Patterns of Wind-Drifted Snow on the Alaskan Arctic Slope Detected with ERS-1 Interferometric SAR

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Introduction

- Strong winter winds cause significant sublimation losses and produce critical changes in the snow depth distribution.
- The redistribution of snow impacts the winter energy balance, and the energy and moisture balance during the snowmelt.
- Investigation of snow-wind interaction by remote sensing is a new application of the InSAR technique.

Wave propagation in dielectric media

- The EM phase delay in media is determined by the refractive index (dielectric constant) of the media

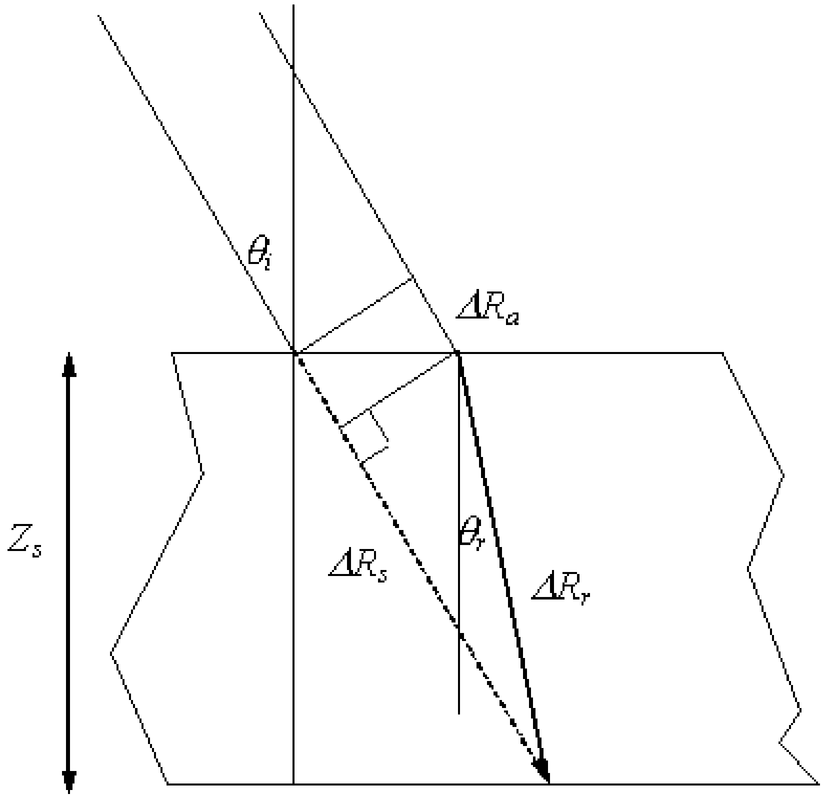
$$n = \mathrm{Re}\left\{\sqrt{\varepsilon}\right\}$$

- For dry snow,

$$\varepsilon'_{ds} = 1 + 1.6\rho_s + 1.8\rho_s^3$$

- Suppose a dry snow layer has a density of 0.3 g cm^{-3}, n = 1.25. This implies that for vertical incidence, radar path length increases by 25% in snow due to refraction.

Geometry of refraction in dry snow. Follow Fig.1 of Guneriussen and others (2001).



- **For slant incidence, the interferometric phase delay in snow is**

$$\Phi_s = \frac{-4\pi}{\lambda_i}\Delta R_s + \frac{4\pi}{\lambda_i}\Delta R_a + \frac{4\pi}{\lambda_s}\Delta R_r$$

$$\Phi_s = \frac{-4\pi}{\lambda_i} Z_s \left(\cos\theta_i - \sqrt{\varepsilon'_{ds} - \sin^2\theta_i}\right)$$

- **where**

λ_i **radar wavelength in vacuum;**

θ_i **incidence angle;**

Z_s **depth of snow cover.**

Interferometric phase caused by change of snow thickness

- For ERS InSAR, the interferometric phase change due to adding (e.g., snow precipitation) or removing (e.g., wind erosion of snow) snow between two acquisitions is

$$\Delta\Phi_s = \frac{4\pi}{\lambda_i} \times 0.87 \Delta SWE$$

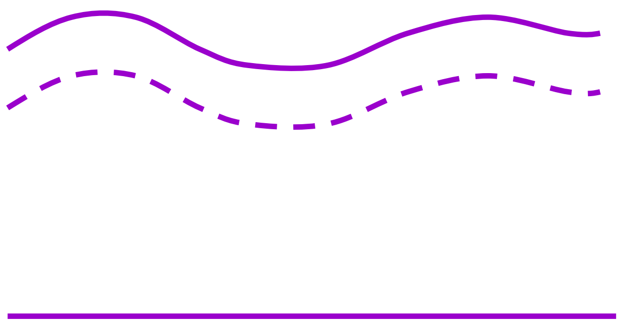
- Where ΔSWE is the change of snow water equivalent.
- This means that change of snow water equivalent by 3.3 cm will cause 2π difference in the interferometric phase.

Coherence

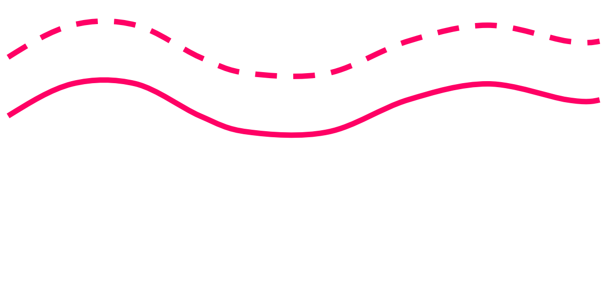
- Repeat-pass interferometric coherence, as defined by Zebker and Villasenor (1992), represents the similarity of the signatures between acquisitions.
- Coherence is a good measure of the homogeneity of the temporal change at each pixel neighborhood.
- Coherence value ranges between 0, a total loss of coherence, and 1, indicating a perfect match.
- When there is heterogeneous temporal change of snow water equivalent in the snow pack between two acquisitions, the coherence tends to be low.

