remote sensing

MDPI

Supplementary Materials:

S1. Repeat-Track Analysis

To determine inter-ICESat elevation change signals for an assessment with the results of the ICESat/ICESat-2 crossover method, data from a 2005 ICESat track are compared to measurements from the same reference track in 2008 over Vestfonna. Those tracks are chosen because both exhibit relatively dense data compared to others in 2003–2008. Although ICESat ground tracks generally follow the same reference track, they do not match exactly, and they are separated, ~180 m apart in this case. Therefore, the effect of topography has to be considered when comparing repeating tracks of different campaigns. A suitable DEM can be used to correct the influence of slope on overlapping footprints (e.g., [1]) or neighboring footprints spaced further apart (e.g., [2]). Because overlapping footprints are missing, the approach of [2] to correct the topographic influence between neighboring footprints with a DEM is used here. For this purpose, the 'S0_DTM5_2010' DEM of Vestfonna from the NPI is used [3]. It originated in 2010, has a resolution of 5 m, and was processed similar to the S0_Terrengmodell described in Section 4.3. Before the actual elevation change assessment is carried out, footprints from both tracks which do not have a neighboring measurement are discarded to ensure that every elevation value from one track can be compared to that of the other track. Next, the track from the 2005 L3B campaign is projected onto the 2008 L3J campaign track. For this purpose, each measurement of the 2005 track is connected with the two nearest 2008 footprints, and a triangle is formed between these three points. The projected location A_{proj} of the 2005 footprint A on the 2008 track is now estimated by calculating the intersection of the height h_c with the line BC between the two 2008 measurements, B and C (Figure S1). After the projection of all measurements on the 2008 track, DEM values are extracted from the location of the original and the projected 2005 footprints. Both DEM values are then subtracted from each other to estimate the height difference induced by the terrain and slope. This difference is now subtracted from the 2005 measurement to remove the influence of topography between both tracks. Next, the elevation measurements of B and C are linearly interpolated to the location of A_{proj}. The DEM-corrected value of 2005 is subsequently subtracted from the interpolated 2008 value to determine the 2005–2008 elevation change. Dividing all derived values with this method by the timespan between both campaigns produces dh/dt values along the 2008 track. Data is again filtered by discarding measurements along the track which exceed three times the mean absolute deviation from the median of all values. According to the same principle described in Section 4.2, ICESat-2 data is now masked to Vestfonna, and elevation change signals at intersections with the 2008 ICESat track are determined. Overall, the ICESat repeat-track analysis produces 238 dh/dt measurements from 2005–2008 in addition to 25 values from the crossover method between 2008–2019.

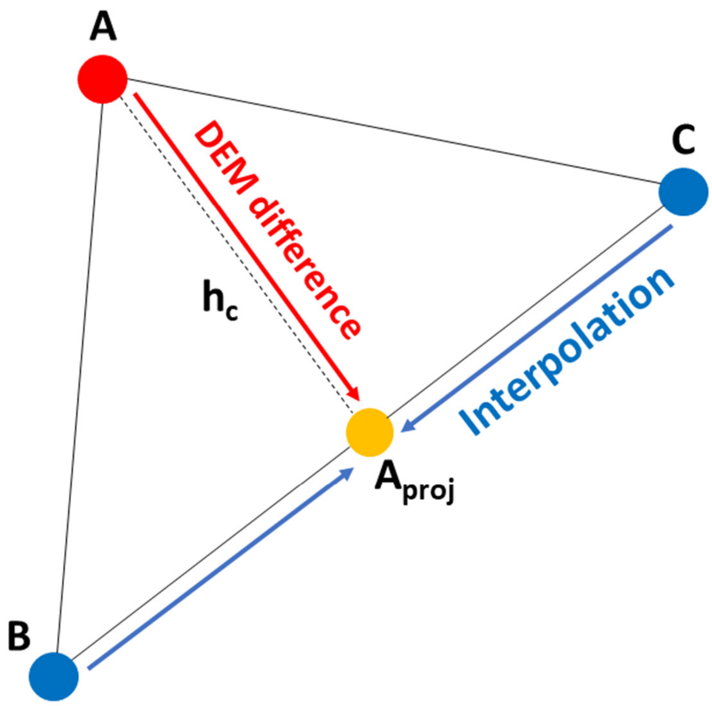

Figure S1. Principle of the projection from one ICESat track onto the other. Red points indicate ICESat campaign L3B footprints from 2005, blue ones indicate footprints from the L3J campaign of 2008. The orange point indicates the location of the projected footprint.

