Diurnal variations in vertical strain observed in a temperate valley glacier

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Abstract. During a period of diurnal fluctuations in glacial flows speed, vertical strain was measured with sub-daily temporal resolution on Unteraargletscher, Switzerland. Mean vertical strain in boreholes up to 300-m deep out of 400-m-thick ice was found to fluctuate diurnally. Vertical strain rates were extensile in the daytime and compressive at night, with a magnitude of up to 10^{-3} day^{-1}. Horizontal surface strain was observed to fluctuate in a manner consistent with the vertical deformation. Diurnal surface flow speed variations correlated well with basal water pressures suggesting a basal control on temporal flow variations. Nevertheless, the strain rate measurements indicated that changes in surface flow speed is affected by internal ice deformation and not a direct measure of local basal motion. Basal conditions in the surrounding neighborhood and their temporal variations take important role in short-term glacial flow fluctuations.

1. Introduction

Temperate valley glaciers often exhibit diurnal variations in surface flow speeds. These variations appear to be triggered by changes in subglacial conditions such as subglacial water pressures and mechanical properties of subglacial sediments [e.g., *Willis,* 1995]. Because corresponding changes in surface slope and ice thickness are small, englacial deformation is generally assumed to have an insignificant effect on surface speeds. Hence, diurnal variations in flow speeds are usually thought to directly express temporal variations in basal motion.

A few direct short time scale studies of basal motion are reported [*Blake et al.,* 1994*; Iverson et al.,* 1995*; Engelhardt and Kamb,* 1998], but none of short-term variations in englacial strain during a period of diurnal fluctuations in surface speeds. In this paper, we present surface flow speeds and vertical strain-rate variation with depth measured on Unteraargletscher in the Bernese Alps of Switzerland in summer. The measurements demonstrate that englacial vertical strain-rate can vary diurnally and significantly affect ice motion at the surface. Horizontal strain also varied over short time scales suggesting that stresses are being transmitted horizontally, possibly in response to spatially non-uniform temporal changes in basal lubrication. It is concluded that in temperate glaciers, basal motion and internal ice deformation cannot be considered as independent processes.

2. Methods

Unteraargletscher is a temperate valley glacier in the Swiss Alps with a length of 11 km and it covers an area of 26 km^2 (Fig. 1A). Motion events, which are increases in the surface flow speed of 200% or more over a few days, usually occur several times in the ablation season on this glacier [*Iken et al.,* 1983*; Gudmundsson et al.,* 2000]. With the initial goal of better understanding such short time scale variations in glacial motion, an extended field experiment was carried out on Lauteraargletscher, a tributary of Unteraargletscher, from June to October 2001. All measurements were made at an altitude of 2480 m, about 100-m below the equilibrium line altitude (Fig. 1B). Maximum ice thickness at the measuring site was about 400 m [*Funk et al.,* 1994*; Bauder et al.* 2002].

2.1 Measurements

Vertical strain variation with depth was measured through repeated high-accuracy borehole depth measurements. We used a hot water technique to drill 50, 150, and 300-m deep boreholes of about 100-mm diameter with roughly 5-m spacing [*Iken,* 1988]. A 1-m long, 64-mm diameter plastic pipe with a 12-mm thick ring-shaped magnet on its upper rim was placed at the bottom of each borehole. The distances from the magnets to reference bars drilled into the surface ice directly above each of the boreholes was measured 1-8 times a day with a TEFLON measuring tape equipped with a magnetic sensor on its end [*Gudmundsson,* 1997]. Judging from repeated measurements, and from a reference experiment using a 1-m deep borehole where no vertical stretching was expected, the measurement error was estimated to be $\pm$3 mm.

Surface velocities close to the drilling site (site 313 in Fig. 1B) were determined using static relative GPS measurements [*Hofmann-Wellenhof et al.,* 2001]. The reference station was situated on the north flank of the glacier about 700 m from the drilling site (Fig 1B). Hourly surface flow speed was calculated from a 4-h running mean of the horizontal displacement. In addition, twice a day (within 2-h of 6:00 and 18:00) from 22 to 27 August, the positions of three other poles forming a triangle with sides of about 300 m (strain array in Fig. 1B) were surveyed. These surveys were used to examine the surface strain pattern.

Subglacial water pressures were registered every 15-30 min with a vibrating wire pressure transducer lowered into a 380-m bottom-reaching borehole at 200-m away from the survey site (Fig. 1B).

