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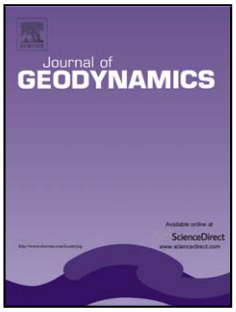

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Impact of Regional Reference Frame Definition on Geodynamic Interpretations

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Abstract

Ten years (1997-2006) of weekly GNSS solutions of 205 globally distributed stations have been used to investigate the impact of the reference frame definition on the estimated station velocities. For that purpose, weekly regional solutions (covering the European region) and global solutions have been respectively stacked to obtain regional and global velocity fields. In both cases, the estimated long-term solutions (station positions and velocities) were tied to the ITRF2005 under minimal constraints using a selected set of reference stations. Several sets of global and regional reference stations were tested to evaluate first the impact of the reference frame definition on the global and regional velocity fields and later the impact on the derived geodynamic interpretations.

Results confirm that the regional velocity fields show systematic effects with respect to the global velocity field with differences reaching up to 1.3 mm/yr in the horizontal and 2.9 mm/yr in the vertical depending on the geographical extent of the network and the chosen set of regional reference stations.

In addition, the estimations of the Euler pole for Western Europe differ significantly when considering a global or a regional strategy. After removing the rigid block rotation, the residual velocity fields show differences which can reach up to 0.8 mm/yr in horizontal component.

In Northern Europe, the vertical ground motion is dominated by the Glacial Isostatic Adjustment (GIA). A proper modeling of this effect requires sub-mm/yr precision for the vertical velocities for latitudes below 56°. We demonstrate that a profile of vertical velocities shows significant discrepancies according to the reference frame definition strategy. In the case of regional solutions, the vertical modeling does not predict any subsidence around 52° as predicted by the global solution and previous studies.

In summary, we evidence the limitation of regional networks to reconstruct absolute velocity fields and conclude that when geodynamics require the highest precisions for the GNSS-based velocities, a global reference frame definition is more reliable.

Keywords: Geodesy; Reference Frame; Methodology; GNSS; Velocity Field; Geodynamic.

1. Introduction

GNSS (Global Navigation Satellite Systems) is often used to produce 3D velocity fields aiming at geodynamic interpretations. Due to the expected small intra-plate deformations in most European regions, the accuracy of the estimated surface displacements must be at the sub mm/yr level in the horizontal and vertical components.

The IGS (International GNSS Service) started its first reprocessing campaign in Feb. 2008 (Steinberger et al., 2008) and is presently reprocessing its global GNSS network data to deliver a set of consistent high quality GNSS products (e.g. orbits, clocks and earth rotation parameters) which will be used by regional GNSS densification networks during their reprocessing. Today, with the improving computing facilities and GNSS data analysis, it has become less demanding to perform a global analysis and regional networks may consider this approach. Within that context, we compared the regional approach to the global approach where global stations located on other continents were added to a regional GNSS network processing.

Historically, two major methods were used to express a GNSS position and velocity solution in a given realization of the ITRF (International Terrestrial Reference Frame): (1) by constraining the positions and the velocities of a selected ITRF subset of stations to ITRF values, (2) by aligning the solution to the ITRF using a 14-parameter Helmert similarity transformation under the minimal constraints approach for a selected set of stations. According to Altamimi (2003), the advantage of the first method is that the solution is well expressed in the ITRF frame, while its disadvantage is that the selected stations will have their coordinates entirely determined by the ITRF selected values. In comparison, the second method has the advantage of preserving the intrinsic characteristics of the solution and avoiding any internal distortion of the original network geometry.

In this paper, we concentrate on the second method and study specifically the alignment of the solutions (regional or global) to the ITRF2005 (Altamimi et al., 2007a) using a 14-parameter similarity transformation under the minimal constraints approach.

In Legrand and Bruyninx (in press), global and regional solutions for station positions have already been compared and it was demonstrated that positions obtained through global solutions are less sensitive to the reference frame definition compared to regional solutions. Wöppelmann et al. (2008) investigated the influence of using different sets of reference stations to express a global solution in a given frame and concluded that the best results were obtained using a large global distribution of reference stations mitigating the individual problems at each of the reference stations.

In this study, we investigate the impact of the size of the GNSS network and the choice of the reference stations on the estimated velocities and the derived geodynamic interpretations. For that purpose, we elaborated several long-term solutions by varying the geographical extension of the network and the reference stations used in the alignment to the same reference frame.

Geodynamic interpretations are often based on GNSS velocities fields stemming from a regional network processing. However, to detect sub-mm/yr motion it is fundamental to pay attention to the GNSS data processing strategy and particularly the reference frame definition. To address that problem, we focused on the Western part of Europe where geodynamics require sub-mm/yr precision for both horizontal and vertical velocities. We used the velocity solutions from our global and regional networks to compare the results of different commonly-used geodynamic modeling strategies, such as the estimation of Euler rotation poles, residuals from rigid block motion and vertical velocity profiles.

2. Data Set and Methodology

The computation of a velocity field from GNSS data consists of several steps.

2.1 Weekly Coordinate Solutions

In a first step, weekly positions of continuous observing GNSS stations are estimated. Ten years (1997-2006) of weekly GNSS solutions produced by ULR (Université de la Rochelle) as its contribution to TIGA (Tide Gauge Benchmark Monitoring Project of the IGS) have been used throughout this paper. The ULR solutions are in the SINEX format, and provide station coordinates together with their covariance information for 225 globally distributed continuous GNSS stations (Figure 1) from which 205 stations have more than 3.5 years of data. The same parameterization and observation modeling were used over the whole 10-year period, estimating station coordinates, satellite orbits, earth orientation parameters, and zenith tropospheric delay parameters every 2 hours. IGS absolute phase centre corrections for both the tracking and transmitting antennas were applied (see Wöppelmann et al. 2009 for further details on the GNSS reprocessing). Each weekly solution was aligned to the ITRF2005 using minimum constraints with seven transformation parameters (translations, rotations and scale) with the CATREF software package (Altamimi et al., 2007b).

FIGURE 1

To study the differences between global and regional solutions, regional weekly solutions have been created from the ULR global weekly solutions by extracting 60 GNSS stations located in Europe, all included in the EUREF Permanent Network (EPN) (Bruyninx, 2004).

2.2 Cumulative Position and Velocity Solution

In a second step, the weekly positions (and their covariance information) were combined to estimate site positions and velocities expressed in a chosen reference frame. Global and regional velocity fields were obtained by stacking both sets of weekly solutions. The stacking was performed with CATREF and tied to the ITRF2005 under minimal constraints using 14 transformations parameters (translations, rotations, scale and their rates) using a selection of ITRF2005 reference stations.

The quality of the alignment of the long-term solution on ITRF2005 depends on the selected set of reference stations; these stations should be of high quality. Their selection is based on the following criteria:

- residuals of the similarity transformation between the solution and the ITRF2005:
    - positions: below 7 and 15 mm in horizontal and vertical components, respectively
    - velocities: below 1.5 and 3 mm/yr in horizontal and vertical components, respectively
- station observation history: at least 3 years in the ITRF, as well as in the ULR time series

- optimal distribution of the reference stations over the network.

In this study, we distinguish two reference frame definition strategies: (1) a first case considering a set of global well distributed reference stations; (2) a second case with regional distributed reference stations.

3. Effect of Reference Frame Definition on Absolute Velocity Fields

To evaluate the impact of the reference stations on the global and regional velocity fields, several sets of reference stations were tested when expressing the cumulative solution in the ITRF2005.

3.1 Stability of the Networks

The impact of outliers (residuals of the similarity transformation between ITRF2005 and the solution exceeding the criteria presented above) in the reference stations and of reducing the number of reference stations (all of them responding to the above mentioned site selection criteria) was tested for the two networks. We observed that the velocities obtained by using different sets of the global reference stations differ below 0.2 mm/yr indicating that in general they behave in a stable way. However, the velocity fields obtained with the regional network were much more sensitive to the set of reference stations used (outliers and geometry) compared to the global network (see section 3.3).

