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Century-scale solar variability and Alaskan temperature change over the past millennium

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[1] Correlation of geologic histories from 130 Alaskan glaciers with a record of solar variation suggests that multidecadal to century-scale temperature variations in the North Pacific and Arctic sectors have been influenced by solar forcing over the past thousand years. Mountain glacier fluctuations are primarily a record of summer cooling and the composite glacial history from three climatic regions across Alaska shows ice expansions approximately every 200 years, compatible with a solar mode of variability. The modulating effects of the cold phases of the Pacific Decadal Oscillation and the Arctic Oscillation may, when in phase with decreased solar activity, serve to amplify cooling, forcing glacier advance. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1824 Hydrology: Geomorphology (1625); 4221 Oceanography: General: Dendrochronology; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance. **Citation:** Wiles, G. C., R. D. D'Arrigo, R. Villalba, P. E. Calkin, and D. J. Barclay (2004), Century-scale solar variability and Alaskan temperature change over the past millennium, *Geophys. Res. Lett.*, *31*, L15203, doi:10.1029/2004GL020050.

1. Introduction

[2] Century-scale solar forcing may have contributed to several key climatic episodes during the Holocene, e.g., the Little Ice Age [*Bard et al.*, 1997; *Beer et al.*, 2000; *Bond et al.*, 2001]. Increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries [*Houghton et al.*, 2001]. Solar variations with a periodicity of 2500 years have been proposed as being instrumental in generating moraine building in the Northern Hemisphere [*Denton and Karlèn*, 1973]. Proxies for drift ice in North Atlantic deep-sea sediment cores compared with a record of solar irradiance based on cosmogenic nuclides from ice cores and tree rings suggests that variations in solar output have affected temperature changes on millennial timescales throughout the Holocene [*Bond et al.*, 2001].

[3] On centennial time scales, the documented 208-year de Vries solar cycle was found to be compatible with a record of drought derived for the past 2600 years in the Maya Lowlands [*Hodell et al.*, 2001] and has been linked to drought in the northern Great Plains over the last 2000 years [*Yu and Ito*, 1999]. In southwestern Alaska, analyses of lake sediments suggest that centennial-scale shifts in Holocene climate may have been modulated by solar activity [*Hu et al.*, 2003]. This variability in Alaska is similar to that in the north Atlantic, suggesting possible sun-ocean climate linkages. On shorter timescales, the association between a 22-year solar cycle and climate variations, especially drought at mid-latitudes, has been recognized [*Cook et al.*, 1997] and some of the mechanisms that amplify the modest variation in solar output have been identified [*Shindell et al.*, 2001].

[4] In this paper we present new indices of glacier activity for three regions in Alaska and compare these results with a record of solar variability. We also consider the possible amplifying effects of the Pacific Decadal Oscillation (PDO) and the Arctic Oscillation (AO) on cooling caused by decreased solar activity.

2. Glacial Record

[5] Based on comparisons with dendroclimatic data, Alaskan glacier activity has been shown to be primarily a record of summer temperature change [*Barclay et al.*, 1999; *Davi et al.*, 2003]. Well-dated histories from 130 non-surging, land-terminating glaciers are compiled from three climatically distinct regions (Figure 1): 1. The Arctic Brooks Range (94 glaciers [*Evison et al.*, 1996; *Solomina and Calkin*, 2003]), 2. The southern transitional interior straddled by the Wrangell and St. Elias mountain ranges (9 glaciers [*Wiles et al.*, 2002]), and 3. The Kenai, Chugach and St. Elias coastal ranges (27 glaciers [*Calkin et al.*, 2001]). The primary data are dendrochronologically-derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens (Figure 1b). Moraine records from the Brooks Range depend on radiocarbon dating for calibration of the lichen curve [*Solomina and Calkin*, 2003] and thus this record is considered less accurate than the southern sites that depend on tree-ring dating methods. The glacial chronologies include advances during the Little Ice Age (LIA; AD 1200–1900), which is bracketed by retracted ice margins during the Medieval Warm Period [*Esper et al.*, 2002] and the recent retreat [*Arendt et al.*, 2002].

