

## Earth tide forcing of glacier drainage

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Received 10 April 2002; revised 9 July 2002; accepted 3 September 2002; published 7 January 2003.

[1] Fourier analysis reveals that winter electrical self potential ( $SP$ ), water pressure ( $P_w$ ), and electrical conductivity ( $EC$ ) time series collected beneath Haut Glacier d'Arolla, Switzerland, are forced by earth and atmospheric tides. Forcing is dominant during periods of expanding bedrock, consistent with glacier substrate deformation periodically driving water from the ice body into the bed. This may modify the strength of subglacial sediments, and could therefore influence glacier drainage and motion on a global scale. **INDEX TERMS:** 1827 Hydrology: Glaciology (1863); 1249 Geodesy and Gravity: Tides—Earth; 1829 Hydrology: Groundwater hydrology; 0915 Exploration Geophysics: Downhole methods. **Citation:** Kulesa, B., B. Hubbard, G. H. Brown, and J. Becker, Earth tide forcing of glacier drainage, *Geophys. Res. Lett.*, 30(1), 1011, doi:10.1029/2002GL015303, 2003.

### 1. Introduction

[2] Earth tides refer to the deformation of the solid body of the Earth on many different timescales as it rotates in the gravity fields of the moon and the sun [Stacey, 1992, pp. 115–133]. Since these earth-tide forces will also cause glacier substrates to deform, subglacial mechanical and hydrological processes are likely to be affected. Indeed, earth tides are known to dilate confined groundwater aquifers [Bredehoeft, 1967; Hsieh *et al.*, 1987], which are effectively analogous to subglacial aquifers [Stone and Clarke, 1993; Kulesa, 2000], thereby inducing well water-level variations of up to several  $10^{-1}$  m [Fitts, 2002] and sometimes considerable groundwater flow [Gieske and de Vries, 1985]. Since Clarke [2002] demonstrated that atmospheric pressure changes can travel to the base of valley glaciers, atmospheric tides (periodic changes in air pressure caused by solar activity) could potentially also be of importance [Rojstaczer, 1988; Ritzi *et al.*, 1991]. However, no empirical evidence of either earth or atmospheric tide forcing of subglacial aquifers has yet been reported. In contrast to ocean tides [Walters and Dunlap, 1987; Echelmeyer and Harrison, 1989; Harrison *et al.*, 1993; Anandakrishnan and Alley, 1997; Bindenschadler *et al.*, 2002], earth tides would affect any grounded ice mass ubiquitously, and could therefore represent an important control on basal drainage and motion at a global

scale. In this study, we interpret borehole-based subglacial hydrological data recorded through the winter months at Haut Glacier d'Arolla, Switzerland, in terms of earth tide forcing.

### 2. Field Site

[3] Haut Glacier d'Arolla is an Alpine valley glacier located at the head of Val d'Hérens, Switzerland. Borehole video and penetrometer studies [Harbor *et al.*, 1997] suggest that the glacier is predominantly underlain by unconsolidated sediments of variable thickness. The glacier typifies a warm-based ice mass, characterized by distributed subglacial drainage during winter [Hubbard and Nienow, 1997]. Under these conditions, basal water pressures are high and invariant, and melt water delivery to the glacier bed is restricted to minor, but relatively steady, basal melting. Once at the bed, water is typically slow-moving and characterized by high and steady  $EC$ s, reflecting long-term solute acquisition [Stone, 1993; Kulesa, 2000].

