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Supplement of

Winter speed-up of quiescent surge-type glaciers in Yukon, Canada

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Supplementary material of "Winter speed-up of quiescent surge-type glaciers in Yukon, Canada" by T. Abe and M. Furuya

This supplementary material documents the surging episodes at four glaciers (Lowell, Tweedsmuir, Ottawa Glacier, and Logan). We show radar intensity changes associated with the opening and closing of crevasses due to the surge; the intensity changes were derived by the RGB method (Yasuda and Furuya, 2013). We also describe the spatial-temporal changes in the ice velocity at the glaciers and terminus advances during their active phases.

1. Surface crevasse formation revealed by SAR intensity analysis

Due to the sudden speed-up, a glacier surge generates new crevasses that will dramatically change the surface roughness and hence enhance the SAR scattering intensities (Yasuda and Furuya, 2013). By co-registrating two temporally separated SAR intensity images and assigning the older image (master) with cyan [(Red, Green, Blue) = (0%, 100%, 100%)] and the newer image (slave) with red [(Red, Green, Blue) = (100%, 0%, 0%)], the composite image tells us where the scattering intensity has remarkably changed. This is called the RGB method, which has also been employed in identifying the emerged/subsided small islands after the 2004 Sumatra Earthquake (Tobita et al., 2006). In the composite image, the cyan shows areas having an intensity increase, whereas the red shows with a decrease. The RGB method allows us to clearly visualize the intensity changes that can be attributed to the initiation of glacier surge. Although the SAR intensities can change by other processes such as surface melt in summer and snow accumulation in winter, we apply this method to the intensity images before and after a significant speed-up event (i.e., surge episodes), which occurred at Lowell, Tweedsmuir and Ottawa Glacier (Fig. 1). We have confirmed that there are few changes except surging glaciers (i.e., non-surging glaciers and off-ice area). Thus, all the intensity changes we show below are attributed to glacier surge.

2. Spatial and temporal variability of surging glaciers

2.1 Lowell Glacier

Lowell Glacier is a famous surge-type glacier located in Kluane National Park near the eastern edge of the St Elias Mountains. According to the Yukon Geological Survey (YGS), Lowell Glacier has surged 5 times in the last 70 years (YGS, 2011). The latest surge began in late 2009 and continued until late 2010 (YGS, 2011; Bevington and Copland, 2014). Pre-surge, the ice velocity was at most ~1 m/d (2007- 2009), it exceeded 5 m/d in the data pair of January and March 2010 (Fig. S1). This is consistent with the YGS report. The ice velocity slowed down in July and September 2010, but a lack of data prevents us from determining exactly when the surge ended.

Figure S2a shows that the terminus advances by up to 4 km from early 2009 to July 2010. The RGB method shows how the radar intensity increases after surge begins (Fig. S2b), and how it decreases after the surge ends (Fig. S2c). We interpret the intensity changes as being due to changes in the roughness of the ice surface that are attributable to the opening and closing of crevasses at the start and end of the surge.

2.2 Tweedsmuir Glacier

Tweedsmuir Glacier is 50-km south of Lowell Glacier in the St. Elias Mountains. According to the United States Geological Survey (USGS), the last surge began around 2007 summer and terminated in 2008 (USGS, 2010). Figure S3 shows the ice velocity evolution, which exhibits a greater velocity with ~6 m/d during the period from August to October 2007, but slows down in January to March 2009. In 2010, we find a summer speed-up, but the velocity magnitude is ~0.3 m/d, which is an order of magnitude slower than that during the surge in 2007.

Figure S4a shows the terminus location changes, which expands several hundreds of meters from the summer in 2007 to 2009. The RGB-method images in Figs. S4b and S4c, analogous to those in Fig. 2 show the surge at its beginning and end.

2.3 Ottawa Glacier - A tributary of Chitina Glacier -

Chitina glacier is a major surge-type glacier that forms the Chitina River Valley system. Although surging episodes have been inferred from satellite image analyses (Clarke and Holdsworth, 2002), we know of no ground-based monitoring at this glacier.

