Trend in April 1st Snow Water Equivalent at Long-Term British Columbia Snow Courses, in Relation to ENSO, PDO and Climate Warming

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INTRODUCTION: The British Columbia Ministry of Environment operates a network of approximately 200 manual snow courses and 50 automated snow pillows. The snow survey program began in 1936, with a few stations in the Okanagan, Kootenay and Greater Vancouver area. Since then, the network has intermittently expanded and contracted over time. Many of the manual snow courses in the current active program have been surveyed since at least the 1950's, and are useful for the examination of long-term tends in snow conditions. Snow conditions at a site vary from year to year as a result of a number of factors, including natural variability resulting from synoptic weather patterns, El Niño/Southern Oscillation (ENSO) effects, Pacific Decadal Oscillation (PDO) effects, and, potentially, climate warming. This report presents the results of the analysis of trends in April 1st snow water equivalent (SWE) over the 50 year period of 1956-2005, with analysis of changes resulting from the ENSO-PDO effects, as well as changes potentially associated with climate warming.

METHODOLOGY: The April 1st snow survey data, for the 50-year period of 1956-2005, were analyzed. The April 1st data represent, generally, the peak snow water of the spring, produced by the weather patterns of the preceding winter. Snow water equivalent data for 73 long-term active manual snow courses were compiled from the River Forecast Centre snow archive website: http://aardvark.gov.bc.ca/apps/mss/stationlist.do . Monthly ENSO and PDO data were compiled from the National Oceanographic and Atmospheric Administration (NOAA) http://www.cpc.ncep.noaa.gov/data/indices . An average ENSO and PDO variable for each April 1st snow survey was calculated as the numeric average of the monthly values from the preceding five months (November to March), corresponding to the winter snow accumulation period.

The data were analyzed with Systat v.11. First, a linear regression was fit to each of the raw 50-year snow water equivalent data sets for each snow course. In general, the regressions were not statistically significant, as a result of the large scatter from year-to-year. However, there were often hydrologically significant trends in the data sets. The trend from 1956 to 2005 was calculated from the regression slope and intercept coefficients. Visual examination of the raw data and residuals of the regression analysis showed a notable discontinuity in the SWE data for many snow courses in relation to the 1976 PDO shift. Therefore, the data were analyzed to test for relationships with the ENSO and PDO signal

The snow water equivalent data sets were regressed against the ENSO and PDO variables. The ENSO and PDO were regressed against the SWE data separately, and in a multivariate model to remove any signal in the snow data that may be related to ENSO and PDO. The residuals from the multivariate model were then examined for trends over the 1956 to 2005 period. The hypothesis in this case is that trends over time in the April

1st SWE data, once the ENSO and PDO effects were removed, may be related to trends in climate warming.

RESULTS AND DISCUSSION: The results are presented in Table 1, and summarized on Figures 1 and 2. Overall, there were substantial downwards trends in April 1st SWE for the 1956 to 2005 period. Of the 73 long-term snow courses analysed, 63 snow courses experienced a reduction in the April 1st SWE, while 10 experienced increases. On average across the province, the April 1st SWE was 18% lower in 2005 than 1956. In some basins the change over time is dramatic. The mid-Fraser (Chilcotin Plateau, Bonaparte, Nicola, etc.) experienced a substantial 47% reduction in SWE. The Kettle basin experienced a 32% reduction; the Thompson basin experienced a 22% reduction; the Kootenay a 23% reduction, the Upper Fraser a 21% reduction; the Columbia a 20% reduction; and the Okanagan a 14% reduction. The Peace, Skeena, Liard and Yukon basins exhibit no notable change over the 50 year period.