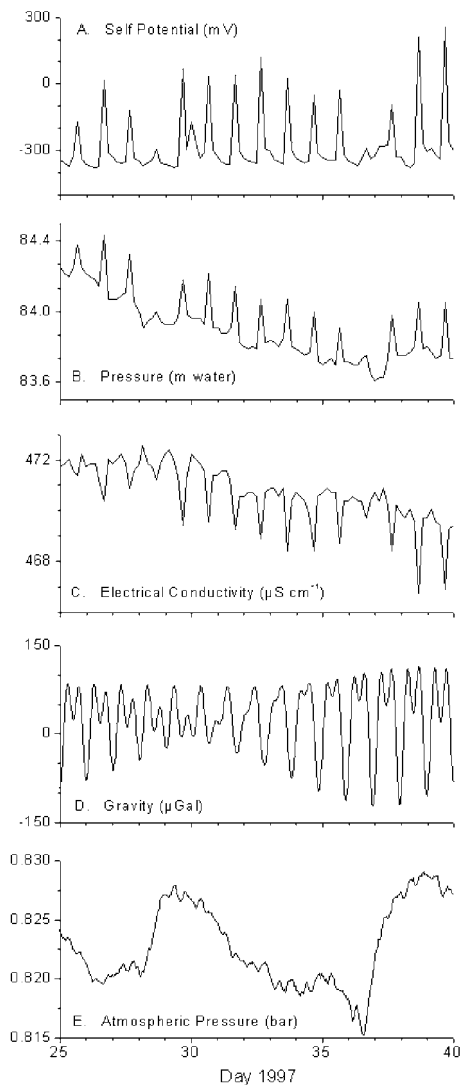
### 3. Methods

[4] In this study, we report subglacial  $SP$ ,  $P_w$ , and  $EC$  data measured in five boreholes, drilled by pressurized, hot water near the eastern margin of the ablation area of Haut Glacier d'Arolla, between September 1996 and May 1997. Subglacial  $SP$  studies are rare, and include measurements of streaming potentials beneath Trapridge Glacier, Canada [Blake and Clarke, 1999], and coincident streaming and electrochemical potentials beneath Haut Glacier d'Arolla during the 1996 melt season [Kulesa, 2000].

[5] The glacier surface locations of all boreholes were determined by optical survey, and the bed locations by borehole inclinometry [Harbor *et al.*, 1997]. Typical borehole depth was  $\sim 95$  m, and borehole bases were located within 30 m of each other. All boreholes were well connected to a major subglacial drainage pathway prior to the reported 1996–97 winter. All sensors were located within 0.5 m of the glacier bed, and all  $SP$  measurements were differential between the glacier bed and an extra-glacial reference electrode.

[6] Changes in gravity are commonly used as a proxy for the periodic vertical deformation of the solid earth caused by earth tides, and air pressure records readily reflect atmospheric tides. However, neither parameter was recorded at our field site. We therefore used the software packages *WPAREXMT* and *MT80W* (available in the public domain of the International Data Center for Earth Tides, <http://www.astro.oma.be>) to determine the changes in gravity at

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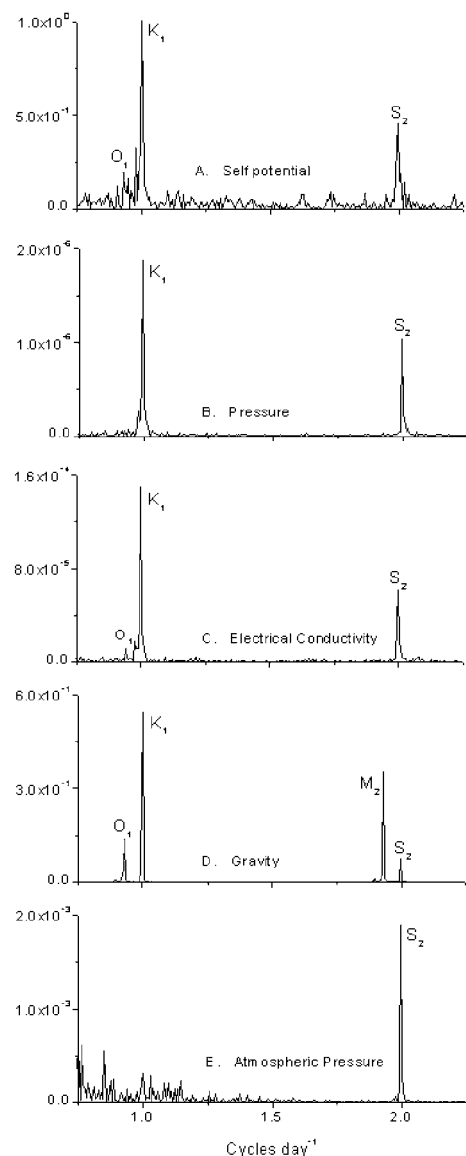
**Figure 1.** Representative time series between days 25 and 40, 1997.

the closest tidal station (Strasbourg, France). Atmospheric pressure data recorded at the closest monitoring station (Evolène, Switzerland; available on order from *MeteoSchweiz*, <http://www.meteoschweiz.ch>) were used as the desired atmospheric pressure proxy.