S2. Error-Assessment

When correcting for across-track slope between two ICESat tracks by using a DEM, the reproduction performance of the relative local topography by that DEM can be used to estimate the errors in the projections [2]. Therefore, the DEM-error ∂_{DEM} is calculated by comparing the measured ICESat along-track elevation differences between all neighboring footprints of the 2005 track with the DEM height differences extracted at those points. The final error estimation is thus an assumption of how well the DEM can recreate the local along-track topography, expressed by the RMSE through the following equation:

$$\partial_{\mathrm{DEM}}=[\sum_{i=1}^{n}(z_i\text{-}z_{\mathrm{DEM}})^2/N]^{1/2} \quad (1)$$

where n and N is the number of the 2005 ICESat track footprints, z_i is the difference between two neighboring ICESat measurements in m, and z_{DEM} is the difference in m from the same two points taken from the DEM. A previous similar approach over Svalbard [2] resulted in an error estimation of 1 - 3.5 m depending on the region. The RMSE value from equation (1) is 1.08 m and thus near the lower boundaries of this range, which indicates a comparable performance.

S3. Results

Figure S2 shows total elevation change values from the ICESat repeat-track and ICESat/ICESat-2 crossover method in relation to latitude over Vestfonna. To clarify change trends, a 6th order polynomial curve is fit to the measurements. Figure S3 and S4 additionally shows a spatially overview of the results of both techniques. The repeat-track method reveals a very heterogenous and noisy pattern of elevation change, although a general trend is recognizable. Going from south to north, thinning rates around 0.5 m yr^{-1} decrease up to an elevation of ~290 m, followed by near balance conditions until ~350 m. Further, dh/dt values exhibit an increasing negative pattern up to the high plateau of the ice cap at altitudes of ~580 m. Thinning increases up to the highest measured rates of ~-1 m yr^{-1} around that peak and stay negative during most of the high plateau. In the upper sections of the northern slope of the ice cap, a thickening trend is observable around elevations from ~570 m to ~260 m. Elevation increase rates first rise up to ~1 m yr^{-1} at ~420 m altitude and diminish afterwards until the northern end of the reference track. Values in this region show again a slight negative trend. In conclusion, the southern side of the ice cap reveals elevation decrease in comparison to a thickening trend in the northern parts. This includes a switch of change rates around the peak. Data are very noisy in most of the southern side and slightly more homogeneous afterwards.

The crossover method exhibits the same pattern, while its results are specified by a decreased noise level and a smaller measurement size in total. The overall fitted trend follows the course of the repeat-track method and is overall slightly more negative. dh/dt values are sparse, but equally distributed, along the ground track. Elevation change rates remain negative over the complete southern side and reach -0.66 m yr^{-1} around the ice cap peak. Moreover, the thickening trend on the northern side is likewise observable and reaches its peak similarly around ~420 m altitude, with the highest measured rates of 0.32 m yr^{-1}. Both techniques show the pattern of thinning at the southern side of the ice cap and thickening trends at the northern side. By splitting the ice cap at 80 °N latitude, decrease rates for the southern side amount to -0.17 m yr^{-1} for the repeat-track method and -0.33 m yr^{-1} for the crossover method. The northern side experienced elevation increases at rates of 0.18 m yr^{-1} and 0.13 m yr^{-1}, respectively.