In the regional network, it was evidenced that the border stations are crucial for a proper datum definition, they could considerably impact the coordinates and velocities of the whole network. Moreover, the estimated coordinates and velocities of the border stations were extremely sensitive to the reference frame definition resulting in unstable estimates dependent on the chosen set of reference stations. This means that in general, even if they are mandatory for the reference frame definition, the coordinates and velocities obtained for the border stations should be treated with care, or even not used at all in the geodynamic interpretation.

3.2 Regional and Global Sets of Reference Stations

Finally, for the global network, 83 geographically well-distributed IGS05 stations (Ferland, 2006), following the criteria defined in section 2.2, were selected as reference stations to express the solution used throughout this paper in ITRF2005 and obtain the V_{GLOB} velocity field. The IGS05 consists of 132 IGS stations based on station performance, track record, monumentation, co-location and geographical distribution selected by the IGS Reference Frame Working Group for the IGS realization of the International Terrestrial Reference Frame.

For the regional network, we selected two sets of reference stations (Figure 2), both following the criteria defined in section 2.2 and having a large probability of being used by users in Europe:

- Selection A: 23 reference stations consisting of all EPN ITRF2005 stations also part of the IGS05

- Selection B: 14 stations, subset of selection A with stations located only on the European continent

The two associated regional velocity fields are V_{REGA} (selection A) and V_{REGB} (selection B).

FIGURE 2

3.3 Comparison of the Velocity Fields

Figures 3 shows the comparison of the horizontal and vertical velocity fields derived from the global (V_{GLOB}) solution with the two regional solutions (V_{REGA} and V_{REGB}) and shows that both regional velocity fields present systematic effects with respect to the global velocity field. As shown in Table 1, the velocity differences are significant with respect to the error ellipses and can reach up to 1.3 mm/yr in the horizontal and 2.9 mm/yr in the vertical components. In zones where the aim is to measure (sub)-mm/yr deformations, such an effect cannot be neglected.

FIGURE 3

TABLE 1

At the start of the computations, the stations in each weekly regional solution have the same coordinates as in the corresponding weekly global solution. Then, during the stacking, station coordinates and velocities are estimated together with a similarity transformation between each weekly solution and the reference datum. Especially in regional networks, these transformations will absorb common mode signals and will slightly change the estimated velocities (effect N_1). Finally, the stacked solution is tied to the ITRF2005 using minimal constraints applied upon different sets of reference stations. The minimal constraints method typically does not alter the network geometry. The choice of the reference stations used to express the long-term solution in ITRF2005 has an impact on the alignment and consequently also changes the estimated velocities (effect N_2). In general, these two effects (N_1 and N_2) are known as the network effect. The effect N_2, which only depends on the choice of the reference stations, is fully explained by a similarity transformation whose parameters are shown in Table 2. These transformation parameters have been estimated with all stations of the regional network; the correlations between the transformation parameters are the same for the two regional networks and are shown in Table 3. The translation rates are strongly correlated with the rotation rates (affecting only the horizontal velocities) and the scale (affecting only the vertical velocities). These transformation parameters explain more than 90% of the velocity differences. The systematic effects observed in the horizontal velocities (see Figure 3, left) are explained by the rotation rates and the translation rates. For the vertical component, the bias (Regional A) and the tilt (Regional B) observed in Figure 3 (right) are explained by the scale rate together with the translation rates. The residuals obtained after the similarity transformations are caused by the effect N_1; they are below 0.2 mm/yr in horizontal and 0.6 mm/yr in vertical (see Table 4) and are the same for the two regional networks. The effect N_1 is correlated with the size and the geometry of the whole network.

Summarized, the differences between the global and regional velocity fields are due to the combined effect of the size of the network and the selection of the reference stations and are called “network effect”.

TABLE 2

TABLE 3

TABLE 4

The disagreement between the velocity fields is amplified when the reference stations cover a smaller geographical area (selection B). This effect is probably increased by the fact that in selection A, some reference stations belong to the American, the African or the Arabian plates; while for selection B, all the reference stations are located on the European plate. Adding reference stations from outside the European continent allows reducing the difference between the regional and global velocity fields.

4. Effect of the Reference Frame Definition on Geodynamic Interpretations

4.1 Impact on Euler Pole Rotation Estimation

Euler Pole rotations are usually used to model the mean rigid block rotation of a tectonic entity (e.g. tectonic plate, tectonic block). Consequently, Euler pole rotation is also used to estimate the residuals from the rigid block motion hypothesis in order to detect strain accumulation areas and/or intra-plate deformations. To quantify the impact of the reference frame definition on the Euler pole rotation estimation, the mean rigid block rotation has been estimated individually for the Western part of Europe from each of the three solutions.

In each case, the same 40 stations were used satisfying the following criteria:

- continuously observed during at least 3 years;
- located on rigid parts of the European tectonic plate;

- formal error of the estimated horizontal velocity (as result of the stacking) below 1.5 mm/y;
- post-fit velocity residual below 1.5 mm/yr, after the estimation of the rotation pole.

TABLE 5

The resulting rotation poles together with the Eurasian rotation pole published in ITRF2005 [Altamimi et al. 2007a] are given in Table 5. From this, it can be seen that the ITRF2005 rotation pole for Eurasia is closer to the rotation pole from Regional B than to the rotation poles from Regional A or Global. Indeed, the reference stations used to tie the Regional B solution to ITRF2005 are only located on the European plate and 12 of these 14 stations were used by [Altamimi et al. 2007a] to estimate the Eurasian rotation pole. As a consequence, due to the principle of the minimal constraints, the Regional B velocities of the European stations are closer to the ITRF2005 values than the two other solutions and finally the rotation pole from Regional B is closer to the rotation pole from [Altamimi et al. 2007a] than the others. Nevertheless, this does not remove the fact that regional solutions behave in an unstable way: any other choice of reference stations could lead to a different rotation pole for Europe. This is confirmed by Table 5 which shows that the three resulting rotation poles estimated from $V_{REGA,}$ V_{REGB} and V_{GLOB} differ significantly. Consequently, the choice of the reference stations during the reference frame definition has a relevant impact on the estimated rotation pole.

4.2 Residuals from Rigid Block Motion Hypothesis in Western Europe

To test the impact of the network effect on the detection of non-rigid deformation, in each case, the modeled rigid block rotation was removed from the horizontal velocities to obtain the residual velocity fields. The order of magnitude of the residuals is the same for V_{REGA}, V_{REGB} and V_{GLOB}. Nevertheless, we observe systematic effects when comparing them (see Figure 4). The RMS of the differences between V_{GLOB} and V_{REGA} is about 0.1 mm/yr and the differences reach up to 0.5 mm/yr. The RMS of the differences between V_{GLOB} and V_{REGB} is 0.2 mm/yr, but the maximal difference reaches 0.8 mm/yr. The velocity residuals of the two regional solutions are similar in the middle of the network, but the differences between the two sets of residuals are larger when getting closer to the edges of the regional networks.

The reference frame definition strategy therefore has a significant impact on the velocity estimation, and this has to be considered when sub-mm/year precision is required for a proper interpretation of the intraplate deformations.

FIGURE 4

4.3 Impact on GIA Model Estimation

In Northern Europe, the vertical motion is mainly due to the post-Glacial Isostatic Adjustment (GIA). According to previous studies the estimated vertical motion can reach 10 mm/yr in the Fennoscandian region (Nocquet et al., 2005). Additionally, the first order of the GIA effect on vertical velocities over Western Europe, is well explained by a 4th order polynomial function (Milne et al., 2001) with uplift in Northern Europe and transitions zones between uplift and subsidence below 56° of latitude. However, the transition between the GIA-induced uplift and subsidence zone is not well constrained due to the small velocities that have to be measured in the Western central part of Europe for regions below 56° of latitude.

