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Stand-alone single-frequency GPS ice velocity observations on Nordenskiöldbreen, Svalbard

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Abstract

Precise measurements of ice-flow velocities are necessary for a proper understanding of the dynamical response of glaciers to climate change. We use stand-alone single-frequency GPS receivers for this purpose. They are designed to operate unattended for multiple years, allowing uninterrupted measurements for long periods with a reasonable temporal resolution. We present the system and illustrate its functioning using data from 9 GPS receivers deployed on Nordenskiöldbreen, Svalbard, for the period 2006–2009. The accuracy of the receivers is 1.62 m based on the standard deviation in the average location of a stationary reference station (NBRef). Both the location of NBRef and the observed flow velocities agree within one standard deviation with DGPS measurements. Periodicity in the NBRef data is explained by the atmospheric influence on the GPS signal and by the GPS satellite configuration. A (weighed) running-average on the observed locations significantly reduces the standard deviation and removes high frequency periodicities, but also reduces the temporal resolution. Results show annual average velocities varying between 40 and 55 m/yr at stations on the central flow-line. On weekly to monthly time-scales we observe a peak in the flow velocities (60 to 90 m/yr) at the beginning of July related to increased melt-rates. No significant lag is observed between the timing of the maximum speed between different stations. This is likely due to the limited temporal resolution in combination with the relatively small distance (max. ±13 km) between the stations.

1 Introduction

At present an estimated 50% of sea level change can be attributed to ice mass loss. One third of this contribution is accounted for by the large ice sheets, whereas two thirds is provided by glaciers and ice caps (IPCC, 2007; Meier et al., 2007). For both glaciers and ice sheets ice dynamics play an important role in volume changes. The dynamical response of glaciers to melt water production refers to increased production of melt water resulting in higher ice-flow velocities, and is a well known phenomenon (see e.g., Iken and Bindschadler, 1986). If the enhanced speeds last long enough, the glacier surface lowers, resulting in increased melt. This positive-feedback mechanism could enable glaciers to react faster than expected to rising temperatures (Meier et al., 2007). Recent evidence suggests that this mechanism also yields higher ice-flow velocities in ice sheets, albeit temporarily (Zwally et al., 2002; Van de Wal et al., 2008; Shepherd et al., 2009).

IPCC (2007) acknowledged the importance of including ice-flow dynamics in sea-level forecasts and attempted to estimate its contribution. However, it also stated that the current state of understanding prevents a best estimate from being made. In more recent years several authors have addressed the effect melt water has on ice-flow dynamics and vise versa, and ultimately on sea-level forecasts (see e.g., Bingham et al., 2008; Pfeffer et al., 2008; Van de Wal et al., 2008).

The IPY (International Polar Year) lead project *the dynamic response of Arctic glaciers to global warming* (GLACIODYN) was initiated to stimulate research to the aforementioned issue by coordinating model and observational studies into the dynamics and mass budget of Arctic glaciers. Within the framework of GLACIODYN, our research focusses on the relation between meltwater input and ice-flow velocities of Arctic glaciers. To assess this relation it is not only crucial to have detailed flow velocity information, but also to have data on the mass budget, ice conditions (thickness and temperature), and surface and bedrock topography as well. In the past, ice-flow velocities were measured with stakes and traditional surveying methods, such as the use of theodolites. Nowadays, we have several airborne and space-borne geodetic techniques at our disposal, such as the Global Positioning System (GPS) (Hinze and Seeber, 1988; King, 2004; Sunil et al., 2007), interferometric synthetic aperture radar (InSAR) (Joughin et al., 2008; Rignot and Kanagaratnam, 2006), and speckle tracking techniques (Kääb et al., 2005). Although satellite remote sensing techniques provide valuable information on entire glaciers and ice sheets, the information is generally only available at time intervals of days to weeks. Therefore, GPS is indispensable in providing ground measurements, validation of the aforementioned techniques, and continuous measurements on a high temporal resolution.

Differential GPS (DGPS) techniques have been used for glaciological applications for several decades (Hinze and Seeber, 1988; Zwally et al., 2002). In May 2000, the Selective Availability, which caused an uncertainty of about 100 m in the location determined by stand-alone single-frequency GPS receivers, was switched off. This resulted in a substantially improvement in the accuracy of these systems (US Air Force, 1996; USA Department of Defence, 2008). As a result, stand-alone single-frequency GPS receivers can now be used for glaciological applications such as ice flow velocity determination (Van de Wal et al., 2008). The Institute for Marine and Atmospheric research in Utrecht, the Netherlands (IMAU) has developed a low cost stand-alone single-frequency GPS unit to perform year-round ice flow velocity observations. The purpose of this paper is to present this system, outline its possibilities and discuss its advantages and limitations. As an example, we present ice-velocity observations using this system on the glacier Nordenskiöldbreen, Svalbard, collected between 2006 and 2009. In the remainder of the paper unless stated otherwise, GPS refers to a single-frequency stand-alone GPS receiver.

First, we describe the technical aspects of the system. Next, the measurements obtained at a stationary reference station are analyzed to illustrate the accuracy of the GPS unit. Subsequently, observations from 9 receivers located on the glacier Nordenskiöldbreen, Svalbard, provide information on the annual velocity of the ice and its velocity variations on shorter time scales.

2 Methods

2.1 GPS

The GPS system consists of a constellation of 24 to 32 satellites. The satellites rotate in semi-synchronous (11:58 h) orbits around the Earth repeating the same ground track ones every 23:56 h. The orbital planes in which the satellites orbit have an inclination angle of 55° relative to the Earth's equator and a radius of about 26 600 km. Each GPS satellite continuously broadcasts information at two frequencies, the so called L1 and L2 bands. A GPS receiver calculates its position by precisely timing and analysing the signals sent by the GPS satellites (US Air Force, 1996; USA Department of Defence, 2008).