Examples of Coherence Variations

High coherence: no change or homogeneous change

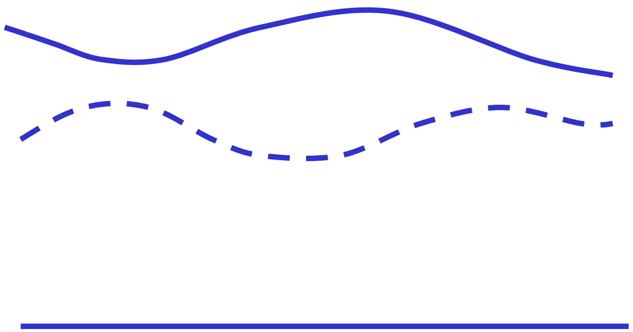


Uniform increase in SWE

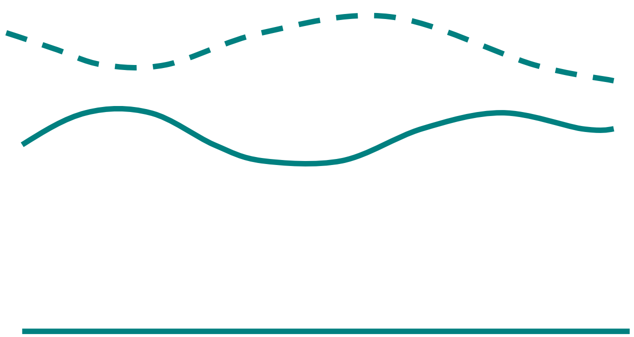


Uniform decrease in SWE

Low coherence: heterogeneous change in SWE

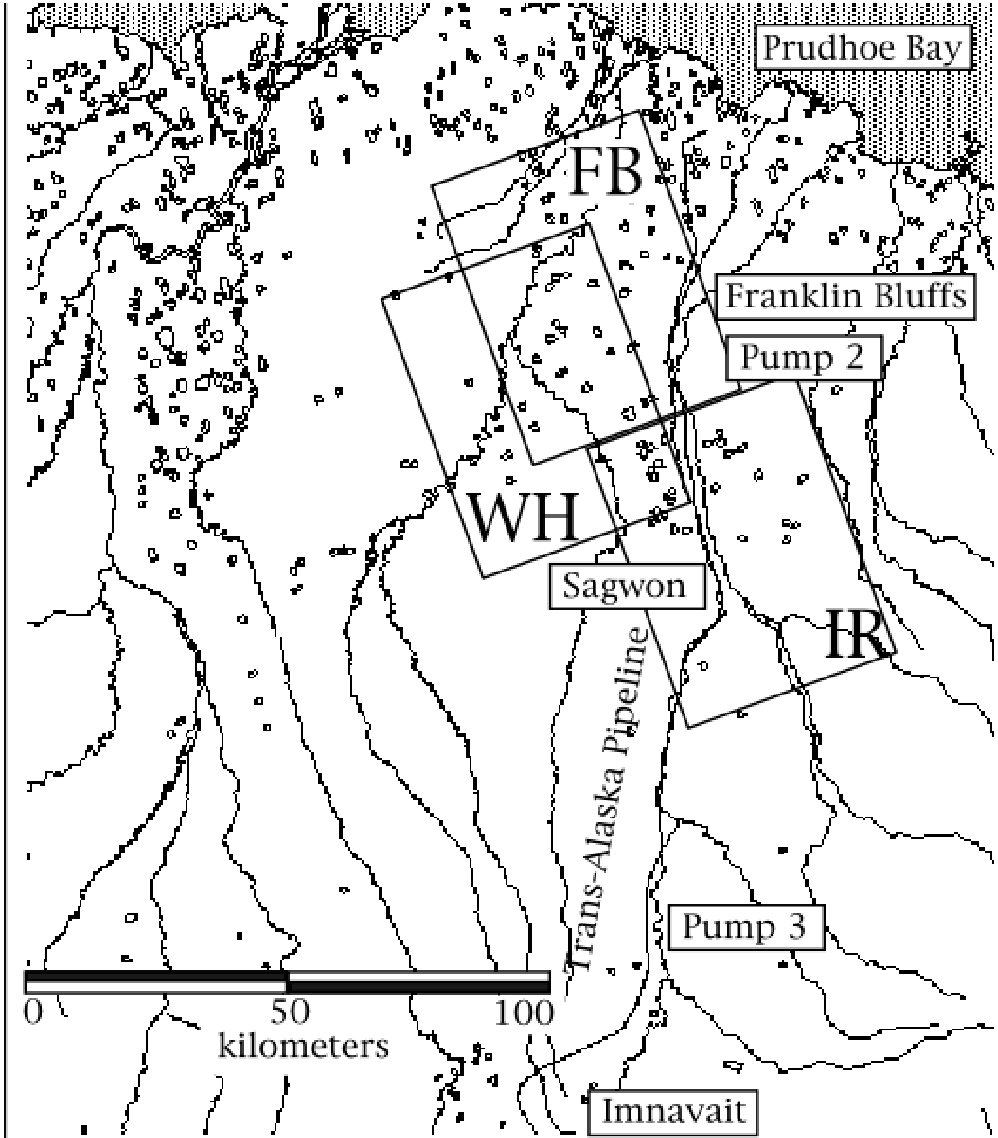


Heterogeneous increase in SWE



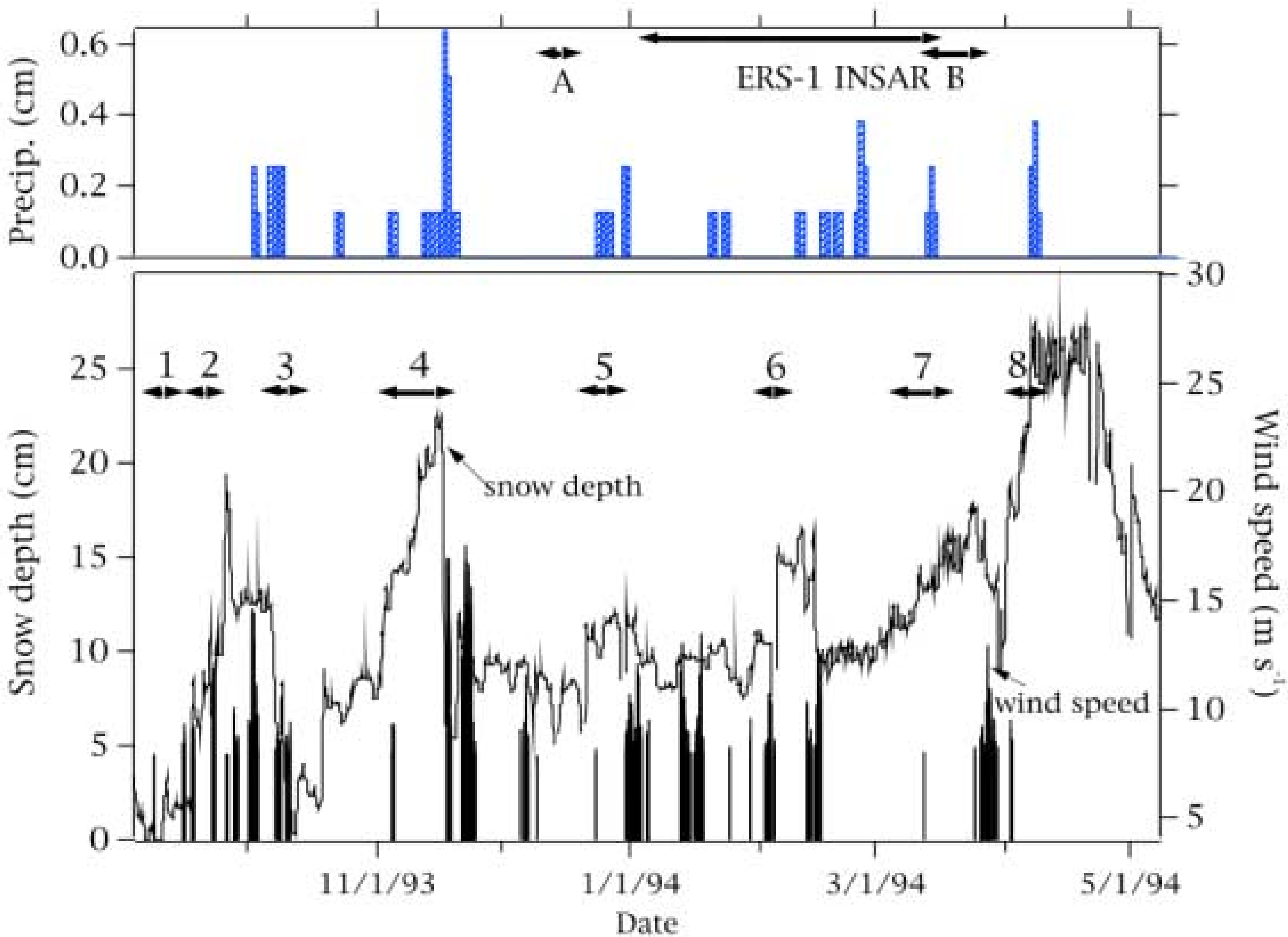
Heterogeneous decrease in SWE

Study Sites (North Slope)