The three vertical velocity fields (V_{GLOB}, V_{REGA} and V_{REGB}) have been used to construct velocity profiles along the European region subject to post-glacial rebound. The stations used for the vertical velocity profiles range from 45° to 71° of latitude and -5° to 35° of longitude.

We estimated the parameters of a 4th order polynomial function from the vertical profiles of the global and two regional solutions to model the contribution of the GIA on the estimated velocities (Figure 5). As can be seen in Figure 5, the velocity of the station TRDS (Trondheim, Norway) is atypical. For that reason, the modeling was done with and without TRDS showing that TRDS influences dramatically the fit of the data and changes the 4th order function parameters.

Table 6 demonstrates that the models from V_{REGA} and V_{REGB} exhibit a constant bias with respect to the modeling from the global solution V_{GLOB} (up to 0.5 mm/yr). This is due to the impact of the reference frame definition on vertical velocities illustrated in Figures 3. The RMS of the difference between the model from V_{REGA} (resp. V_{REGB}) and the model from V_{GLOB} can reach 0.3 mm/yr (resp. 0.5 mm/yr). Consequently, when a velocity field is derived from a regional network, GNSS stations located far outside the studied region should also be integrated to minimize the effect of reference frame definition on the estimated site velocities.

In agreement with the GIA models, subsidence is predicted (maximum subsidence of 0.2 mm/yr at 51.7° latitude) by the global solution, while the regional solutions do not show subsidence at all, but a minimum uplift of 0.3 mm/yr at that latitude. Consequently, to detect mm and sub-mm/yr vertical velocities from GNSS data modeling, the regional approach is not appropriate. In our case, the transition between subsidence and uplift in northern Europe is important for example to investigate long-term sea level rise in the northern part of Belgium.

FIGURE 5

TABLE 6

5. Conclusion

In order to express a GNSS solution in the ITRF, it is possible to constrain the positions and velocities of some sites to their ITRF values or to align the solution to the ITRF using a 14-parameter similarity transformation under minimal constraints. In this study, we focused on the minimal constraints approach to express our GNSS solutions in ITRF2005 and we investigated the influence of the reference frame definition - in terms of reference station selection and network extension - on the estimated velocity field.

It was shown that based on identical sets of weekly positions as the basis, different velocity vectors (up to 1.3 mm/yr in the horizontal and 3 mm/yr in the vertical) can be estimated depending on geographical extent of the network (regional versus global). The obtained velocity differences are due to a network effect which depends on the selection of the reference stations. The disagreement between the global and regional velocity fields is amplified when the reference stations cover a smaller geographical area. In the regional network, the border stations have the most unstable velocity estimates.

The Euler rotation poles estimated from the regional networks differ significantly from the rotation pole estimated from the global solution. After removing the rigid block rotation, the residual velocity fields show differences up to 0.9 mm/y. We also proved that, in contrary to the global solution and the GIA models, none of the regional solutions could predict subsidence around 52° latitude.

In conclusion, when expressing a GNSS solution in the ITRF2005 using minimal constraints, the network effect due to the size of the GNSS network and the choice of the reference stations has a significant influence on the estimated velocity field and consequently might cause wrong geodynamical interpretations. Consequently, when sub-mm/year precision is required for a proper interpretation of intraplate deformations or vertical velocities, a global approach should be considered.

Acknowledgements

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Figures

Fig. 1. Global (black triangles) and regional (white triangles) networks used in this study. The dashed area corresponds to Figure 2.

Fig. 2. Stations used for the reference frame alignment of regional solutions. Selection A: stations are indicated with black and white triangles; selection B: stations are indicated with white triangles.

Fig. 3. Difference between global and regional velocity fields (mm/yr). Left: horizontal differences, Right: vertical differences. Top: VREGA - VGLO, bottom: VREGB - VGLO. Error ellipses are at the 99% confidence level.

Fig. 4. Differences between residuals from rigid block motion of the global solution with the regional selection A (top) and regional selection B (bottom). Error ellipses are at the 99% confidence level.

Fig. 5. Vertical profiles and best fit 4th order polynomial function for: a): global solution; b) regional solution, selection A; c) regional solution, selection B. The lines are the best fits from GNSS data with (thin) and without (bold) TRDS. The best fit from the global solution is repeated in b) and c) (dashed lines). Error bars at the 99% confidence level.

Tables

	Horizontal (mm/yr)			Vertical (mm/yr)		
	Mean ±RMS	*Max*	*Mean of 1σ Error Ellipses*	*Mean ±RMS*	*Max*	*Mean of 1σ Error Ellipses*
V_{REGA} - V_{GLO}	0.3 ± 0.4	0.9	0.03	0.3 ± 0.5	1.2	0.04
V_{REGB} - V_{GLO}	0.6 ± 0.7	1.3	0.03	0.1 ± 1.0	2.9	0.04

Table 1. Statistics of the differences between the global and regional velocity fields.

Transformation parameters between		$\dot{T}_X$ (cm/yr)	$\dot{T}_Y$ (cm/yr)	$\dot{T}_Z$ (cm/yr)	$\dot{S}$ (10^{-9}/yr)	$\dot{R}_X$ (mas/yr)	$\dot{R}_Y$ (mas/yr)	$\dot{R}_Z$ (mas/yr)
V_{GLOB} and **V_{REGA}**		-0.099	-0.162	0.004	0.057	-0.058	0.023	0.028
	±	0.025	0.033	0.024	0.034	0.010	0.009	0.008
V_{GLOB} and **V_{REGB}**		-0.153	-0.483	0.093	0.059	-0.169	0.046	0.061
	±	0.025	0.033	0.024	0.034	0.010	0.009	0.008

Table 2. Translation, scale and rotation rates between the global and regional velocity fields.

	$\dot{T}_X$	$\dot{T}_Y$	$\dot{T}_Z$	$\dot{S}$	$\dot{R}_X$	$\dot{R}_Y$
$\dot{T}_Y$	-0.088					
$\dot{T}_Z$	-0.216	0.018				
$\dot{S}$	-0.511	-0.034	-0.682			
$\dot{R}_X$	-0.092	0.884	-0.008	0.000		
$\dot{R}_Y$	-0.826	0.080	0.685	0.000	0.086	
$\dot{R}_Z$	0.088	-0.740	-0.002	0.000	-0.388	-0.041

Table 3. Correlations between the translation, scale and rotation rates estimated in Table 2. The correlations larger than 0.5 are shown in grey.

	Horizontal (mm/yr)		***Vertical (mm/yr)***	
	Mean ±RMS	*Max*	*Mean ±RMS*	*Max*
V_{REGA} - V_{GLO}	0.0 ± 0.06	0.2	0.0 ± 0.14	0.6
V_{REGB} - V_{GLO}	0.0 ± 0.06	0.2	0.0 ± 0.14	0.6

Table 4. Statistics of the velocity residuals after the estimation of the translation, scale and rotation rates shown in Table 2.

Pole estimation strategy	*Longitude* (°)	*Latitude*(°)	*W* (°/Ma)
Global solution	-102.02 +/- 0.82	53.02 +/- 0.56	0.252 +/- 0.002
Regional solution A	-100.51 +/- 0.91	53.35 +/- 0.59	0.251 +/- 0.002
Regional solution B	-97.77 +/- 1.00	55.15 +/- 0.58	0.256 +/- 0.002
ITRF2005 [Altamimi et al. 2007a]	-95.98 +/- 0.97	56.33 +/- 0.55	0.261 +/- 0.003

Table 5. The rotation poles estimated from V_{REGA}, V_{REGB} and V_{GLOB} solutions and comparison with the Eurasian rotation pole from ITRF2005 published in [Altamimi et al. 2007a].