The GPS setup (Fig. 1) evaluated in this paper determines its location based on a single-frequency signal (L1). The achievable horizontal accuracy of a single observation using such a stand-alone single-frequency setup is about 6 m (USA Department of Defence, 2008). The most important error sources in positioning are inaccuracies in the signal arrival time measurement, satellite orbital and clock information, atmospheric influences on the signal, multipath errors and satellite geometry (US Air Force, 1996). The largest uncertainty is introduced by the influence of the atmosphere on the signal, especially the influence of the ionosphere.

Our system determines and records its position at a preset time interval. From the consecutively stored locations, distances and thus velocities can be derived. For each stored observation, the GPS switches on for a period of 3 min until a stable signal is reached. This procedure is to minimize the error caused by the signal arrival timing. Every 24 h the system goes through an entire start up cycle. For each subsequent observation, deviations from the first observation are determined and stored. Information about the satellites used in a single observation are not logged, making it impossible to apply the differential technique to minimize errors introduced by inaccuracies in the satellite orbital and clock information. In order to minimize the multi-path error,

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

our system uses a patch antenna, which is an antenna that only looks upward. The resulting accuracy of the observations are discussed in Sect. 4.

The GPS units can be placed on a tripod or mass balance stake. They are equipped with enough memory capacity and power supply to function unattended for at least one year. In order to continuously monitor a glaciers velocity GPS units equipped with an Argos transmitter are also available. First results obtained with this GPS instrument have been published in Van de Wal et al. (2008).

2.2 Data processing

To obtain ice-flow velocities from the locations measured by the GPS, the data is subjected to several processing phases. Firstly, we automatically remove the outliers. Next, the stored positions are averaged. Subsequently, the distance between two positions is calculated and from that the velocities are determined. Finally, we average the velocities.

To remove outliers, the average $(\bar{\phi}(t),\bar{\lambda}(t))$ and standard deviation $(\sigma_\phi(t),\sigma_\lambda(t))$ of the latitudinal (ϕ) and longitudinal (λ) position are calculated over a period of n_{av} hours. An entire record is excluded when the difference between two consecutive standard deviations $(\Delta\sigma_\phi(t),\Delta\sigma_\lambda(t))$ exceeds a given threshold standard deviation for either the latitude or the longitude coordinate $(\Delta\sigma_\phi,\Delta\sigma_\lambda>\Delta\sigma_{\mathrm{th}})$.

To reduce the positional error, running averages for the latitudinal and longitudinal coordinate are calculated over a preset period of n_{p} samples. The distance between two consecutive positions $(d\phi,d\lambda)$ and the direction of the displacement is then calculated taking into account the curvature of the Earth (Vincenty, 1975). From the calculated distances the velocities (v_ϕ,v_λ) are calculated by simply dividing the distances by the time interval (Δt). As a last step a running average is applied to the velocities using a period of n_{v} samples. Note that to prevent double use of data n_{p} is less or equal to n_{v}. Note also that, n_{p} and n_{v} need not necessarily be the same as n_{av}. In the following $\sum_i$ is short for $\sum_{i=-n/2}^{n/2}$ and i refers to number of timesteps:

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | I▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

$$\overline{v_\phi}(t) = \frac{1}{\sum_i f_i} \sum_i f_i v_\phi(t+i)$$
$$\overline{v_\lambda}(t) = \frac{1}{\sum_i f_i} \sum_i f_i v_\lambda(t+i)\ . \qquad (1)$$

For calculation of the running averages it is possible to use different weighing functions (f_i) for the used averaging window. Possible window functions are e.g. a square, Bartlett, Welch, Hann or Gaussian window (Press et al., 2003). Except for the square window these window functions assign a heavier weight towards the centre of the window, which represents the observational time the average is assigned to.

To obtain the combined average velocity $\bar{v}(t)$, the velocity components v_ϕ and v_λ are averaged vectorial. A period average velocity can be determined in several ways. We present values determined by averaging all velocity values for a given period (V_{av}) and values determined by taking the distance between two (averaged) positions with the same time interval (V_{be}), the begin-end method. Both values are compared with velocities determined by DGPS measurements (V_{dgps}), if available. The begin-end method has the advantage that it is similar to the DGPS method to determine velocity, but has the risk of incorporating a relatively large error in one of the values depending on the chosen averaging period (n_{p}).

3 Data

The data analyzed in this paper have been collected between March/April 2006 and May 2009 on Nordenskiöldbreen, Svalbard. Nordenskiöldbreen is a polythermal glacier located centrally on Spitsbergen (78.6° N, 17.1° E), the main island of the Svalbard archipelago (Fig. 2). The glacier is an outlet glacier of the Lomonosovfonna ice plateau, which highest point is situated 1250 m a.s.l. (above sea-level). While the glacier used to be a grounded tidewater glacier, recent retreat has caused it to currently partly terminate on land. The glacier is about 17 km long and 5 km wide (Hagen et al., 2005). The average thickness of the ice is approximately 300 m, with a maximum of 600 m at the flat middle part of the glacier (R. Petterson, personal communication, 2010). The average equilibrium line of the glacier is around 650 m (Hagen et al., 2005).

In total 10 GPS receivers provided hourly data during (a part of) the three year period (Table 1). Of these 10 stations, 9 are placed on the glacier (NBX) and one on rock serving as a reference site (NBRef). Of the stations on the glacier NB3, NB4 and NB6-NB9 are located on, or close to, the main flow line, with ±100 altitude meters between stations (Fig. 2). Because the lower part of the glacier is heavily crevassed, NB5H is placed away from the main stream line and stations NB1 and NB2 are placed on a side stream. Additionally, at NB5H a sonic ranger is installed to measure the change in surface height to determine the temporal variations in melt/accumulation. NBRef is situated on the nunatak Terrierfellet.