The analysis indicates that as much as one-half to two-thirds of the change over time in the British Columbia April 1st SWE data results from variability associated with the ENSO and PDO signals, with the PDO effect being the dominant forcing factor. A substantial change to conditions of reduced snow occurred in conjunction with the shift of the PDO from a cool phase to a warm phase in 1976. Once the ENSO-PDO effect is removed, the average change amongst the 73 snow courses over the 50 years is reduced to -4%. The overall average change over time in most basins becomes very small, with some exceptions. The mid-Fraser stands out as having experienced significant non-ENSO/PDO reductions in April 1st SWE over the 1956 to 2005 period, consistent with what would be anticipated from a climate warming trend. Conversely, the Peace, Skeena, Liard and Yukon all show a trend to increased SWE after excluding the ENSO and PDO effect.

The non-ENSO/PDO trends in SWE over time show a very slight relationship with elevation, with low elevation snow courses experiencing slightly greater reduction than high elevation snow courses. However, very little of the British Columbia snow survey network is located at low elevation, making it difficult to determine the relationship between snow trend and elevation. The most significant relationship in the ENSO/PDO-removed data appears to be with aridity. Areas with small, shallow snowpacks have experienced loss of snow water over time. Dry, rain shadow areas such as the mid-Fraser and lower Thompson accumulate only very small winter snowpacks (often < 200 mm SWE). These shallow snowpacks relinquish water quickly during mid-winter melt events. Mid-winter melt occurring on deeper snowpacks usually infiltrates into the snowpack and refreezes. The snowpack may become shallower and more dense, but it doesn't relinquish the melt water as readily. This suggests that a threshold of snowpack depth is an important consideration for determining climate warming effects on accumulated snow water.

CONCLUSION: Peak winter snow accumulation in British Columbia experienced substantial reduction over the 1956 to 2005 period. In most major river basins, except the north (Skeena, Peace, Liard, Yukon), April 1st SWE was reduced from 14 to 47%. Much of this reduction over the 50 year period is related to variability in the ENSO and PDO signals, with the PDO having the most significant effect. The transition to a warm phase of the PDO in 1976 is marked by a sharp reduction in April 1st SWE at many snow courses. Once the ENSO and PDO effect is removed, however, a climate warming trend appears to be evident in the snow data. In particular, it is evident that locations in the central interior with shallow winter snowpacks have experienced reductions consistent with winter warming. Climate warming effects in these arid areas is evident, I suggest, because the snowpacks are too shallow to buffer the effects of mid-winter warming. Any mid-winter melt that occurs is potentially lost to groundwater. In areas with deeper snowpacks, mid-winter melt is generally reabsorbed into the snowpack. There may be a change in snowpack depth and density, but not necessarily a change in snow water equivalence. The arid portions of the central interior (Chilcotin plateau, Bonaparte, lower Thompson, Nicola, etc.) are moving towards a condition of substantially reduced winter snow accumulation, and increased frequency and spatial extent of periods of no snow. This has potential to result in negative effects on community water-supply, instream flows for fish and other aquatic organisms, and other things.

Table 1. Trends in April 1st Snow Water Equivalence at British Columbia long-term snow courses,
Results are shown for the raw, unadjusted data, and for the snow data once the effect of ENSO and PDO variability are removed.