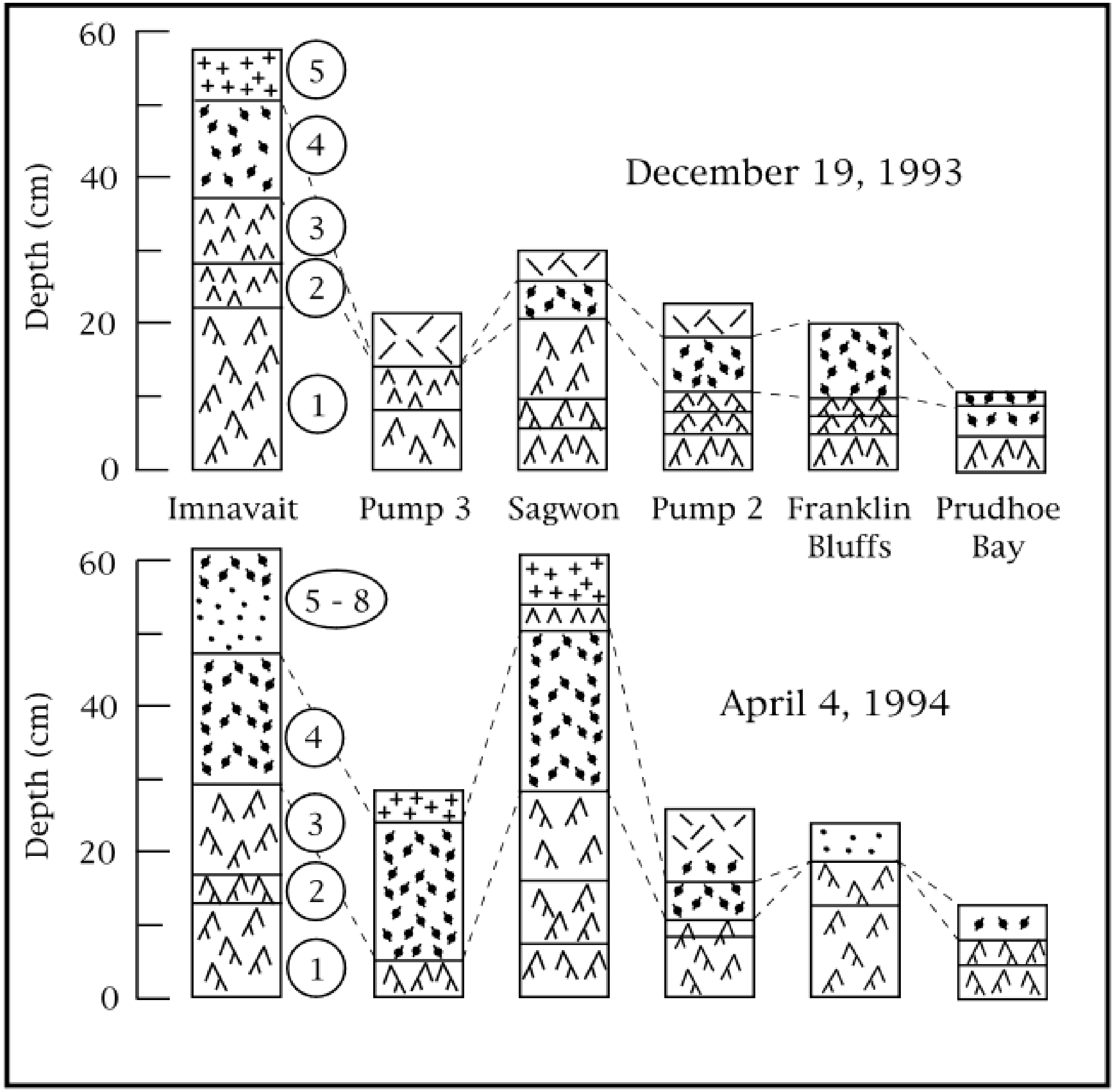


- FB – Franklin Bluffs.
- WH – White Hills.
- IR – Ivishak River

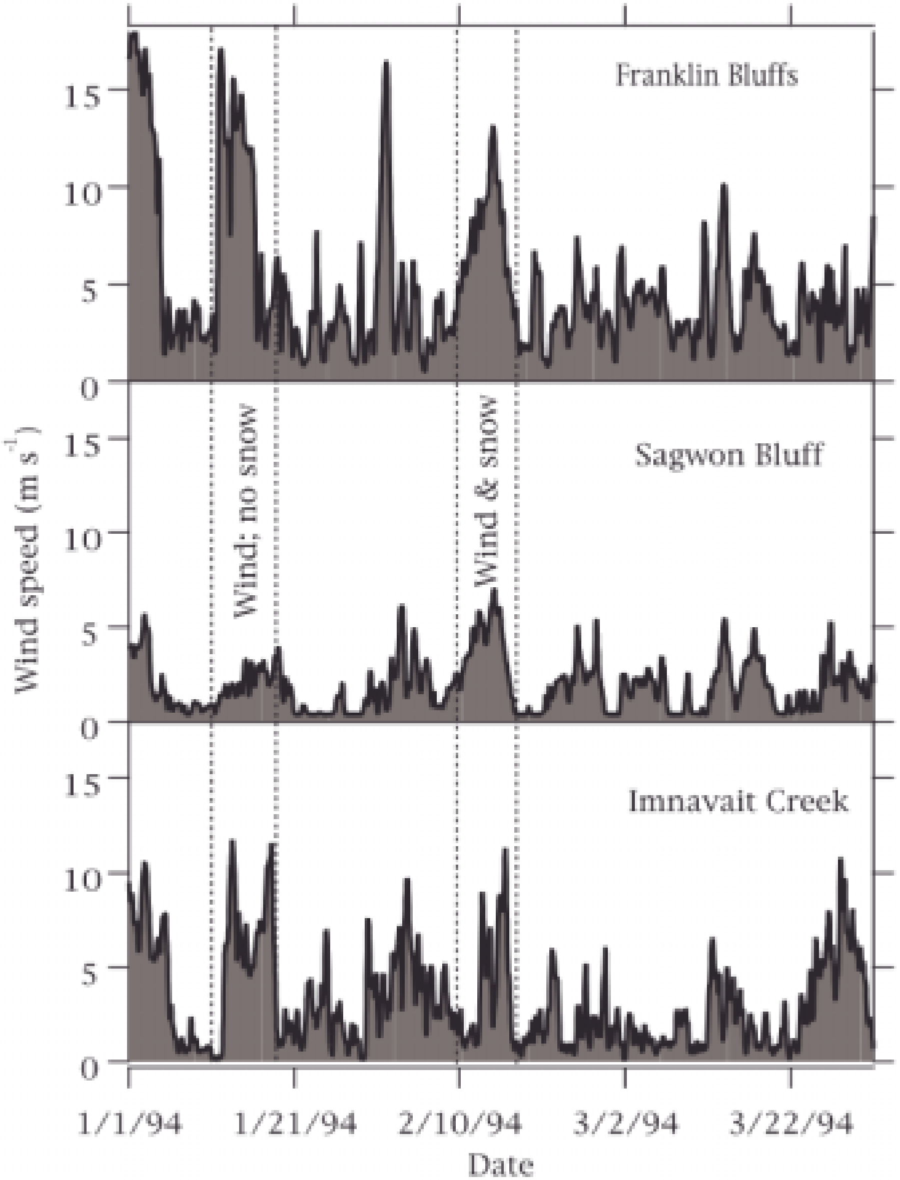
Snow Record (sonic sounders)



Snow stratigraphy

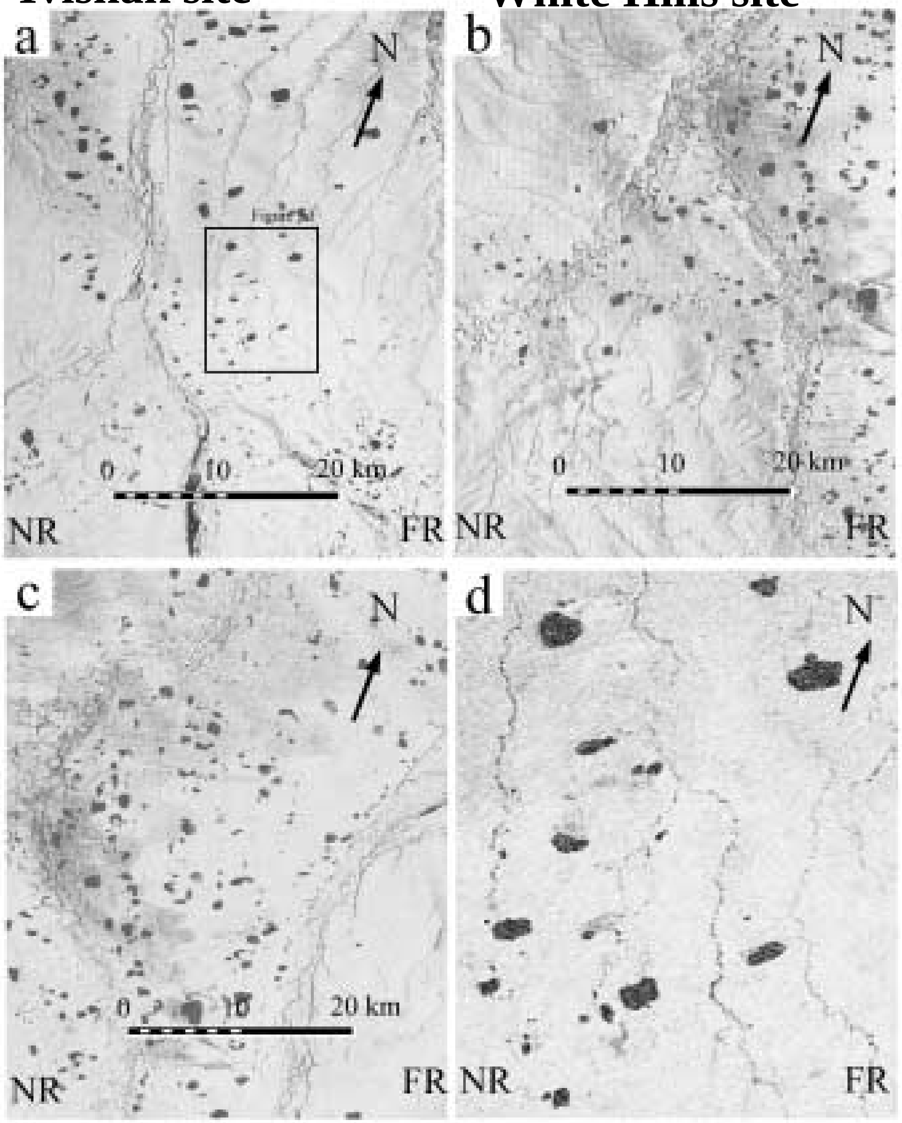


Wind Events and SAR Acquisitions



Spatial Variation of Coherence

Ivishak site White Hills site



Franklin Bluffs site central part of Ivishak

Jan. 8-14, 1994 – no recent snow and other major weather event.