For comparison, the positions of the GPS stakes have been measured once a year with Trimble R7GNSS and DataGrid mk 3 receivers in DGPS mode. The accuracy this system can achieve after processing is about 0.02 m.

4 Results

4.1 Reference station (NBRef)

The fixed location of the reference station (NBRef) enables us to investigate the accuracy of our system in terms of the spread around the average observed location. It also provides an opportunity to investigate the effect of the automatic outlier removal and averaging procedures on the measured location and possible artifacts in our signal. Furthermore, measurements with the DGPS provide an additional valuable indication of the accuracy of the GPS measurements.

The purpose of removing the outliers is to reduce the standard deviation in the data set, without losing relevant information. Analysis of different combinations of the averaging period n_{av} and threshold standard deviation $\Delta\sigma_{th}$ shows that averaging over 60 h and a $\Delta\sigma_{th}$ of 0.1 m yields less than 1% data loss at NBRef, while the standard deviation is reduced to ±0.5% of the annual average velocities encountered on Nordenskiöldbreen (Table 2). Although the removal of outliers does not significantly change the annually averaged measured position of the reference station or the spread in the observations (Table 2), it is an important step for stations that show more outliers. In the remainder of the paper, the outliers are removed in the discussed data sets.

The standard deviation of the annually averaged position of NBRef is 1.24 m in the latitudinal direction and 1.04 m in the longitudinal direction. Assuming that the two standard deviations are statistically independent, the combined standard deviation is 1.62 m (Table 2). This number is significantly smaller than the expected achievable horizontal accuracy of about 6 m for a single measurement using a stand-alone single-frequency receiver (USA Department of Defence, 2008), which can partly be explained by the 3 min in our system in which the signal can stabalize before the observation is stored. The difference in standard deviation between the two orientations is due to the latitude of the observations, in combination with the orientation of the glacier and the slope of the nunatak on which NBRef is placed. Since the GPS satellites orbital planes make a 55° angle relative to the Earth's equator, the maximum angle of the satellites above the horizon at 78.5° N is ±60°. As a result the location error caused by satellite geometry is larger in the latitudinal direction than the longitudinal direction. Shielding of the GPS is less important due to the gentle slope of the nunatak, the slope orientation of the nunatak and the other mountains surrounding the glacier.

The difference between the annually averaged position of NBRef and the DGPS is 1.16 m in 2007 and 0.60 m in 2008 (Table 3 and Fig. 3). The distances are within one standard deviation of the measured NBRef location. Part of the resulting difference can be explained by the fact that the DGPS was not placed on exactly the same location as NBRef necesitating a correction. In both years, the offset is approximately in the same direction.

Based on the 1.62 m standard deviation in the NBRef observations in combination with our observational sample time of one hour and observed ice velocities of about 45 m/y it is necessary to average the data to increase the signal to noise ratio in the observations. Figure 4 presents the combined standard deviation σ in the NBRef observations when applying different averaging periods n and window types. After extensive testing we adopted a Welch window in our averaging procedure. Although the square window resulted in the fastest decrease of σ with increasing window length n it introduced spurious waves in the velocity time series. Therefore, a non-square function is preferred, of which the Welch window showed the fastest decrease in σ with increasing n. When applying a window length of 240 h σ reduces to about 0.2 m, which is less than 0.5% of the observed average annual velocities. This averaging period removes all variability on time scales of days and smaller but ensures that variability on weekly and larger timescales is maintained. Note that this poses a limit to our temporal resolution. Velocities will be presented using $n_p = n_v = 240$ h.

To check the data for any artificial or natural periodicities, we performed a frequency analysis of the non-averaged NBRef data. Results are presented in Fig. 5. This analysis shows significant (95% confidence) peaks at 24 h, 12 h, 8 h, 6 h and shorter periods. The strength of these peaks is not influenced by the automatic outlier removal procedure. The peaks are also present in the data collected at the stations on the glacier itself.

The observed periodicities are most likely explained by the influence of the atmosphere on the accuracy of the GPS signal introducing a 24 h cycle. The traveling time of the signal send by GPS satellites is susceptible to atmospheric conditions (atmospheric tide), most markedly to those in the ionosphere. The atmospheric tide is the result of periodic heating of the atmosphere by solar radiation. In the ionosphere solar radiation ionizes particles resulting in conductive layers which refract the GPS signal, increasing the traveling time. In the stratosphere and troposphere periodic heating of water vapor and ozone through absorption of solar radiation also result in refraction of the GPS signal. The effect is stronger higher in the atmosphere where it has a period of 12 h while in the lower atmosphere the period is 24 h. In addition, its higher harmonics of 8 h and 6 h match the observed peaks.

Besides the atmospheric tide, other possible explanations of the observed periodicities are the orbital repeat time of the GPS satellites (11:58 h and 23:56 h) and the resetting of our GPS every 24 h. The periodicity of these last factors is difficult to assess. However, especially the resetting of the GPS is expected to be small in comparison to the periodicity induced by the atmospheric tide. Note that all these frequencies are eliminated when applying a running average with $n>24$ h.

4.2 Velocity observations

The main purpose of the GPS observations is to determine the surface velocity of a glacier and its spatial and temporal variations. As an example we present the results obtained at Nordenskiöldbreen. Firstly, we present the annual average velocities and a comparison with DGPS determined velocities. Secondly, we discuss the velocity variations on weekly to monthly time scales.

4.2.1 Annual velocity variations

Table 4 presents a comparison between GPS and DGPS determined period average velocities. The GPS average velocities cover the same period as the DGPS velocities, and are calculated in the two different ways described in Sect. 2.2 (V_{av},V_{be}). In both cases they are based in data in which $n_{\mathrm{p}}=n_{\mathrm{v}}=240$ h.

