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Supplement of

Impact of dust deposition on the albedo of Vatnajökull ice cap, Iceland

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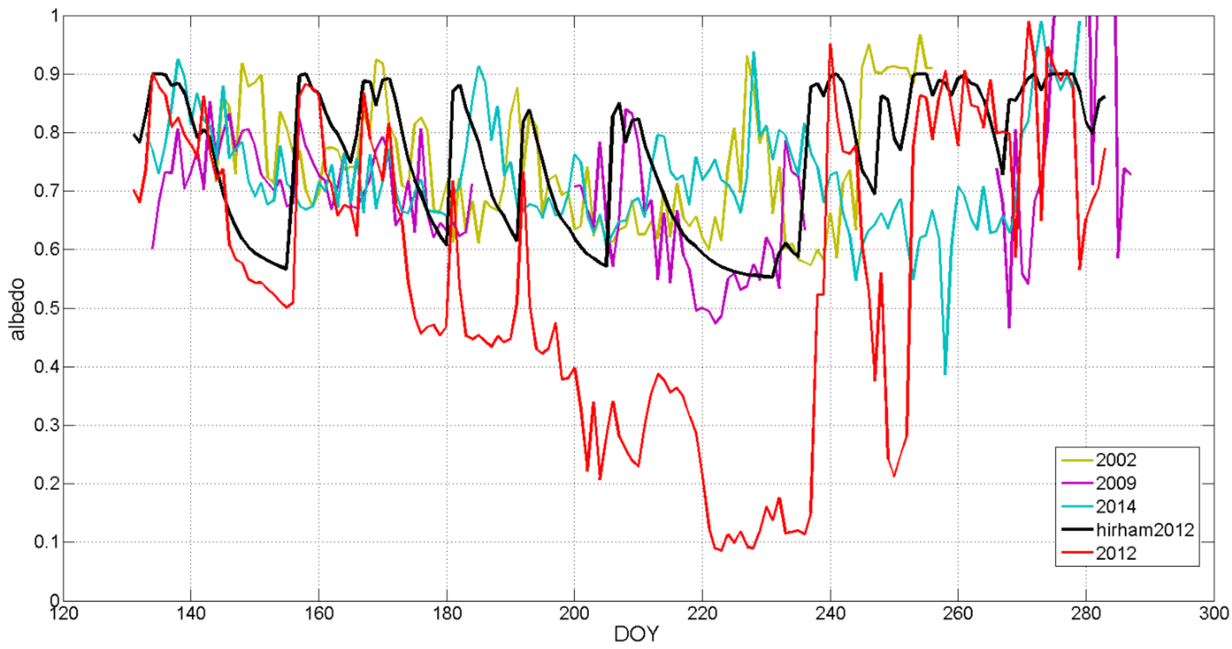

Figure S1: Albedo measurements for the AWS station B13 for the years 2002, 2009, 2012, 2014 (2002, 2009, 2014 are years of little or none surface dust) compared to the modelled surface albedo by Hirham5 (no surface dust assumed in the model) for 2012.

Albedo at station B13, which is close to the ELA is shown in Figure S1. The year 2012 was modelled by HIRHAM5 (in black) and compared to the AWS (in red) and to 3 other years of albedo measurements showing high albedo, but no melt out of the previous summer surface and a similar speed of albedo drop after a snow event. Also interesting is that after snowfall events the albedo usually peaks up to 0.9 even in the summer. If there is dust on the surface, prior to snowfall, light penetrates through the fresh thin snow cover, thus some light is absorbed by the dust and albedo will be lower than 0.9. This may help explain the low (~0.7) value of albedo in 2012 after snowfall events between days 180 and 200.

