Real time drought monitoring and forecasting over the Canadian Prairies using the Variable Infiltration Capacity model

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1. Objective and methodology

- A real-time drought monitoring and seasonal prediction system is being developed for the Canadian Prairies (http://www.meteo.mcgill.ca/~leiwen/vic/prairies/)
- The system uses the Variable Infiltration Capacity (VIC) land surface macroscale hydrology model to simulate daily soil moistures for three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) starting from 1 January, 1950, and continually running through present into the future with a 15-day lead time
- The system is driven by daily maximum and minimum air temperatures and precipitation from 1,167 meteorological stations for monitoring runs, and from the operational Canadian GEM (Global Environmental Multiscale) model and 40-number super ensemble forecasts for forecasting VIC runs
- The system is updated daily at present
- The VIC soil moisture is used together with the 56-yr climatology (1950-2005) to calculate a soil moisture index SMAPI (Soil Moisture Anomaly Percentage Index) for measuring the severity of both agricultural and hydrological droughts; the prairie drought history starting from 1 January, 1950 up to present can then be reconstructed using SMAPI
- The calculated SMAPI explains well most documented severe drought events on the Prairies over the past 60 years; and compares favorably with the North American drought monitor and Agriculture and Agri-Food Canada drought maps

Establishment of VIC model over the Prairies

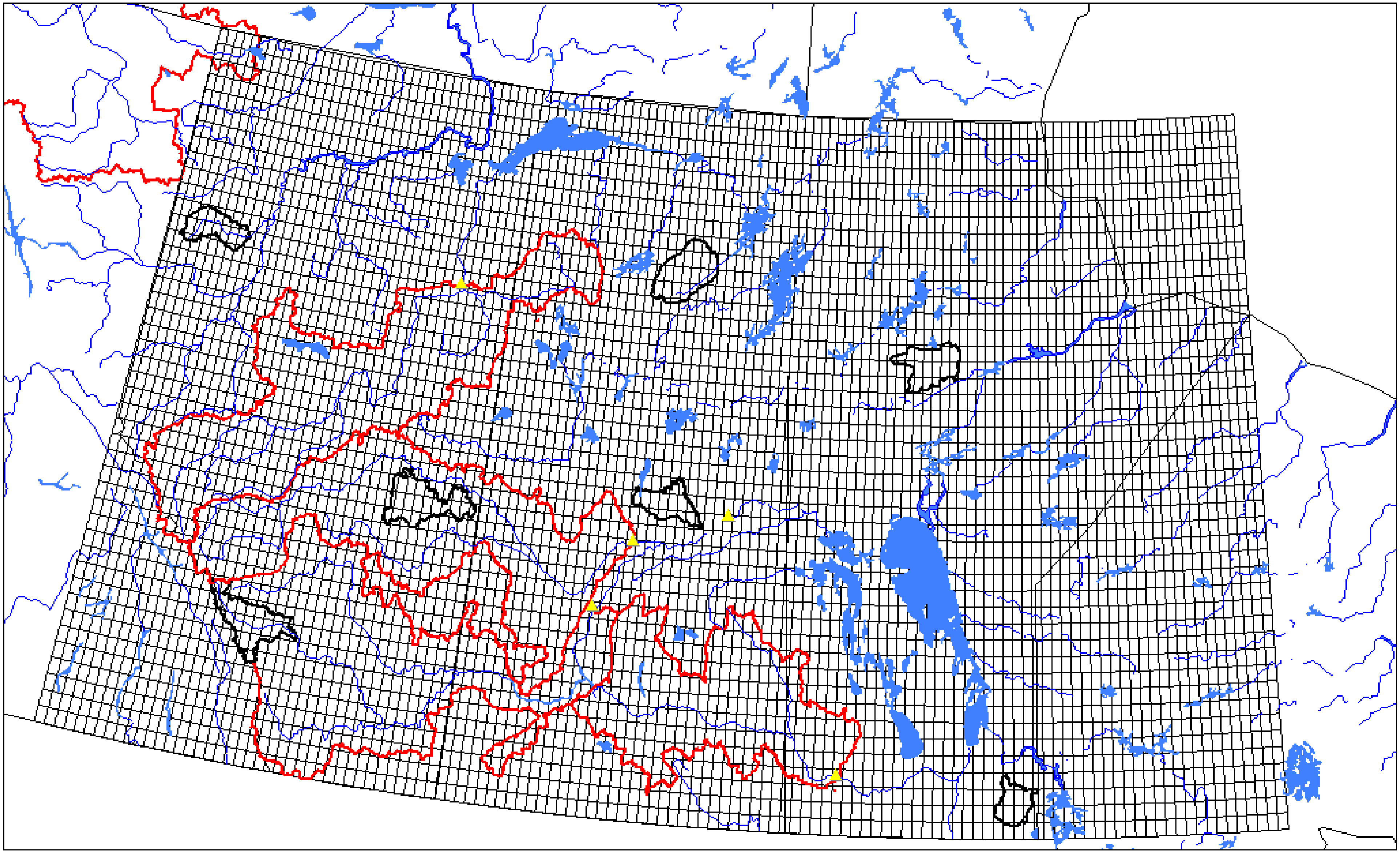
"*A key task in hydrology is to attempt to unravel the organization of the complexity of hydrologic processes at various scales*" Dooge (2004).

