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Phase 1 update May 2015: trend changes in ground subsidence in Groningen

The views expressed in this paper are those of the author and do not necessarily reflect the policies of Statistics Netherlands.

F.P. Pijpers, D.J. van der Laan

Contents

Nederlands

Deze rapportage is een verslag van onderzoek dat is uitgevoerd in het kader van fase 1 van een onderzoeksproject door het CBS in opdracht van Staatstoezicht op de Mijnen (SodM). Dit onderzoek is ten behoeve van een statistische onderbouwing van het meet- en regelprotocol voor gasexploitatie in de provincie Groningen. Het onderwerp van dit rapport is een heranalyse van trends in de bodemdaling in de provincie Groningen, gerapporteerd in fase 0, in December 2014. Voor de voorliggende analyse is de tijdreeks voor de GPS gegevens aangevuld tot aan 3 Januari 2015. Daarnaast zijn alle GPS data opnieuw gecalibreerd, in een onafhankelijk onderzoek uitgevoerd door de TU Delft.

Zoals ook bleek uit de eerdere analyses is er een statistisch significante trendbreuk in de bodemdaling ongeveer 2 maanden nadat de productie sterk was gereduceerd. De trendwijziging kan zich geleidelijk gemanifesteerd hebben over een periode van enkele weken, en er is daarom een onzekerheid van ruwweg een week of twee over de centrale datum van deze overgang.

English

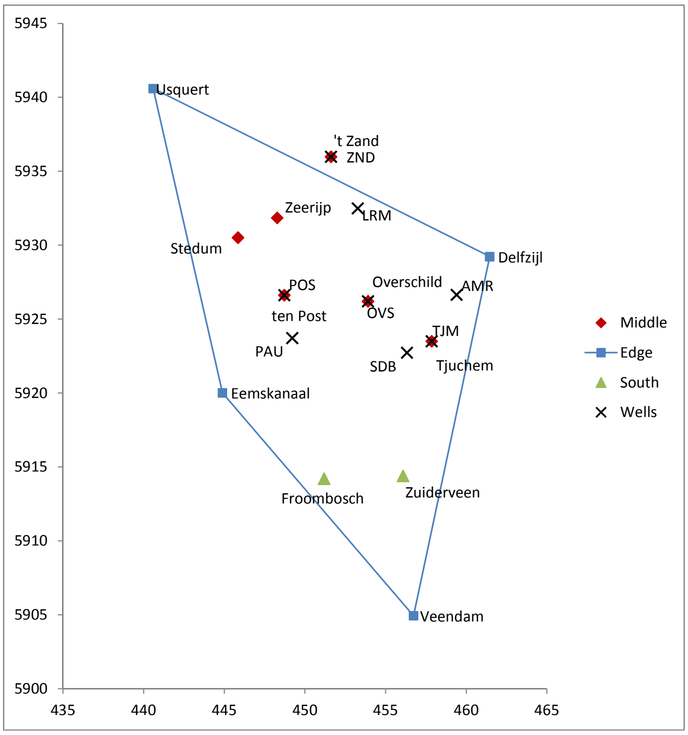
This is a report on the research that has been carried within phase 1 of a project being carried out by Statistics Netherlands and commissioned by State Supervision of Mines (SodM). This research is part of the underpinning of the statistical methods employed to support the protocol for measurement and regulation of the production of natural gas in the province of Groningen. The subject of this report is to re-analyse the trends in the ground subsidence in and around that region, first reported in phase 0, in december 2014. For this re-analysis the time series of the GPS data has been updated with more recent measurements up to Jan. 3 2015. The entire GPS data set has also be re-calibrated, independently from the previous calibrations, by researchers at the TU Delft.

In accordance with the earlier report, it is found that there has been a significant change in the ground subsidence. The changeover in the trend of ground subsidence can have become manifest gradually over a period of several weeks, which implies that the central date of the transition is also uncertain by roughly a week or two.

1 Introduction

In this update for the most part the same methods are applied to the new time series of GPS data. For this reason the reader is referred to the earlier report for an overview of the methods and the methodological background. The time series being analysed in this report contains the entire period that was analysed in the previous report, but is extended forward to cover the epoch up to January 3 2015. Also, the most up-to-date information is being used regarding reference stations. In practice this means that the entire set of GPS data is re-calibrated for all of the stations, and for the entire period.