Figure S5 shows flow velocity at Chitina Glacier from the oldest at the top left to the most recent at the bottom right. Starting in fall 2009, the velocity increases at the confluence between Chitina and Ottawa Glacier (Fig. S5l). On Feb-Mar 2010, it speeds up to 4 m/d at Ottawa Glacier (Fig. S5p-q), and we regard it as the active surging phase. Meanwhile, the velocity in the upstream region of Chitina Glacier gradually increases as winter approaches (Fig. S5k-o). In contrast to the surge, the winter speed-up occurs every winter, which thus indicates that the wintertime acceleration in the upstream of Chitina Glacier is independent of the surge at Ottawa Glacier. Moreover, the winter speed in the upstream region is comparable to and sometimes higher than that in spring/early summer in 2010 (Fig. S5s), which we believe had not been observed before. The higher speed in the middle to downstream (Fig. S5q-t) may have been triggered by the surge at Ottawa Glacier.

The increase of radar scattering intensity coincides with the surge initiation (Fig. S6a). Later, in summer 2010, the flow velocity changes (Fig. S5t). This indicates that Ottawa Glacier underwent a surging episode that terminated around summer 2010. Figure S6b shows the surge at the end.

2.4 Logan Glacier

Logan glacier is also a major glacier that consists of the Chitina River Valley system. Figure S7a shows the spatial and temporal changes in the velocity. In 2007 and 2008 winter, the speed at 20 km point from the terminus is about 0.4 m/d. However, it is up to 0.8 m/d in 2010 and 2011. The winter speeds appear to increase from one year to the next. This is a clear feature for surging. Figure S7b also shows the velocity increase year to year. Thus we consider it as the initiation of a new surging episode.

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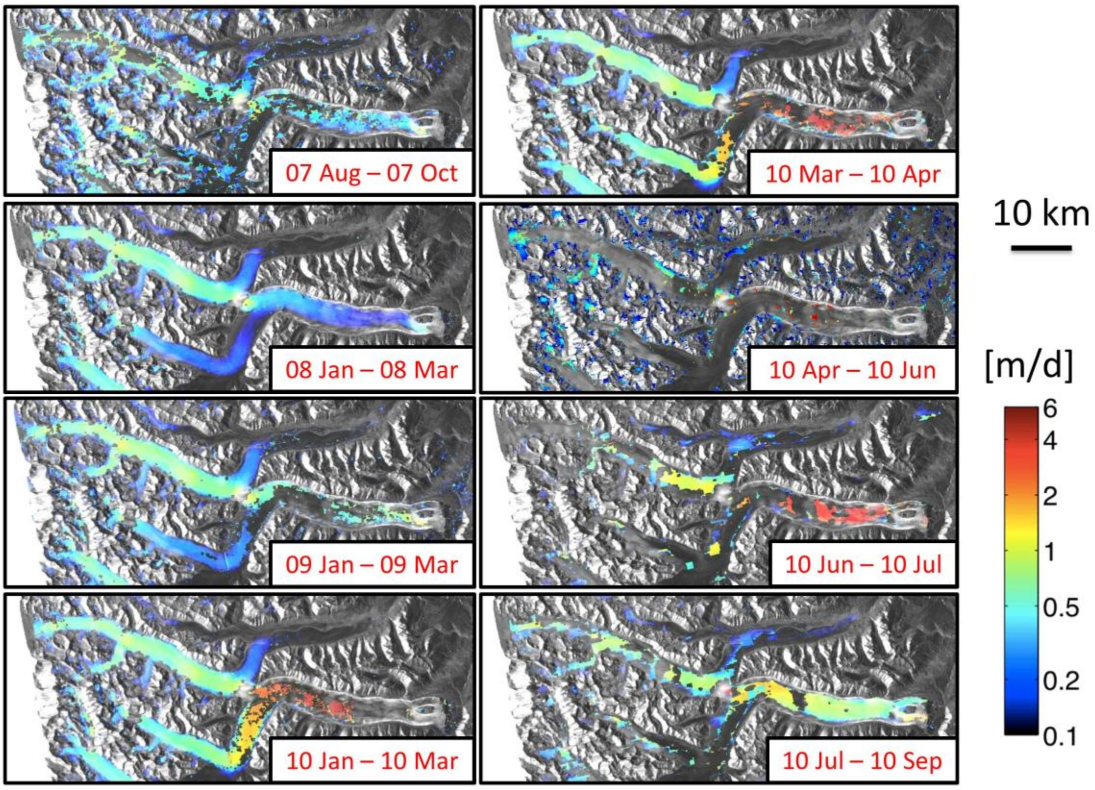

Figure S1. Surface velocity evolution on Lowell Glacier. The color scale is logarithmic.