Effectively modeling rainfall-runoff processes at various temporal and spatial scales has always been the wish (dream) of hydrologists. "*The philosophical debate on the development of hydrological models seems to be centered on the avenue chosen from either the 'upward' approach or the 'downward' approach*" (Sivapalan et al., 2003). Natural hydrological system is sufficiently complex and nonlinear that it is impossible to include all details of hydrologic phenomena in one method for modeling rainfall-runoff processes at different scales. To do so is also unnecessary. Heterogeneity effects of land covers and soil textures as well as characteristics of simultaneous occurrence of different runoff component generations and flow concentrations may behave differently at different scales. "*Processes important at one scale may not necessary be important at other scales*" (Blöschl and Sivapalan, 1995). "*Certain details proven to be important at small scales may average out at large scales. Mainly due to the existence of nonlinearity in the natural hydrologic system, formulations appropriate at a given scale usually are not applicable at others*" (Klemes, 1986). As Dooge (1986) pointed out: "*the history of science suggests that progress is not made by a continuous progression from one scale to another*"; therefore, how to achieve a meaningful conceptualization of physical processes at a specific scale poses an immediate problem for hydrological modelers when formulating the rainfall-runoff relation at that scale. Such a conceptualization is used as the scientific base for the development of a macroscale hydrological model such as VIC.