	V_{REGA} - V_{GLO} (mm/yr)		V_{REGB} - V_{GLO} (mm/yr)	
	With TRDS	*Without TRDS*	*With TRDS*	*Without TRDS*
Mean bias	0.3	0.2	0.5	0.5
RMS	0.3	0.3	0.4	0.4

Table 6. Mean biases and RMS between modeled functions from V_{REGA} or V_{REGB} solutions and global solution

Figure 1

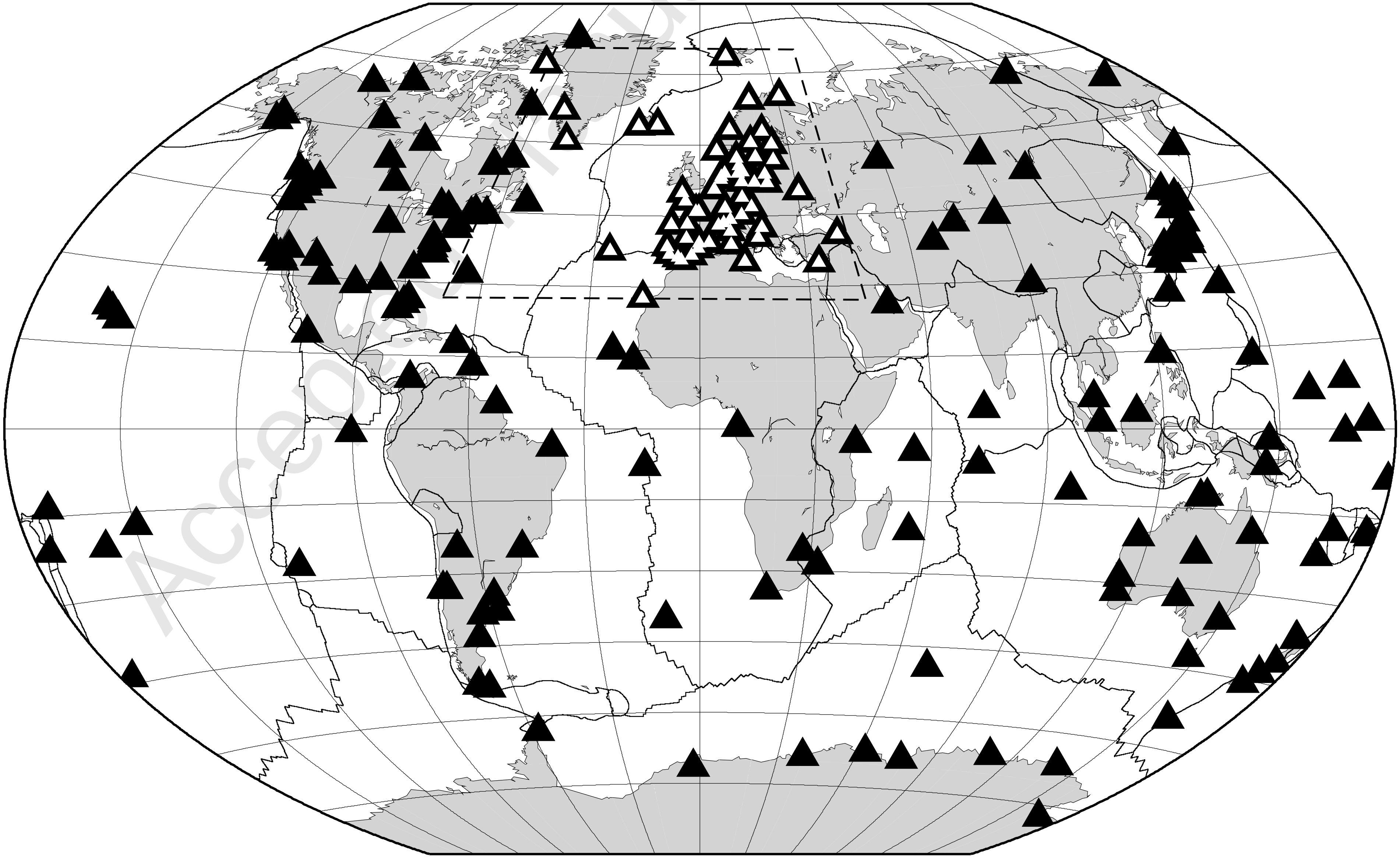


Figure 2