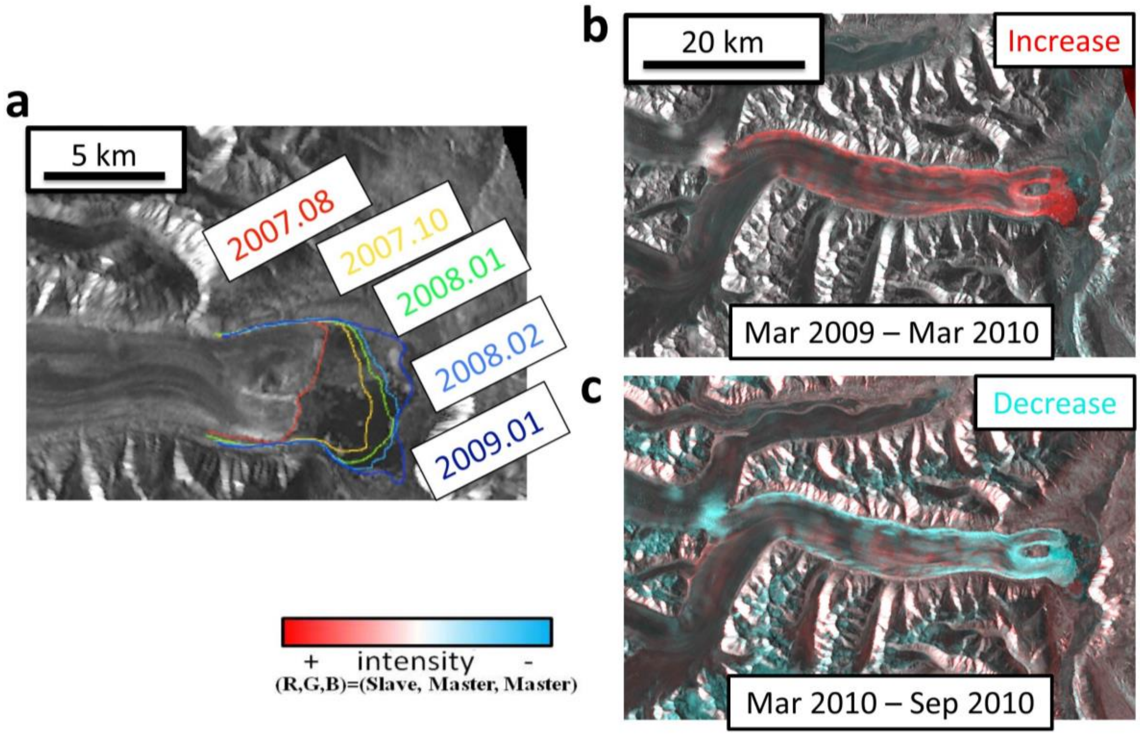

Figure S2. Surging event on Lowell Glacier. (a) Terminus locations based on PALSAR intensity images. (b) An RGB composite image derived from the images on 3 March, 2009 and 6 March, 2010. The red region indicates where the scattering intensity has increased. (c) A composite image derived from the images on 3 March, 2010 and 10 September, 2010. The cyan region indicates where the scattering intensity has decreased.