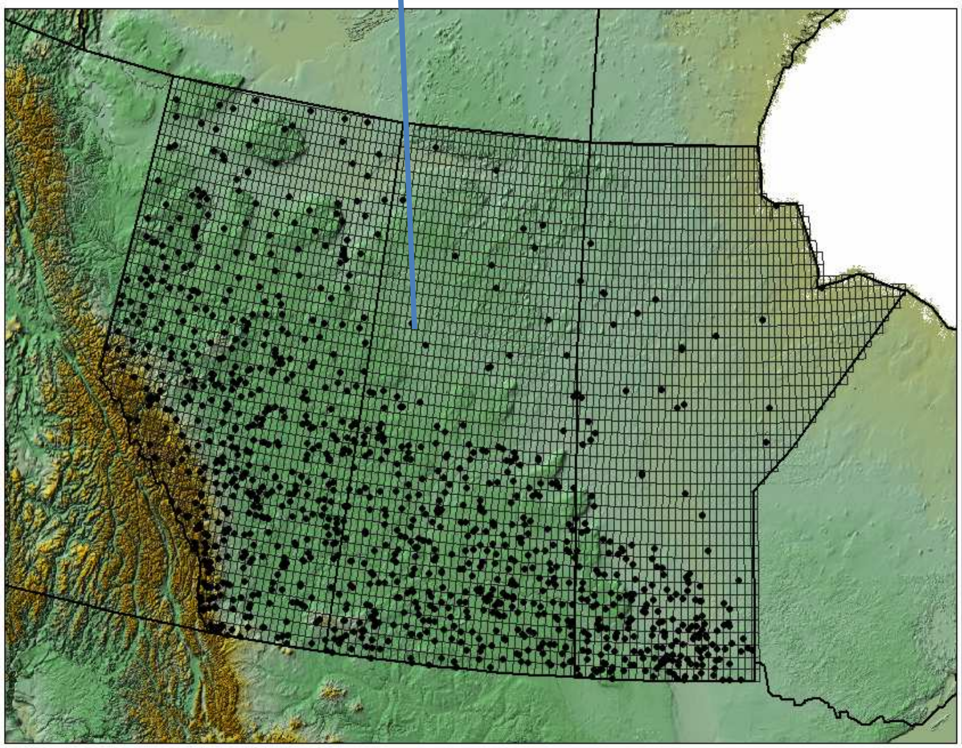
Because of the complexity observed on the prairie terrain and the source issue of multiple flow supplements, as well as the availability of supporting date, it would be more perorate to use a macroscale conceptualized hydrological model for the prairie hydrological simulation, rather than using a fully physically-based model. As the rainfall-runoff relationship in a conceptual model is conceptualized, successfully simulating the relationship for a specific basin is not necessarily connected to the physical reality of the basin terrain. The macroscale rainfall-runoff relationship is a macro concept. The main reason for conceptual models being able to apply to many basins with different terrain conditions is through model calibration process. Diversified calibrated parameter values can reflect different terrain conditions. This is the art of a conceptual model.

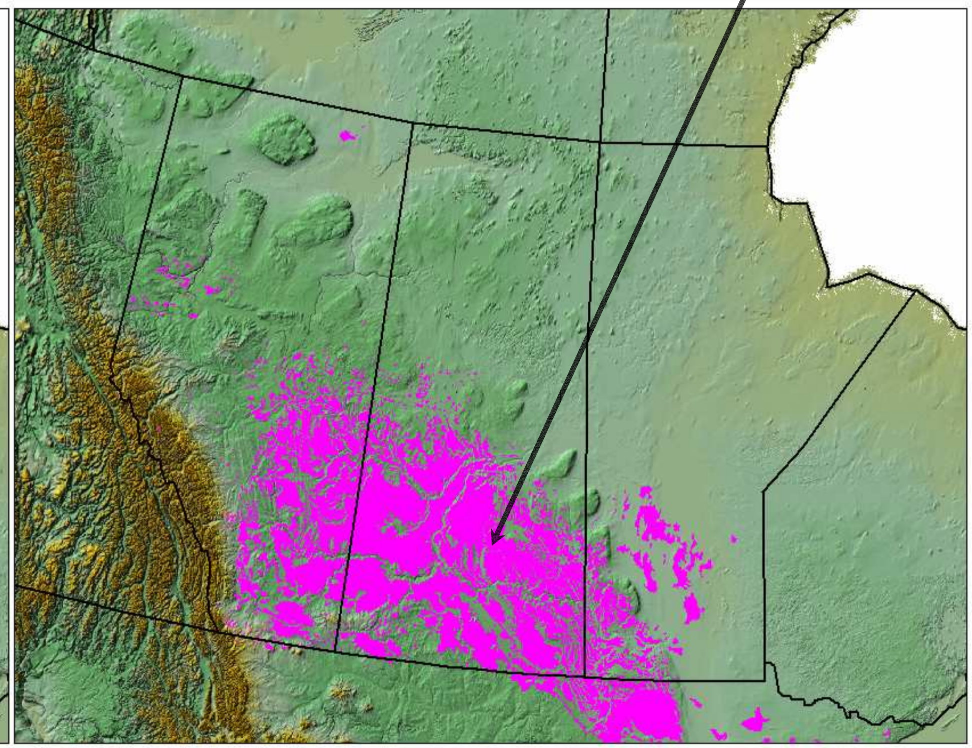
2. VIC set up over the Prairies (1,964,000 km²)