2.2 Calculation of strain rates

Successive measurements of the borehole depths were used to determine the vertical strain-rate variation. The relative displacements plotted in Figs. 2B, 3B, and 4B reflect both the vertical strain and horizontal shear between each magnet and the surface. Assuming laminar flow, the horizontal shearing over the uppermost 300 m was estimated to be 2×10^{-4} m day^{-1} or less from the surface position measurements [*Paterson,* 1994], which is negligible compared with the measured displacements. Therefore, we assume that the relative displacement equals the total vertical strain over the borehole depth, and its rate of change is the vertical flow speed relative to the surface ice at the depth of each magnet. The vertical flow speeds at 50, 150, and 300 m were measured at the same times and then linearly interpolated (relative vertical speed is zero at z=0 m) to obtain a vertical speed distribution through out the day. This data, temporally interpolated to each 0.25-day interval, are plotted in Figs. 2C and 3C. From the spatially interpolated data, the vertical strain rate was calculated as the derivative of the speed along the depth.

From 22 to 27 August, we calculated the horizontal strain rate on the surface from the displacements of three poles surveyed twice a day [*Jaeger* 1969]. The strain rates in Fig. 4C were determined as a function of compass bearing for each period of 6:00-18:00 and 18:00-6:00 everyday. Deformational ellipses, representing deviation from a unit circle due to the deformation of the ice after a unit time, were averaged in the two periods and are shown in a magnified form in Fig. 4D.

3. Results

We focus on measurements from three distinct observational periods in summer 2001: from 20 June to 5 July, from 18 July to 1 August, and from 22 to 27 August. The first series of measurements shows how the ice responded to a heavy rainstorm on 27 June, which caused a clear change in surface speed (Fig. 2a). The storm started at 15:00 with precipitation reaching 6.3 mm per hour at 18:00. Shortly thereafter around 17:00, the surface flow speed started to increase and a maximum speed of 0.2 m day^{-1}, about twice the pre-storm speed, occurred at 22:00. Before this event, the depths of the three boreholes had increased monotonically (Fig. 2B) and the vertical strain rates were positive (extensile) and constant with time throughout the depth (Fig. 2C). On 28 June, the strain rate became negative. Close inspection of the data revealed that the compression started near the surface and then moved deeper into the ice. In the following days, rather complex patterns of temporal and spatial variation in vertical strain were observed. For example, large temporal variations in borehole depths were observed with the 300-m borehole becoming 50-mm deeper overnight from 30 June to 1 July. Although the surface flow speed reverted to its pre-storm pattern, the speed up on 27 June left a lasting impact on the englacial strain-rate distribution.

Another conspicuous event occurred from 18 July to 1 August (Fig. 3). In the beginning of this period, weather was cold with occasional snowfall, but on 21 July, temperature rose sharply causing intense surface melting of 70-mm water equivalent day^{-1}. Then a clear diurnal variation in the surface flow speed was established as a result of substantial melt water input in the daytime (Fig. 3A). The maximum speed occurred in the evening and the minimum speed in the morning. By 18 July, the 50-m borehole had closed off due to the freezing of water near the surface, but depth measurements could be continued for the other two boreholes. From 27 July to 1 August, large diurnal fluctuations in vertical strain were observed with the depths of the boreholes changing by up to 30-40 mm a day (Fig. 3C). In the daytime, the strain rate in the shallower region was extensile on the order of 10^{-3} day^{-1}, and at night it became compressive. Weaker, but similar, diurnal signals also occurred throughout most of 18-27 July. Furthermore, the strain rate was spatially non-uniform, particularly from 30 July to 1 August, with the deeper regions being compressive while the shallower regions were extensile.

Clear diurnal fluctuations in the surface flow speed were again observed from 22 to 27 in August (Fig. 4A), but fluctuations were smaller than in the previous period. By 22 August, the 150-m borehole was frozen near the surface and the 300-m borehole was closed at 173-m below the surface, probably due to the ice deformation. However, the measurement was continued without the magnet by feeling the decreased tension in the tape when the magnetic sensor contacted the pinched-off point at 173 m. Repeated measurements indicated an uncertainty of ± 5 mm. Although data is available only for 4 days, diurnal oscillations in borehole depth are clearly observed (Fig. 4B).