The coherence is generally high.

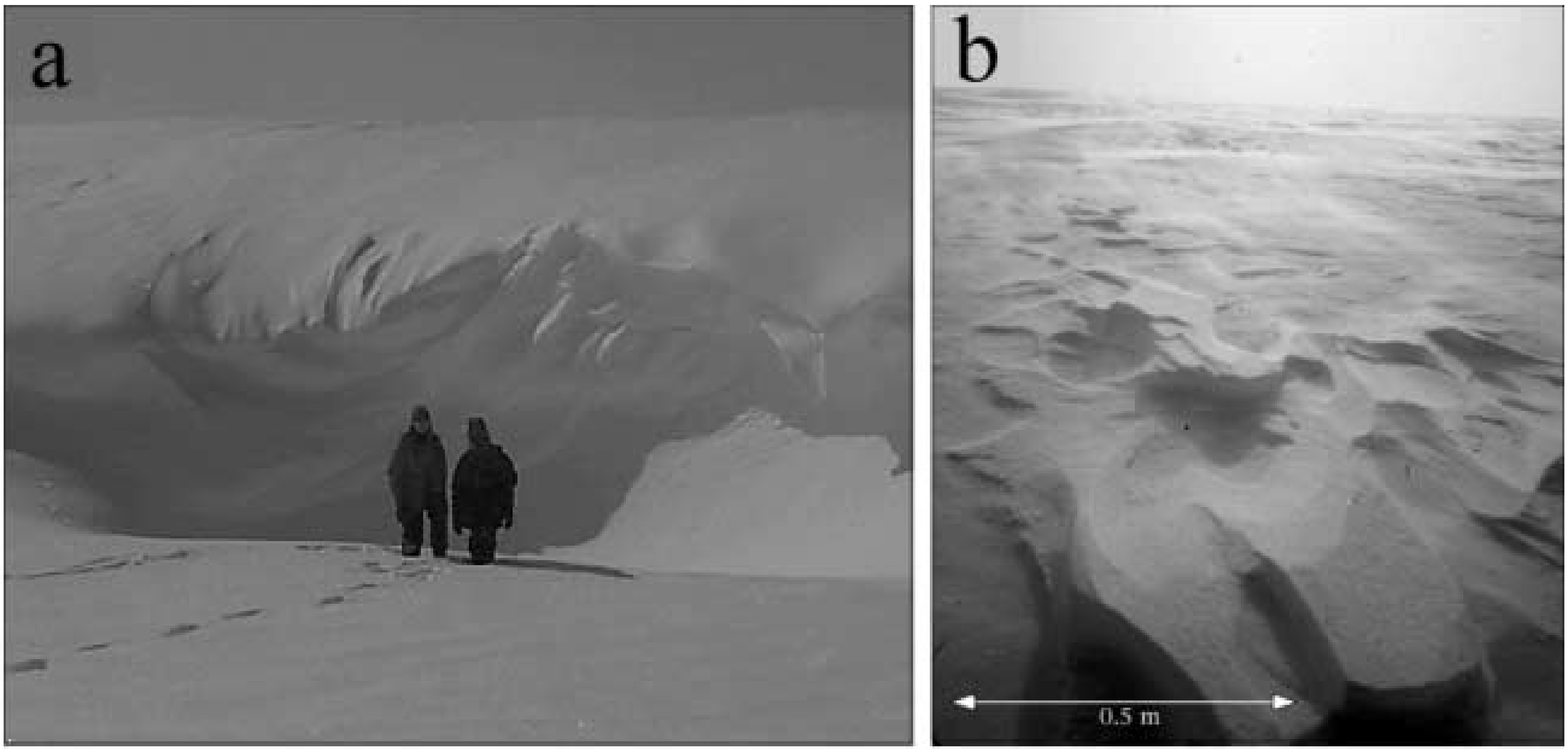
Areas of low coherence:

Lakes - active lake ice growth.

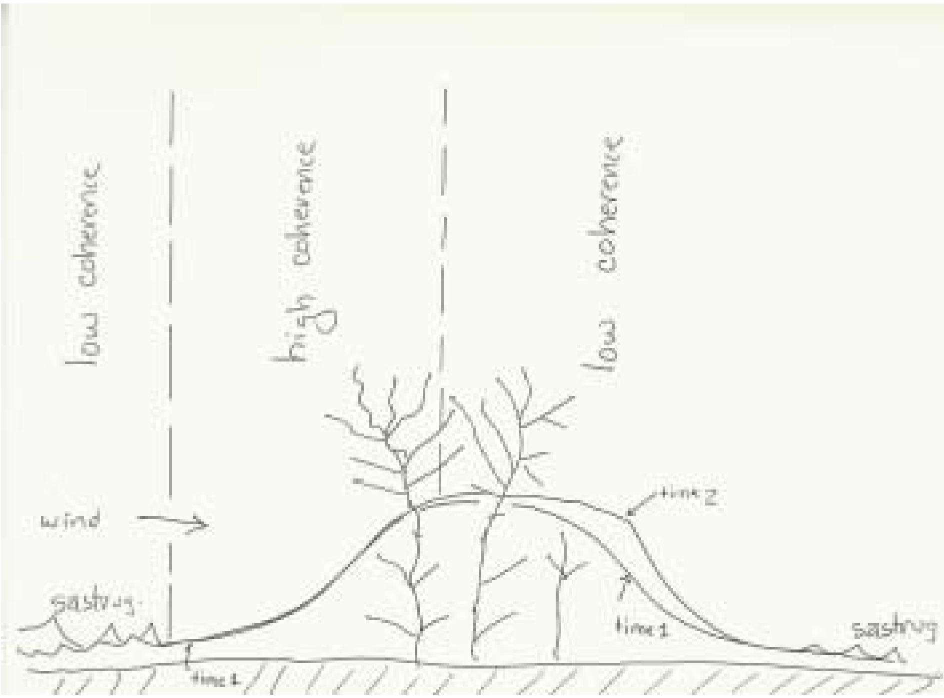
River channels, - river ice growth.

Small creeks - deposition of drift snow.

A large drift in the lee of a stream cutbank and snow dunes (sastrugi) on level tundra