The VIC model is applied over a Prairies domain consisting of 4393 grid points
with a resolution of 0.25 ° x 0.25 °



1,167 met stations (black dot); providing VIC with meteorological driving forces for monitoring runs





Flat terrain and non-contributing drainage areas; bring challenges to hydrological modeling

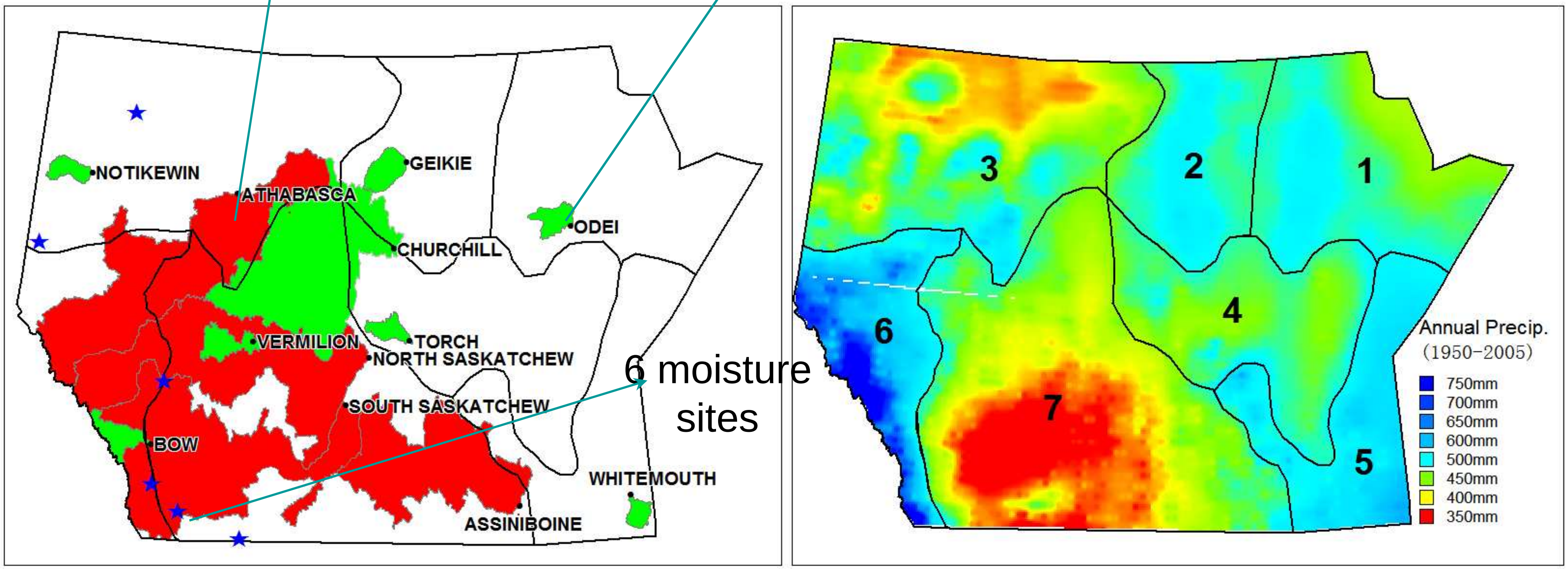
3. VIC calibration and validation over 12 catchments

from 7 hydrological simulation regions on the Prairies

- Calibration period 1994-1999
- Validation period 1975-2001
- Only water balance mode is used
- 24-h time step for main process
- 1-h time step for snow band solving
- VIC calibration and validation are done using observed hydrographs
- VIC is forced by observed max and min temperature and precipitation
- The IDW method is used for the driving forces interpolating
- Temperature lapse rate (C/100 m) = 0.75 °C
- Precipitation lapse rate (%/100 m) = 5 mm

4 additional validation catchments in **red**

7 calibration catchments in **green**;



- ➢ We calibrate the six VIC user-calibrated hydrological parameters using observed daily hydrographs at the outlets of each of the 7 calibration catchments.
- ➢ The validation of the calibrated VIC over the Prairies involves the following three parts.