#### 4. Results

[7] Through the 1996–97 winter, base (minimum daily) *SPs* were consistently negative but of different mean magnitude ( $< -300$  mV to  $> -100$  mV) in the four boreholes studied.  $P_W$  was approximately equal to ice overburden pressure ( $\sim 85$  m equivalent borehole water level), and base *EC* was high ( $\gg 100$   $\mu\text{S cm}^{-1}$ ) relative to that measured during the preceding summer melt season ( $10^0$  to  $10^1$   $\mu\text{S cm}^{-1}$ ). Diurnal cycles in *SP*,  $P_W$ , and electrical conductivity persisted throughout the 1996–97 winter, and had typical magnitudes of  $10^2$  mV (Figure 1a),  $10^{-1}$  m (Figure 1b), and  $10^0$   $\mu\text{S cm}^{-1}$  (Figure 1c) respectively. However, *SPs* occasionally exceeded  $10^3$  mV towards the end of the winter, and reached a maximum amplitude of  $> 2.3 \times 10^3$  mV in one

borehole at the beginning of May 1997 [Kulesa, 2000], ranging among the largest *SP* anomalies measured near the Earth's surface [Reynolds, 1997, p. 492]. Relative to these diurnal cycles, higher-frequency, but generally lower magnitude, *SP* variations were also present in the records (Figure 1a). These diurnal and higher-frequency *SP* cycles were typically in phase with the  $P_W$  cycles, and opposed to the *EC* cycles (Figures 1a to 1c). The magnitudes of the gravity variations (at Strasbourg) through the 1996–97 winter often exceeded  $100$   $\mu\text{Gal}$ , and the complex signal pattern clearly reflects the presence of several superimposed tidal components (Figure 1d). Atmospheric pressure (at Evolène) also varied on different temporal scales, but predominantly semi-diurnal fluctuations with characteristic magnitudes of  $\sim 10^{-3}$  bar were typically superimposed on



**Figure 2.** Fourier power spectra for the 1996–97 winter.  $K_1$ ,  $O_1$ ,  $S_2$ , and  $M_2$  respectively represent the luni-solar diurnal, principal lunar diurnal, principal solar semi-diurnal, and principal lunar semi-diurnal components.

**Table 1.** Major Components of the Daily Earth Tide Signal in the Power Spectra Illustrated in Figure 3

Tide Component	Frequency ( $Cycles\ d^{-1}$ )				
	Self Potential	Pressure	Conductivity	Gravity	Atmospheric Pressure
$K_1$	1.002	1.002	1.002	1.002	1.002
$O_1$	0.932	–	0.943	0.932	–
$S_2$	1.998	1.998	1.998	1.998	1.998
$M_2$	–	–	–	1.934	–

$K_1$ ,  $O_1$ ,  $S_2$ , and  $M_2$  respectively represent the luni-solar diurnal, principal lunar diurnal, principal solar semi-diurnal, and principal lunar semi-diurnal components.

longer-term background changes that had characteristic magnitudes of  $\sim 10^{-2} bar$  (Figure 1e).

## 5. Influence of Earth Tides

[8] Throughout the winter the little surface melt water generated re-freezes within the snow pack. Geothermal melting at the glacier bed is temporally and spatially uniform. The winter diurnal and higher-frequency  $SP$ ,  $P_W$ , and  $EC$  cycles cannot therefore be explained in terms of concomitant variations in melt water production or delivery. Method-related influences are also discounted, since  $SP$  cables were of the same color and of similar length; they were attached to the same data logger; they were thermally isolated beneath the surface snow-pack; they were exposed as a bundle along the same side of the pole on which the data logger was mounted; and all  $SP$  measurements were taken relative to the same extra-glacial reference electrode. Earth and atmospheric tide forcing therefore represents the only mechanism that could generate the recorded cycles.