[6] For each of the three regions, we have generated a Glacier Expansion Index (GEI; Figure 2, curves B–D) that

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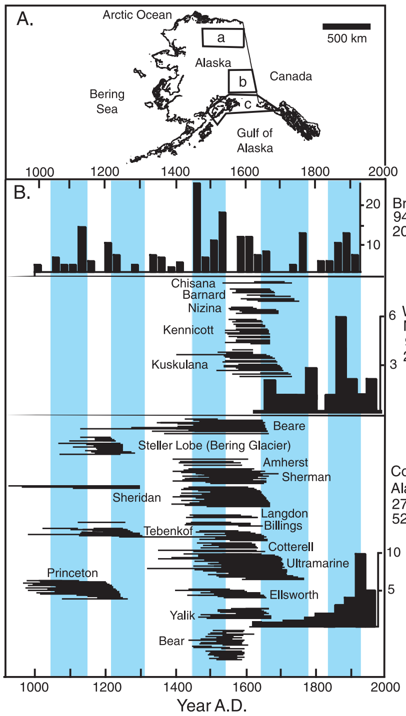

Figure 1. (a) Alaska glacier sites. The Arctic Brooks Range (a), the Wrangell-St. Elias Range (b) and the Kenai, Chugach and St. Elias Mountains (c). (b) Summary diagram showing glacial histories. Histograms are lichen and tree-ring dated moraines. Horizontal bars represent individual tree-ring, cross-dated logs overrun by ice. The shaded bars are intervals of advance.

distills the glacial geologic record into a frequency distribution of glacier advance for succeeding 25-year periods. Age classes with a greater number of observations are intervals of stronger advance. Generation of the GEI uses adjusted glacial geologic data to correct for minimum-limiting (moraine ages) and maximum-limiting dating (tree-ring crossdates). In addition to the three separate GEIs for the Alaskan transect, we have created a composite GEI that is an average of the three normalized GEIs (Figure 2, curve F). Averaging the individual normalized series minimizes potential bias due to uneven sample sizes for each region. Due to the discontinuous nature of the terrestrial glacier record we have chosen to perform analyses on the composite GEI; this combined series is considered a more complete record of glacier expansion across Alaska.

3. Comparison With Solar Irradiance and Discussion

[7] Visual inspection of the individual and composite GEI (Figure 2) suggests an approximate 200-year rhythm of glacial activity. The peaks in the composite GEI (Figure 2, curve F) begin shortly after AD 1100, and are centered on ~1300, 1450, 1650 and 1850. A Blackman-Tukey (BT) spectral analysis [*Jenkins and Watts*, 1968] of the composite series shows peaks at cycles of 65, 104, and 170–210 years (Figure 3a). The statistical significance of the spectral character in the glacial series is difficult to evaluate due to the low number of observations ($n = 34$); however, the 170–210-year peak is consistent with the timing of the observed pulses of glacial activity (Figure 2).

[8] This 200-year rhythm in the glacial record and its possible link to the de Vries 208-year solar cycle is explored by comparing the composite GEI and a solar proxy record (Figure 2). We chose to use the ^{14}C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability. [*Bond et al.*, 2001; *Stuiver et al.*, 1998] (Figure 2). The production rate of cosmogenic radiocarbon is linked to solar irradiance [*Bard et al.*, 1997] with decreased solar irradiance associated with higher production rates.

[9] We averaged the solar ^{14}C series over 25-year intervals to match the resolution of the GEI and its spectral peaks are between 170–210, and at 625 years (Figure 3b). The solar and composite GEI series correlate at 0.26 for the full period. Since the peaks during the 16th century are based on the Brooks Range GEI, we consider the largest peak at AD 1450 to represent glacier expansion at this time. Correlation with the solar record improves to 0.37, significant at the 0.5 level, if the three other peak values from the 16th century are removed from the analysis. We also tested for coherency between the solar and glacier records (Figure 3c). The composite GEI is highly coherent with the solar series (squared coherence = 0.8) for cycles between 170–210 years. Taken together, the visual inspection and statistical analyses suggest that the composite glacial index shows general intervals of ice advance (cooling) during intervals of decreased solar irradiance (Figures 2 and 3).

[10] The three individual GEIs show intriguing spatial patterns from northern to southern Alaska. Not all regions