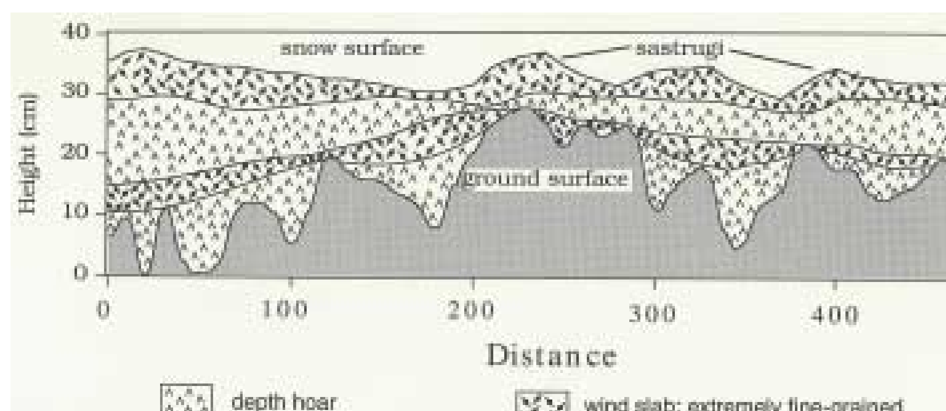
Coherence vs. wind-drift patterns



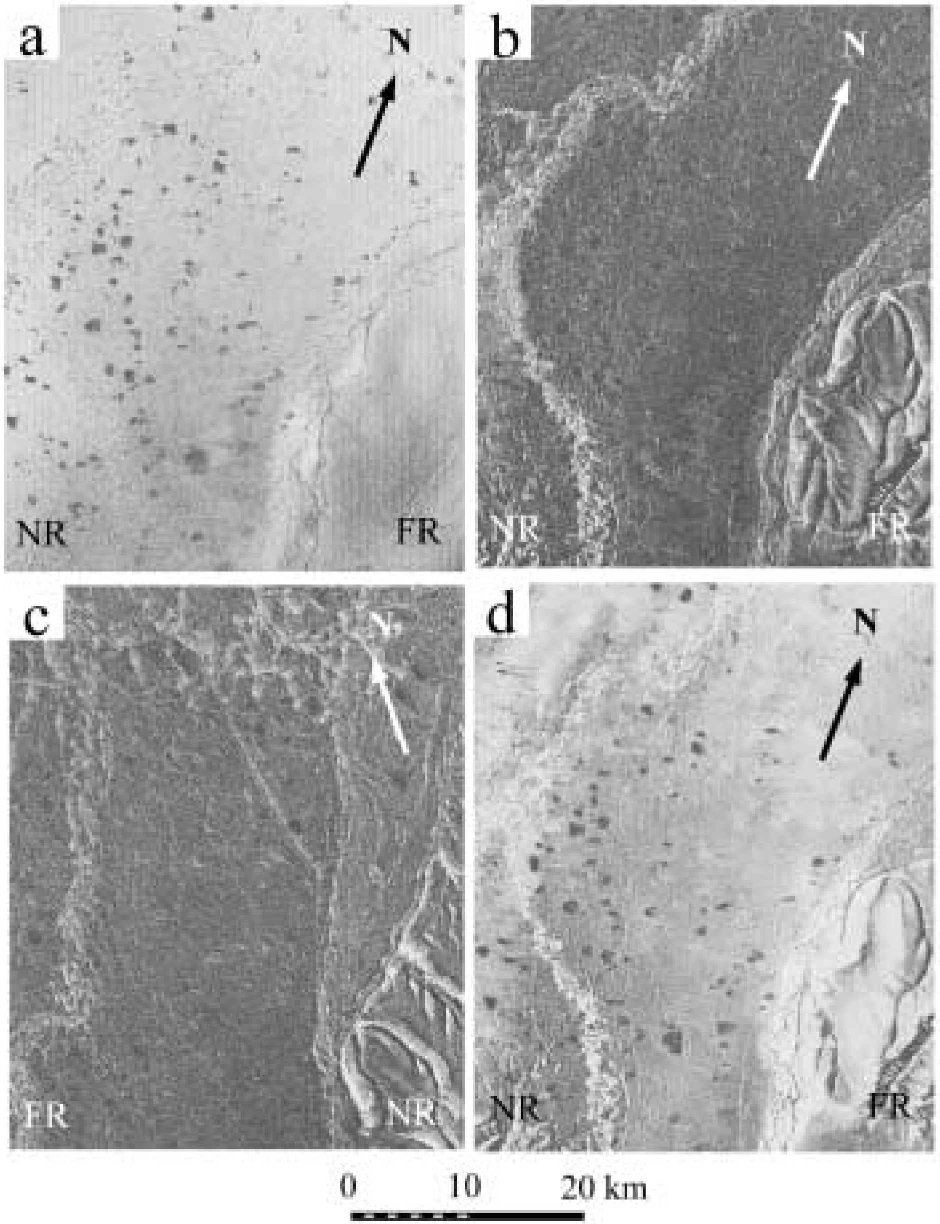
Snow deposition in the lee of small depressions, such as river channels and creeks, causes low coherence.

Snow deposition amongst the willows in the bottom of creeks also causes low coherence.

Sastrugi causes low coherence.



Temporal changes after snow precipitation



(a) Feb. 4 – 7, 1994 (It spans a 7-cm snow event).

(b) Feb. 13 - 16 from east looking orbits.

(c) Feb. 12 - 15 from west looking orbits.

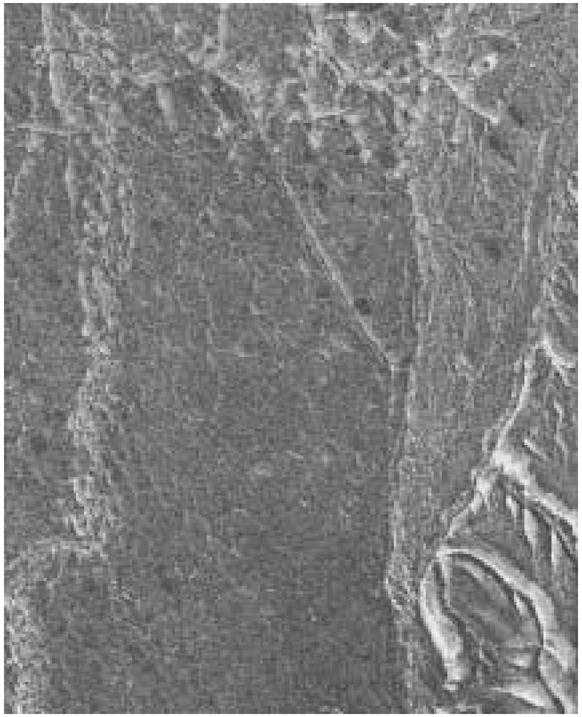
(d) Feb. 25 – 28, 1994.

Weather Events

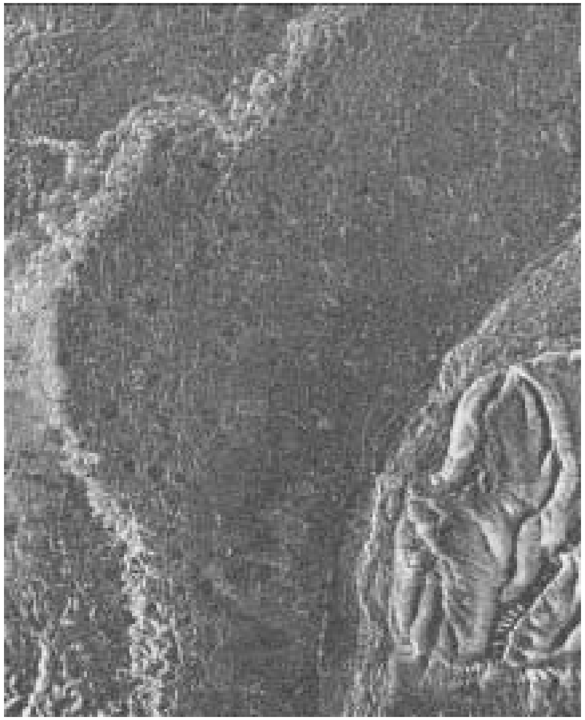
On Feb. 5, about 7 cm of snow fell on the region.

Between 10 and 15 February, persistent strong westerly winds with speeds reaching 12 m s-1 swept the area

Example – Wind Effects



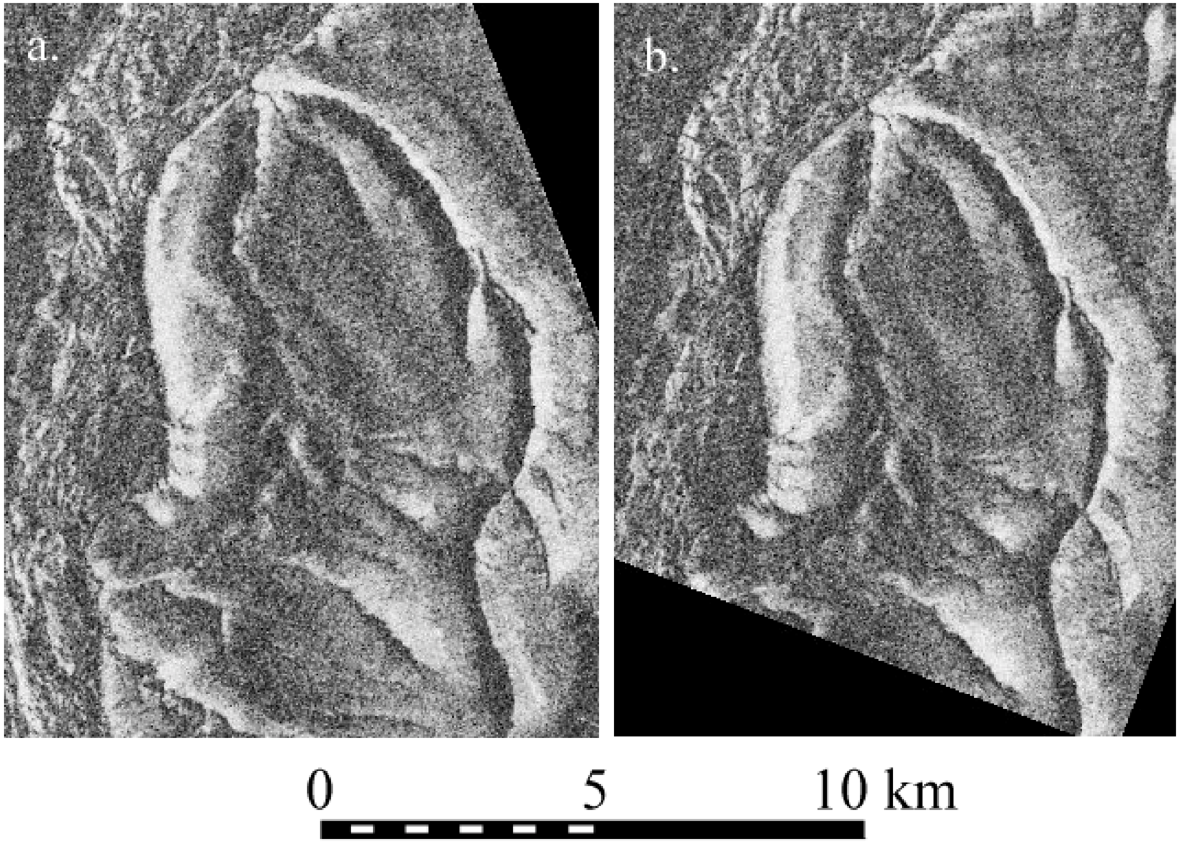
Coherence map (Feb. 12-15) from descending passes.