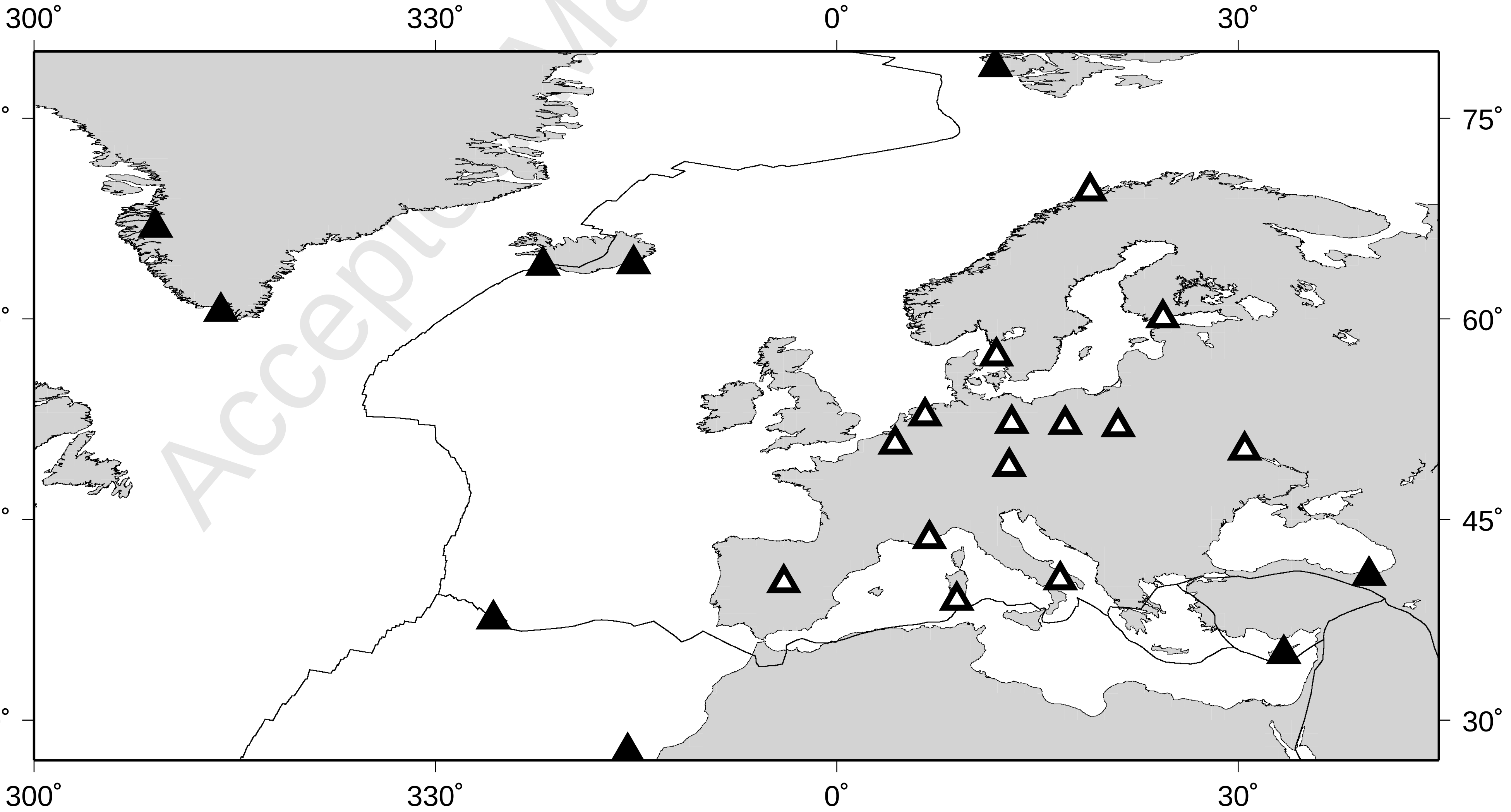


Figure 3 a top left

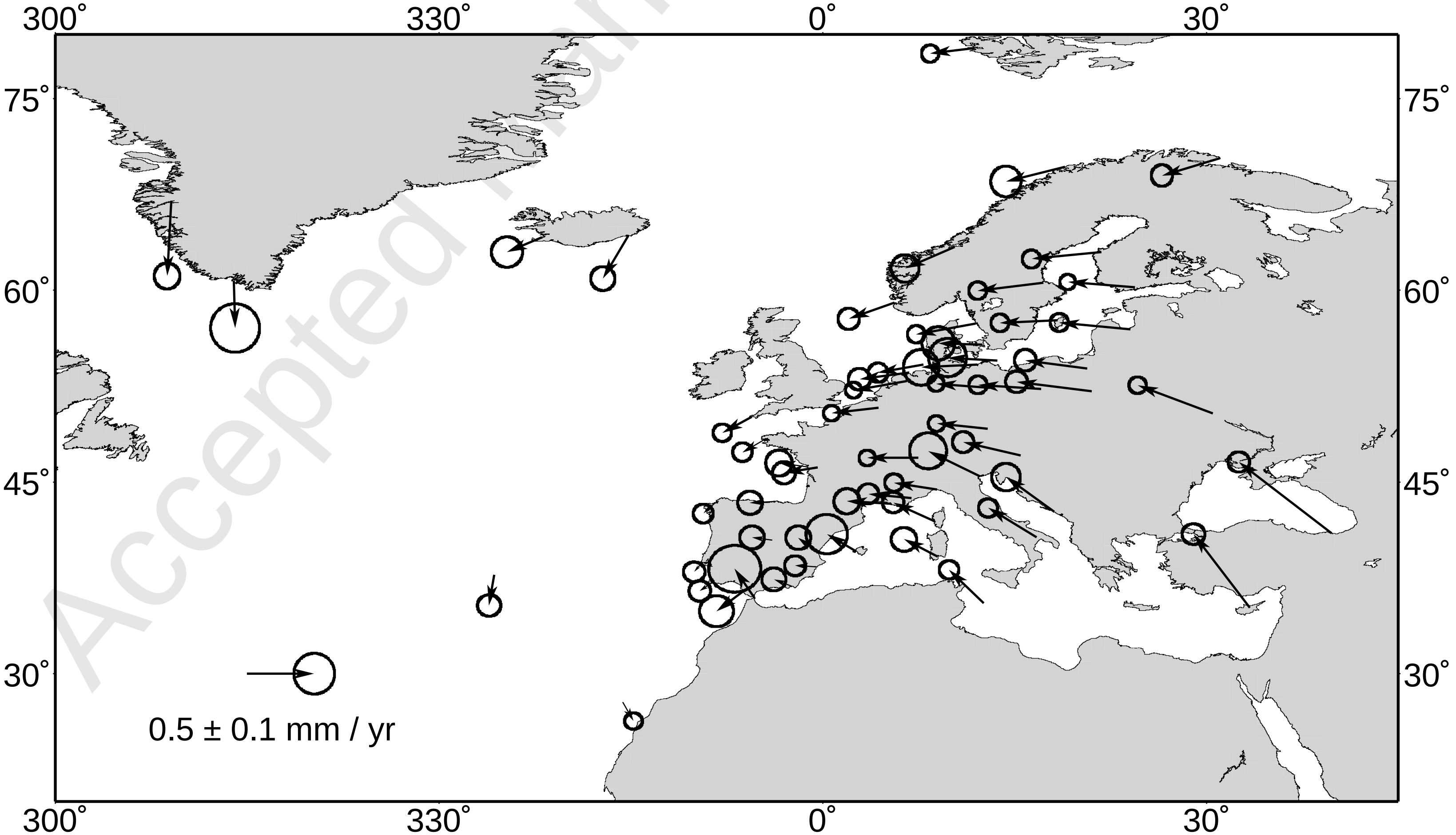


Figure 3 b top right

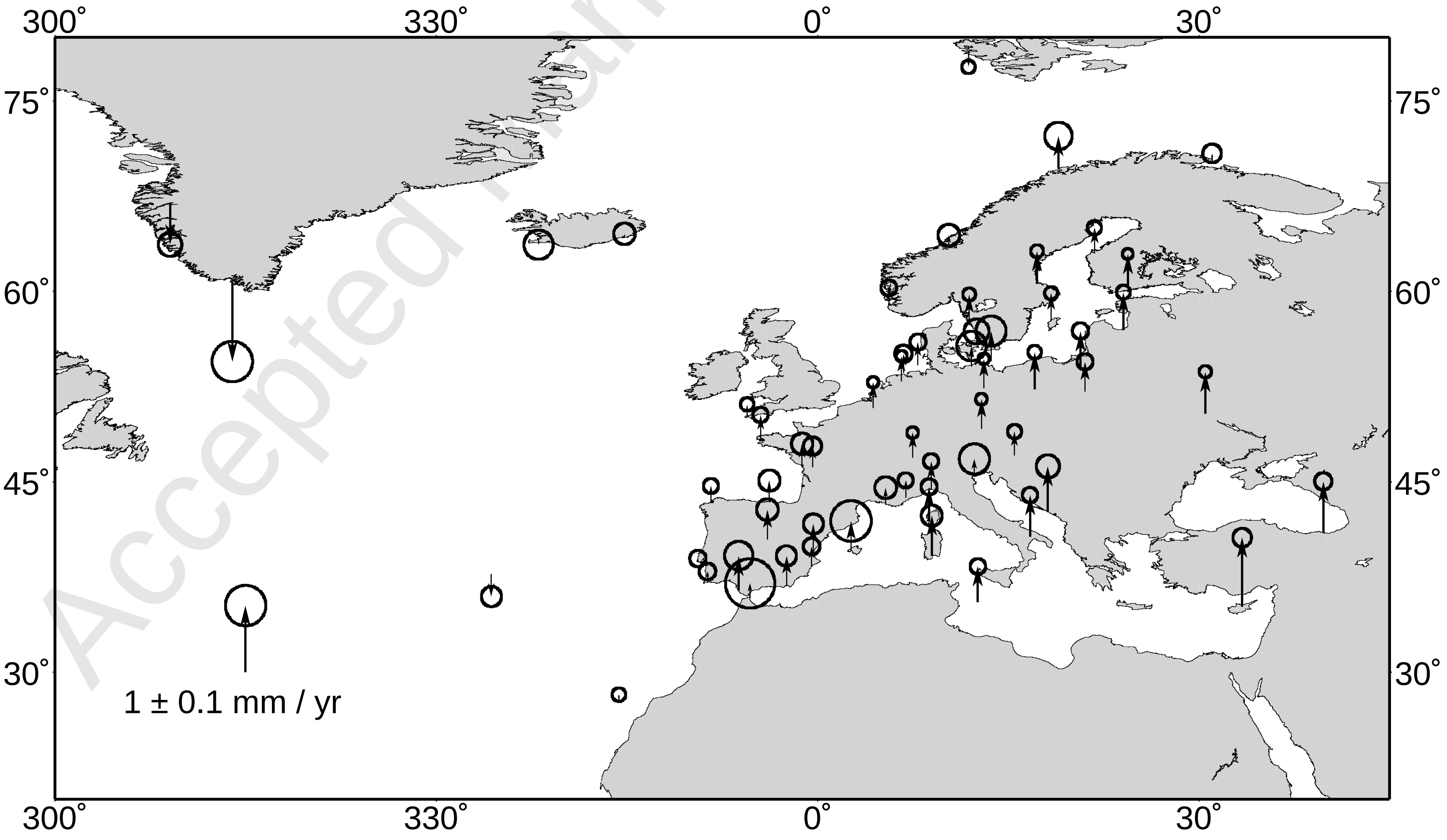


Figure 3 c bottom left