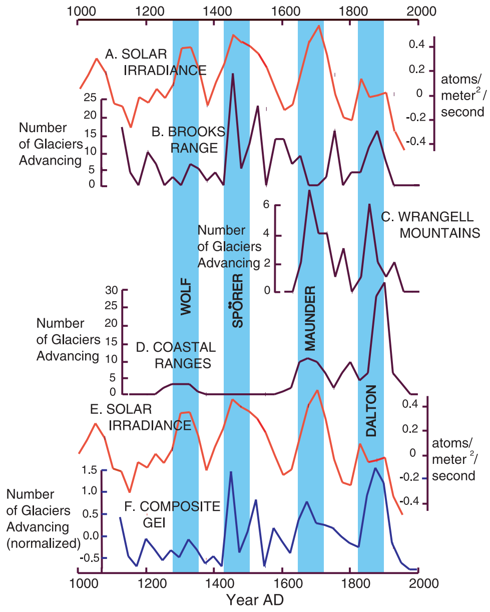

Figure 2. Glacier expansion indices (GEI; B–D, F) compared with the production rate of radiocarbon (solar irradiance, A, E). Curve F is generated by adding normalized (difference from the mean divided by the standard deviation) individual series (A, B and C). Solar irradiance has been averaged over a 25-year window and has been inverted. Positive values indicate times of decreased solar irradiance. The shaded bars here and on Figure 4 mark intervals of solar minima.

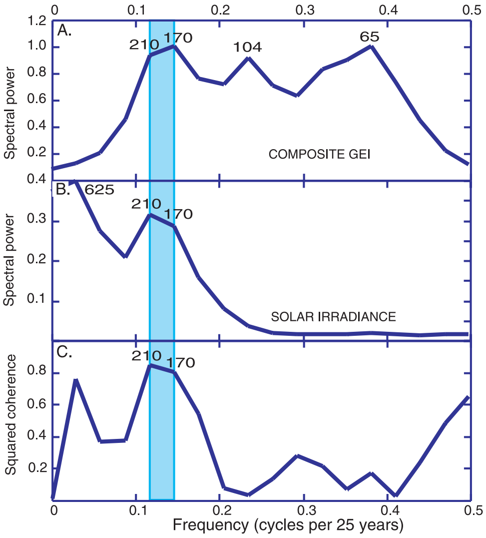

Figure 3. (a) Blackman-Tukey power spectra of the normalized composite GEI. (b) Power spectra for the solar irradiance. (c) Squared coherence from cross-spectral analysis exceeds 0.8 for the 210-year peak.

show all the glacial advances evident in the composite GEI. The earliest major ice activity is from the Brooks Range beginning about AD 1100 (Figures 1a and 2, curve B) This advance closely follows the decrease in solar irradiance centered on AD 1050 (Figure 2, curve A).

[11] A significant decrease in solar irradiance, initiating the Wolf solar minimum about AD 1300, correlates with expansions reconstructed from calendar dates on ice-overrun forests at 4 glaciers (Figures 1 and 2, curve D). This advance is also supported by radiocarbon dating at two glaciers in the Wrangell Mountains [*Wiles et al.*, 2002], but only weakly by moraine building in the Brooks Range (Figures 1 and 2, curve B).

[12] The strongest Holocene interval of moraine building [*Solomina and Calkin*, 2003] in the Arctic Brooks Range shows 27 glaciers expanding at AD 1450 with a second and lower peak at ~AD 1500 (Figures 1a and 2, curve B). Concurrent glacier activity to the south is suggested by radiocarbon-dated ice advance at 3 of 27 glaciers in the Kenai Mountains and Prince William Sound [*Wiles et al.*, 1999; *Calkin et al.*, 2001]. The Spörer minimum centered on ~AD 1450 matches this strong interval of Arctic moraine-building (Figure 2).

[13] Glacier advances recorded in the mid to late AD 1600s in both the Wrangell and southern coastal mountains are well documented by glacier-overrun, tree-ring crossdated logs (Figures 1b, 1c, and 2, curves C and D) and by cooler summer temperatures inferred from tree-rings for both the Wrangell Mountains and coastal regions [*Davi et al.*, 2003; *D'Arrigo et al.*, 2001]. Most moraine building associated with this advance occurred during the late AD 1600s through early 1700s (Figures 1b and 1c). The Maunder solar minimum corresponds with this peak in glacial activity (Figure 2). This interval is not evident in the glacial record from the Brooks Range (Figure 2, curve B). Similarly the mid-late AD 1600s interval is not a time of strong cooling in the Arctic, based on a multi-proxy reconstruction [*Overpeck et al.*, 1997], however it is strong elsewhere in the extratropical lower latitudes of the Northern Hemisphere according to temperature reconstructions [*Esper et al.*, 2002].