Table 4 shows that V_{av} and V_{be} are in agreement. The estimated uncertainty in V_{be} is slightly larger because a small offset in one or both of the values can lead to a larger error. However, the larger n_{p} and n_{v} the smaller this effect is. Note that for NB8 only about 80% of the datapoints are correct compared to more than 99% for the other stations. Comparing the GPS velocities with the DGPS velocities (V_{dgps}), the agreement is fairly good. On average the velocities differ by about 4% from the DGPS velocity; the difference is never larger than 11%. The largest difference is found for NB8 2006–2007 which can be explained by instrumental problems. In general the differences for the period 2006–2007 are larger than those for 2007–2008. We do not have an explanation for this.

In Table 5 the average annual velocities (V_{av}) are presented. V_{av} varies between 40 m/yr on the flatter parts of the main flow line to more than 50 m/yr on the steeper parts of the flow line. The stations placed on the side stream, NB1 and NB2, only move a few meters per year. Station NB5H, is also not located on the main flow line, and moves with intermediate velocities due to increased side drag. Highest velocities are observed closest to the front and higher up on the flow line. The local topography is likely the main determinant of the velocity and its variations along the flowline. However, the correlation between driving stress, which is proportional to the ice thickness and the surface slope, and annual velocity is weak (not shown). This can partly be explained by the limited knowledge of bedrock topography, ice thickness, and thus driving stress, but might also be caused by not negligible longitudinal stresses.

4.2.2 Short term velocity variations

A major advantages of the used GPS system is the temporal resolution of the obtained velocities. Because the accuracy of the GPS is in the order of 1.6 m, averaging over the right period is essential to discern the signal from noise. Larger averaging periods decreases the amplitude of the velocity variations and increase the period of the variations.

Figure 6 shows the velocities of all stations on the central flow line of Nordenskiöldbreen. The figure shows that the velocities vary around the annual averages of 40 to 50 m/y as presented in Table 5, with a marked increase in velocities in summer. Furthermore, throughout the time series, but best visible in winter, the observed velocities show variations on time scales of 15 to 20 days.

The observed increase in velocity in summer is related to the increase in amount of available meltwater. The observed maximum values can reach up to twice the annual average value. In the summer of 2006 all three available stations show a clear peak, with the highest maximum velocity of 85 m/yr occurring at NB7. However, in 2007 only the two lower stations NB3 and NB4 show a well-defined maximum, while the higher stations (NB7-NB9) have a much broader peak. In 2008, it is the other way around, a broad peak for NB3 and NB4 and a more distinct peak for NB6–NB9. An interesting feature in 2008 is the very strong temporary increase in velocity at NB3, NB4 and NB6–NB8 in September. This peak can be related to high September temperatures in combination with more than average amount of precipitation (Fig. 7). A similar peak has been observed on glaciers on Vestfonna and Austfonna in the north east of Svalbard and on Kronebreen in the north west of Svalbard (M. Sund, personal communication, 2010).

Correlation analyses shows no significant lag between the timing of the maximum velocity at the different sites on the glacier. The most likely reason is the relatively small distance between the stations (largest distance between two sites is ±13 km) in combination with a fast response time of the system and the limited temporal resolution of our observations.

The observed fluctuations on time scales of 15 to 20 days could be related to the GPS satellite configuration (see Sect. 2.1) having an exact orbital repeat time of 15 days. The frequency analysis of NBRef data does show a peak at periods of 15 days. This peak is, however, barely significant at the 5% level. Another explanation could be oceanic tide. Recent radar observations show bed elevations below sea level from the front up to NB7 (R. Petterson, personal communication, 2010). On the other hand, we also observed these type of fluctuations on other glaciers on Svalbard and Greenland. For most of these glaciers oceanic tide is not a likely explanation. Furthermore, there is no significant correlation in timing of the fluctuations between the different glaciers, making the influence of the GPS satellite configuration unlikely.

To investigate to what extend the velocity variations are related to temperature and/or mass balance (gradients) we correlate these quantities. Figure 7 shows the time series of the GPS stations NB4 and NB6 located on the central flow-line over 2008, in combination with observed temperature and changes in the surface height illustrating melt rates. From auto-correlation analysis (using data with $n_p = n_v = 24\,\mathrm{h}$) a significant positive correlation is found between temperature and velocity in the summer months (150–250 days), with temperature leading velocity by about 3 days. For the same period a significant correlation is found between melt rates and velocity, melt rate leading velocity by about 4 days. Furthermore, the timing of the velocity peak in summer coincides with the first half of the melting period and peak velocities are reached about 40 days after the onset of melt. Note that the fact that we have to average our data makes it impossible to find correlations on shorter time scales than a few days. The observed velocities fluctuations in winter show no correlation with either temperature or melt rates.

5 Discussion

Nordenskiöldbreen is not a very fast-flowing glacier with annual average velocities of about 45 m/yr, compared to e.g., Kronebreen, which shows velocities up to 600 m/yr close to the front (Kääb et al., 2005). Nevertheless, the glacier does exhibit a relation between the melt rate and the flow speed, with a velocity peak of about twice the annual average value in the melting season. However, due to the short summer and the limited temporal resolution the relation between melt water and velocities is rather diffuse making it difficult to correlate the increased velocities to either the start of the melt season or a peak in melt rates.

Comparison of the velocity fluctuations of Nordenskiöldbreen with observations from other glaciers is only possible for the summer period, since detailed winter measurements are scarce. The variation in summer in surface motion of glaciers in the Alps, such as described in Iken and Bindschadler (1986) and Mair et al. (2003) show several episodes with high velocities occurring directly related to meltwater pulses. A similar direct relation has been found on the Greenland ice sheet by Joughin et al. (2008), Van de Wal et al. (2008) and Shepherd et al. (2009), but also on other glaciers on

Svalbard (Nuttall and Hodgkins, 2005; Rippin et al., 2005). Compared to the aforementioned studies the direct relation between melt water pulses and flow velocity is not as strong on Nordenskiöldbreen as on Alpine glaciers or the Greenland ice sheet. This is partly due to the reasonably low mean velocity of Nordenskiöldbreen in combination with the necessity to average our data in order to distinguish signal from noise. Note also that the latter two studies are difficult to compare to our observations due to the different time scales (one to several days) of their observations.