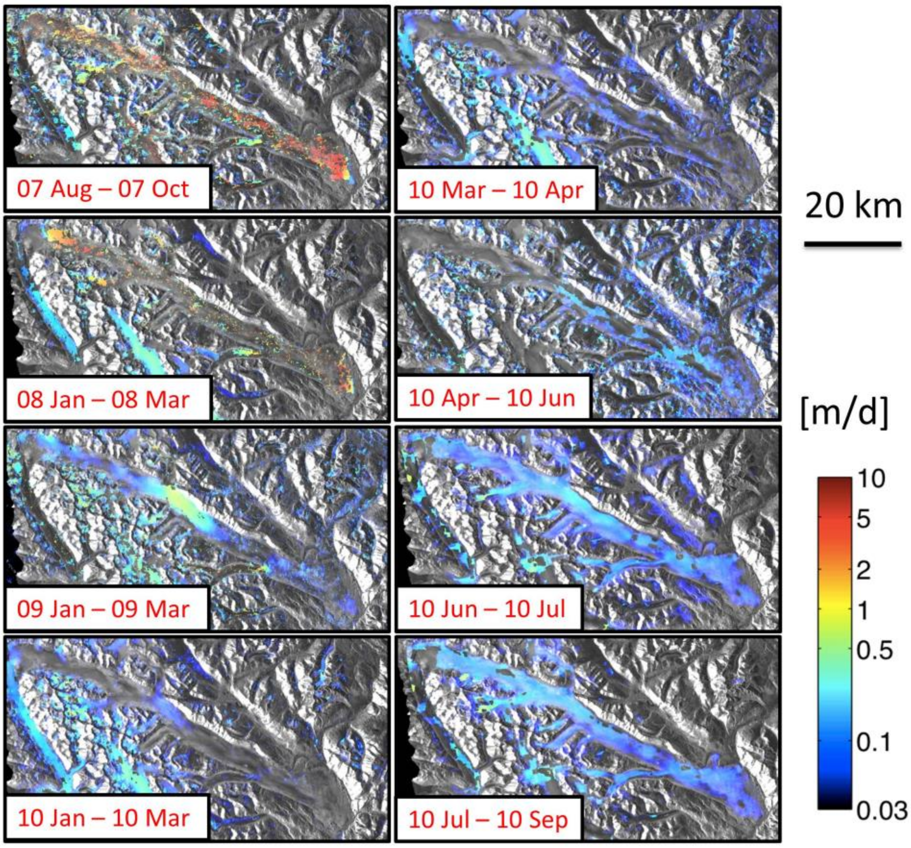

Figure S3. Surface velocity evolution on Tweedsmuir Glacier. The color scale is logarithmic.

