A GCM-based analysis of circulation controls on $\delta^{18}O$ in the southwest Yukon, Canada: implications for climate reconstructions in the region

Robert D. Field[1], G.W.K. Moore[1], Gerald Holdsworth[2] , Gavin A. Schmidt[3]

[1]. Department of Physics, University of Toronto, Toronto, Canada

[2]. Arctic Institute of North America, University of Calgary, Calgary, Canada

[3]. NASA Goddard Institute for Space Studies, New York, USA

Running title: Controls on $\delta^{18}O$ in the SW Yukon

Abstract

To improve our understanding of paleoclimatic records in the southwest Yukon, we examined controls on precipitation $\delta^{18}O$ using an isotopically-equipped atmospheric general circulation model (GCM). Our results show that, particularly during the cool-season, elevated $\delta^{18}O$ is associated with a deeper Aleutian Low and stronger southerly moisture flow, while lower $\delta^{18}O$ is associated with the opposite meteorological conditions. These results suggest that the large mid-19th century shift towards lower $\delta^{18}O$ values seen in paleoclimate records from the region was associated with a shift towards a weaker Aleutian Low. While in disagreement with a previous interpretation of this shift, it is consistent with records of glacial advance and tree-ring growth during the same period, and observational studies of Aleutian Low controls on temperature and precipitation in the region.

1. Introduction

Stable water isotopes preserved in ice cores and other paleoclimatic sources are an important source of climate information prior to the instrumental record [Dansgaard, 1964; Jones and Mann, 2003]. Our interest is in better understanding isotopic records from the southwest Yukon region, and any information they might contain about past atmospheric circulation. In particular, a significant drop in mean $\delta^{18}O$ occurred during the middle of the 19thcentury in two separate ice cores extracted from Mt. Logan in the southwest Yukon, just to the east of the Gulf of Alaska [Holdsworth et al., 1992; Fisher et al., 2004], and in sediment carbonate $\delta^{18}O$ recovered from a lake also in the SW Yukon [Anderson et al., 2005]. The $\delta^{18}O$ record from the Northwest Col at 5340m asl shows this shift as a 2-3‰ depletion during the late 1840s (Figure 1). Using an analytical model, Fisher et al. [2004] interpreted this shift as being caused by a stronger Aleutian Low (AL), which brought moisture originating from more distant, southerly sources, and owing to this greater distance, enhanced isotopic depletion.

It is difficult to reconcile this interpretation of the $\delta^{18}O$ shift, however, with climate reconstructions in the region during the 19th century. D'Arrigo et al. [2005], for example, used tree-ring samples ringing the North Pacific to reconstruct the strength of the AL since the 17th century, identifying a significant mid-19th century weakening of the AL, in disagreement with the interpretation of Fisher et al. In this study we used an isotopically-equipped general circulation model (GCM) to better understand controls on the $\delta^{18}O$ composition of precipitation in the SW Yukon, in order better interpret isotopic archives in the region.

2. Data and methods

Since their development in the 1980s [Joussaume et al., 1984], isotopically-equipped GCMs have been an important tool in identifying controls on precipitation $\delta^{18}O$. In these GCMs, the fractionation between heavy and light isotopes is modeled through all stages of the hydrological cycle. Unlike the GCM, steady-state models such as that used in Fisher et al. [2004] rely upon a number of empirical factors, such as the balance between zonal and meridional transport, being prescribed in order to produce a realistic present-day climatology. Isotopically-equipped GCMs have been used to better understand controls on $\delta^{18}O$ over the polar ice sheets and other major ice-coring sites [eg. Werner and Heimann, 2002; Vuille et al., 2003].

In this paper, we used the GISS ModelE GCM [Schmidt et al., 2005], run at a $4^o x 5^o$ horizontal resolution with 20 vertical levels for 45 years starting in 1954, forced with interannually-varying sea-surface temperature and sea-ice fields from the HadISST 1.1 dataset [Rayner et al., 2003]. The choice of simulation period was arbitrary and, as such, ours is an analogue study, where we assume that any immediate meteorological controls on precipitation $\delta^{18}O$ are persistent across time.