Coherence map (Feb. 13-16) from ascending passes

- Striking patterns of windward scouring and leeward deposition were revealed for drift events between 12-16 February when west wind reached 10-15 m/s.

Windward scouring and leeward deposition revealed by interferometric coherence



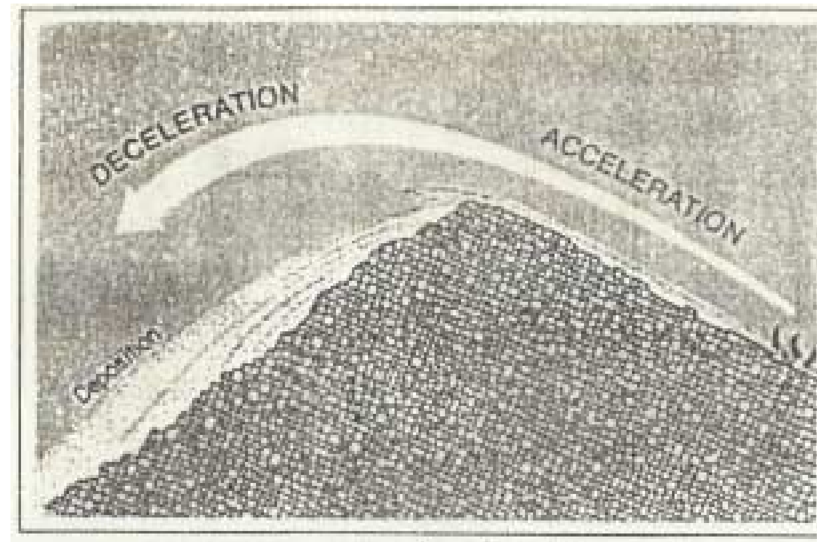
13 - 16 February from east looking orbits;

12 - 15 February from west looking orbits;

Figure 9: Li and Sturm

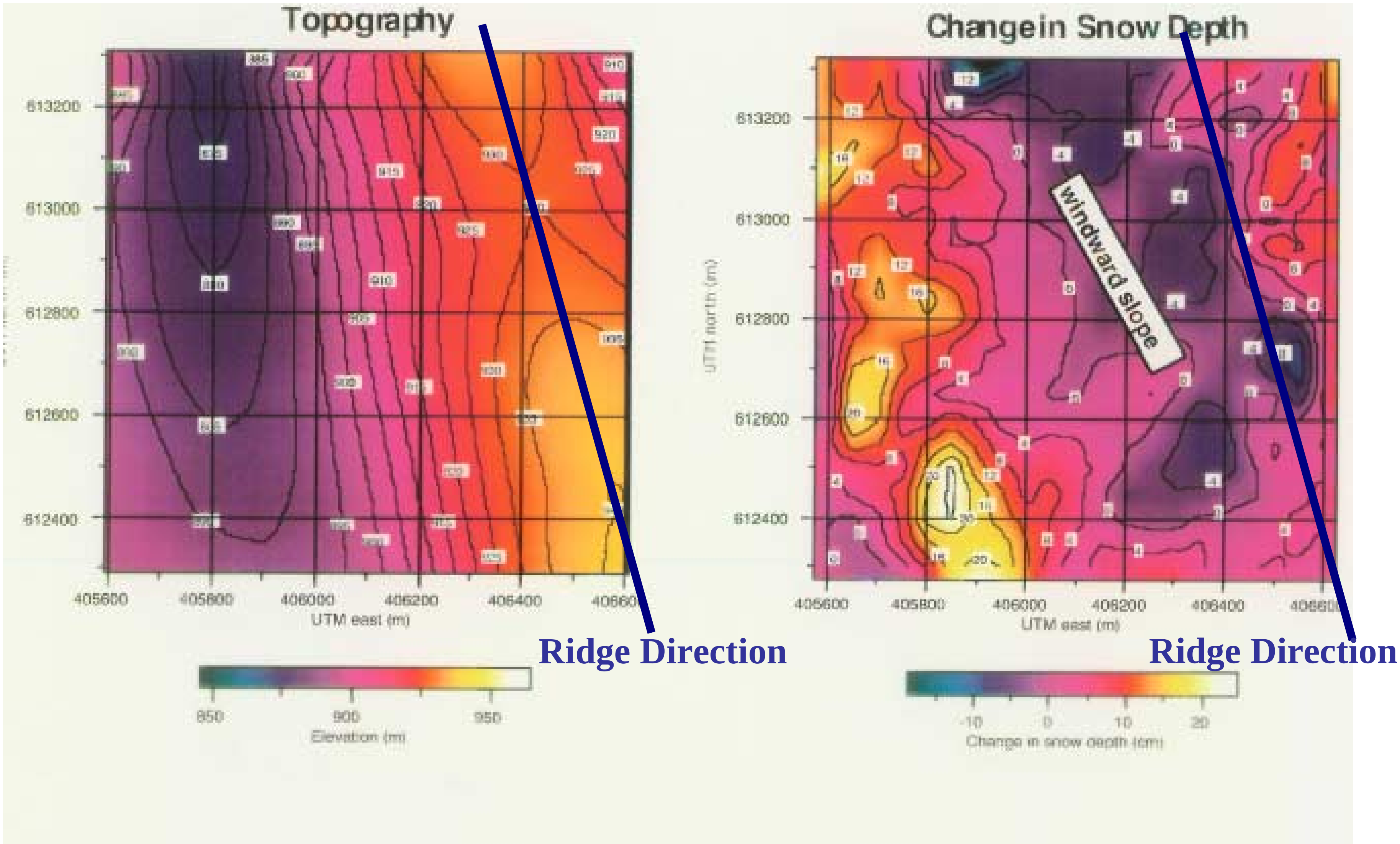
Windward scouring and leeward deposition revealed by interferometric coherence

13 - 16 February from east looking orbits;