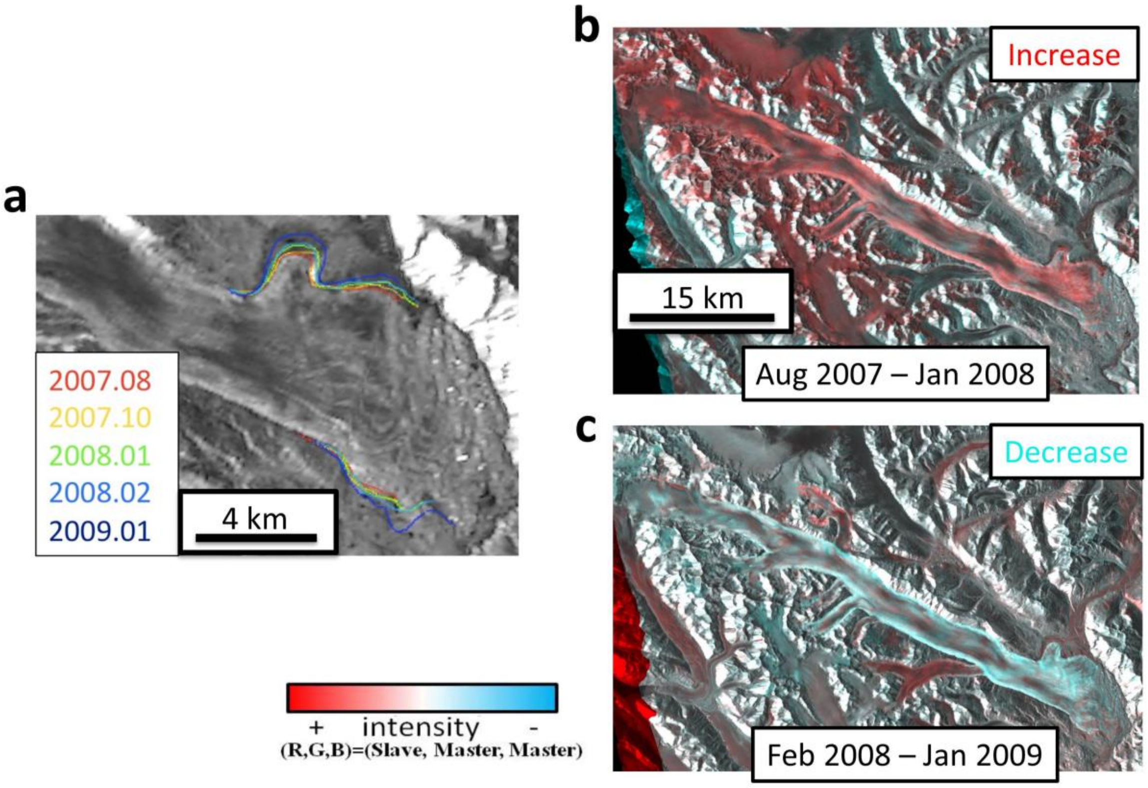

Figure S4. (a) Terminus locations on Tweedsmuir Glacier based on PALSAR intensity images. (b) An RGB composite image derived from the images on 29 August, 2007 and 14 January, 2008. (c) A composite image derived from the images on 29 February, 2008 and 16 January, 2009.

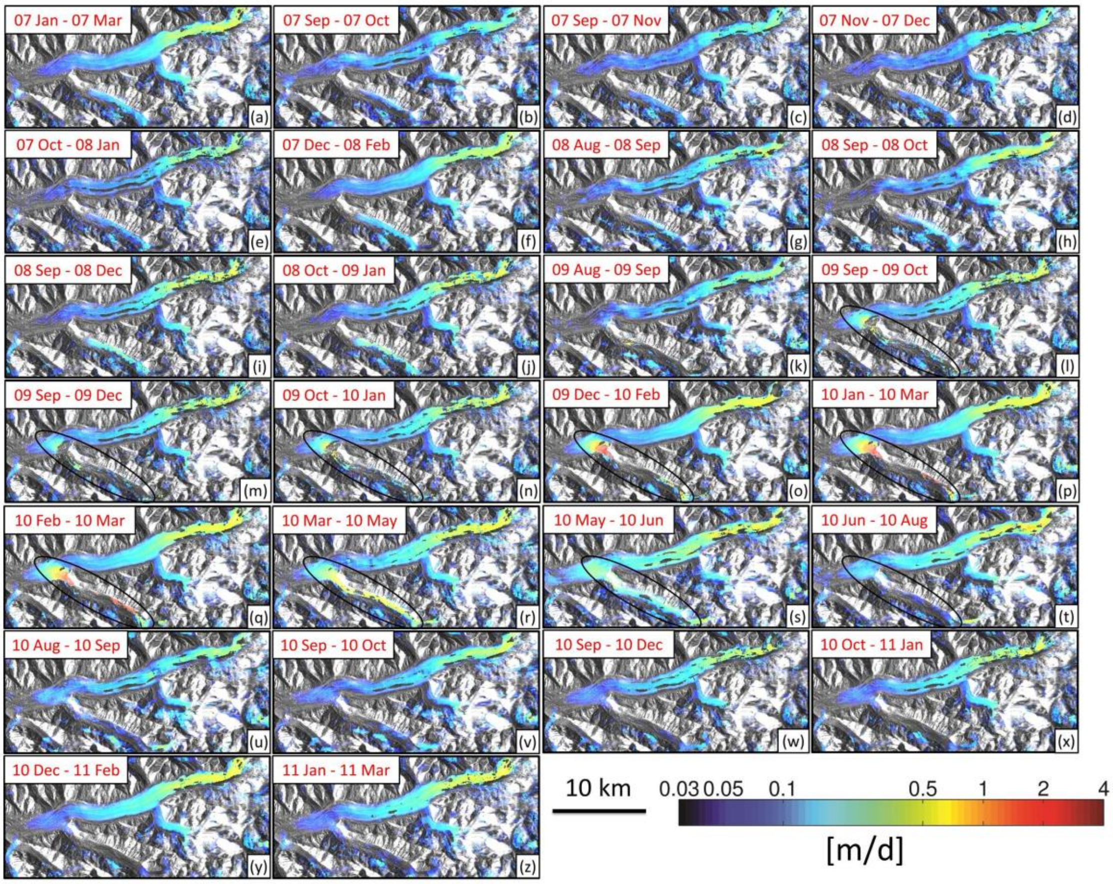

Figure S5. Surface velocity time-series (from upper left to lower right) at Chitina Glacier. Images are arranged in the order of middle date between the first and second acquisitions for each pair. The color scale is logarithmic. The black ovals mark a surge from autumn 2009 to summer 2010 on Ottawa Glacier.