The horizontal strain rate showed diurnal oscillation in the direction of and perpendicular to the glacier flow with only the exception of 24 August (Fig. 4C). Strain ellipses in Fig. 4D display general figures of surface strain regimes in the daytime (6:00-18:00) and at night (18:00-6:00). Their distinguishing features are compressive strain along the flow direction in the daytime and transversal extensile strain at night of about 10^{-4} day^{-1}. Combined with the vertical strain rate measured in the borehole, the ice deformation in the upper half of the glacier can be described as follows. From morning to evening, ice contracts horizontally in the flow direction and expands vertically. From evening to the next morning, it expands horizontally across the flow direction and contracts vertically.

4. Discussion

The important aspect of the vertical strain measurements in the first period is the temporal reversal in vertical strain rate at the rainstorm. Similar strain-rate reversal has been observed previously during a major motion event in the same glacier [*Gudmundsson*, 2002]. Before the fast flow on 27 June, the observed steady and uniformly distributed extensile vertical strain rate is consistent with the spatial distribution of annual velocities determined by aerial photographs [*Gudmundsson and Bauder,* 1999]. The compressive vertical strain from June 27 to 28 is presumably related to spatially uneven acceleration of the glacier as a response to the large amount of water input by the rainstorm. This event may have triggered an evolution in subglacial hydrological conditions and caused the subsequent vertical strain rate fluctuations.

An unexpected finding in this study is the diurnal fluctuations in the strain rate at the end of July and in August. One of the clues to understand the cause for the strain oscillation can be found in the subglacial water pressure variations. The water level was well correlated with the flow speed and borehole depth (Figs. 3A, B, 4A, B). Furthermore, during the period of diurnal strain rate oscillations, water levels changed by more than 100 m a day, indicating a high drainage efficiency of the subglacial hydrological system. The hydrological drainage system was expected to progressively develop up the glacier in the ablation season, and its evidence is seen in the water level trend from 23 July to 2 August (Fig. 3A). While the melt rate remained approximately constant, the diurnal peak-to-peak variation in water level increased with time and the daily minimum level decreased. This suggests the following interpretation of the diurnal fluctuations in the strain regime. When the water pressure increases in the daytime, the glacier accelerates. This acceleration is higher in the upper reach because the subglacial drainage system there has not developed as well as that in the study area, and so the water pressure is higher in the upper reach. Higher flow speed in the upper reach causes longitudinal compression in the study area, which affects the vertical and surface strain regime in the daytime. At night, the flow speed in the upper reach decreases to about the same speed as that in the study area and then the longitudinal compression disappears.

Interestingly, the vertical strain rate was not uniform with depth when the vertical strain varied diurnally. This sort of vertically non-uniform strain rate has been suggested theoretically to be associated with short-scale spatial variations in basal motion [*Balise and Raymond,* 1985; *Vonmoos,* 1999]. When the basal conditions are non-uniform along the glacier, as we expect for the periods of the diurnal strain rate signals, predicted vertical strain rate is no longer constant with depth. Although the previous theoretical works have been limited to small amplitude perturbations and linear rheology, non-uniformity in vertical strain-rate distribution is also appeared in a numerical study with more realistic ice rheology. [*S. Sugiyama et al*, Numerical investigation of the effects of temporal variations in basal lubrication on englacial strain-rate distribution, submitted to the *Annals of Glaciology,* 2002].