1. First, we validate VIC using observed daily hydrographs from the same 7 calibration catchments taken over different periods than for calibration.
2. Second, we further validate VIC using observed daily hydrographs from 4 additional catchments.
3. Third, we compare simulated soil moisture anomalies with *in situ* observations from 6 Alberta sites.

We define 7 VIC simulation regions over the Prairies; which are based on annual precipitation from 1950 to 2005

4. Results

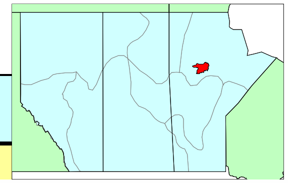
11 Catchments' information and VIC calibration and validation results

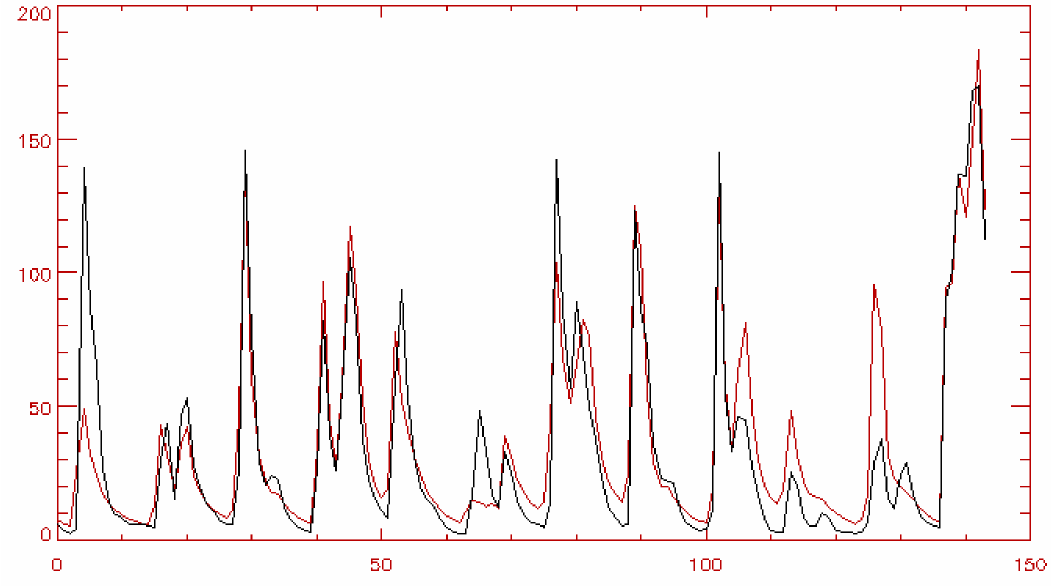
ID		River Name	Station Name	Station ID	Station Lat	Station Long	Drainage Area (km^2) Gross	Effective	(%)	ELEV	AVG_T	ANN_PREC
1	Cal.	ODEI	THOMPSON	05TG003	55.996	-97.356	6110	6110	100.0	259	-3.1	508.7
2	Cal.	GEIKIE	WHEELER	06DA004	57.589	-104.203	7730	7730	100.0	501	-3.4	492.7
3	Cal.	NOTIKEWIN	MANNING	07HC001	56.919	-117.618	4680	4660	99.6	791	-0.8	483.0
4	Cal.	TORCH	LOVE	05KE002	53.588	-104.161	4650	4650	100.0	513	0.0	454.9
5	Cal.	WHITEMOUTH	WHITEMOUTH	05PH003	49.939	-95.956	3750	3750	100.0	325	2.1	592.6
6	Cal.	BOW	CALGARY	05BH004	51.050	-114.050	7870	7740	98.3	1953	-1.5	690.7
7	Cal.	VERMILION	MARWAYNE	05EE007	53.491	-110.397	7270	3110	42.8	649	1.9	418.1
8	Val.	ATHABASCA	MCMURRAY	07DA001	56.781	-111.400	133000	131000	98.5	807	0.2	532.8
9	Val.	NORTH SASKATCHEWAN	PRINCEALBERT	05GG001	53.203	-105.768	131000	72300	55.2	814	1.5	465.3
10	Val.	SOUTH SASKATCHEWAN	SASKATOON	05HG001	52.140	-106.643	141000	88100	62.5	965	3.0	433.1
11	Val.	ASSINIBOINE	BRANDON	05MH013	49.871	-100.100	93700	36500	39.0	576	1.9	433.5