Figure 1 The relative locations with names of each of the GPS stations from which data are available. The red diamond symbols are locations within the area of the production field `Middle', where production has been reduced. The stations indicated with blue squares are locations outside of the main field, collectively designated as `Edge', although at the southwestern station Eemskanaal there are wells in production. The two stations indicated with green triangles are also production locations in a separate part of the field `South' where production has not been reduced. Well locations where production has been reduced are shown as black crosses, with in addition three wells very close to this region (AMR, TJM, SDB). The indicated scales are in km



2 The filtered time series for each station

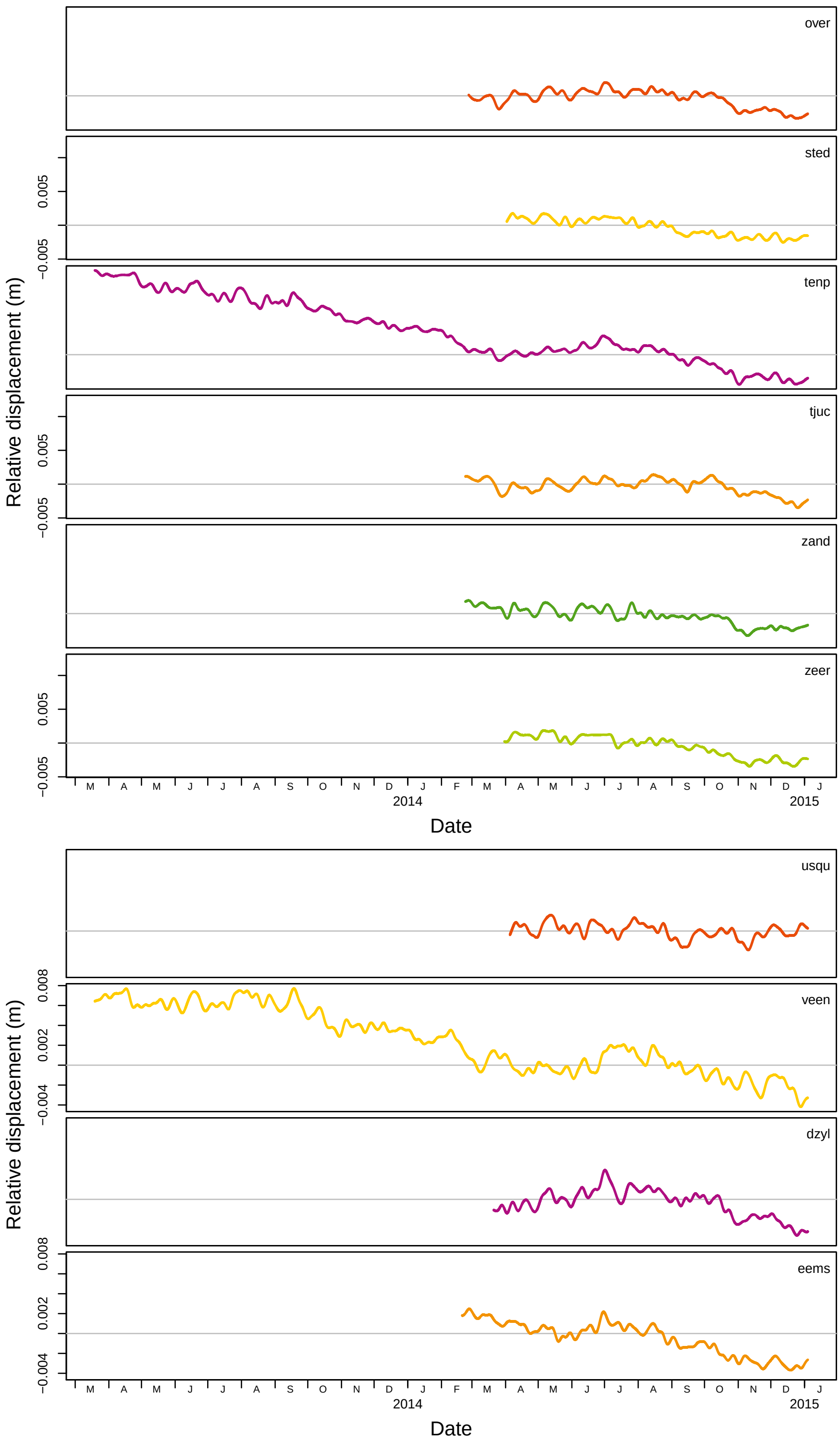
The first processing step of the time series of the GPS stations is to apply the filtering procedure with the filter factors as derived in the previous report. As is done in the previous report, the average height of each station is subtracted. The results are shown in figure 2

The quantity of interest is the 'sagging' of the stations in group 'Middle' and in group 'South' with respect to those in group 'Edge'. It is this differential displacement over a spatial scale of the order of, or smaller than, the field that will lead to the build-up of stresses. Therefore the displacements, averaged for each group, are subtracted in the sense 'Middle' minus 'Edge' and 'South' minus 'Edge'. The result is shown in figure 3.

To assess the extent to which correlations might still be present in the differential displacement, two additional differential time series are shown in figure 4.