Correlation maps were created between precipitation $\delta^{18}O$ over the SW Yukon and sea-level pressure and moisture flux in the spatial domain. Moisture flux between 974 hPa and 909 hPa was computed as a vertically-integrated quantity following Peixoto and Oort [1992]. As in Werner and Heimann [2002], we considered the $\delta^{18}O$ values spanning several grid points (58 to 64N, 142 to 132W) rather than a single grid point. In calculating $\delta^{18}O$ averages, monthly values were weighted by precipitation amount, and we allowed for different seasonal controls by also constructing correlation maps separately for the warm season (March through August) and cool season (September through February). We also substituted surface temperature and precipitation amount for precipitation $\delta^{18}O$ over the SW Yukon, to understand circulation controls on basic climate parameters.

Finally, we constructed correlation maps between mid-tropospheric moisture circulation and vapor $\delta^{18}O$ over the SW Yukon analysis region. Identifying controls on vapor $\delta^{18}O$ provided an additional check on controls on the moisture reservoir above the ice core site, the topography around which is only very coarsely resolved by the GCM. and which does not allow the model to capture the altitude-driven depletion at the ice core drill sites, Moisture-weighted, mean vapor $\delta^{18}O$ was calculated between 760 and 470 hPa over the analysis region, and correlated against the fields of moisture circulation between 760 and 470 hPa and geopotential height at 630 hPa.

3. Results

Observed $\delta^{18}O$ values at GNIP stations in the region were generally well-simulated by the GCM (Table 1). At Barrow on Alaska's North Slopes, modeled DJF and JJA $\delta^{18}O$ means of -22.7‰ and -15.8‰, respectively, were close to the observed means of -21.1‰ and -14.7‰. Modeled and observed values were also in good agreement for Bethel, in the southwest corner of Alaska. The model did not capture the cold season depletion in Whitehorse, or at the plateau of the two Logan drill sites (~ -32 ‰), where the sharp orographic rainout cannot be captured by the low topographic resolution of the model Further inland at Yellowknife in the NWT, however, the modeled DJF and JJA $\delta^{18}O$ means of -24.2 ‰ and -14.9 ‰ are in good agreement with the observed means of -

25.1‰ and -16.8‰. We emphasize that any controls identified reflect those over the SW Yukon in general, and not for a specific proxy site.

Annually, there is some evidence of control on SW Yukon precipitation $\delta^{18}O$ by atmospheric circulation in the North Pacific (Figure 2a), with an indication of less depleted $\delta^{18}O$ being associated with southerly flow and a negative SLP correlation over southwestern Alaska. There is stronger evidence of control over vapor $\delta^{18}O$ (Figure 2b), with an additional center of positive 630 hPa geopotential height correlation east of the analysis region, which is associated with anticyclonic circulation and, given its position, southeasterly flow into the analysis region. The strongest annual controls are on precipitation amount (Figure 2c) and temperature (Figure 2d). The negative correlation pattern centered over the Gulf of Alaska associates a deeper Aleutian Low with enhanced precipitation and warmer temperatures over the analysis region. During the warm season (Figure S1), the circulation controls are generally weaker than for the annually-averaged cases.

The circulation controls on precipitation $\delta^{18}O$ over the SW Yukon are much stronger during the cool season (Figure 3a), with a strong association between less depleted precipitation $\delta^{18}O$ and more southerly moisture flux around a deeper Aleutian Low. The same relationship appears for vapor $\delta^{18}O$ in the mid-troposphere (Figure 3b), but as part of a tripole, with a positive, anti-cyclonic center over western North America and a negative, cyclonic centre over the eastern US. To varying degrees across seasons, tropical Pacific signatures appear in the SLP correlations, with less depleted $\delta^{18}O$, and wetter and warmer conditions over the SW Yukon, associated with positive pressure anomalies over the western Pacific.

We note that similar cool-season controls on $\delta^{18}O$ were identified using composite maps (not shown). These composites were associated with a ~1.5‰ difference in low and high $\delta^{18}O$ years over the SW Yukon, slightly less than the observed mid-19th century shift in the ice core.