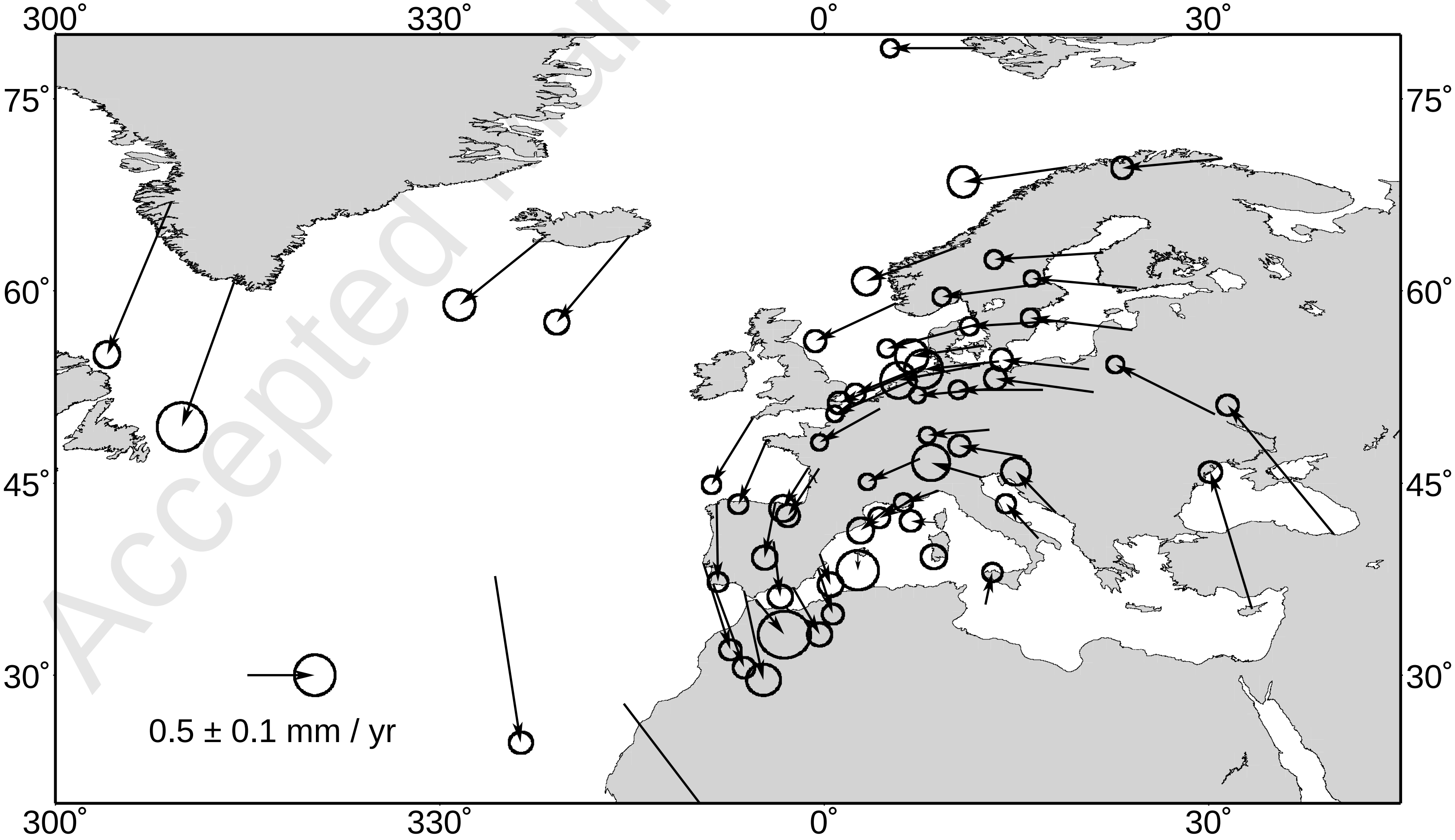
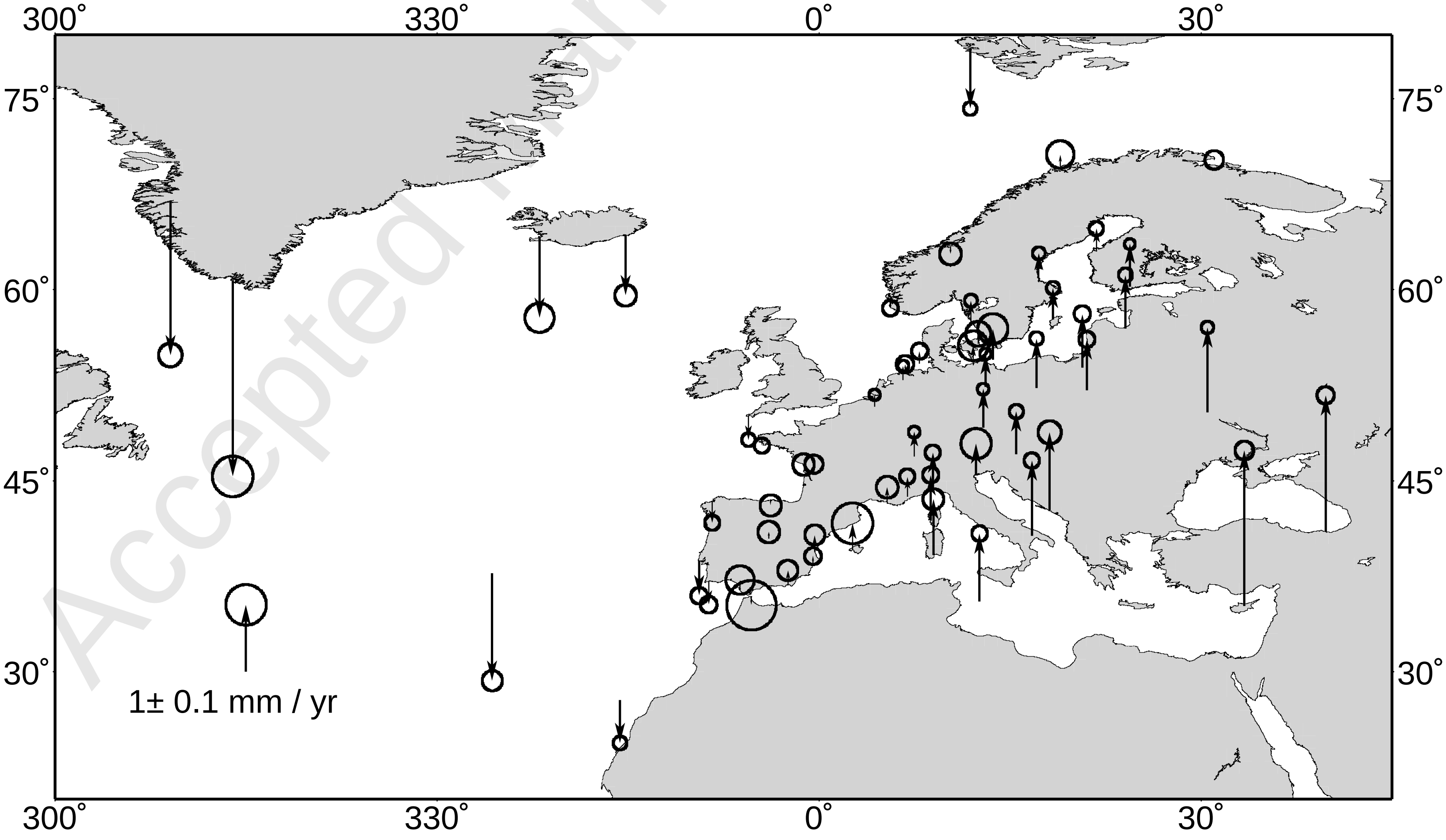
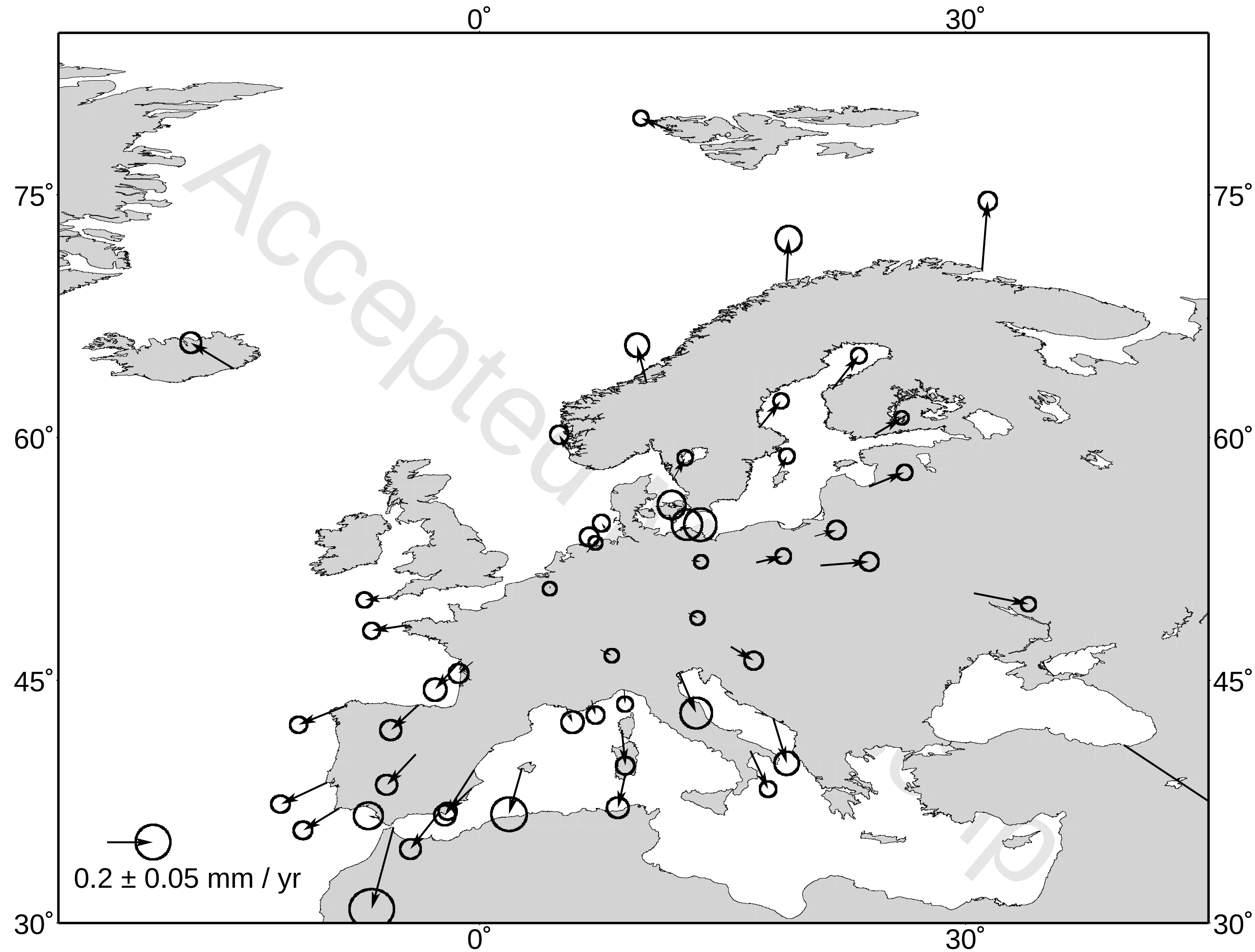
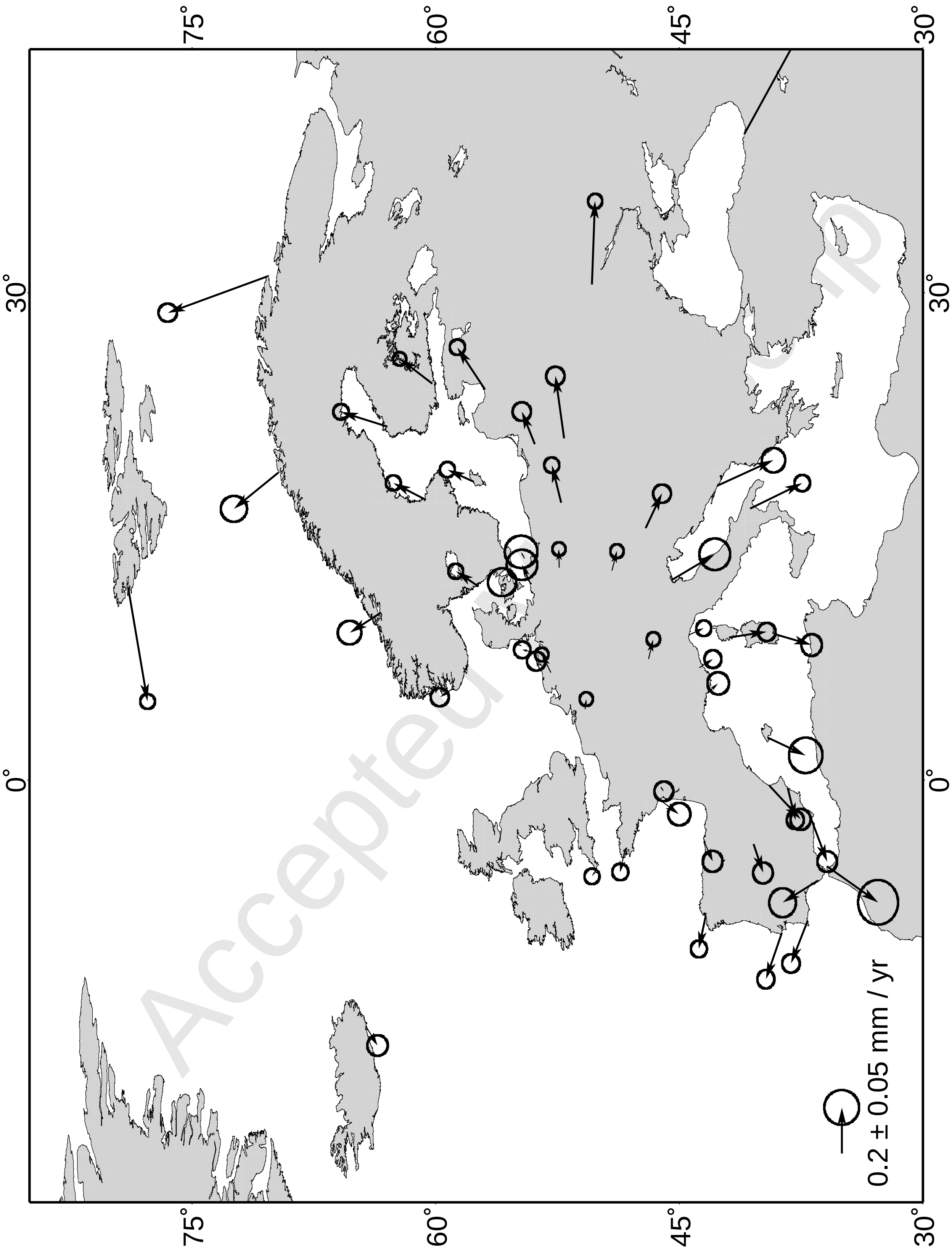