ID		River Name	Period	INFILT	Ds	Ds_MAX	Ws	DEPTH_2	DEPTH_3	Err. (%)	Nash (day)	Nash (Mon)
1	Cal.	ODEI	1994-2005	0.04	0.026	25.5	0.31	0.68	0.62	7.3	0.73	0.82
2	Cal.	GEIKIE	1994-2005	0.03	0.059	26.5	0.39	0.62	1.12	-4.8	0.75	0.77
3	Cal.	NOTIKEWIN	1994-2005	0.09	0.022	2.5	0.71	0.47	0.63	2.7	0.64	0.75
4	Cal.	TORCH	1982-1987	0.03	0.031	2.0	0.92	0.72	0.33	-23.1	0.68	0.69
5	Cal.	WHITEMOUTH	1994-2005	0.11	0.011	24.0	0.34	0.83	0.66	19.1	0.61	0.70
6	Cal.	BOW	1990-1999	0.06	0.038	28.5	0.28	0.46	1.85	-0.4	0.80	0.87
7	Cal.	VERMILION	1981-1990	0.01	0.001	0.5	0.58	0.48	0.40	31.6	0.40	0.58
8	Val.	ATHABASCA	1966-1975							13.9	0.57	0.62
9	Val.	NORTH SASKATCHEWAN	1991-2000							-5.1	0.59	0.69
10	Val.	SOUTH SASKATCHEWAN	1951-1960							-8.8	0.55	0.66
11	Val.	ASSINIBOINE	1977-1987							-5.4	0.62	0.77

Calibration result

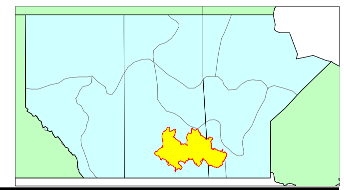
River Name	Period	Err. (%)	Nash (day)	Nash (Mon)
ODEI	1994-2005	7.3	0.73	0.82