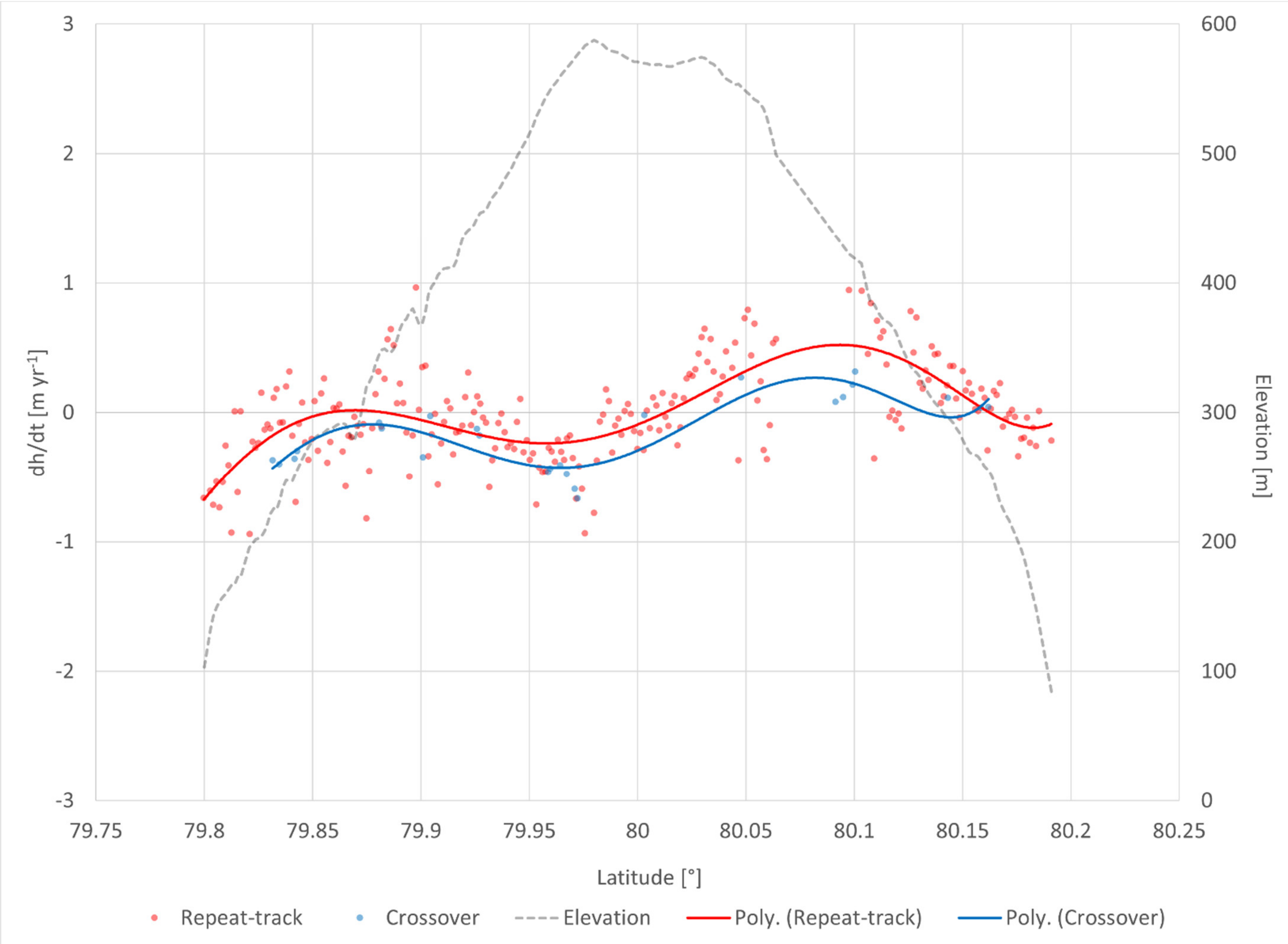

Figure S2. Elevation change rates (dh/dt) along the 2008 ICESat ground track from the repeat-track method in 2005–2008 and the crossover method in 2008–2019. The grey dotted line shows DEM-elevation at the measured repeat-track points. Solid lines are 6th order polynomial fits.