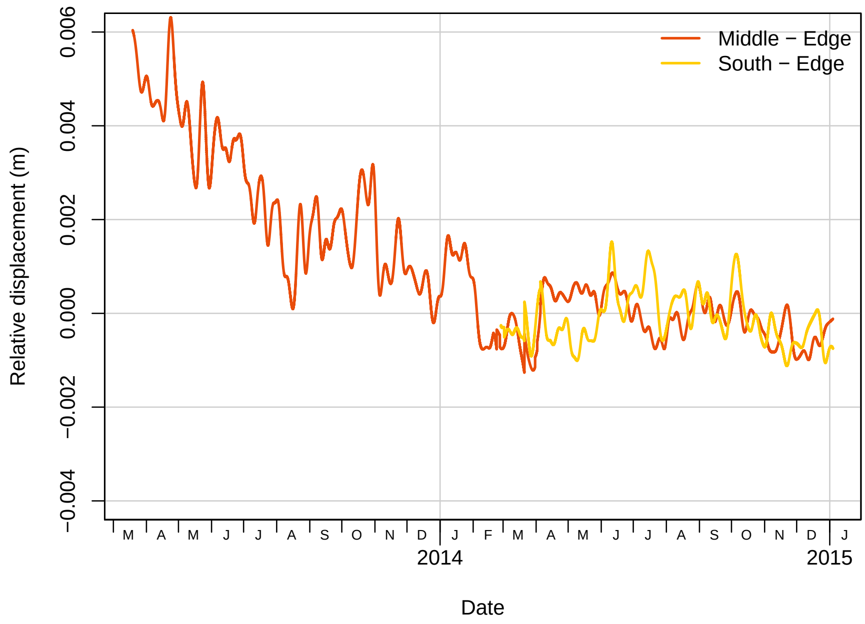
One measure concerns the differential displacement between stations that are all within group 'Middle', in the sense (Zeerijp+ten Post) – (Stedum+Overschild) which is shown as an orange

Figure 2 The time series of the GPS height, after filtering out intermediate time scale variations. For presentational purposes for each station the average of its time series over the period from day 50 to day 214 is subtracted. The vertical scale is in m. Top Panel: GPS stations near the centre of the production field, bottom panel: GPS locations in group edge.



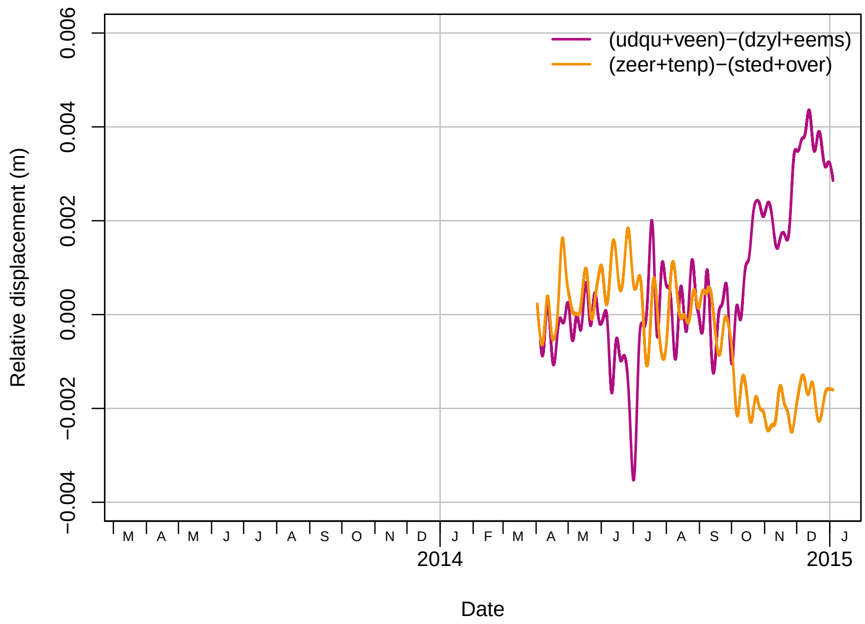
line. The other concerns the differential displacement between stations that are all within group 'Edge', in the sense (Usquert+Veendam) – (Delfzijl+Eemskanaal) shown as a purple line. In the absence of remaining biases these differential measurements should not show any trends.

Figure 3 The time series of the filtered GPS height for the differences between the group averages `Middle' — `Edge' (in red), and `South' — `Edge' (in yellow).



While it is clear that for most of 2014 no trend is present in these sets of differential

Figure 4 The differential time series of the filtered GPS height within groups. Purple line: differential measurements between stations all within group `Edge'. Orange line: differential measurements between stations all within group `Middle'.



displacements, in October there is a sudden change in particular in the group 'Edge', but also to some extent in the group 'Middle'. At this stage it is unclear whether this is caused by further calibration issues that require resolving, or whether the altered spatial pattern of production could have influenced these measures.