4. Discussion

Our results indicate that less depleted $\delta^{18}O$ over the SW Yukon is associated with southerly moisture flux into the region. This moisture flux, in turn, is associated with enchanced cyclonic circulation around a deeper Aleutian Low. In the mid-troposphere, our results indicate the presence of the tripole-like control on vapor $\delta^{18}O$ (Figure 3b) as well as a surface feature related to the AL (Figure 3a). These features are similar to the Pacific-North America (PNA) teleconnection identified by Wallace and Gutzler [1981] whose surface expression is the AL. The positive SLP correlations across the western equatorial Pacific, although less robust across seasons, are indicative of warm ENSO conditions. This relationship between warm ENSO, a deeper AL and positive PNA is consistent with observational studies [Trenberth and Hurrell, 1994] and controls on Mt. Logan snow accumulation [Moore et al., 2002].

Seasonality is important in controlling $\delta^{18}O$, due mainly to persistent features such as AL often being wintertime-only phenomena [Trenberth and Hurrell, 1994]. The effects of seasonality on $\delta^{18}O$ controls has also been observed for Greenland, where a strong NAO signature was seen in winter months, but only weakly during summer months [Rogers et al., 1998], due to the relative summer weakness of North Atlantic features such as the Icelandic Low. Stronger wintertime circulation controls were also observed in the Mt. Logan snow accumulation [Moore et al., 2002; Rupper et al., 2004].

The results that we have presented have important implications for the analysis of ice core δ^{18}O, which, in all but a few studies, are conducted using annually-averaged data. In the case of the Mt. Logan ice cores, the inclusion of weakly-controlled summer values in taking an annual average could mute any strong controls present during the winter. Use of a winter-only δ^{18}O record from the ice core may lead to more consistent relationships between the isotopic records and paleoclimate reconstructions from other sources such as AL strength from tree-rings, and enhance reconstructions of winter-only teleconnections such as the PNA using the ice core record. This will be done for the Mt. Logan ice core in a future study.

In interpreting these circulation controls in a paleoclimatic context, we therefore found no evidence that the 1840s to 1850s shift towards more depleted δ^{18}O values observed at Mt. Logan and Jellybean Lake was associated with a strengthening of the Aleutian Low. Rather, our results suggest that the dominant effect of a deepened AL is to reduce isotopic depletion during transport to the SW Yukon. Physically, the less-depleted precipitation δ^{18}O in the SW Yukon under these conditions could be attributed to several processes, namely: enhanced evaporative recharge or reduced rainout along a more southern path, increased mixing with less isotopically-depleted air masses under eddy-dominated moisture transport [Alley and Cuffey, 2001], or weaker isotopic fractionation under warmer conditions. Although there is likely some entrainment of sub-tropical moisture, the observational analysis of Zhu et al. [2007], for example, showed no cyclones originating south of 30N; the Fisher et al. [2004] association between stronger AL with more depleted δ^{18}O is possibly due to an unrealistically large contribution of tropical moisture.

There is also the possibility that the mid-19th century shift can be explained not by a change in the AL strength, but rather by a change in precipitation seasonality. While we can not fully exclude this, we do note that the controls identified here are consistent with the north Pacific circulation reconstruction of D'Arrigo et al. [2005], and other types of evidence during the mid 19th century. Observational analyses during the instrumental period have shown that a stronger AL is also associated with warmer temperatures over Alaska [Mock et al., 1998] and northwestern North America in general [Trenberth and Hurrell, 1994], which was observed consistently in controls on temperature and precipitation inferred from our GCM analysis. If a mid-19th-century deepening of the Aleutian Low had occurred, it would-have presumably been accompanied by warmer regional temperatures, but t independent paleoclimate records exist in the region which show no such shift. Land-based glaciers in the Gulf of Alaska region underwent a period of advance during the last half of the 19th century in Southern Alaska, thought to indicate persistently cooler temperatures [Calkin et al., 2001; Wiles et al., 2004]. In addition, tree-ring based reconstructions of January-September temperature across the entire Gulf of Alaska region showed a significant cold shift in the 1840s [Wilson et al., 2007]. Furthermore, there is an apparent increasing trend in the Logan $\delta^{18}O$ since the mid 20th century, which, under the controls identified here, would be consistent with the trend towards a deeper wintertime AL observed over the same period [Bograd et al., 2002].