[14] Wide-scale moraine building is well documented for the mid to late AD 1800s in all three Alaskan regions (Figures 1 and 2, curves B, C, and D). Many of these early to mid-19th century advances brought ice margins to their Holocene maxima [*Calkin et al.*, 2001]. This record of glacial moraine building closely follows the Dalton solar minima (Figure 2). Lake records [*Finney et al.*, 2000; *Overpeck et al.*, 1997] and tree rings [*D'Arrigo et al.*, 2001] show the early decades of the 1800s as a cold interval in many areas, forced, in part, by changes in solar irradiance and increased volcanism. Since the AD 1800s, minor mid-20th century moraine-building and glacier retreat has been dominant across Alaska [*Arendt et al.*, 2002; *Calkin et al.*, 2001].

[15] The regional differences in the glacial record for Alaska: include the Brooks Range showing the strongest advance about AD 1450, whereas the strongest evidence for advance in the coastal southern mountain sites was at AD 1650–1700. Despite these differences, the overall close correspondence of the GEI with the record of irradiance suggests that solar forcing has played a role in late Holocene glaciation of Alaska (Figures 2 and 3).

[16] However, solar irradiance changes alone are not likely to be sufficient to force significant temperature change for glacier advance [e.g., *Bond et al.*, 2001; *Shindell et al.*, 2001]. We suggest that one means to enhance the solar-induced cooling and, in part, to explain regional differences in the glacial record, is to take into account the effects of two key modes of atmosphere-ocean circulation known to differentially impact the three regions. These are the Pacific Decadal Oscillation (PDO), in southern Alaska [*Mantua et al.*, 1997], and the Arctic Oscillation (AO) [*Thompson and Wallace*, 2001] in the Brooks Range.

[17] In the North Pacific, the ocean-atmosphere system has a tendency to fluctuate between two decadal modes. The cool-phase or negative mode of the PDO leads to cooler temperatures and lower winter precipitation in coastal and interior Alaska as warmer air masses are prevented from penetrating northward from the southern coast. Cool PDO phases can persist for several decades as is evident in the instrumental record and in the tree-ring based reconstructions [*Mantua et al.*, 1997; *Cook*, 2002].

[18] The normalized composite glacier record for Alaska is compared with the solar record and a tree-ring-based reconstruction of the Pacific Decadal Oscillation (PDO) for the spring and summer months (Figure 4). The PDO reconstruction spans AD 1479–1977 and is based on tree-ring data from Mexico to Alaska [*Cook*, 2002]. The comparison (Figure 4) shows that sustained intervals of low PDO indices and cold temperatures during the AD1600s and 1800s are coupled with the Maunder and Dalton solar minima and perhaps the earlier Spörer minimum as well (Figure 4). The correlation between the composite GEI, which is dominated by the southern glacier record for this interval, and the PDO is −0.44, supporting the link between the two. We postulate that a sustained negative phase of the PDO, when combined with decreased solar output, can result in the inferred cooling we observe in Alaska.

[19] We further suggest that during the Spörer minimum (~AD 1450) a negative phase of the AO may have had a

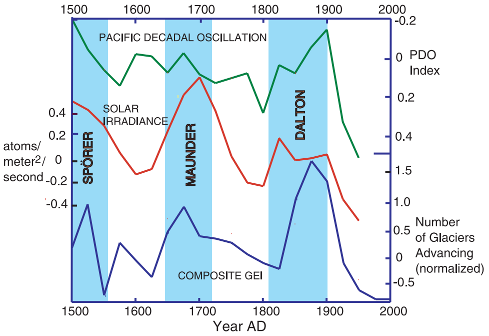

Figure 4. The composite GEI (blue) compared with solar irradiance (red) and the reconstructed PDO (green [*Cook*, 2002]).

role in the cooling to favor glaciation in the Brooks Range, an interval which is not strongly expressed in the glacial record to the south. The decadal modes of the AO impacts temperature and during a sustained negative phase of the AO, the frigid air at high latitudes spills southward across Alaska favoring glaciation there.

[20] Taken together the glacial records from the Brooks Range and the southern mountain regions place climate change in the North Pacific and Arctic sectors in a century-scale perspective. The 200-year rhythm in the composite glacial record of Alaska presented here provides an overall framework for the Little Ice Age and suggests a solar influence in multi-decadal to century-scale cooling (Figures 1 and 2). Regional differences between the Arctic and southern Alaska glacial records may be due, in part, to the interplay of the effects of solar minima along with the amplifying effects of sustained negative phases of the PDO and AO, or both at times of solar minima.

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References

Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine (2002), Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, *297*, 382–386.

Barclay, D. J., G. C. Wiles, and P. E. Calkin (1999), A 1119–year tree-ring-width chronology from western Prince William Sound, southern Alaska, *Holocene*, *9*, 79–84.