3 Drift trends

Since the reduction of the gas production at some locations near stations in the group 'Middle' has been rapid, it is of interest to explore whether a break can be found in the linear component of the downward drift for the time series for 'Middle' minus 'Edge'. To this end one can fit not only a single straight line, using standard least-squares fitting, but also introduce a break-point with a different straight line fit before and after that point. Given that the latter fit has more degrees of freedom than the former, this should be accounted for in assessing whether the two-section fit with a break is genuinely better than a single straight line. The Akaike Information Criterion (AIC) is an equivalent measure to the reduced χ^2 measure used in the previous reports.

Figure 5 AIC score as a function of the position of a break in the linear model fit of the difference between the group averages of `Middle' and `Edge'. The minimum for `jump' is at 2014-02-06 and that of `kink' at 2014-04-02.

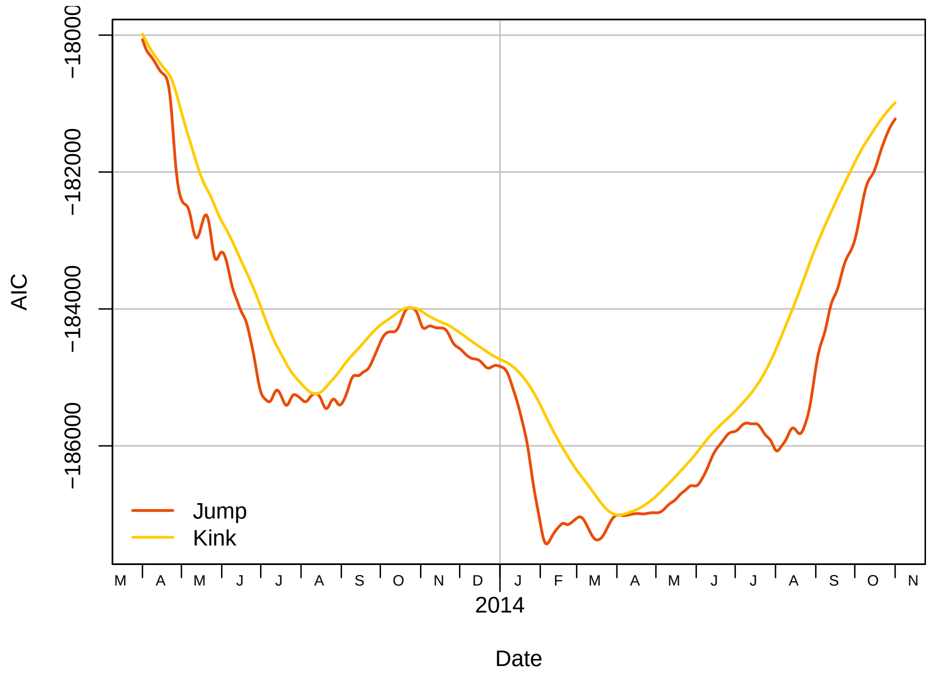
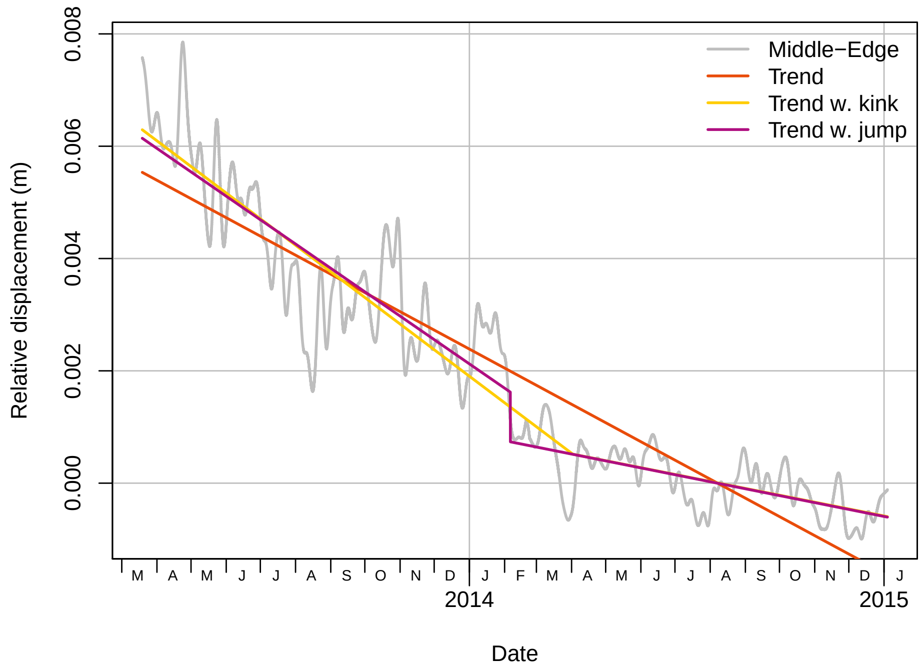


Figure 6 Filtered times series for the group averages of `Middle' and `Edge' with the fitted trends.