Our GCM analysis of circulation controls on the SW Yukon $\delta^{18}O$, when considered alongside other paleoclimatic evidence, suggests that the observed shift in the middle of the 19th century was associated with a weakening of the Aleutian Low and weakened southerly moisture transport. An associated cooling in the Gulf of Alaska region would contrast with the shift towards warmer conditions seen across much of the rest of the Arctic [Smol et al., 2005], illustrating the importance of considering regional changes in paleoclimatic reconstructions [Jones and Mann, 2003]. A similar phenomenon was found in modeling the temperature difference between the late 17th and 18th centuries, when emergence from the Maunder Minimum corresponded to a widespread winter-warming across the Northern Hemisphere, with the exception of the Gulf of Alaska and North Atlantic regions, which exhibited significant cooling [Shindell et al., 2001]. The Gulf of Alaska, in particular, would appear to be a region where inter-decadal temperature changes are frequently out of phase with those across the North American and Eurasian land masses.

Acknowledgements

This work was supported by the Canadian Foundation for Climate and Atmospheric Sciences through the Polar Climate Stability Network, and for RF by a graduate scholarship from the Natural Sciences and Engineering Research Council of Canada. We thank Allegra LeGrande and Sophie Lewis for assistance with the GCM.

References

Alley, R. B., and K. M. Cuffey, Oxygen- and Hydrogen-Isotopic Ratios of Water in Precipitation: Beyond Paleothermometry, 527-553 pp., Reviews in Mineralogy and Geochemistry, Mineralogical Soc. America, Washington DC, 2001.

Anderson, L., M. B. Abbott, B. P. Finney, and S. J. Burns, Regional Atmospheric Circulation Change in the North Pacific During the Holocene Inferred From Lacustrine Carbonate Oxygen Isotopes, Yukon Territory, Canada, *Quaternary Research*, *64*(1), 21-35, 2005.

Bograd, S., et al., On the changing seasonality over the North Pacific, *Geophys. Res. Lett.*, *29*(9), artn 1333, doi: 10.1029/2001gl013790, 2002.

Calkin, P. E., G. C. Wiles, and D. J. Barclay, Holocene coastal glaciation of Alaska, *Quat. Sci. Rev.*, *20*(1-3), 449-461, 2001.

Dansgaard, W. (1964), Stable Isotopes in Precipitation, *Tellus*, *16*(4), 436-468.

D'Arrigo, R. et al., Tropical-North Pacific Climate Linkages Over the Past Four Centuries, *J. of Clim.*, *18*(24), 5253-5265, 2005.

Fisher, D. A. et al., Stable isotope records from Mount Logan, Eclipse ice cores and nearby Jellybean Lake. Water cycle of the North Pacific over 2000 years and over five vertical kilometres: sudden shifts and tropical connections, *Geographie physique et Quaternaire*, *58*(2-3), 337-352, 2004.

Holdsworth, G., H. R. Krouse, and M. Nosal, Ice core climate signals from Mount Logan, Yukon, A.D. 1700-1897, in *Climate since A.D. 1500*, edited by R. S. Bradley and P. D. Jones , pp. 483-504, Routledge, London, 1992.

IAEA (2001), GNIP Maps and animations, International Atomic Energy Agency, Vienna.http://isohis.iaea.org.

Jones, P. D. and M. E. Mann, Climate Over Past Millennia, *Rev. of Geophys.*, *42*(2), 2004.

Joussaume, S., et al. (1984), A General-Circulation Model of Water Isotope Cycles in the Atmosphere, *Nature*, *311*(5981), 24-29.

Mock, C. J., P. J. Bartlein, and P. M. Anderson, Atmospheric circulation patterns and spatial climatic variations in Beringia, *Int. J. Clim.*, *18*(10), 1085-1104, 1998.

Moore, G. W. K., G. Holdsworth, and K. Alverson, Climate Change in the North Pacific Region Over the Past Three Centuries, *Nature*, *420*(6914), 401-403, 2002.

Peixoto, J. P. and Oort, A. H. Physics of Climate. 520pp. 1992. New York, NY., AIP Press.

Rayner, N. A., et al. , Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res., [Atmos.]*, *108*(D14), 2003.

Rogers, J. C., J. F. Bolzan, and V. A. Pohjola, Atmospheric Circulation Variability Associated With Shallow-Core Seasonal Isotopic Extremes Near Summit, Greenland, *J. Geophys. Res., [Atmos.]*, *103*(D10), 11205-11219, 1998.

Rupper, S., E. J. Steig, and G. Roe, The Relationship Between Snow Accumulation at Mt. Logan, Yukon, Canada, and Climate Variability in the North Pacific, *J. Clim.*, *17*(24), 4724-4739, 2004.