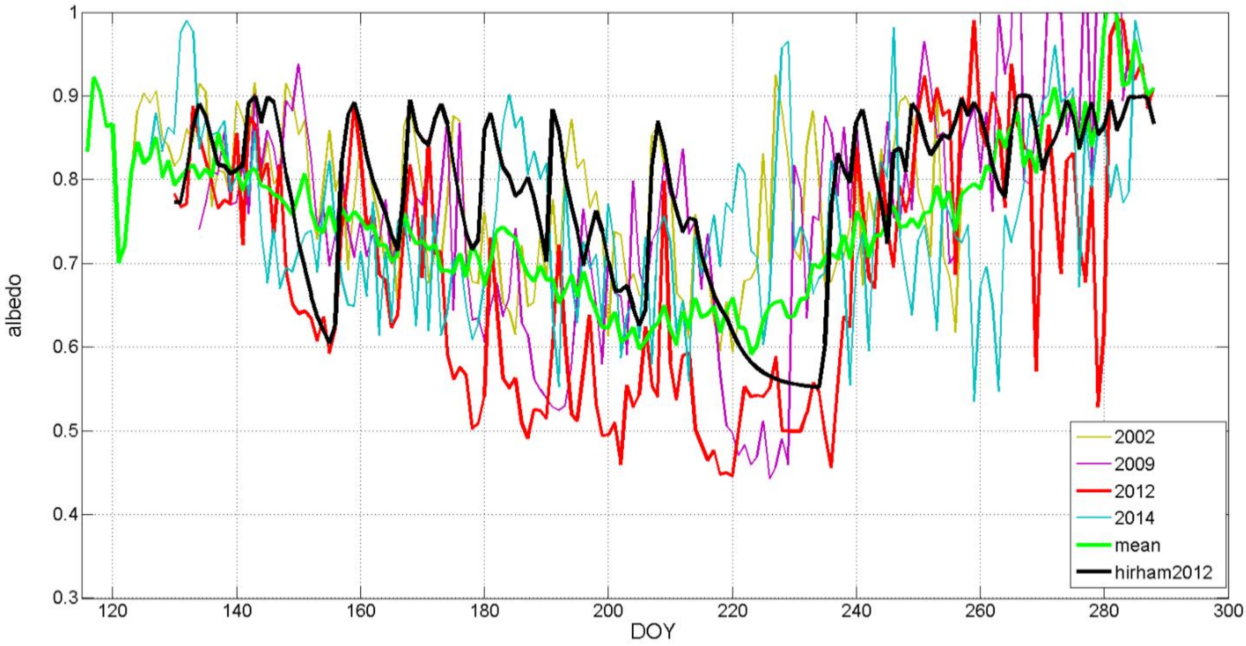

Figure S2: Albedo measurements at the AWS station B16 in the years 2002, 2009, 2012, 2014 (years of clean surface) compared to the modelled surface albedo by Hirham5 for 2012 (black curve) and the measured albedo mean for all years since 1997 (green curve).

The average measured albedo at B16 (Figure S2 in green) since 1997. In black the albedo estimate from HIRHAM5 model run for 2012 is shown (no dust on surface assumed), showing similar character as the measured albedo for the other years.