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Figure Captions

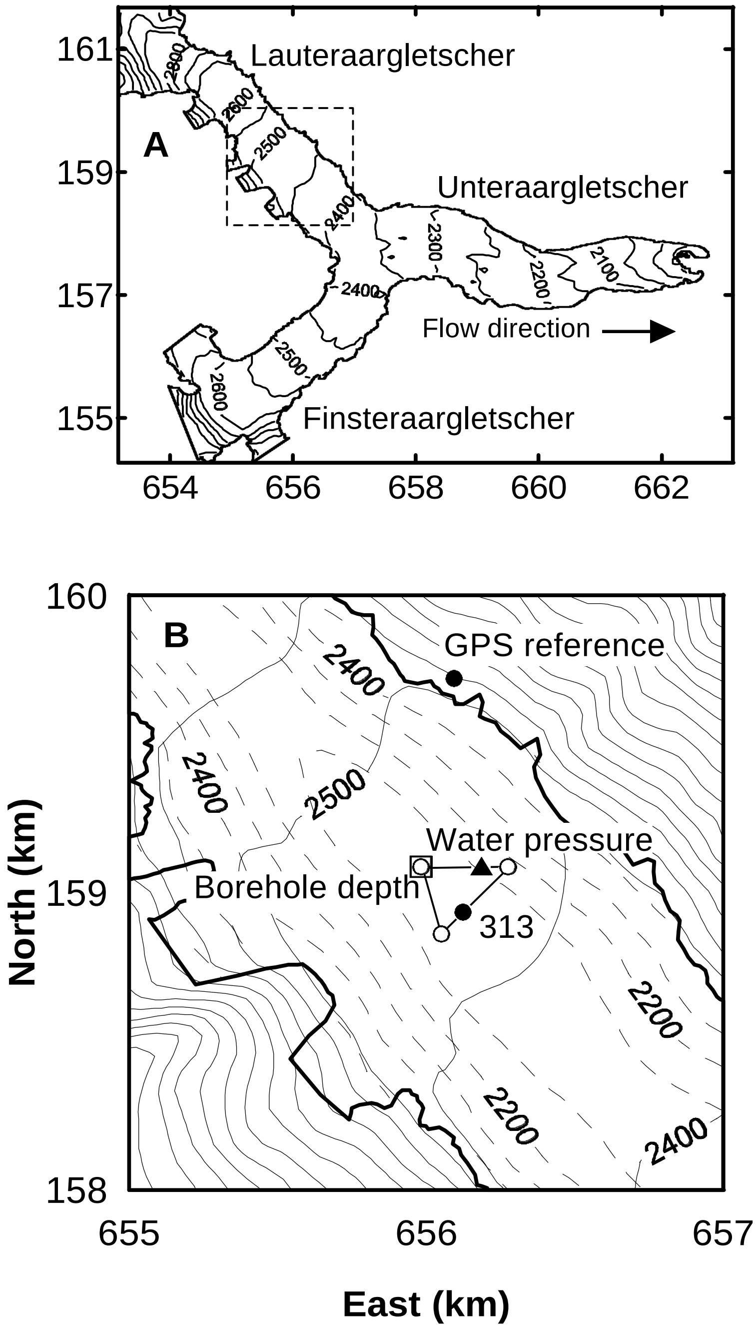
Figure 1. (**A**) Map of Unteraargletscher and its tributaries. (**B**) The study area on Lauteraargletscher (smaller square in (**A**)). Solid and broken contour lines indicate the surface and bed topography, respectively. Elevations are in meters above sea level. Solid circles are positions of a pair of GPS antennas for continuous measurement of surface flow. Open circles connected with solid lines are the strain array, the open square is the location of the boreholes, and the solid triangle is the location of the water pressure measurements. Coordinates correspond to the official Swiss coordinate system.

Figure 2. (**A**) Surface flow speed (red) and hourly precipitation rate. Precipitation was measured on the north flank of the lower reach of the glacier. (**B**) Relative borehole depths in the 50-m (solid square), 150-m (open circle), and 300-m (solid circle) boreholes. (**C**) Depth

distribution of vertical flow speed and vertical strain rate (right side) during late June and early July 2001. Ticks of the temporal axes indicate 0:00 local time. The arrow in (**A**) shows the motion event described in the text. In (**B**), measurements in the 150-m borehole were interrupted 1-4 July because snow temporarily clogged in the borehole. In (**C**), z-axis is pointing upward from the origin at the glacier surface.

Figure 3. The same measurements as Fig. 2, but later in summer. Black curve in (**A**) shows water level in the bottom-reaching borehole measured from the glacier bed instead of precipitation.

Figure 4. (**A**) Surface flow speed (red) and borehole water level. (**B**), Changes in the 173-m borehole depth. (**C**), Horizontal strain rate on the surface. Strain rates were measured twice a day at 0:00 and 12:00, and the contours estimated by linear interpolation along the time axis. (**D**), Mean strain rate ellipses of horizontal deformation in each time period of a day during late August 2001. These represent the original state (black), after the deformation from 6:00 to 18:00 (blue) and that from 18:00 to 6:00 (red) in magnified forms by a factor of 5×10^3. On the right side in (**D**) is a scale that shows 10^{-4} day^{-1} of extensile strain rate in N-S and the equivalent compression in W-S.