4 Alternative model

One possible issue with the previous fit of the break in the trend, is that the number of measurement contributing to each of the average lines changes with time. Before Februari 2014 there is only one measurement station contributing to each of the lines. The previous model does not take this into account: one would expect the model to give more weight to differences at later dates as more measurement stations are contributing to the averages.

One possibility to avoid this problem is to not calculate the difference, but to model all time series combined. The difference in slopes between the two groups can be modelled explicitly and it is possible to test if this difference is significant.

A piecewise linear continuous fit can be written as

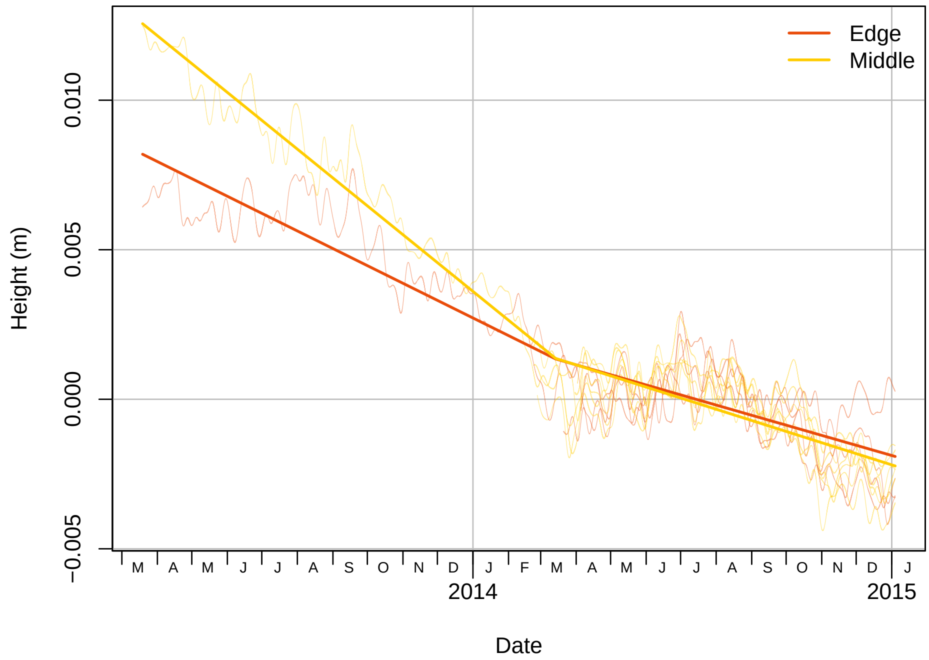
$$y_i = \beta_0 + \beta_1 t_i + \beta_2 s(t - t_0) t_i + e_i, \qquad (1)$$

with $s(t)$ the step function ($s(t) = 1$ for $t \geq 0$ and 0 otherwise). We can then fit each of the time series with a piecewise linear continuous fit:

$$y_i = \begin{cases} \beta_0 + \beta_1 t_i + \beta_2 s(t - t_0) t_i + e_i & \text{if 'Edge',} \\ (\beta_0 + \beta_3) + (\beta_1 + \beta_4) t_i + (\beta_2 + \beta_5) s(t - t_0) t_i + e_i & \text{if 'Middle'.} \end{cases} \qquad (2)$$

We can then test if the coefficient β_5 is zero. In figure 7 the coefficient significantly differs from zero. Also in 'Edge' the discontinuity is significant ($beta_4 \neq 0$). Therefore, both 'Edge' and 'Middle' decrease in time and for both this decrease decreases from approximately 2014-03-14. However, for 'Middle' this decrease is much stronger than for 'Edge', suggesting that this difference is related to the gas production.

Figure 7 Filtered time series of each of the measurement stations in `Edge' and `Middle' with the fitted model. The break is located at 2014-03-14.