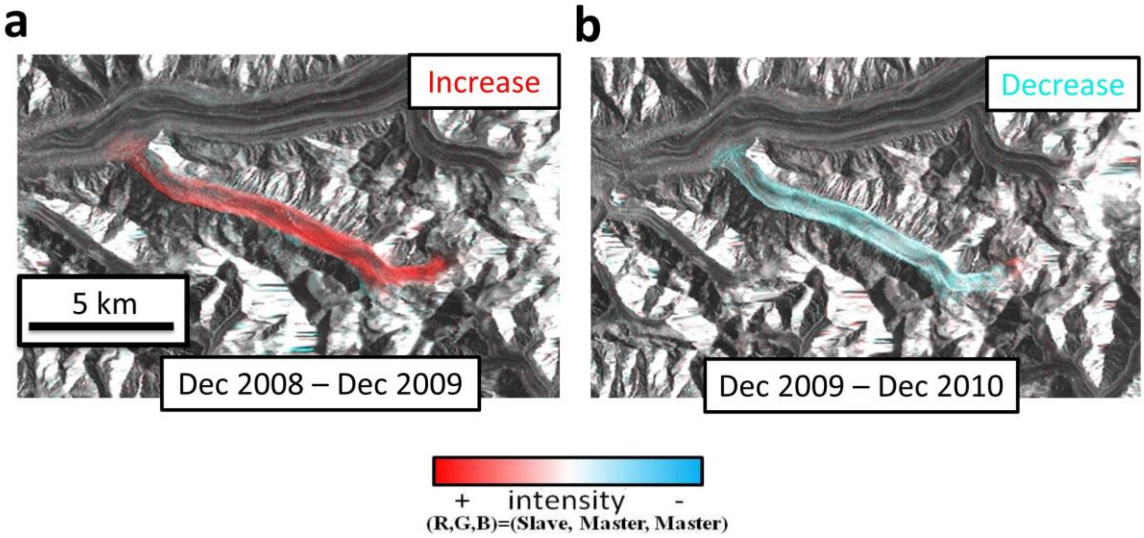

Figure S6. Composite images on Ottawa Glacier. The larger glacier at the top is Chitina Glacier. (a) An RGB composite image derived from the images on 23 December, 2008 and 26 December, 2009. (b) A composite image derived from the images on 26 December, 2009 and 29 December, 2010.

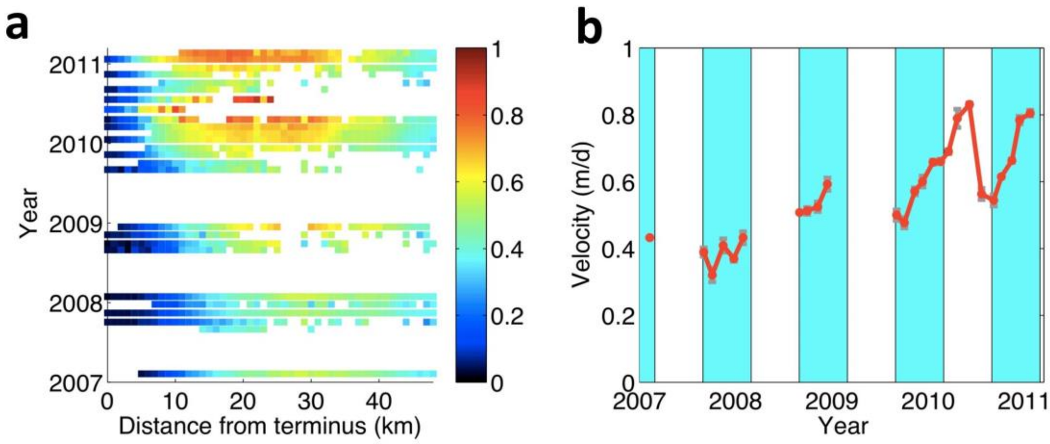

Figure S7. (a) Spatial and temporal evolution of the ice velocity profile along the flow lines of Logan Glacier. The flow lines are marked in Fig. 1. (b) Averaged time-series plot at the section between 18 and 21 km. Cyan shades stand for winter season (Sep - Feb).