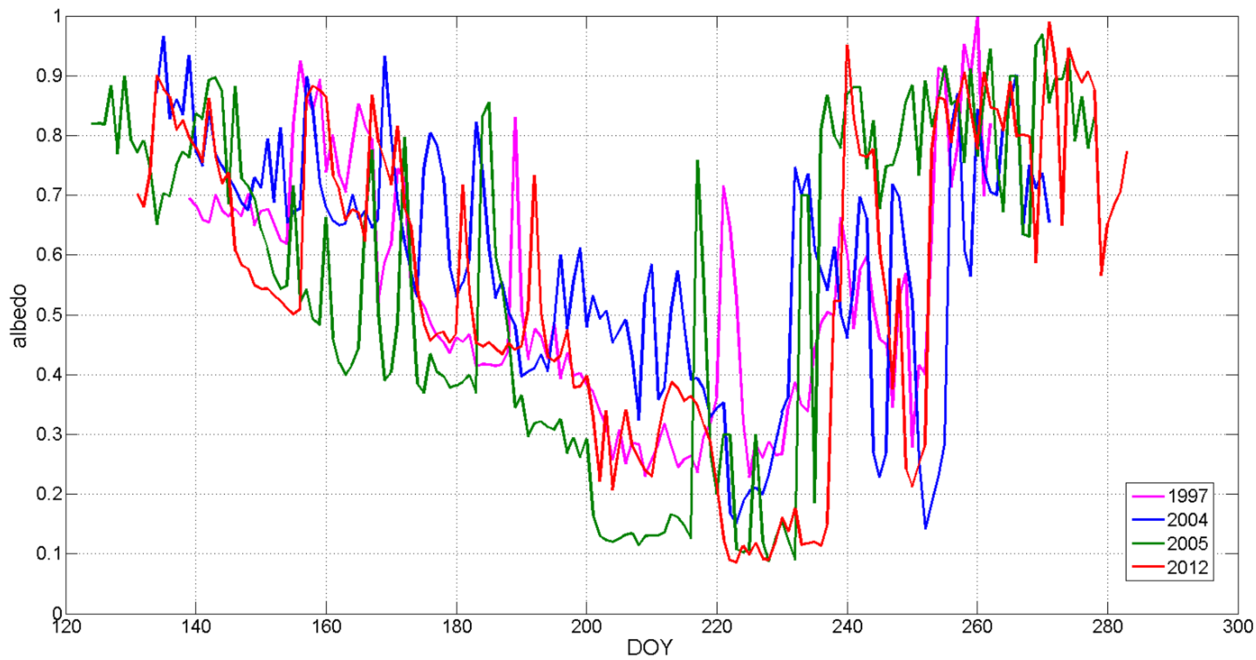

Figure S3: Albedo measurements at the AWS station B13 for selected years of very low albedo, 1997, 2004, 2005 and 2012.

Figure S3 shows years with very low albedos like in 2012 (red). The surface dirt causing the low albedo in 1997 is related to the Gjálp eruption in 1996, and the following huge jökulhlaup with deposition of fine grained particles on Skeiðarársandur sandur plain. This was a vast source of dust in the dry and warm 1997 summer. The low albedo in 2005 and 2012 is related to the 2004 and 2011 Grímsvötn eruptions (e.g. Guðmundsson et al. 2004, Möller et al. 2013.) In 2004 increased melting rates due high wind-driven turbulent heat fluxes in the end of July followed by exceptionally warm and sunny weather in August sped up melting into old firn (Guðmundsson et al. 2006).

- Modelling of albedo evolution in dust free conditions with HIRHAM5

HIRHAM5 combines the dynamical core of the HIRLAM7 numerical forecasting model (Eerola, 2006) with the physical schemes from the ECHAM5 general circulation model (Roeckner et al., 2003). Model simulations have been validated over Greenland using AWS and ice core data (e.g. Lucas-Picher et al., 2012; Langen et al., 2015). Using the same method described in Langen et al. (2015), we run the surface scheme in HIRHAM5 by forcing it with atmospheric parameters from a previous model run. This method allows us to implement an improved albedo scheme (Nielsen-Englyst, 2015) without running the full model. One drawback of this method is that it neglects feedbacks between the surface and the atmosphere. However, since we are only interested in the albedo, and the temperature of the glacier surface of Vatnajökull in the summer is typically around the melting point, the error due to neglected feedbacks is likely small. The simulated albedo was interpolated to the AWS positions using bilinear interpolation of the four nearest grid points.

The albedo parameterization is similar to that described in Oerlemans and Knap (1998), with the albedo decaying exponentially after a fresh snow fall depending on the age of the snow at the surface. However, unlike in Oerlemans and Knap (1998), the decay rate and the minimum albedo of the model depend on the surface temperature. If the surface temperature is -2°C or lower, no melt occurs and we characterise the snow as dry.

For each model time step, the albedo is updated using

$$\alpha_{snow}^{n+1} = \left(\alpha_{snow}^{n} - \alpha_{\{d,m\}}\right) \exp\left(\frac{-\delta t}{\tau_{\{d,m\}}}\right) + a_{\{d,m\}} \quad (3)$$

where α^n is the albedo from the previous day, $\alpha_{\{d,m\}}$ is the minimum albedo, which depends on whether the snow is under dry or melt conditions; δt is the model time step, and $\tau_{\{d,m\}}$ is a timescale which determines how fast the albedo reaches its minimum values under dry or melting conditions.

Under both melting and dry conditions, the albedo can only be refreshed to a higher value due to snowfall. In order to take the effect of rain into account, the albedo is refreshed if a certain amount of the total precipitation is snow. The model has a partial refreshment scheme, where the value of the albedo is refreshed and depends on the amount of snow. The refreshment rate is

$$rate = \min\left[1, \frac{S_f}{\delta t \cdot S_0}\right] \tag{4}$$

where S_f is the snowfall in metres and S_0 is the critical snowfall in metres per time step, equal to 0.3 m, which is needed to refresh the albedo to its maximum value. The albedo will be updated at each time step using

$$\alpha_{snow}^{n+1} = \alpha_{snow}^{n} + \mathrm{rate} \cdot (\alpha_{\mathrm{max}} - \alpha_{\mathrm{snow}}^{\mathrm{n}}). \tag{5}$$

In the case of small snow depths, the surface is affected by the underlying surface and an Oerlemans-Knapp transition (Oerlemans and Knap, 1998) is used to ensure a smooth transition between snow and ice.