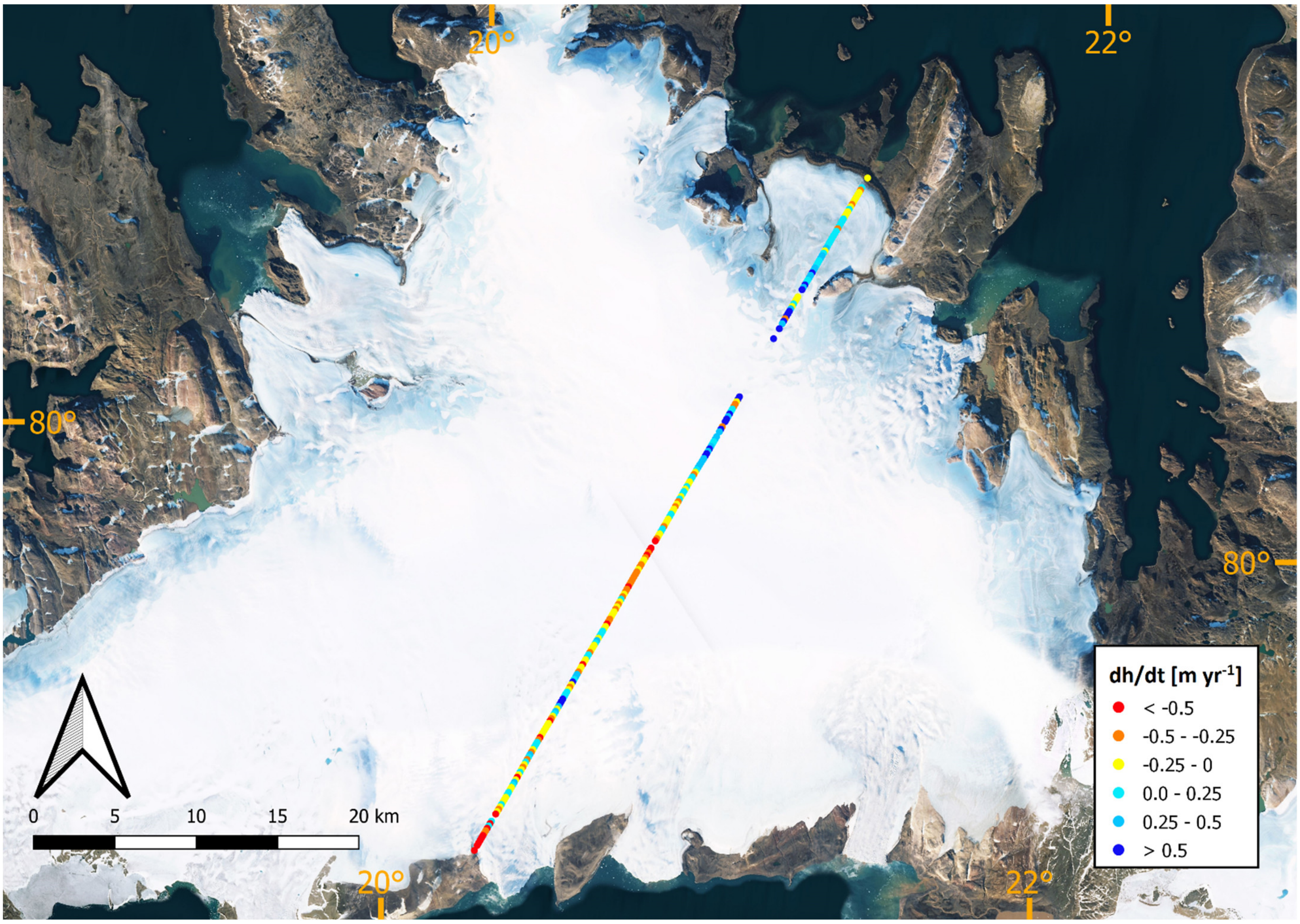

Figure S3. dh/dt rates from the repeat-track method along the 2008 ICESat ground track in Vestfonna. Background © Bing Satellite.