Bard, E., G. M. Raisbeck, F. Yiou, and J. Jouzel (1997), Solar modulation of cosmogenic nuclide production over the last millenniun: Comparison between ^{14}C and ^{10}Be records, *Earth Planet. Sci. Lett.*, *150*, 453–462.

Beer, J., W. Mende, and R. Stellmacher (2000), The role of the Sun in climate forcing, *Quat. Sci. Rev.*, *19*, 403–415.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani (2001), Persistent solar influence of North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136.

Calkin, P. E., G. C. Wiles, and D. J. Barclay (2001), Holocene coastal glaciation of Alaska, *Quat. Sci. Rev.*, *20*, 449–461.

Cook, E. R. (2002), Reconstructions of Pacific decadal variability from long tree-ring records, *Eos Trans. AGU*, *83*(19), Spring Meet. Suppl., Abstract S133.

Cook, E. R., D. M. Meko, and C. W. Stockton (1997), A new assessment of possible solar and lunar forcing of the bi-decadal drought rhythm in the western United States, *J. Clim.*, *10*, 1343–1356.

D'Arrigo, R., R. Villalba, and G. Wiles (2001), Tree-ring estimates of Pacific decadal variability, *Clim. Dyn.*, *18*, 219–224.

Davi, N. K., G. C. Jacoby, and G. C. Wiles (2003), Boreal temperature variability inferred from maximum latewood density and tree-ring width data, Wrangell Mountain region, Alaska, *Quat. Res.*, *60*, 252–262.

Denton, G. H., and W. Karlèn (1973), Holocene climatic variations: Their patterns and possible cause, *Quat. Res.*, *3*, 155–205.

Esper, J., E. R. Cook, and F. H. Schweingruber (2002), Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, *Science*, *295*, 2250–2253.

Evison, L. H., P. E. Calkin, and J. M. Ellis (1996), Late-Holocene glaciation and twentieth-century retreat, northeastern Brooks Range, Alaska, *The Holocene*, *6*, 17–24.

Finney, B. P., I. Gregory-Eaves, J. Sweetman, M. S. V. Douglas, and J. P. Smol (2000), Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years, *Science*, *290*, 795–799.

Hodell, D. A., M. Brenner, J. H. Curtis, and T. Guilderson (2001), Solar forcing and drought frequency in the Maya lowlands, *Science*, *292*, 1367–1370.

Houghton, J., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu (Eds.) (2001), *Climate Change 2001: The Scientific Basis*, 944 pp., Cambridge Univ. Press, New York.

Hu, F. S., D. Kaufman, S. Yoneji, D. Nelson, A. Shemesh, Y. Huang, J. Tian, G. Bond, B. Clegg, and T. Brown (2003), Cyclic variation and solar forcing in the Alaskan subarctic, *Science*, *301*, 1890–1893.

Jenkins, G. M., and D. G. Watts (1968), *Spectral Analysis and its Applications*, 541 pp., Holden-Day, Boca Raton, Fla.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific decadal climate oscillation with impacts on salmon, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Overpeck, J. T., et al. (1997), Arctic environmental change of the last four centuries, *Science*, *278*, 1251–1256.

Shindell, D. T., G. A. Schmidt, M. E. Mann, D. Rind, and A. Waple (2001), Solar forcing of regional climate change during the Maunder Minimum, *Science*, *294*, 2149–2152.

Solomina, O., and P. E. Calkin (2003), Lichenometry as applied to moraines in Alaska, U.S.A. and Kamchatka, Russia, *Arctic Antarct Alpine Res.*, *35*, 129–143.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, G. McCormac, J. van der Plicht, and M. Spurk (1998), INTCAL98 Radiocarbon age calibration, 24,000–0 cal BP, *Radiocarbon*, *40*, 1041–1083.

Thompson, D. W. J., and J. M. Wallace (2001), Regional climate impacts of the Northern Hemisphere annular mode, *Science*, *293*, 85–89.

Wiles, G. C., D. J. Barclay, and P. E. Calkin (1999), Tree-ring dated Little Ice Age histories of maritime glaciers from western Prince William Sound, Alaska, *The Holocene*, *9*, 163–174.

Wiles, G. C., G. C. Jacoby, N. K. Davi, and R. P. McAllister (2002), Late Holocene glacier fluctuations in the Wrangell Mountains, Alaska, *Geol. Soc. Am. Bull.*, *114*, 896–908.

Yu, Z., and E. Ito (1999), Possible solar forcing of century-scale drought frequency in the northern Great Plains, *Geology*, *27*, 263–266.

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