6 Summary and conclusions

Precise measurements of ice-flow velocities are necessary for a proper understanding of the dynamical response of glaciers to climate change. We use stand-alone single-frequency GPS receivers for this purpose. Our system can operate unattended for multiple years, allowing uninterrupted measurements for long periods at a reasonable temporal resolution.

The low cost of one of our single receivers (±2000 Euro) makes it possible to deploy several receivers on a single glacier and study spatial patterns. The system can therefore provide information on locations where space-borne techniques struggle due to a lack of distinguishable features or coverage. The combination of the low cost and the ability to function for longer time periods is a major advantage of this system for glaciological applications. A limiting factor is its accuracy. In order to distinguish signal from noise it is necessary to average the obtained time series, decreasing the temporal resolution. As a result, the stand-alone system works less well on slow moving glaciers. However, depending on the average velocity of the measured ice flow, velocity-events on time scales of days to weeks are distinguishable throughout the year.

As an example of the functioning of the stand-alone single-frequency GPS receivers we presented data from 9 receivers deployed on Nordenskiöldbreen, Svalbard. The presented data cover the period March 2006 until May 2009.

Data from a stationary reference site show a standard deviation of 1.62 m in its average location. DGPS measurements of the reference site are within the found standard deviation. In addition, DGPS determined velocities agree reasonably well with our observations. Spectral analyses of the reference site data show periodicities in the data that can be attributed to the GPS satellite configuration and the atmospheric influence on the GPS signal.

Nordenskiöldbreen is not a very fast flowing glacier showing annual average velocities between 40 and 55 m/yr on the central flow-line, and lower values closer to the edge due to side drag. On weekly to monthly time-scales we observe a peak in the ice-flow velocities at the beginning of July during the period with the highest melt-rates. However, due to the limited temporal resolution the relation between melt water and velocities is rather diffuse making it difficult to correlate the increased velocities to either the start of the melt season or the peak in melt rates. The highest measured velocities vary between 60 and 90 m/yr. No significant lag can be observed between the timing of the maximum speed in the lower and higher stations. Likely, this is a result of the short distance between the sites (largest distance between two sites is ±13 km) and the necessity to average the data limiting our temporal resolution. In summer the ice velocity is significantly correlated with air temperature and melt rates showing lags of about 3 and 4 days, respectively. Velocity fluctuations in winter are not related to temperature or mass-balance changes. Possible explanations for the found variability in winter are the satellite configuration having an exact orbital repeat time of 15 day, or oceanic tidal effects. However, we also observed winter fluctuations on this time scale on other glaciers on Svalbard and Greenland where oceanic tidal influence is less likely. Furthermore, we did not find a significant correlation in timing of the fluctuations between the different glaciers, making the influence of the GPS satellite configuration an unlikely explanation. At present we do not have an explanation for the observed winter variations.

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Table 1. Characteristics of the different GPS stations on Nordenskiöldbreen, Svalbard. Note that NB3 and NB9 were only active during the second year, while NB6 was lost in the second year.

Station	Altitude [m a.s.l.]	Period	Description
NBRef	±520	1 Apr 2006 to 28 Mar 2009	Terrierfjellet
NB1	±135	1 Apr 2006 to 28 Mar 2009	Side stream
NB2	±225	1 Apr 2006 to 28 Mar 2009	Side stream
NB3	±335	28 Mar 2007 to 29 May 2009	Main flow line
NB4	±345	31 Mar 2006 to 29 May 2009	Main flow line
NB5H	±435	30 Mar 2006 to 28 Mar 2009	Sonic Ranger
NB6	±525	29 Mar 2006 to 17 Mar 2007	
		4 Apr 2008 to 23 Mar 2009	Main flow line
NB7	±590	1 Apr 2006 to 29 May 2009	Main flow line
NB8	±675	1 Apr 2006 to 29 May 2009	Main flow line
NB9	±875	27 Mar 2007 to 27 Mar 2009	Main flow line

Table 2. Description of the raw and processed data of the reference station NBRef. n is the total number of records in 1 data set, σ_r is the combined standard deviation of the raw data, % is the percentage of correct data points, σ is the combined standard deviation of the filtered non-averaged data, and σ_ϕ and σ_λ are the standard deviations in the latitudinal (ϕ) and longitudinal (λ) direction, respectively.

Year	n	σ_r [m]	%	σ [m]	σ_ϕ [m]	σ_λ [m]
2006–2007	8592	1.80	99.4	1.76	1.39	1.08
2007–2008	9000	1.62	99.7	1.61	1.20	1.07
2008–2009	8614	1.51	99.6	1.47	1.11	0.96
2006–2009	26 205	1.65	99.6	1.62	1.24	1.04

Table 3. Comparison between GPS and DGPS measurements at NBRef. $\Delta\phi$ and $\Delta\lambda$ are the differences in the latitudinal and longitudinal direction, respectively, where negative values denote the positions to the south and/or west of NBRef. Δtotal is the combined distance between the instruments, and Dir is the direction from the GPS towards the DGPS location.

Date	$\Delta\phi$ [m]	$\Delta\lambda$ [m]	Δtotal [m]	Dir [°]
25 Mar 2007	−1.04	0.52	1.16	153
3 Apr 2008	−0.15	0.58	0.60	104

Table 4. Comparison between GPS and DGPS determined velocities of Nordenskiöldbreen. V_{av} is calculated using Equation 1, with $n_p = n_v = 240$ h. V_{be} is based on the distance between the 240 h averaged beginning and end points of a GPS and V_{dgps} is based on the yearly DGPS measurements. GPS values are calculated over the same period as spanned by the individual DGPS observations, which is about one year. Uncertainties in the GPS determined velocities are based on the standard deviations in the 240 h average locations.