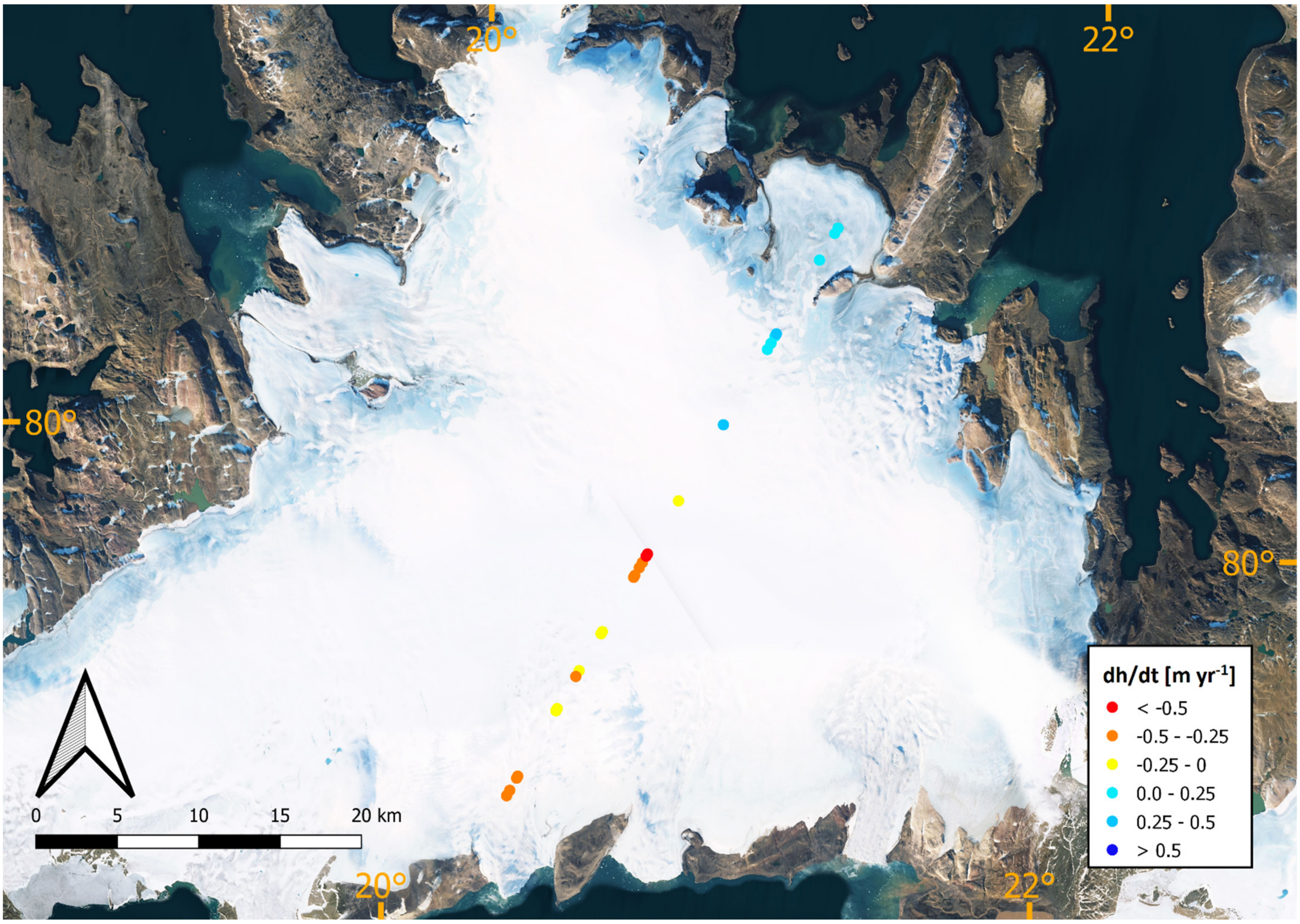

Figure S4. dh/dt rates from the crossover method along the 2008 ICESat ground track in Vestfonna. Background © Bing Satellite.