Basin	STN NAME	STN ID	Elevation	Mean (mm)	Raw Data		With PDO-ENSO Removed	
					Change 1956-2005 (mm)	% Change	Change 1956-2005 (mm)	% Change
Upper Fraser	Prince George Airport	1A10	690	119	-108	-60%	-66	-42%
Upper Fraser	Pacific Lake	1A11	770	608	-129	-19%	-29	-5%
Upper Fraser	Kaza Lake	1A12	1190	336	16	5%	50	16%
Upper Fraser	MCBRIDE (UPPER)	1A02	1580	439	-171	-32%	-85	-17%
Upper Fraser	LONGWORTH (UPPER)	1A05	1740	751	-27	-4%	56	8%
Upper Fraser	YELLOWHEAD	1A01	1860	504	-77	-14%	-6	-1%
Upper Fraser Average Change, 1956-2005				**460**	**-83**	**-21%**	**-13**	**-7%**
Nechako	TAHTSA LAKE	1B02	1300	1137	100	9%	210	20%
Nechako	MOUNT WELLS	1B01	1490	503	-68	-13%	-2	0%
Nechako Average Change, 1956-2005				**820**	**16**	**-2%**	**104**	**10%**
Middle Fraser	BROOKMERE	1C01	980	205	-109	-42%	-74	-31%
Middle Fraser	NAZKO	1C08	1070	57	-69	-74%	-47	-58%
Middle Fraser	PAVILION	1C06	1230	45	-89	-97%	-41	-61%
Middle Fraser	LAC LE JEUNE (LOWER)	1C07	1370	104	-63	-46%	-27	-23%
Middle Fraser	BRALORNE	1C14	1450	161	-55	-28%	-22	-13%
Middle Fraser	MOUNT TIMOTHY	1C17	1660	318	-104	-27%	-27	-8%
Middle Fraser	MCGILLIVRAY PASS	1C05	1800	599	-84	-13%	20	3%
Middle Fraser Average Change, 1956-2005				**213**	**-82**	**-47%**	**-31**	**-27%**
South Thompson	ANGLEMONT	1F02	1190	347	-120	-29%	-59	-16%
North Thompson	KNOUFF LAKE	1E05	1200	147	-70	-38%	-37	-22%
South Thompson	ABERDEEN LAKE	1F01A	1310	142	-56	-33%	-25	-17%
North Thompson	TROPHY MOUNTAIN *	1E03A	1860	550	-55	-10%	11	2%
South Thompson	ENDERBY	1F04	1900	997	20	2%	72	8%
Thompson Average Change, 1956-2005				**437**	**-56**	**-22%**	**-8**	**-9%**
Upper Columbia	CANOE RIVER	2A01A	910	104	-121	-73%	-64	-47%
Upper Columbia	GLACIER	2A02	1250	710	-105	-14%	-4	-1%
Upper Columbia	FIELD	2A03A	1280	146	-35	-22%	-18	-12%
Lower Columbia	WHATSHAN (UPPER)	2B05	1450	664	-16	-2%	48	8%
Lower Columbia	BARNES CREEK	2B06	1620	523	-32	-6%	25	5%
Upper Columbia	KICKING HORSE	2A07	1650	348	-89	-23%	-39	-11%
Lower Columbia	KOCH CREEK	2B07	1860	767	-36	-5%	-2	0%
Upper Columbia	FIDELITY MOUNTAIN	2A17	1870	1249	-188	-14%	48	4%
Upper Columbia	BEAVERFOOT	2A11	1890	215	-114	-40%	-42	-17%
Upper Columbia	GOLDSTREAM	2A16	1920	1139	-68	-6%	107	10%
Upper Columbia	MOUNT ABBOTT	2A14	1980	1241	-151	-11%	21	2%
Columbia Average Change, 1956-2005				**646**	**-87**	**-20%**	**7**	**-5%**
West Kootenay	FERGUSON	2D02	880	584	-85	-14%	9	2%
West Kootenay	NELSON	2D04	930	380	-120	-27%	-35	-9%
West Kootenay	SANDON	2D03	1070	348	-58	-15%	-10	-3%
East Kootenay	FERNIE EAST	2C07	1250	331	-140	-35%	-69	-19%
East Kootenay	SINCLAIR PASS	2C01	1370	127	-36	-24%	-2	-2%
East Kootenay	SULLIVAN MINE	2C04	1550	318	-140	-36%	-61	-17%
West Kootenay	GRAY CREEK (LOWER)	2D05	1550	464	-56	-11%	23	5%
Kootenay Average Change, 1956-2005				**365**	**-91**	**-23%**	**-21**	**-6%**
Kettle	CARMI	2E02	1250	137	-90	-48%	-63	-37%
Kettle	MONASHEE PASS	2E01	1370	349	-64	-17%	-11	-3%
Kettle Average Change, 1956-2005				**243**	**-77**	**-32%**	**-37**	**-20%**
Okanagan	SUMMERLAND RESERVOIR	2F02	1280	218	-57	-23%	-16	-7%
Okanagan	MCCULLOCH	2F03	1280	153	-59	-32%	-22	-14%
Okanagan	POSTILL LAKE	2F07	1370	217	-26	-11%	2	1%
Okanagan	GREYBACK RESERVOIR	2F08	1550	228	-21	-9%	3	1%
Okanagan	WHITEROCKS MOUNTAIN	2F09	1830	562	-83	-14%	-12	-2%
Okanagan	SILVER STAR MOUNTAIN	2F10	1840	725	52	7%	121	18%
Okanagan	TROUT CREEK	2F01	1860	176	-25	-13%	18	10%
Okanagan Average Change, 1956-2005				**326**	**-31**	**-14%**	**13**	**1%**
Similkameen	HAMILTON HILL	2G06	1490	344	-170	-39%	-83	-21%
Similkameen	MISSEZULA MOUNTAIN	2G05	1550	213	-26	-11%	4	2%
Similkameen	LOST HORSE MOUNTAIN	2G04	1920	225	-18	-8%	15	7%
Similkameen Average Change, 1956-2005				**261**	**-71**	**-19%**	**-21**	**-4%**