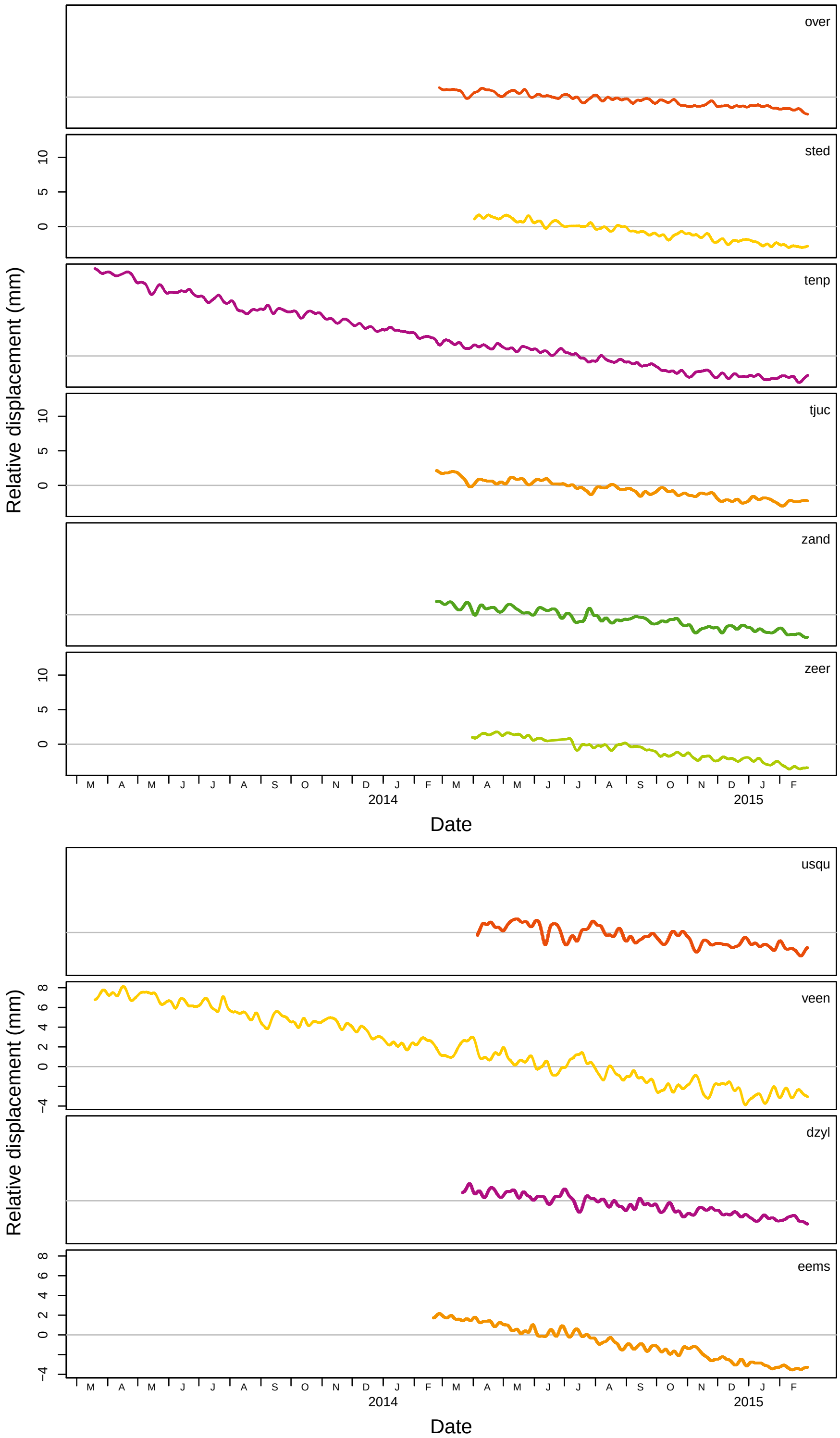
5 Re-processing of GPS data by TU Delft

The GPS data used has been processed from the original satellite measurements using one standard algorithm and associated method. In order to assess some of the assumptions regarding sources of error and their effect, a different algorithm has been applied, developed at the TU Delft. Their dataset of reduced GPS signal per GPS ground location has been made available, so that the same difference technique can be applied, as has been done for the previous reduced GPS datasets. The data are shown in figure 8, which is the equivalent of figure 2.

Fig. 9 shows the 'sagging' of the stations in group 'Middle' and in group 'South' with respect to those in group 'Edge' , ie. the equivalent of what is shown in figure 3.

The differential displacement between stations that are all within group 'Middle', in the sense (Zeerijp+ten Post) − (Stedum+Overschild) is shown as an orange line in figure 10. The other measure concerns the differential displacement between stations that are all within group 'Edge', in the sense (Usquert+Veendam) − (Delfzijl+Eemskanaal) shown as a purple line. In the absence of remaining biases these differential measurements should not show any trends. Comparing figure 10 with figure 4 shows that for the differential time series between the stations that are all in the group 'Edge' the behaviour after October 2014 is very different. This would appear to indicate that in that epoch there are indeed some calibration issues in the earlier dataset which the reprocessing by the TU Delft have resolved. The same epoch does still show some anomalies for the time series involving stations within the group 'Middle'.

Figure 8 The time series of the GPS height as determined by the TU Delft method, and after filtering out intermediate time scale variations. Note that the vertical scale is in mm. Top Panel: GPS stations near the centre of the production field, bottom panel: GPS locations in group edge.



5.1 fitting to the TU Delft data without additional filtering

While the fitting procedures used are robust to the precise properties of the errors, it is worthwhile to explore to what extent the point-to-point correlation introduced by the filtering

Figure 9 The time series of the TU Delft processed GPS height data, and after filtering, for the differences between the group averages `Middle' – `Edge' (in red), and `South' – `Edge' (in yellow). Note that the vertical scale is in mm.