Schmidt, G. A., G. Hoffmann, D. T. Shindell, and Y. Y. Hu, Modeling Atmospheric Stable Water Isotopes and the Potential for Constraining Cloud Processes and Stratosphere-Troposphere Water Exchange, *J. Geophys. Res., [Atmos.]*, *110*(D21), 2005.

Shindell, D. T., G. A. Schmidt, M. E. Mann, D. Rind, and A. Waple, Solar Forcing of Regional Climate Change During the Maunder Minimum, *Science*, *294*(5549), 2149-2152, 2001.

Smol, J. P. et al., Climate-Driven Regime Shifts in the Biological Communities of Arctic Lakes, *Proc. Natl. Acad. Sci. U. S. A.*, *102*(12), 4397-4402, 2005.

Trenberth, K. E. and J. W. Hurrell, Decadal Atmosphere-Ocean Variations in the Pacific, *Clim. Dyn.*, *9*(6), 303-319, 1994.

Trenberth, K. E., et al., Progress During Toga in Understanding and Modeling Global Teleconnections Associated With Tropical Sea Surface Temperatures, *J. Geophys. Res., [Oceans]*,, *103*(C7), 14291-14324, 1998.

Vuille, M., R. S. Bradley, M. Werner, R. Healy, and F. Keimig, Modeling Delta O-18 in Precipitation Over the Tropical Americas: 1. Interannual Variability and Climatic Controls, *J. Geophys. Res., [Atmos.]*, *108*(D6), 2003.

Wallace, J. M., and D. S. Gutzler (1981), Teleconnections in the Geopotential Height Field During the Northern Hemisphere Winter, *Mon. Weather Rev.*, *109*(4), 784-812.

Werner, M. and M. Heimann, Modeling Interannual Variability of Water Isotopes in Greenland and Antarctica, *J. Geophys. Res., [Atmos.]*, *107*(D1-D2), 2002.

Wiles, G. C., R. D. D'Arrigo, R. Villalba, P. E. Calkin, and D. J. Barclay, Century-scale solar variability and Alaskan temperature change over the past millennium, *Geophys. Res. Lett.*, *31*(15), 2004.

Wilson, R., G. Wiles, R. D’Arrigo, and C. Zweck, Cycles and shifts: 1,300 years of multi-decadal temperature variability in the Gulf of Alaska, *Clim. Dyn.*, *28*(4), 425-440, 2007.

Zhu, X. J., J. L. K. Sun, Z. Y. Liu, Q. Y. Liu, and J. E. Martin, A Synoptic Analysis of the Interannual Variability of Winter Cyclone Activity in the Aleutian Low Region, *J. of Clim.*, *20*(8), 1523-1538, 2007.

List of figures

Figure 1. The Mt. Logan Northwest Col annual $\delta^{18}O$ record from Holdsworth et al. [1992].

Figure 2. Annual circulation and moisture-flux correlation maps for: a) precipitation $\delta^{18}O$ b) mid-tropospheric vapor $\delta^{18}O$ c) precipitation amount and d) surface temperature over the SW Yukon, bounded by the black box. The colored shading indicates the correlation between the climate parameter over the SW Yukon and SLP (panels a, c, d) and geopotential height at 630hPa (panel b). Vector lengths indicate the correlation between the climate parameters over the SW Yukon and moisture flux in each of the u and v direction, for surface (panels a, c, d) and mid-tropospher eic (panel b) moisture flux. For all meteorological fields, only correlations significant at a 95% level are shown.

Figure 3. Same as Figure 2, but for cool-season (September to February).

Tables

Table 1. Precipitation δ^{18}O (‰) observed at GNIP stations and modeled under GISS.