Lauteraargletscher
A
Unteraargletscher
Flow direction
Finsteraargletscher
2800
2600
2500
2400
2300
2200
2100
161
159
157
155
654
656
658
660
662
B
GPS reference
Water pressure
Borehole depth
313
North (km)
East (km)
160
159
158
655
656
657

Fig.1

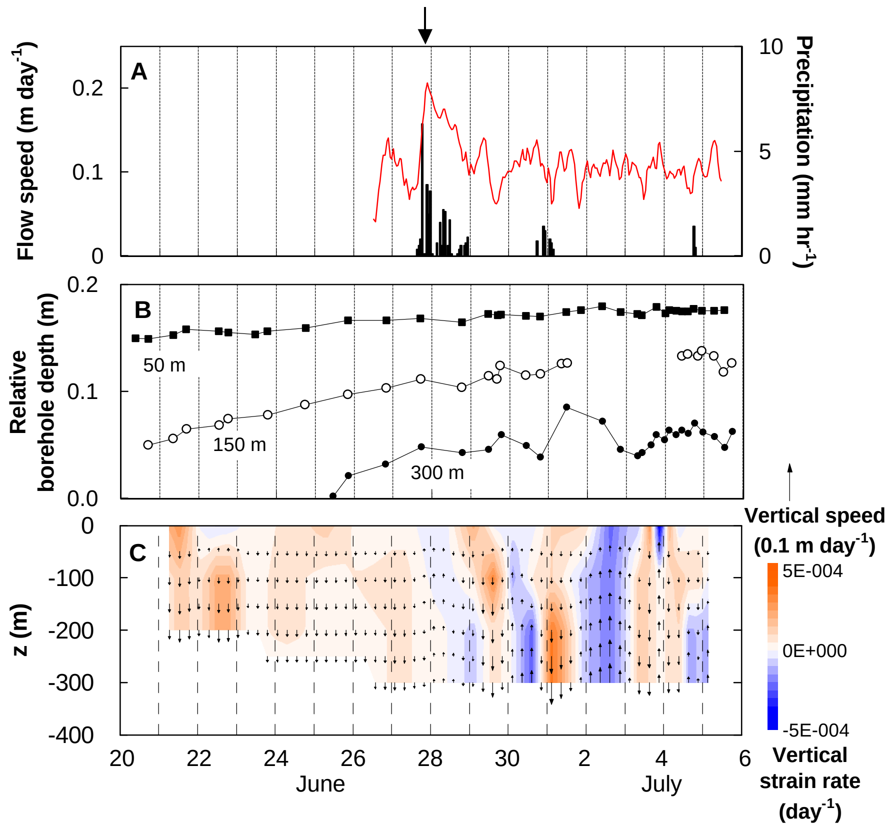
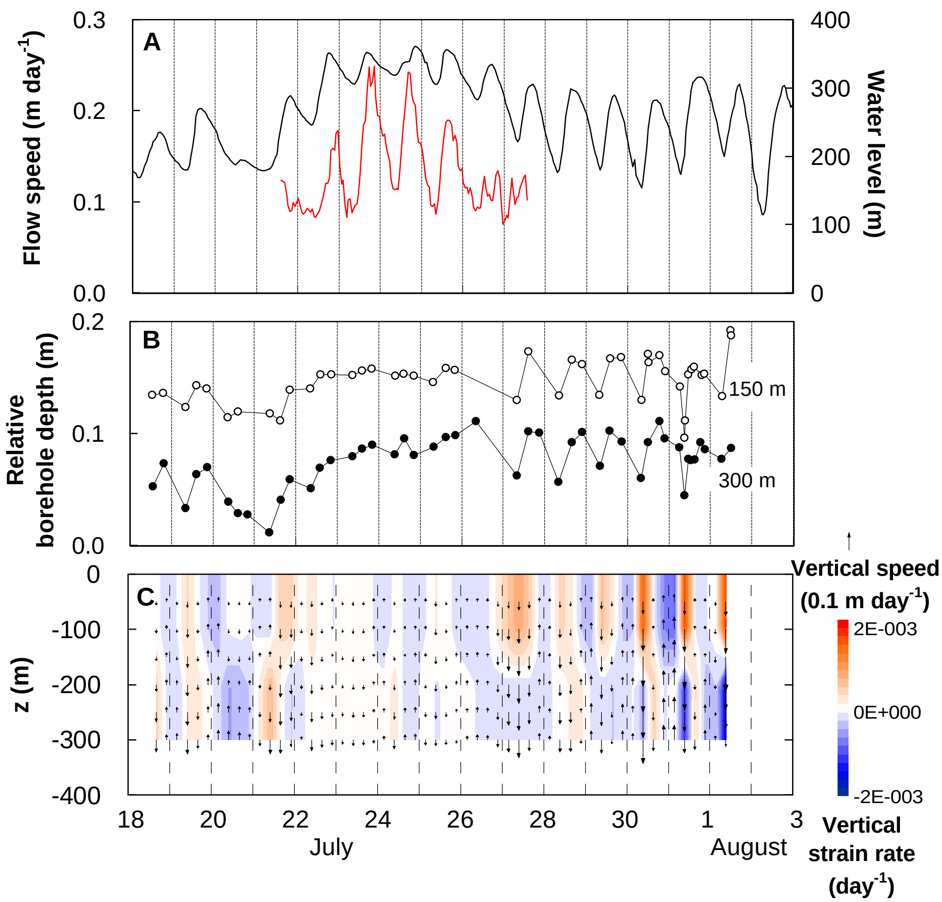
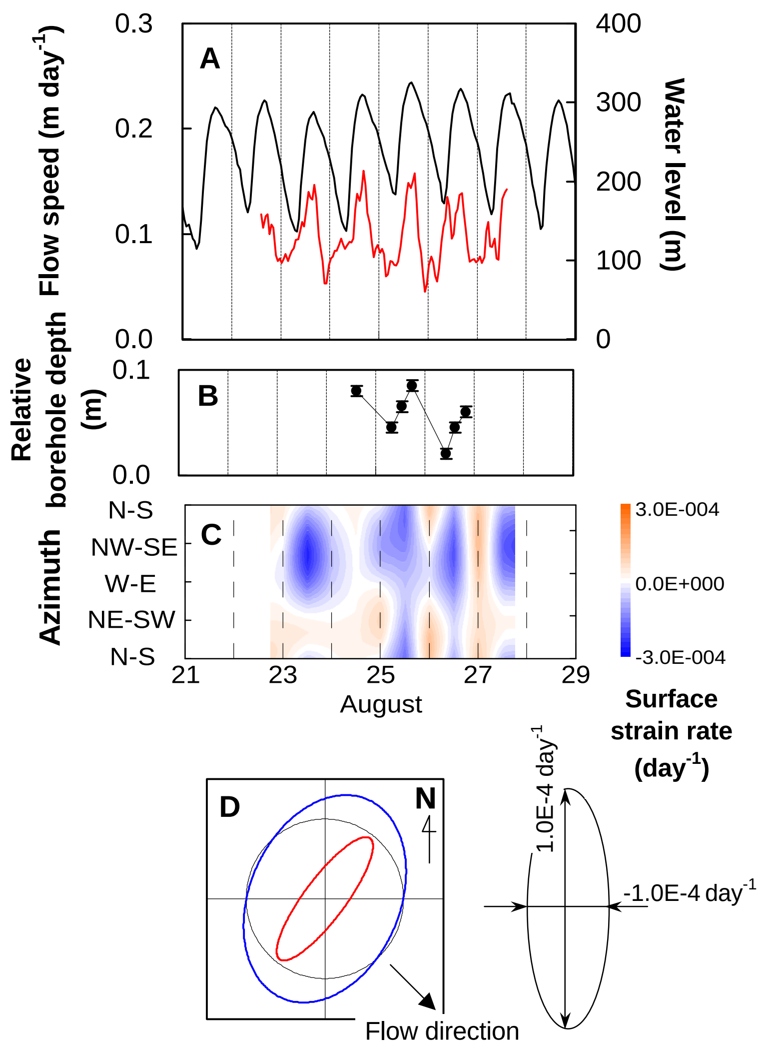

