to enter.

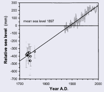


Figure 5. Relative sea level (RSL) at Venice from tide gauges (continuous grey line, period 1872–2000) and from Canaletto's and Bellotto's paintings (white dots with error bars, period 1727–1758). RSL from paintings was estimated from the difference in level of the algae belt as it was in the paintings and as it is today.

Figure : Sea level rise constant in Venice since 1700 (Camuffo)

Include Dutch data from 1700–1800

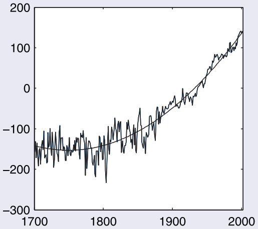


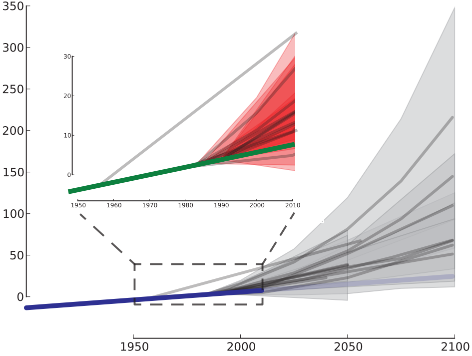
Figure 1. Sea level reconstruction since 1700, the shadow represents the errors of the reconstruction. The fitted curve is a second order polynomial fit.

Figure : Jevrejeva 2008

Ignore bias in historic forecasts

Overestimated forecasts

Global and Northsea Forecasts



Reformulate

Report maxima

Sea level has not been as high since n years ago (often true for a positive trend).

Report short scope rise in centuries

The sea level rose at a rate of 1m / century this year (from -0.5 to 0.5cm).

Outline

Best practices

Falsifiability Use well defined periods. Predict the trend evolution.

Reproducibility Make all data (station selections), models, and tools available.

Perspectives Include opposing perspectives. Use the whole modeling toolbox.

Statistical Report the whole model (not just 1 parameter). Use the linear model as a reference forecast.

Skill Compare old forecasts (1980s) to observed data to test our skill. Use longer verification periods for new forecasts (30+ years).