S4. Discussion

The intra-ICESat repeat-track analysis over Vestfonna produces numerous measurements along one track, while exhibiting a high noise level with values ranging from ~-1 to ~1 m yr^{-1}. The repeat-track performance is expected to be strongly dependent on the quality of the DEM, the complexity of the local terrain, and the spatial and temporal spacing between the two ICESat tracks. The error assessment described in Section 2 resulted in a ∂_{DEM} of 1.08 m, which is similar to the lower boundaries error of ~1 m estimated by a similar approach in a previous study [2]. The high resolution 5 m DEM used here is therefore assumed to sufficiently reproduce the local terrain and to be suitable for a correction of slopes between the ~180 m separated tracks. The large noise is expected to result from two factors. First, the relatively small spacing between ICESat measurements compared to ICESat/ICESat-2 crossover values can inhibit many different local change patterns through ablation, accumulation, and wind drift, thus resulting in measurement variations. Second, the resolution of the DEM (5 m) is much smaller than the footprint size of ICESat (~65 m), which could lead to decreased correspondence of slope and aspect between the data. DEM-Smoothing could have compensated such variations [2] and is expected to possibly reduce noise levels. Since the error assessment showed an overall sufficient reproduction of terrain, smoothing was however not expected to be particularly necessary.

The crossover of the 2008 track with ICESat-2 data resulted in significantly fewer measurements, while showing less noise. This is probably a result of the larger timespan between the data in combination with strongly increased spacing between the measurements and therefore the removal of small local change patterns. The multi-beam architecture and enhanced spatial coverage of the ICESat-2 data additionally ensured sufficient spatial coverage over the complete track, despite being limited to only 25 crossovers. Both methods showed a similar pattern of elevation change with thinning at the southern side and thickening trends over the northern parts, even if the amplitude differs slightly. The crossover method sacrificed spatial coverage for a decreased noise level and more accuracy, whereas the repeat-track method covered almost the entire track with a ~172 m spacing at the cost of high noise. Depending on the research objectives, both methods could therefore be more suitable through either enhanced measurement coverage, or higher accuracy. Nevertheless, both techniques have shown to sufficiently reproduce the same north–south change pattern over Vestfonna, which is also commonly observed in other investigations (e.g., [4]).

References

1. Slobbe, D.; Lindenbergh, R.; Ditmar, P. Estimation of Volume Change Rates of Greenland's Ice Sheet from ICESat Data Using Overlapping Footprints. *Remote Sensing of Environment* **2008**, *112*, 4204–4213, doi:10.1016/j.rse.2008.07.004.
2. Moholdt, G.; Nuth, C.; Hagen, J.O.; Kohler, J. Recent Elevation Changes of Svalbard Glaciers Derived from ICESat Laser Altimetry. *Remote Sensing of Environment* **2010**, *114*, 2756–2767, doi:10.1016/j.rse.2010.06.008.
3. Norwegian Polar Institute (2014). Terrengmodell Svalbard (S0 Terrendmodell) [Data set]. *Norwegian Polar Institute* **2014**, doi:10.21334/npolar.2014.dce53a47.
4. Braun, M.; Pohjola, V.A.; Pettersson, R.; Möller, M.; Finkelnburg, R.; Falk, U.; Scherer, D.; Schneider, C. Changes of Glacier Frontal Positions of Vestfonna (Nordaustlandet, Svalbard). *Geografiska Annaler: Series A, Physical Geography* **2011**, *93*, 301–310, doi:10.1111/j.1468-0459.2011.00437.x.