Station	Period	V_{av} [m/yr]	V_{be} [m/yr]	V_{dgps} [m/yr]
NB4	2006–2007	47.5±1.0	47.5±1.7	46.3±0.02
NB5H	2007–2008	24.8±0.8	23.4±0.9	24.9±0.02
NB6	2006–2007	42.9±1.1	42.9±1.8	40.2±0.02
NB7	2006–2007	46.0±1.1	46.0±2.0	50.3±0.02
	2007–2008	47.1±0.5	47.2±1.7	48.5±0.02
NB8	2006–2007	40.5±0.8	40.5±1.7	36.6±0.02
	2007–2008	41.7±0.5	41.7±1.6	43.0±0.02
NB9	2007–2008	55.8±1.2	55.8±2.0	54.2±0.02

Table 5. Annual flow velocities of Nordenskiöldbreen. V_{av} (m/yr) is calculated using Eq. (1), with $n_p = n_v = 240$ h. A velocity year runs from day 91 to day 90 of the following year. Period refers to multi-year averages: 2006–2009, NBRef, NB1, NB2, NB4; 2007–2009, NB3, NB5H, NB9; 2006–2007 and 2008–2009, NB6. Bold values represent values based on less than 95% correct records.

Station	2006–2007	2007–2008	2008–2009	Period
NBRef	0.4±0.9	0.2±0.5	0.1±0.3	0.1±0.3
NB1	3.6±0.9	3.0±0.5	2.8±0.3	3.1±0.3
NB2	0.8±1.0	1.3±0.5	1.4±0.2	1.1±0.2
NB3	–	53.3±0.9	54.6±0.4	53.9±0.6
NB4	47.2±1.0	48.7±0.5	50.9±0.3	49.0±0.5
NB5H	**22.9±2.5**	24.8±0.8	26.9±0.4	25.6±0.4
NB6	42.9±1.1	–	47.5±0.4	45.2±0.4
NB7	45.9±1.0	47.2±0.5	**52.1±0.3**	46.6±0.5
NB8	40.3±0.8	41.9±0.5	**48.2±0.3**	41.1±0.5
NB9	–	55.8±1.2	58.2±0.5	57.0±0.5

Fig. 1. GPS unit attached to a mass-balance stake.

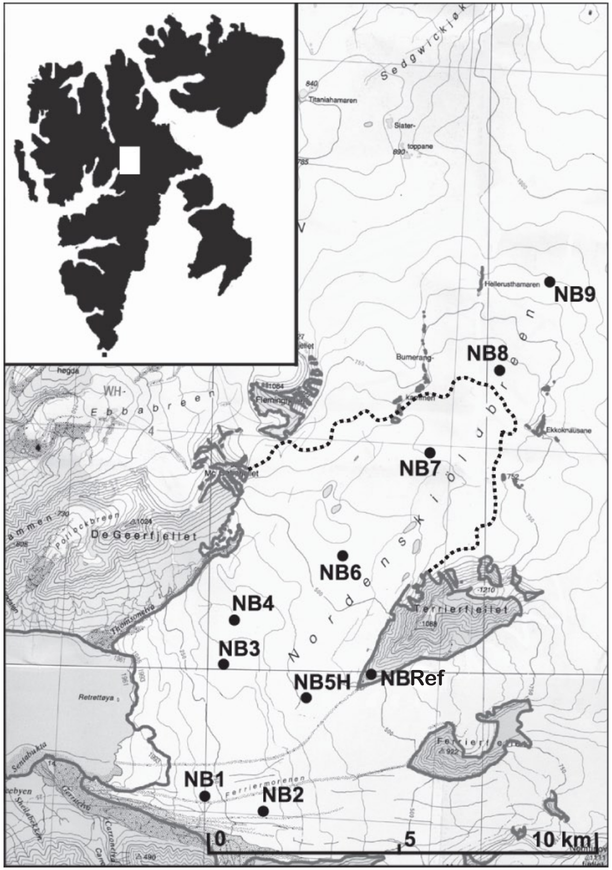

Fig. 2. Map of Nordenskiöldbreen, Svalbard with the locations of the GPS stations (NB1–NB9) and sonic ranger (NB5H) on the glacier, and the reference station on Terrierfjellet (NBRef). The approximate equilibrium line is indicated with a dashed line (Hagen et al., 2005).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