A
B
C
Flow speed (m day-1)
Precipitation (mm hr-1)
0.2
0.1
0
10
5
Relative borehole depth (m)
0.2
0.1
0.0
50 m
150 m
300 m
z (m)
0
-100
-200
-300
-400
20
22
24
26
28
30
2
4
6
June
July
Vertical speed (0.1 m day-1)
5E-004
0E+000
-5E-004
Vertical strain rate (day-1)

Fig. 2



A
B
C
Flow speed (m day^{-1})
Water level (m)
0.3
0.2
0.1
0.0
400
300
200
100
0
Relative borehole depth (m)
0.2
0.1
0.0
150 m
300 m
z (m)
0
-100
-200
-300
-400
18
20
22
24
26
28
30
1
3
July
August
Vertical speed (0.1 m day^{-1})
2E-003
0E+000
-2E-003
Vertical strain rate (day^{-1})

Fig. 3



A
B
C
D
Flow speed (m day-1)
Water level (m)
0.3
0.2
0.1
0.0
400
300
200
100
0
Relative borehole depth (m)
0.1
0.0
Azimuth
N-S
NW-SE
W-E
NE-SW
N-S
21
23
25
27
29
August
3.0E-004
0.0E+000
-3.0E-004
Surface strain rate (day-1)
N
Flow direction
1.0E-4 day-1
-1.0E-4 day-1

Fig. 4