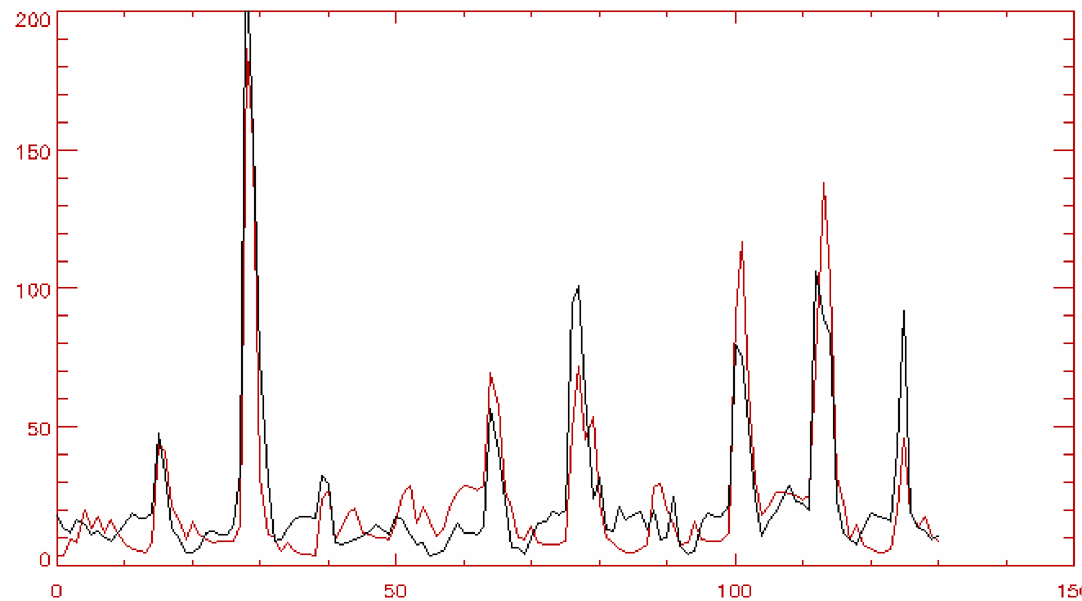


At Odei basin

Validation result



River Name	Period	Err. (%)	Nash (day)	Nash (Mon)
ASSINIBOINE	1977-1987	-5.4	0.62	0.77