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					Raw Data		With PDO-ENSO Removed	
Basin	**STN NAME**	**STN ID**	**Elevation**	**Mean (mm)**	**Change 1956-2005 (mm)**	**% Change**	**Change 1956-2005 (mm)**	**% Change**
South Coast	PALISADE LAKE	3A09	880	1471	-251	-16%	-39	-3%
Vanc Isl	UPPER THELWOOD LAKE	3B10	980	1538	-326	-19%	-186	-11%
South Coast	DOG MOUNTAIN	3A10	1080	1181	-202	-16%	52	4%
South Coast	GROUSE MOUNTAIN	3A01	1100	278	-271	-20%	3	1%
Vanc Isl	FORBIDDEN PLATEAU	3B01	1130	1586	-350	-20%	-226	-13%
Lower Fraser	TENQUILLE LAKE	1D06	1680	1156	-164	-13%	7	1%
South Coast - Vancouver Isl Average Change, 1956-2005				**1202**	**-261**	**-17%**	**-65**	**-4%**
Skagit	KLESILKWA	3D03A	1130	282	-181	-48%	-14	-5%
Skagit	LIGHTNING LAKE	3D02	1220	305	-106	-29%	-33	-10%
Skagit Average Change, 1956-2005				**294**	**-143**	**-39%**	**-23**	**-8%**
Peace	WARE (LOWER)	4A04	980	188	12	6%	27	16%
Peace	PHILIP LAKE	4A13	980	288	-69	-21%	-36	-12%
Peace	TUTIZZI LAKE	4A06	1070	257	0	0%	31	13%
Peace	TSAYDAYCHI LAKE	4A12	1160	404	-50	-11%	13	3%
Peace	PULPIT LAKE	4A09	1310	406	9	2%	35	9%
Peace	FREDRICKSON LAKE	4A10	1310	248	-33	-12%	-10	-4%
Peace	TRYGVE LAKE	4A11	1400	359	-5	-1%	19	5%
Peace	PINE PASS	4A02	1430	1139	91	8%	183	18%
Peace	LADY LAURIER LAKE	4A07	1460	502	16	3%	89	20%
Peace	GERMANSEN (UPPER)	4A05	1500	347	-41	-11%	9	3%
Peace	WARE (UPPER)	4A03	1570	253	-15	-6%	3	1%
Peace Average Change, 1956-2005				**399**	**-8**	**-4%**	**33**	**7%**
Skeena	KIDPRICE LAKE	4B01	1370	878	50	6%	147	18%
Skeena	JOHANSON LAKE	4B02	1540	293	7	3%	30	11%
Skeena Average Change, 1956-2005				**586**	**29**	**4%**	**89**	**15%**
Yukon	LOG CABIN	4E01	880	356	135	47%	117	40%
Liard	SIKANNI LAKE	4C01	1400	267	-7	-2%	17	7%
North Average Change, 1956-2005				**312**	**64**	**23%**	**67**	**23%**
PROVINCIAL AVERAGE CHANGE, 1956-2005				**474**	**-71**	**-18%**	**-0**	**-4%**