Figure 3 c bottom right




0°
30°
75°
60°
45°
30°
0.2 ± 0.05 mm / yr


75°
60°
45°
30°
30°
0°
0.2 ± 0.05 mm / yr

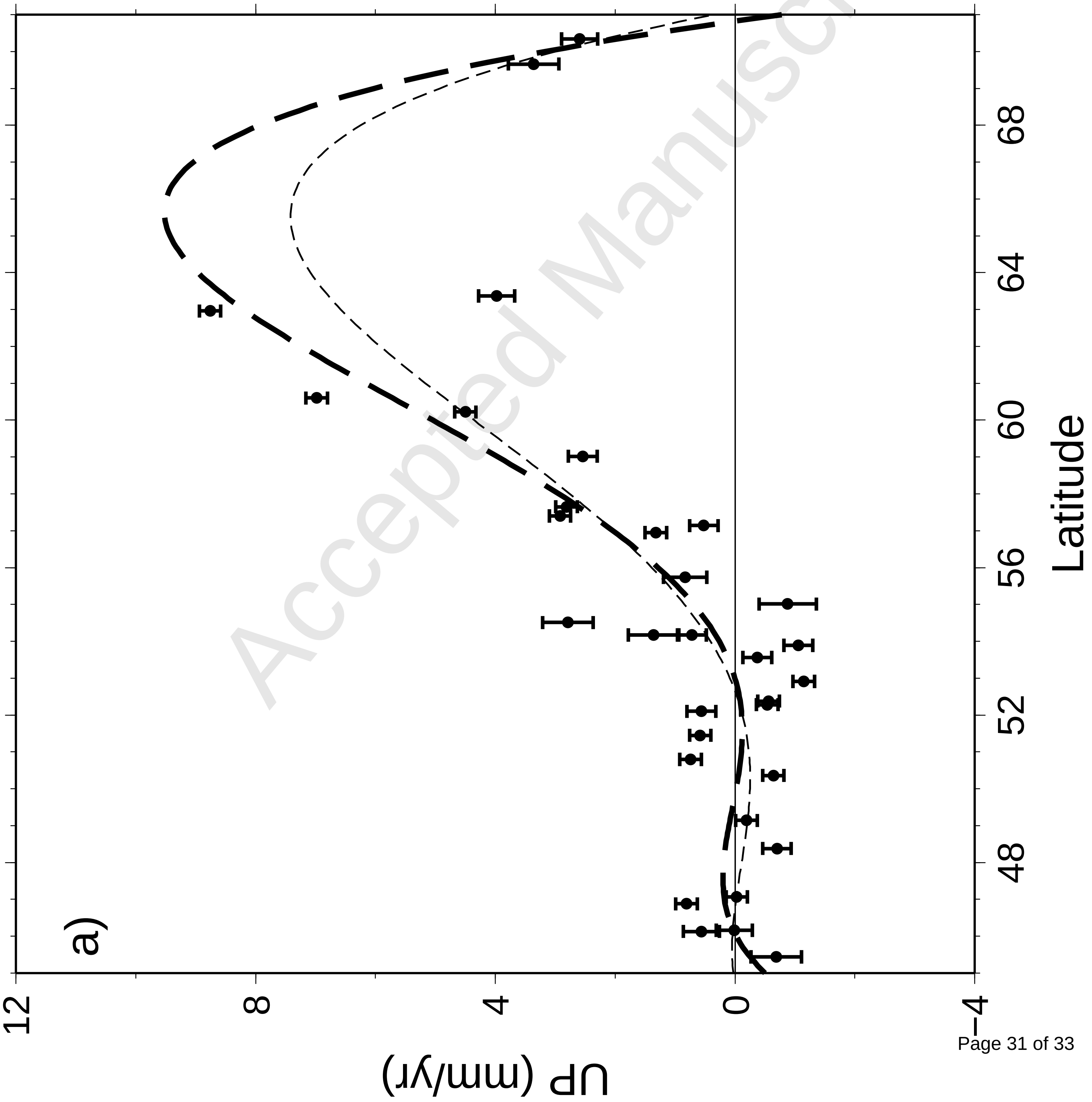

a)
UP (mm/yr)
Latitude
12
8
4
0
−4
48
52
56
60
64
68

Figure 5 b bottom left

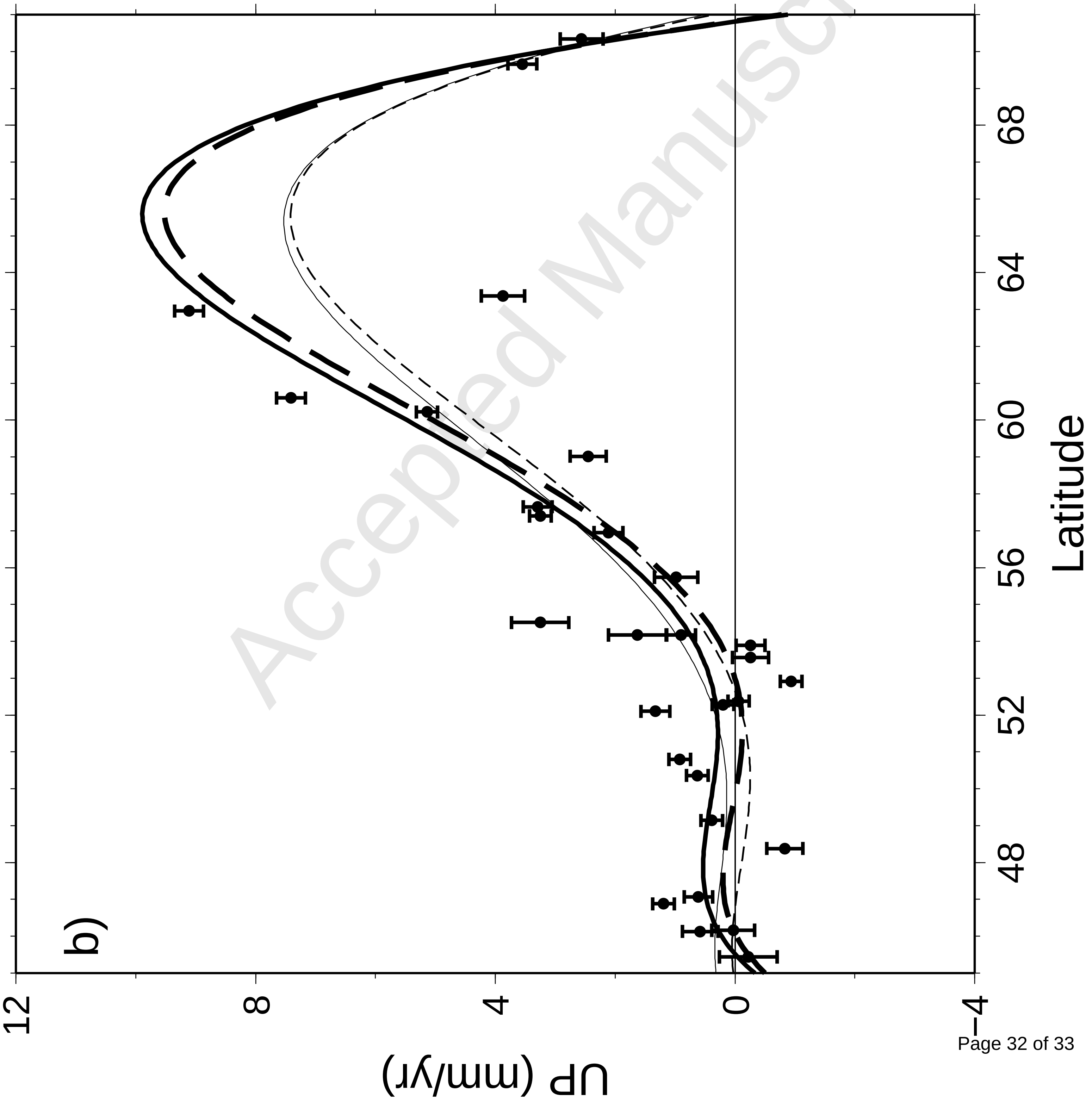


Figure 5 c bottom right