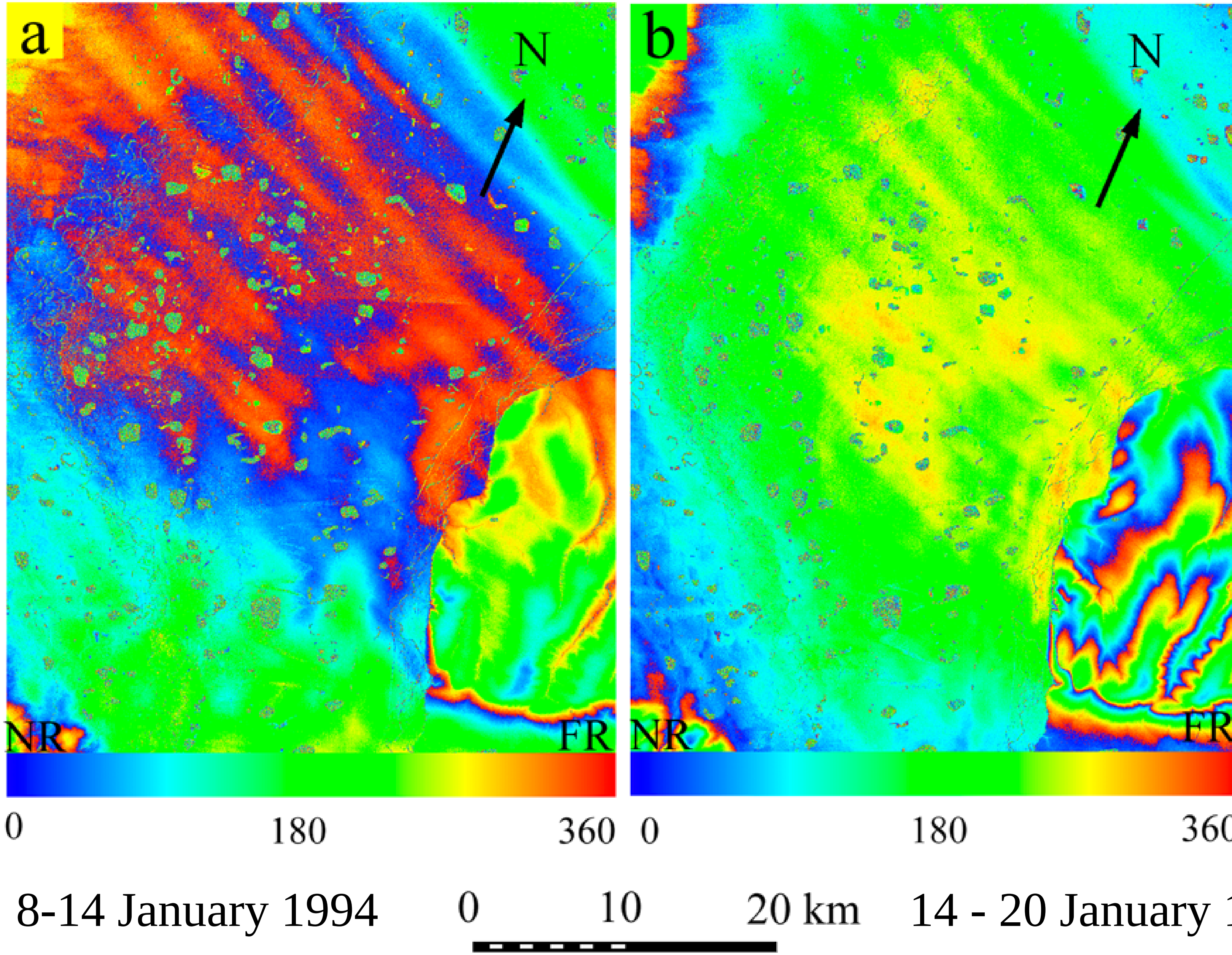


Between 10 and 15 February, persistent strong westerly winds with speeds reaching 12 m s^{-1} swept the area

Wind Scouring on the windward Slopes

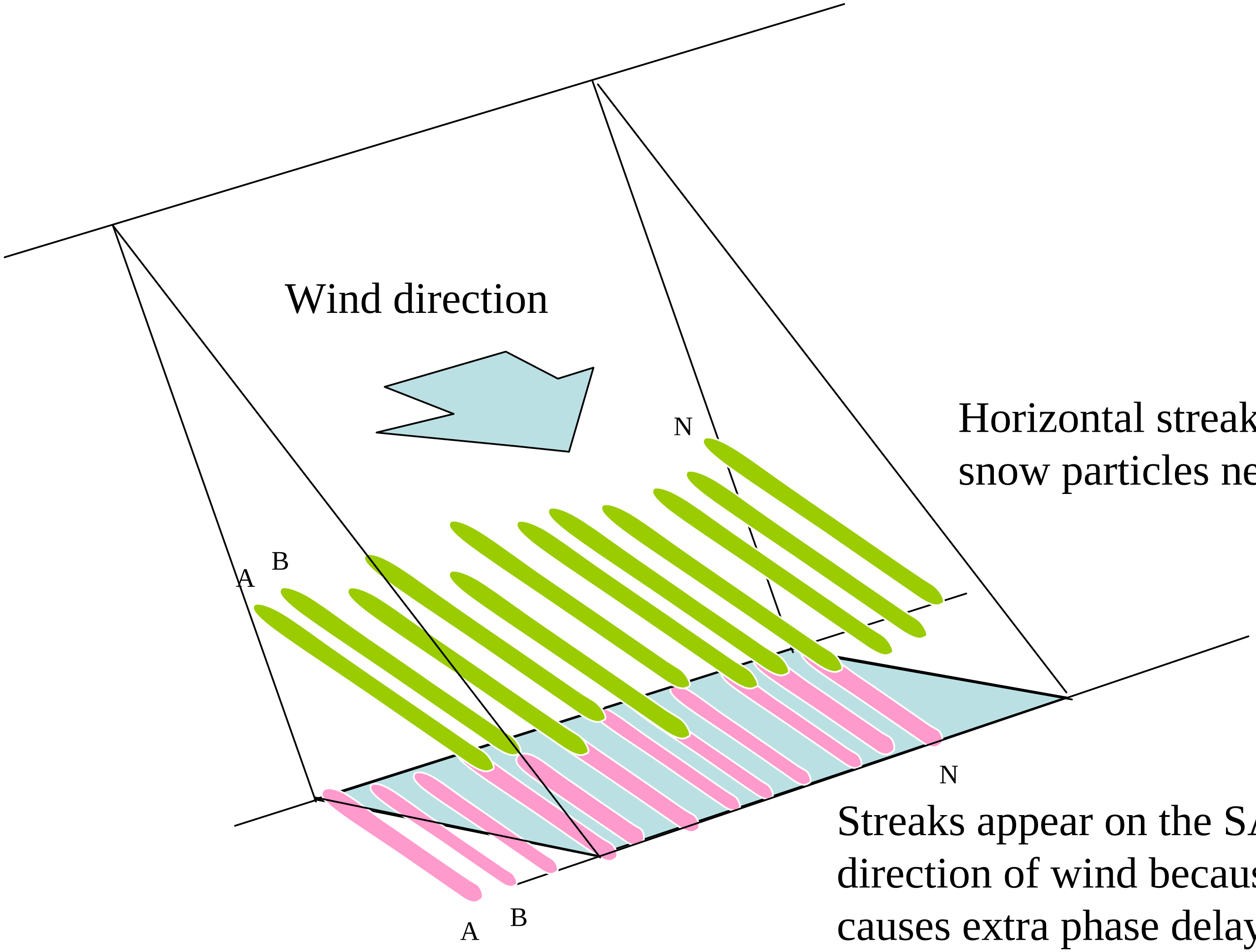


Streaks on Interferograms



8-14 January 1994 14 - 20 January 1994

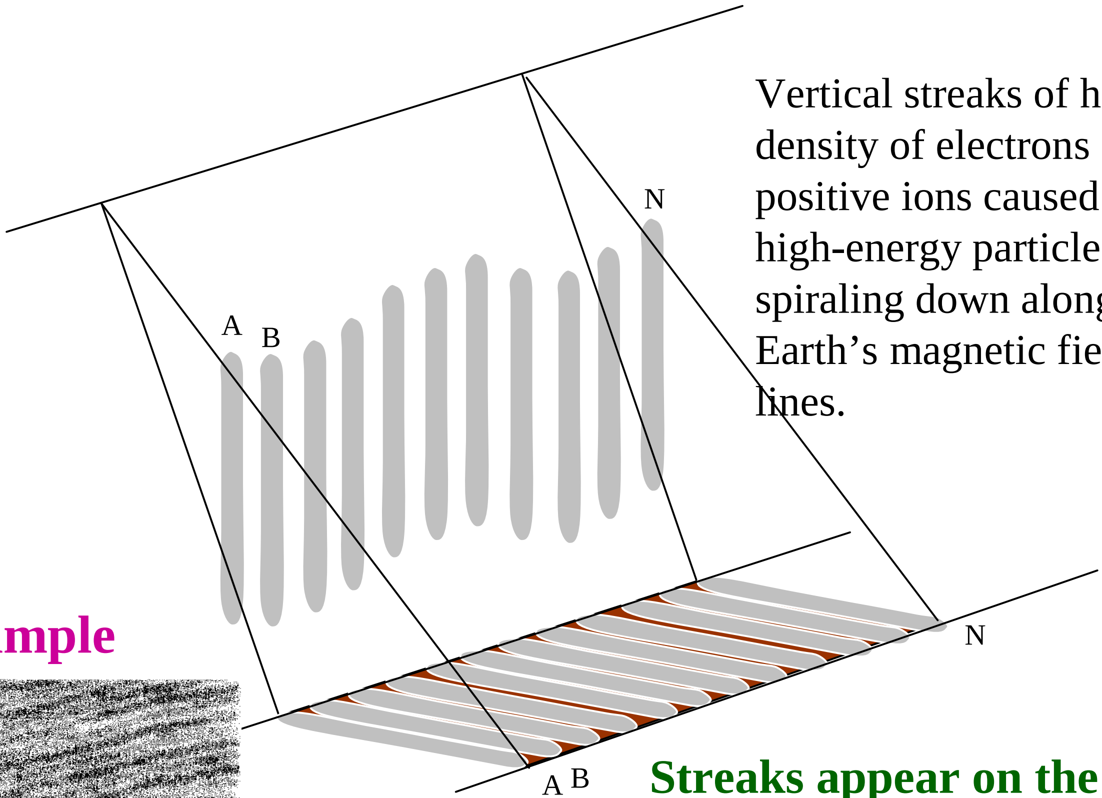
Explanation 1 - Streaks caused by horizontal streaks of airborne snow near the ground



Horizontal streaks of airborne snow particles near the ground.