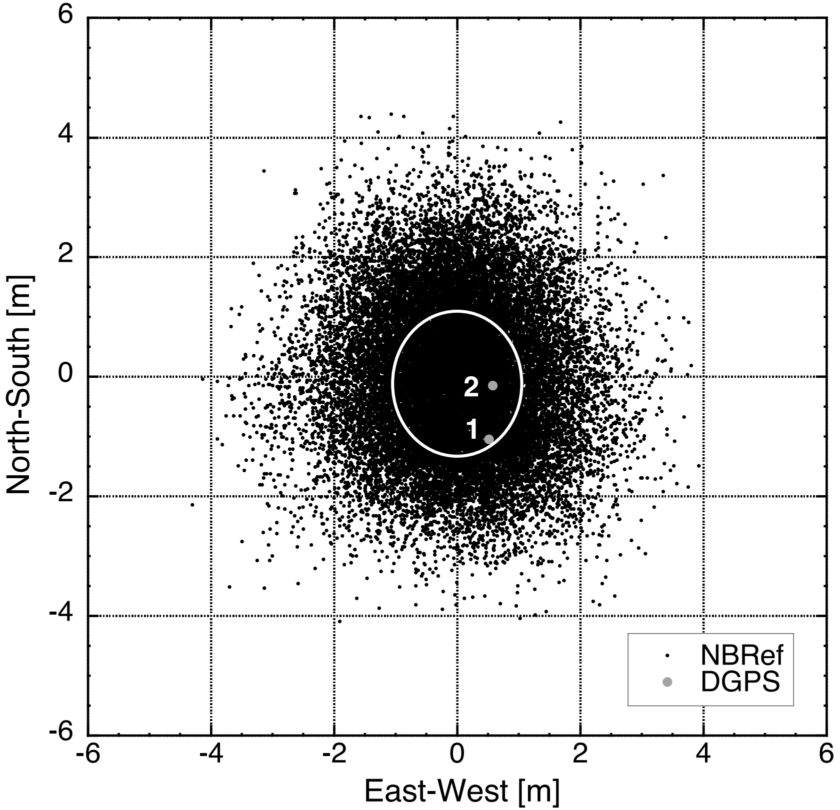

Fig. 3. Scatter plot of three years of non-averaged NBRef observations (black dots) with respect to the average location, negative values denote the records to the south and/or west of the average position. The grey dots indicate the location of the DGPS with respect to the averaged location, 1=2007, 2=2008. The circle denotes one standard deviation of the non-averaged NBRef data.

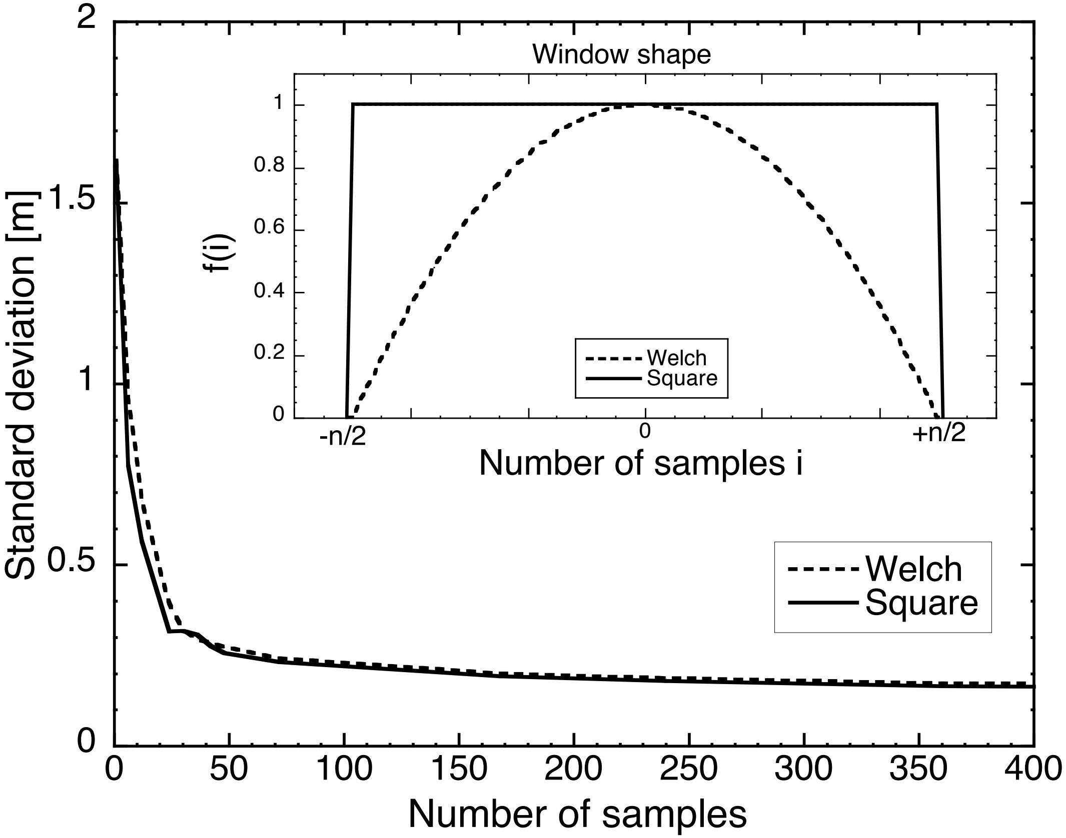

Fig. 4. Standard deviation of the NBRef data as a function of number of samples for a square and Welch window. Note that with a sample time of one hour the number of samples is equivalent to hours. In the inset the shapes of the Welch and square weighing functions are displayed.

