Introduction
In recent years, Devon Ice Cap (Figure 1), along with the other glaciers and ice caps in the Canadian Arctic Archipelago (CAA) have seen an increased rate of ice mass wastage due to anomalously high summer temperatures (Sharp et al., 2011; Gardner et al., 2011). Snow accumulation and surface melt patterns form up to five distinct facies zones on the surface of glaciers (glacier ice, superimposed ice, saturation, percolation, and dry snow zones; Figure 1) (Muller 1962; Koerner 2005). The progression of these facies zones to higher elevations can therefore be indicative of an increase in surface melt and warmer summer temperatures.

Recently, remote sensing has been widely used to discriminate glacier facies (Parington 1998; Wolken et al. 2009; Casey and Kelly 2010). The strength of the backscattered signal (sigma nought, $\sigma_0$) from SAR data can be collected to determine melt extent and characterize facies. $\sigma_0$ is determined by the individual scatterers on the glacier surface and is expressed in decibels (dB), which signifies the intensity of the returned signal. Percolation and saturation zone facies (Figure 2) have a higher backscatter due to the presence of effective scatterers such as ice lenses and pipes. Comparatively, superimposed ice and glacier ice facies at lower elevations have a lower backscatter due to the lack effective scatterers. The division between the superimposed ice zone and saturation zone is where the largest contrast in backscatter is seen and is termed the firn line (Figure 2).

Methods
ENVISAT ASAR Wide Swath imagery (150 m spatial resolution) was used from 2003 to 2011 during post freeze-up (autumn) periods to detect glacier facies and the progression of the firn line between years (Figure 3). Using PCI Geomatics OrthoEngine, the ASAR images were orthorectified using a rigorous math model and a digital elevation model (DEM). A radiometric correction option is selected in the orthorectification process which returns the units in calibrated $\sigma_0$. This process outputs a radiometric terrain corrected image in decibel (dB) values. The images were then imported into ArcMap where the $\sigma_0$ values were extracted along the GPR transect (Figure 1) and graphed with the corresponding ice cap elevation (Figure 3).

A 450MHz Ground Penetrating Radar (GPR) was towed behind a snowmobile along a northwest transect of DIC (Figure 1) in May 2011 (Figure 4) and repeated in May 2012 (Figure 5). The GPR was used to map the near surface (depths of ~12m) of the northwest sector of DIC and to provide validation of the ENVISAT ASAR signal (e.g. Figures 4, 5, 6, 7). Data from the Sverdup Glacier Automated Weather Station (Figure 1) was also used to compare changes in glacier facies elevation with annual positive degree days (PDD) (Figure 8).

Results
The location of the firn line identified in the GPR radagrams (Figure 4-5) relates to the area of highest contrast in the extracted $\sigma_0$ ENVISAT graphs (Figure 3). The elevation of the firn line shows a clear trend towards increasingly higher elevations from 2003 to 2011 (Figure 9). The firn line ranged from 1520 m in 2009 to 1673 m in 2009. When comparing the firn line elevations to PDDs there is a correlation of 0.6 from 2003 to 2011.

Discussion and Conclusions
High summer temperatures since 2005 relate to an increase in elevation of the firn line, which signifies an increase in the glacier facies zones to higher elevations over this period. In recent years, Wolken et al (2009) showed that the dry snow zone is an intermittent phenomenon in the Arctic, as melt is ubiquitous at all elevations during warm years. The ground-based GPR measurements show a distinct firn line, whereas the ENVISAT ASAR signal can be less obvious in some years. In addition, the relative ASAR $\sigma_0$ values are seen to have generally consistent patterns from year to year.

By using the GPR results to calibrate and validate the ENVISAT ASAR signal it is possible to identify the approximate location of the firn line since 2003. If warming continues it is expected that the firn line and glacier facies zones will continue increasing in elevation due to an increase in surface melt. In future work, estimates of melt rates could be completed by relating in situ summer balance measurements at a single point with its corresponding $\sigma_0$ value, which could then be extracted across the entire ice cap.

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References