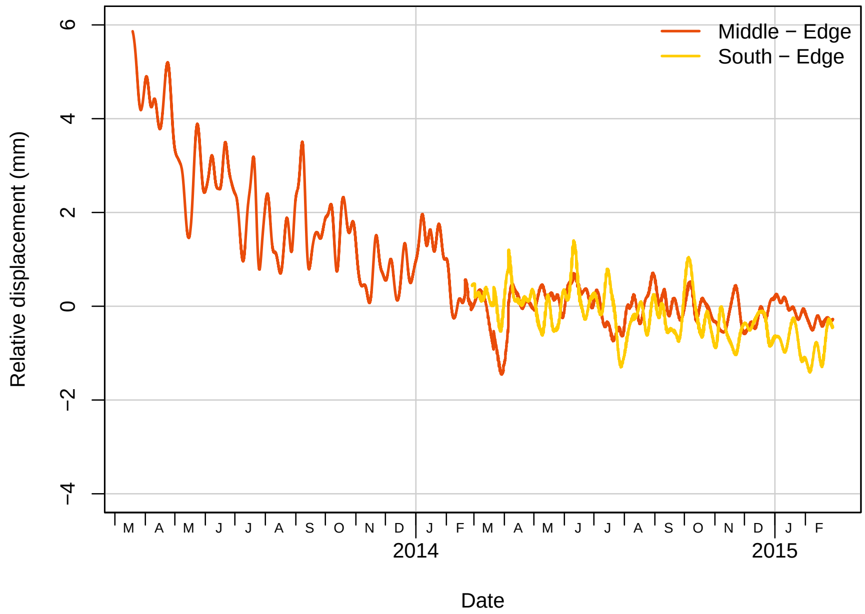
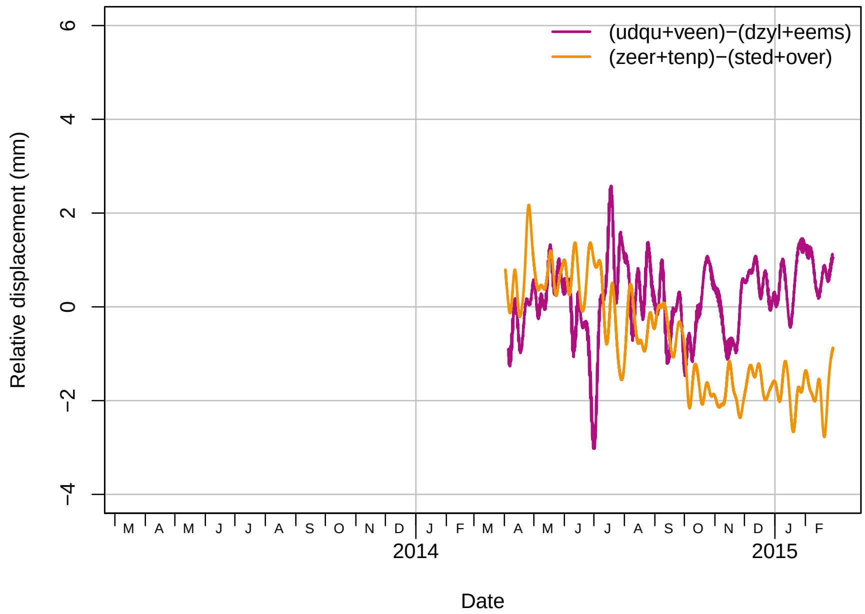


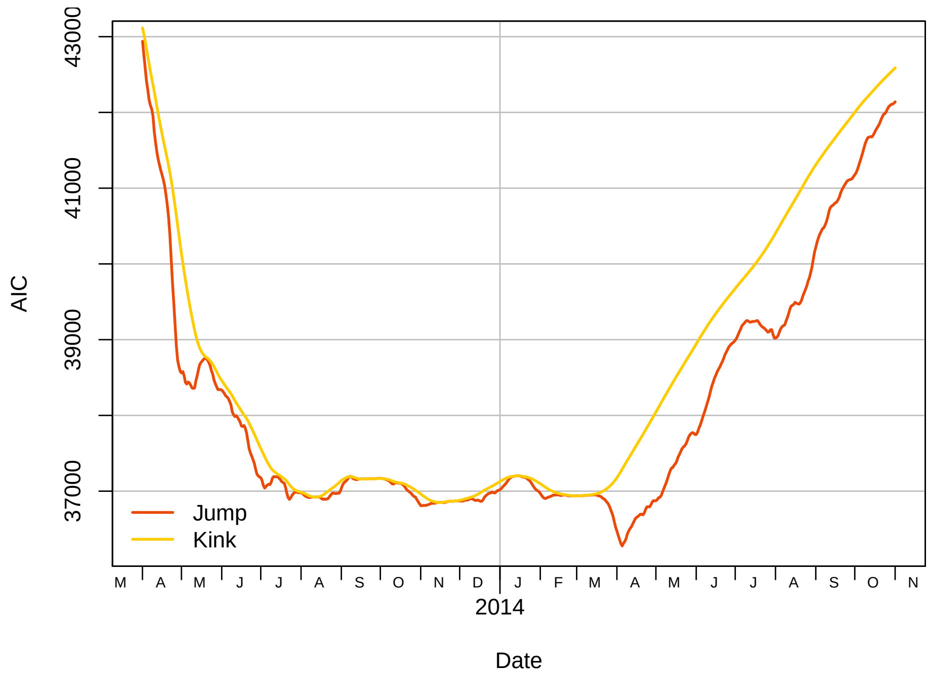
Figure 10 The differential time series of the TU Delft processed GPS height data, and after filtering, within groups. Purple line: differential measurements between stations all within group `Edge'. Orange line: differential measurements between stations all within group `Middle'.