[9] In order to elucidate the nature of the tidal forcings, we applied the Fast Fourier Transform to our records. Each power spectrum in Figure 2 was normalized by dividing through the number of data points in the time series to allow comparison of the relative strength of the different spectral components. The FFT power spectra of the recorded  $SP$ ,  $P_W$ , and  $EC$  time series are dominated by several components falling broadly into a bimodal distribution, with major modes at  $\sim 1\ d^{-1}$  and  $\sim 2\ d^{-1}$  and a minor diurnal mode at a slightly lower frequency (Figures 2a to 2c). The major diurnal frequencies in all three components are  $1.002\ d^{-1}$ , and the minor diurnal frequencies (measured only in  $SP$  and  $EC$ ) are respectively  $0.932$  and  $0.943\ d^{-1}$ . The major semi-diurnal frequency is  $1.998\ d^{-1}$  for all three components. Gravity (Figure 2d) has major and minor diurnal modes at  $1.002\ d^{-1}$  and  $0.932\ d^{-1}$ , and major and minor semi-diurnal modes at  $1.998\ d^{-1}$  and  $1.934\ d^{-1}$ , while atmospheric pressure is only characterized by a major semi-diurnal mode at  $1.998\ d^{-1}$  (Figure 2e). These different frequencies present in our records are summarized in Table 1, along with the dominant components of the corresponding astronomical tides, which are equal to those commonly observed at confined groundwater aquifers [Bredehoeft, 1967; Ritz et al., 1991]. The major (in all records except atmospheric pressure) and minor (in gravity,  $SP$  and  $EC$  only) diurnal modes respectively correspond to the luni-solar ( $K_1$ ) and principal lunar ( $O_1$ ) diurnal tidal components. The major and minor (in gravity only) semi-diurnal modes respectively correspond to the principal solar ( $S_2$ ) and principal lunar ( $M_2$ ) semi-diurnal tidal components. These exact corre-

pondences provide compelling evidence that the diurnal and semi-diurnal winter borehole fluctuations recorded at Haut Glacier d'Arolla were forced by earth tides.

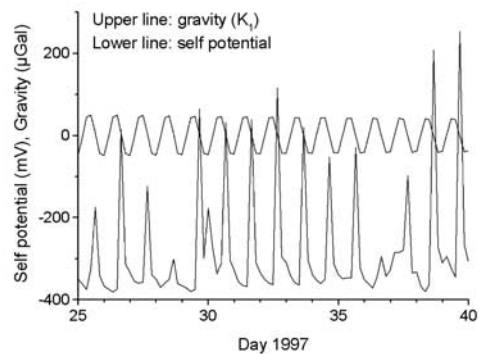
## 6. Influence of Atmospheric Tides

[10] It is remarkable to note that the strong principal lunar semi-diurnal earth tide component ( $M_2$ ) is absent from all borehole records (Figures 2a to 2c). This suggests that glacier drainage is less susceptible to semi-diurnal than to diurnal earth tide forcing, considering that the luni-solar diurnal earth tide component ( $K_1$ ) is dominant in all of these records, and the principal lunar diurnal earth tide component ( $O_1$ ) is also present in  $SP$  and  $EC$ . The fact that the principal solar tidal component ( $S_2$ ) is strong in all boreholes records (Figures 2a to 2c) would contradict this inference in the first instance, since this component is much weaker than the principal lunar semi-diurnal component ( $M_2$ ) in the earth tide spectrum (Figure 2d). This apparent contradiction may however be resolved if we allow atmospheric tides to force our records, observing that  $S_2$  is the dominant component in the atmospheric tide spectrum (Figure 2e). With specific regard to Clarke's [2002] recent arguments and the fact that confined groundwater aquifers are often forced by atmospheric tides (above), we therefore suggest that the atmospheric principal solar tidal component ( $S_2$ ) could have produced a measurable effect in our subglacial aquifer records (Figures 2a to 2c).