			GNIP		GISS	
Location	Lat	Lon	DJF	JJA	DJF	JJA
Barrow, AK	71°17N	156°45W	-21.1	-14.7	-22.7	-15.8
Bethel, AK	60°47N	161°45W	-15.1	-11.0	-15.7	-12.1
Whitehorse, YK	60°43N	135°03W	-23.8	-18.7	-18.3	-18.2
Yellowknife, NWT	62°27N	114°24W	-25.1	-16.8	-24.2	-14.9

Figures

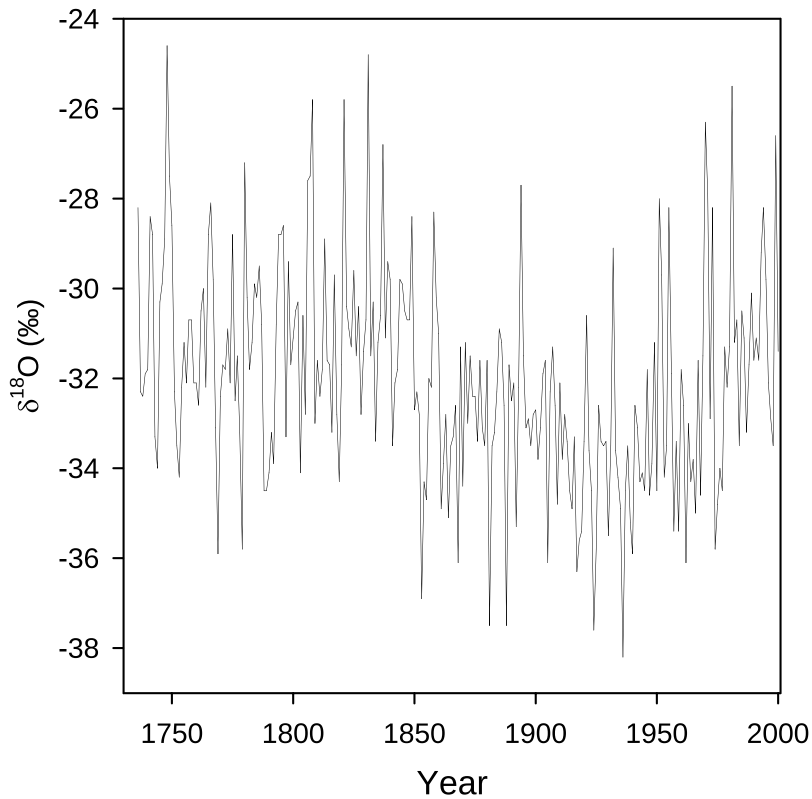

Figure 1. The Mt. Logan Northwest Col annual $\delta^{18}O$ record from Holdsworth et al. [1992].