process affects the conclusions drawn from the trend fitting. At this stage it is worth remembering that the choice of fits does not have an underlying physical model for the subsidence. The intention is merely to assess whether one can reject the hypothesis that there is no change in average subsidence rate over the entire period of observation.

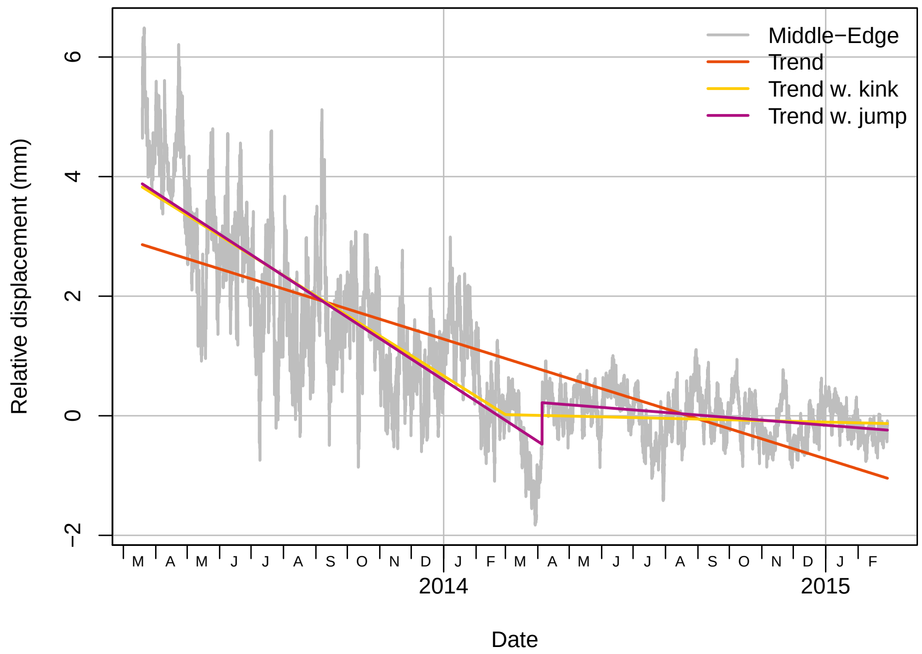
Figure 11 is the equivalent of figure 5 but now the fitting is done on GPS data as processed by the TU Delft without any additional filtering by CBS. While there are differences in the AIC for

Figure 11 AIC score as a function of the position of a break in the linear model fit of the difference between the group averages of `Middle' and `Edge'. The minimum for `jump' (red curve) is at 2014-04-05. For the `kink' (yellow curve) there are several choices which are equally valid, which can be seen from the three broad minima. The final minimum on 2014-03-01 coincides within the uncertainties with what is obtained for the filtered data (fig. 5)



the fits as determined for the filtered and unfiltered data, as one would expect, in both cases one concludes that fits for which the average subsidence rate changes over the period of observation are superior and statistically significantly so. The data appear to point to a trend change in late March early April 2014, with an uncertainty of a few weeks either way, possibly because the change is not quite as abrupt as the fits are.

Figure 12 The fitted models, with either a jump or a kink, to the data as processed by the TU Delft without any additional filtering for the best-fitting position of that break in the linear model fit of the difference between the group averages of `Middle' and `Edge'.



6 Conclusions

From the GPS data it can be concluded that there is continued subsidence of the ground in the area of the wells where production was reduced in the month of January of 2014. However the rate of subsidence is lower after a date. The date of this break has been redetermined with the more extended and re-calibrated set of GPS data. In addition a completely independent data reduction of the GPS data, developed at the TU Delft, leads to the same conclusions in our analysis. The location of the break is around mid-March or very early in April, ie. about 9 weeks after the reduction in production, but there is a fair margin of uncertainty (some 2 weeks) around the exact value of the time gap.

While there is clear statistical evidence that a break has occurred in the subsidence rates, and the reduction in subsidence speeds is measurable with a high degree of precision, research is now in progress to perform a more systematic analysis of the correlation between the production time series and the GPS height time series.

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