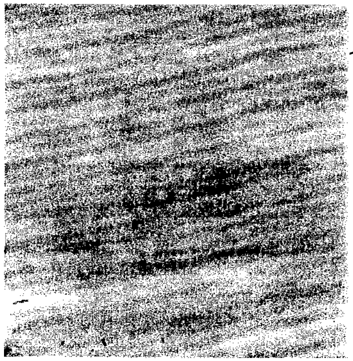
Streaks appear on the SAR images in the direction of wind because airborne snow causes extra phase delay in Radar propagation.

Explanation 2 - Streaks caused by vertical ion streaks in the ionosphere

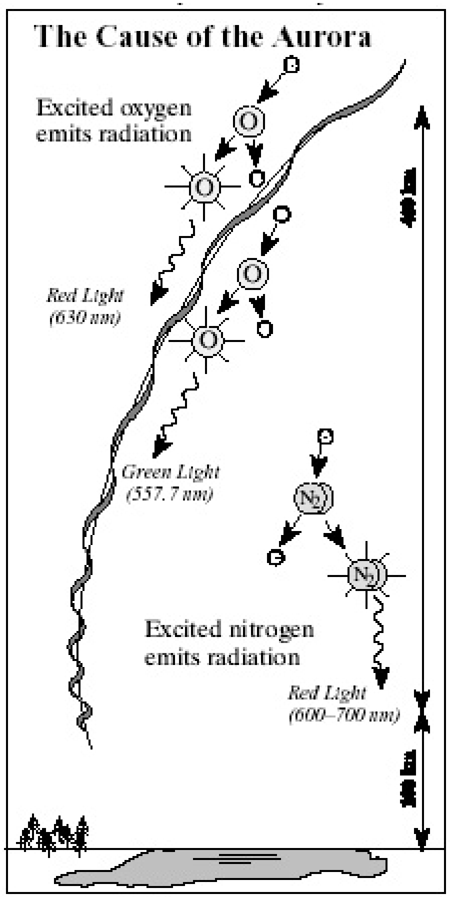


Vertical streaks of high density of electrons and positive ions caused by high-energy particles spiraling down along the Earth's magnetic field lines.

Example

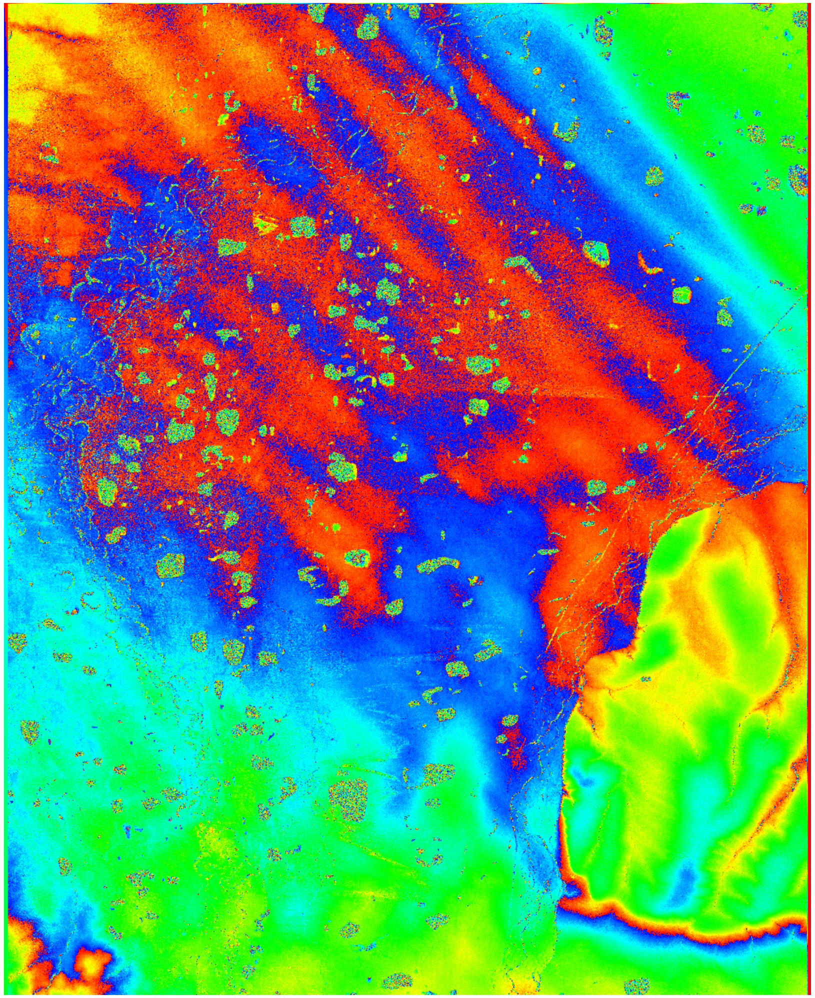


Streaks appear on the SAR images approximately in the range direction



Streaks on Interferograms

(airborne snow with a SWE of 2-3 mm in the atmospheric columns)

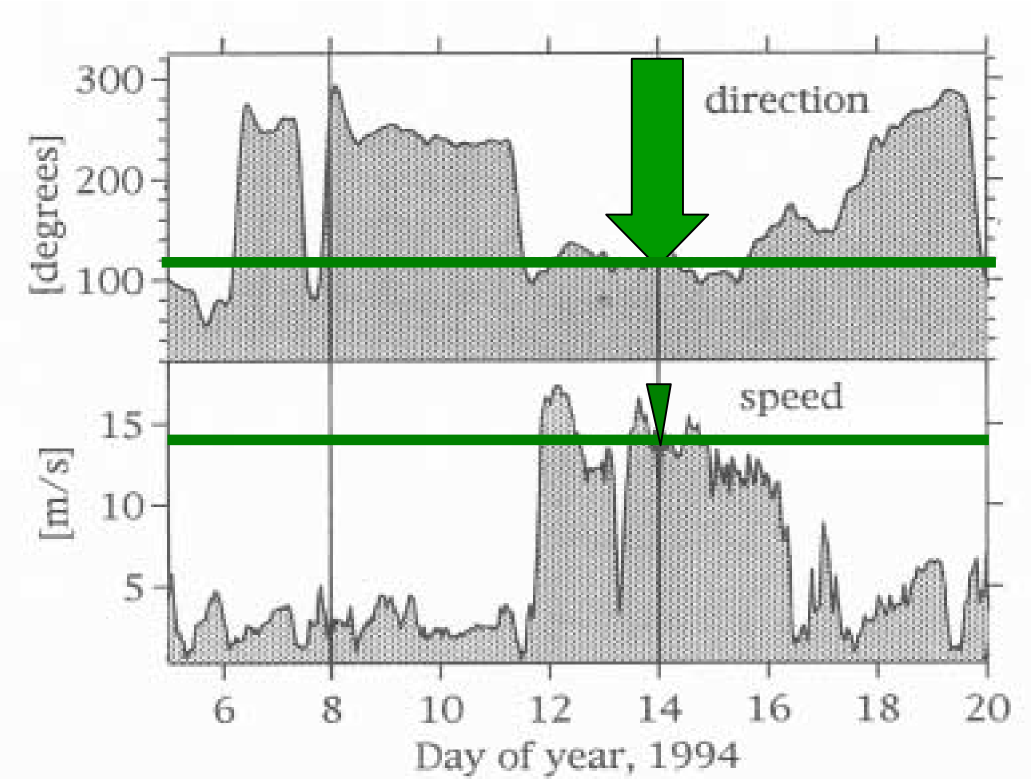


8-14 January 1994

The auroral eletrojet index –background level (explanation 1 rejected)

Wind direction: 110-120°

Wind speed: 14 m/s



Conclusions

- Large scale striking patterns of windward scouring and leeward deposition have been revealed.
- Conspicuous interferometric bands a few kilometers wide and thirty kilometers long were formed downwind of a mountain ridge. It was probably caused by large-scale alterations in the concentrations of moving snow particles.
- Patterns of drift redistribution created by erosion and deposition can be "visualized" or mapped over a wide range of scales using SAR coherence interferograms.