## 7. Tide-Induced Basal Processes

[11] In order to elucidate the principal, diurnal forcing mechanism, we focus on the luni-solar diurnal earth tide component ( $K_1$ ), which is strongest in all borehole records (Figures 2a to 2c) and in the gravity spectrum (Figure 2d). We compare this component, filtered out of the Strasbourg gravity variations (Figure 1d), with the  $SP$  data, which were most responsive to tidal forcing (Figures 2a to 2c), in Figure 3. It is readily apparent the positive  $SP$  pulses consistently coincide with falling gravity, and therefore with an 'expanding' earth.

[12] Our records indicate that  $SP$  and  $P_W$  typically varied in phase, and that  $SP$  and  $EC$  typically varied out of phase (Figure 1). This pattern is consistent with the dominance of streaming potentials over electrochemical potentials [Blake



**Figure 3.** Time series of the luni-solar diurnal ( $K_1$ ) gravity component (calculated) and subglacial electrical  $SP$  between days 25 and 40, 1997.

and Clarke, 1999; Kulesa, 2000]. Since positive streaming potential pulses coincided with falling gravity (Figure 3), we therefore infer that during times of subglacial bedrock expansion water flow was driven past the *SP* sensors. At the same time as this flow occurred, slight increases in  $P_W$  and slight decreases in *EC* were recorded (Figures 1a to 1c). Since the bed of Haut Glacier d'Arolla is perennially at the pressure melting point, it is likely that our sensors were contained within unfrozen basal water pockets that were linked to a diffuse subglacial drainage system. It is also likely that these water pockets were stratified in terms of their *EC*, reflecting contact with reactive minerals at their base (generating high *EC*) and the presence of increasingly pure water away from the glacier bed [Gordon et al., 2001]. In this situation, for water flow to occur (generating streaming potentials),  $P_W$  to rise, and for *EC* to fall, some borehole water must be driven down the borehole towards the glacier bed. This periodic mechanism is consistent with deformation of the ice body due to earth-tide controlled bedrock expansion.

[13] Earth tide forcing of the basal hydraulic system can have at least two important implications. First, basal  $P_W$  variations will have an effect on the strength of the subglacial sediments that they saturate. Since the rheology of subglacial sediments can be approximated as a Coulomb-plastic with a failure strength that scales inversely with pore-water pressure [Clarke, 1987], any increase in the latter will decrease the material's bulk strength, and vice versa. Earth tide forcing of subglacial  $P_W$  can therefore be expected to cause periodic variations in the strength of the sediment layers underlying affected ice masses. This implies that the motion speed of the ice mass itself could be modified on a similar time scale, complementing the effects of ocean tides on motion speed where ice masses terminate on water [Echelmeyer and Harrison, 1989; Harrison et al., 1993]. Second, the character and precise timing of subglacial drainage reorganization events could be influenced by earth tidal cycles. This is particularly true for the initial reorganization following the winter months (*May event* [Kulesa, 2000]), where earth tide induced diurnal *SP* amplitudes were at a maximum (above), consistent with enhanced basal water flow rates.

## 8. Conclusions

[14] Our inferences strongly suggest that earth tides influence the basal water system at the beds of warm-based ice masses. The luni-solar diurnal earth tide component ( $K_1$ ), in particular, forces melt water stored at the base of Haut Glacier d'Arolla by deforming the glacier substrate and the ice body itself. Here, times of particularly strong induced water flow, directed out of the borehole and into the subglacial water system, consistently coincided with diurnal periods of expanding subglacial bedrock. Using indirect arguments we further implied that forcing by the principal solar semi-diurnal atmospheric tide component ( $S_2$ ) may have dominated semidiurnal subglacial water flow phenomena. However, it is likely that the precise nature of the earth and suspect atmospheric tide influences will vary from glacier to glacier, depending on the magnitude of the local

tidal potentials, and the physical characteristics of the subglacial aquifer and the overlying ice body. Thus, the exact mechanism of such tidal forcings, how they relate to ocean tide influences at tidewater glaciers and ice streams, and how they impact on the rheological properties of the glacier bed demands detailed future investigations.

[15] **Acknowledgments.** We acknowledge the financial support of the NERC (Grant GR9/2530) and the UW Aberystwyth. The ICET and MeteoSchweiz provided gravity software and atmospheric pressure data. We thank S. Anandakrishnan, an anonymous referee, R. Alley, and M. Sharp, for helpful comments, as well as all field drillers and surveyors.

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