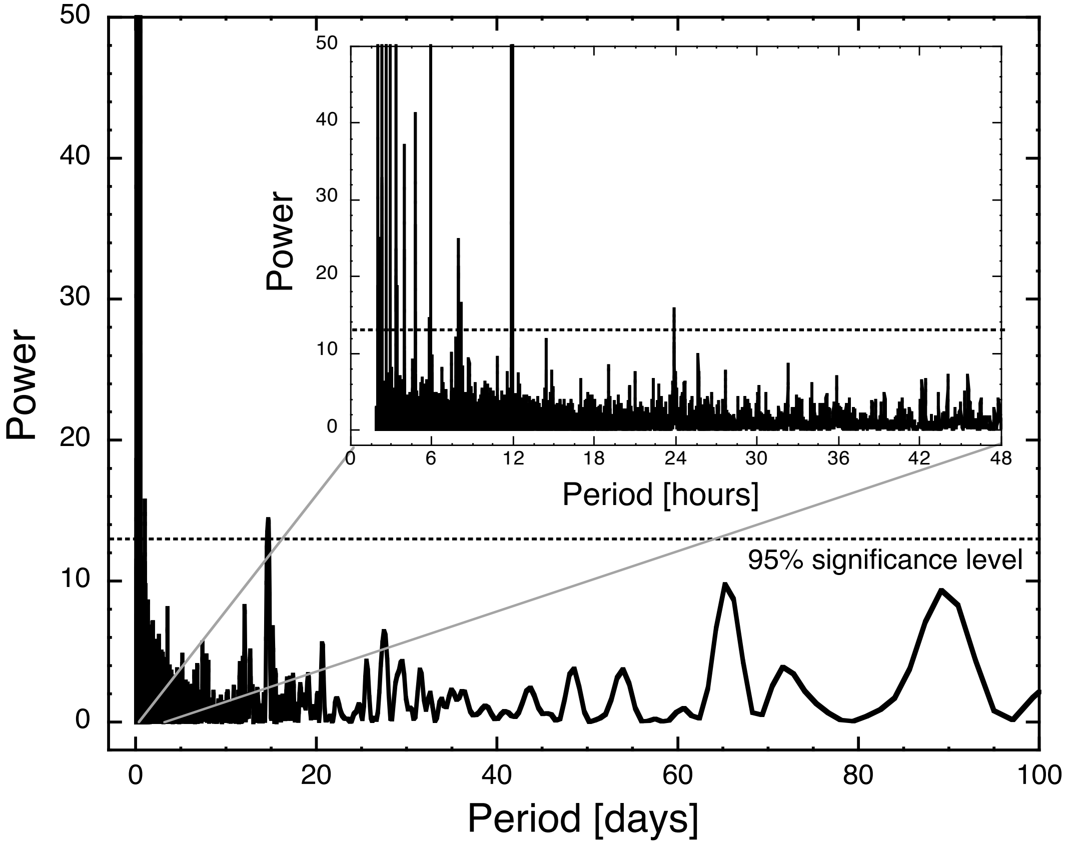

Fig. 5. Power spectrum of NBRef data collected between March 2006 and April 2008.

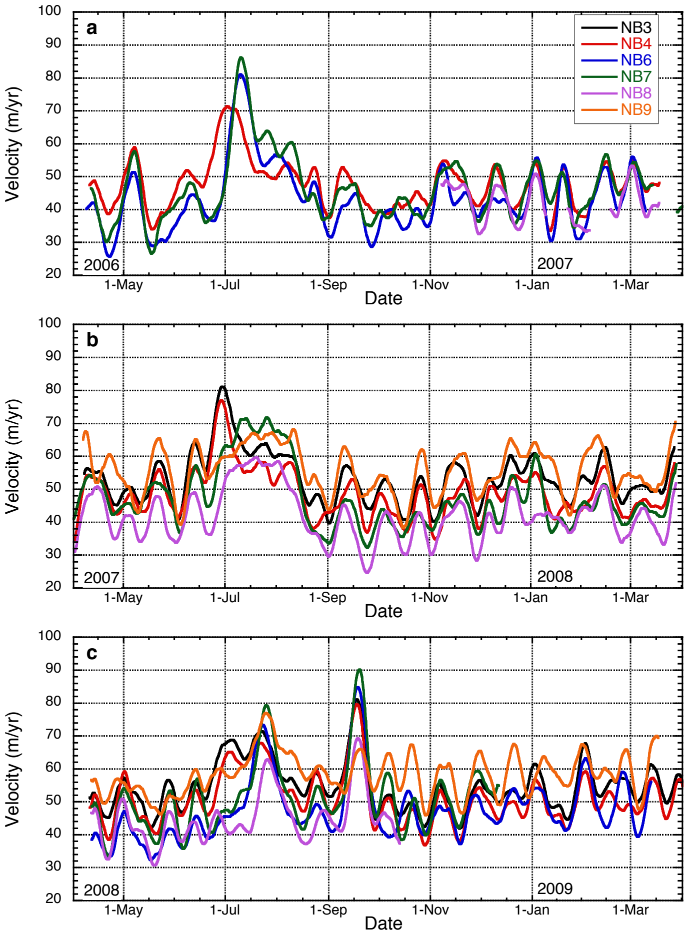

Fig. 6. Time series of velocity measurement of the stations on the central flow-line for the period 2006–2007 **(a)** 2007–2008 **(b)** and 2008–2009 **(c)**. A running average of 240 h is applied.

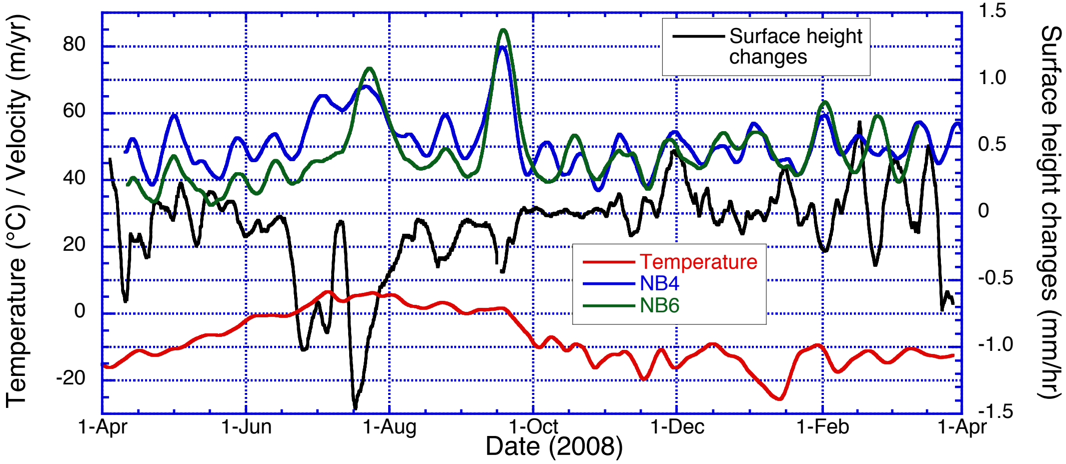

Fig. 7. Time series of temperature, surface height changes and velocity of two stations, NB4 and NB6, for 2008. Negative surface height changes illustrate melt rates. All variables are calculated with a running average of 240 h.