Figure 1. Trend in April 1st Snow Water Equivalence at long-term British Columbia snow survey sites, 1956-2005

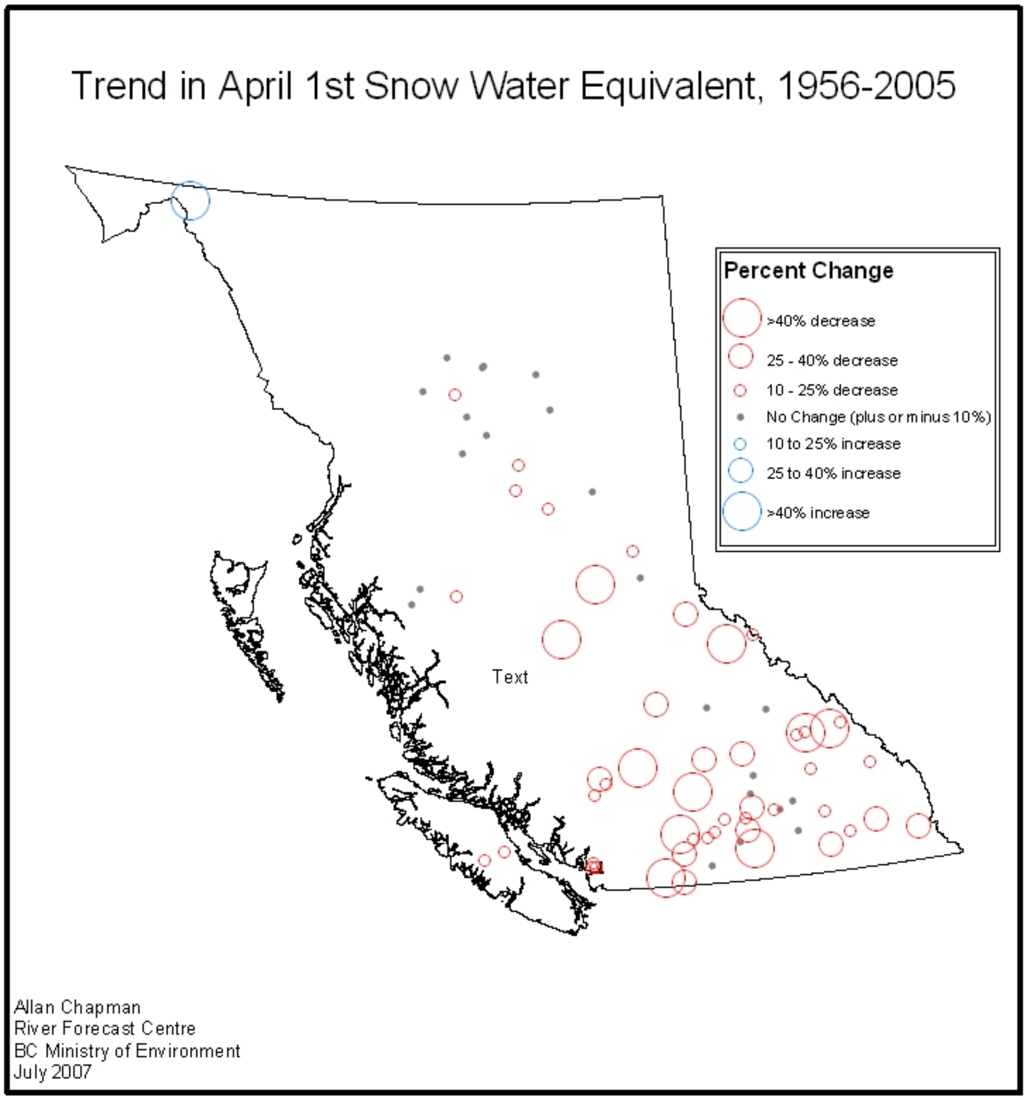

Figure 2. Trend in April 1st Snow Water Equivalence at long-term British Columbia snow survey sites, excluding the effect associated with the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), 1956-2005