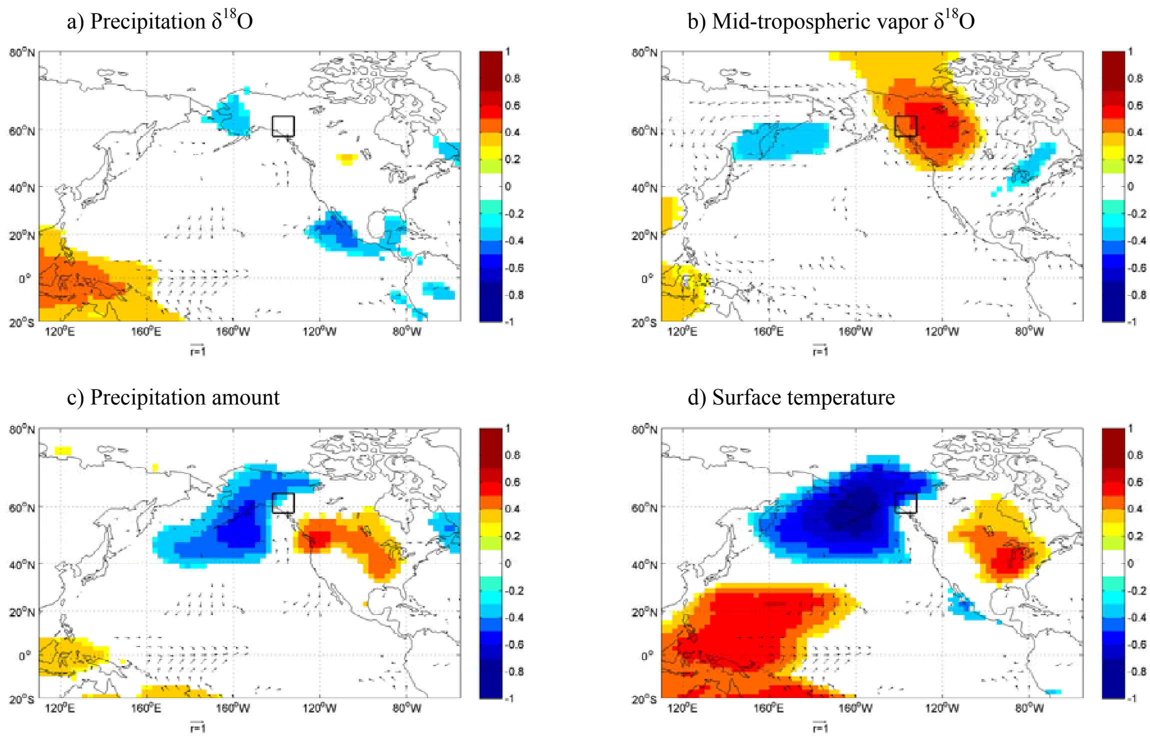

Figure 2. Annual circulation and moisture-flux correlation maps for: a) precipitation $\delta^{18}O$ b) mid-tropospheric vapor $\delta^{18}O$ c) precipitation amount and d) surface temperature over the SW Yukon, bounded by the black box. The colored shading indicates the correlation between the climate parameter over the SW Yukon and SLP (panels a, c, d) and geopotential height at 630hPa (panel b). Vector lengths indicate the correlation between the climate parameters over the SW Yukon and moisture flux in each of the u and v direction, for surface (panels a, c, d) and mid-tropospehereic (panel b) moisture flux. For all meteorological fields, only correlations significant at a 95% level are shown.

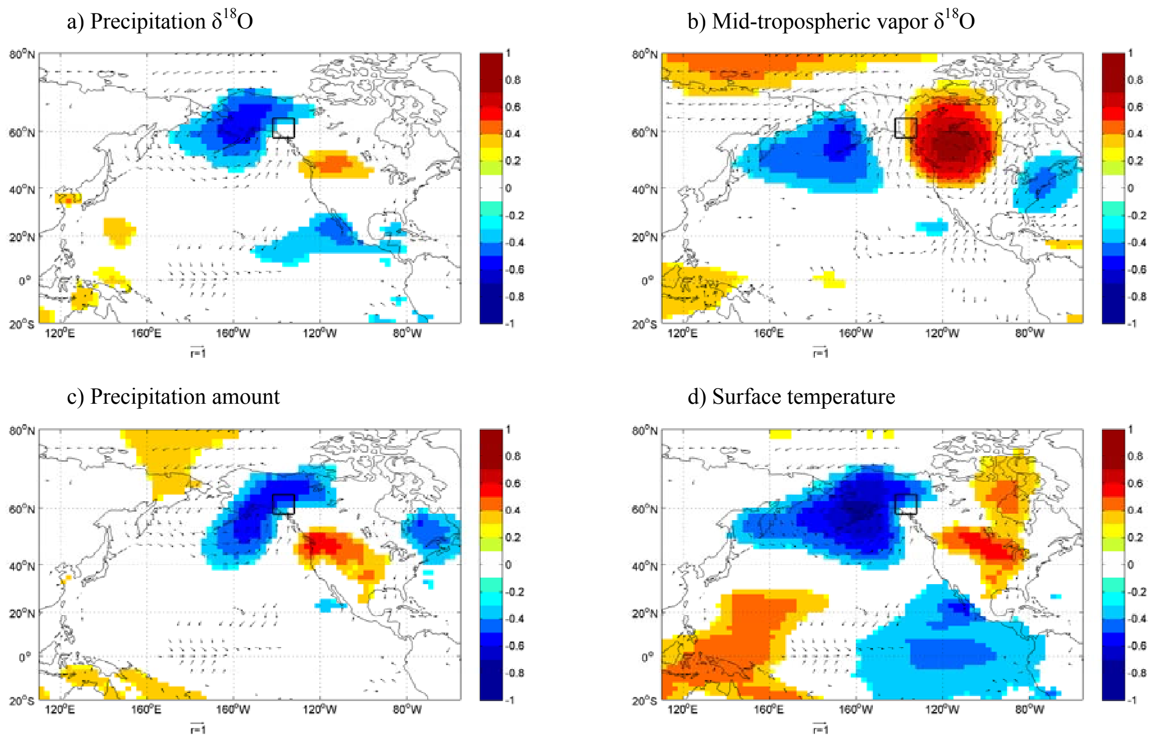

Figure 3. Same as Figure 2, but for cool-season (September to February).