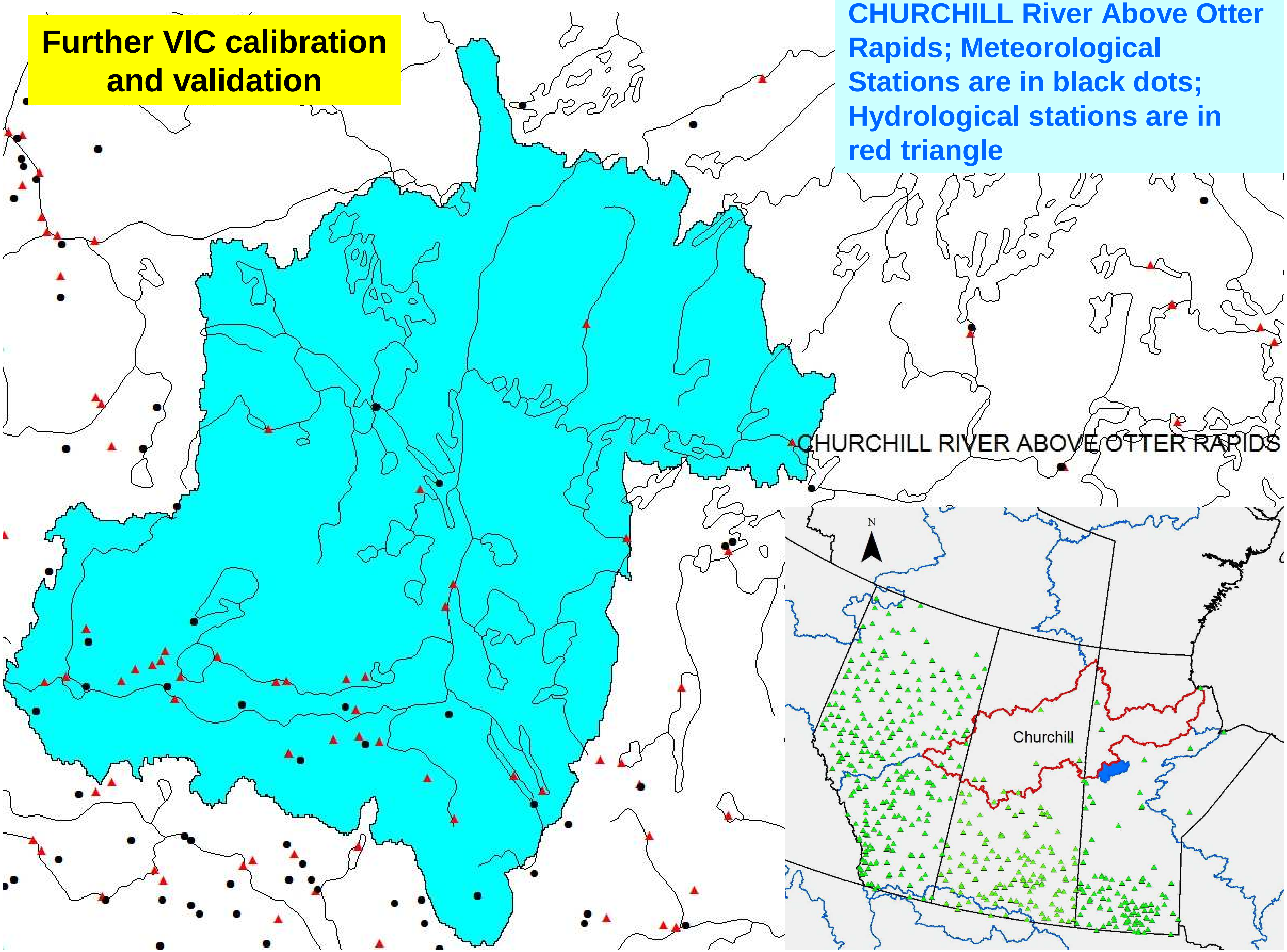


At Assinboine basin

Note: VIC is NOT specifically calibrated at this basin; instead, VIC uses calibrated parameters from the simulation regions of 5 and 7 for this basin simulation

Further VIC calibration and validation

CHURCHILL River Above Otter Rapids; Meteorological Stations are in black dots; Hydrological stations are in red triangle

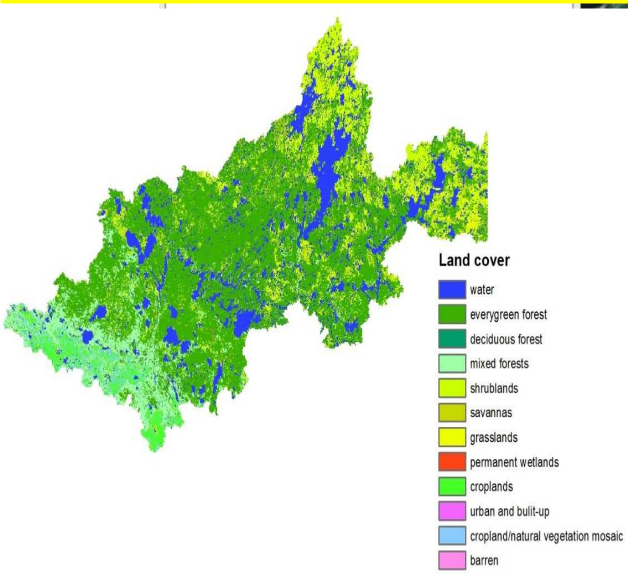


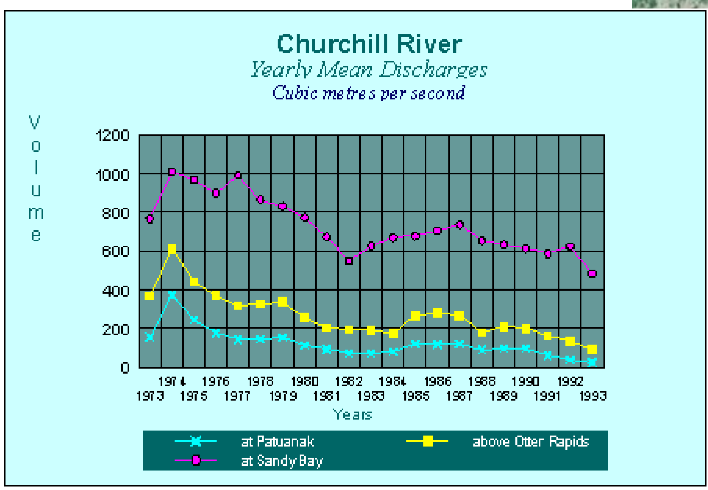
CHURCHILL Basin:

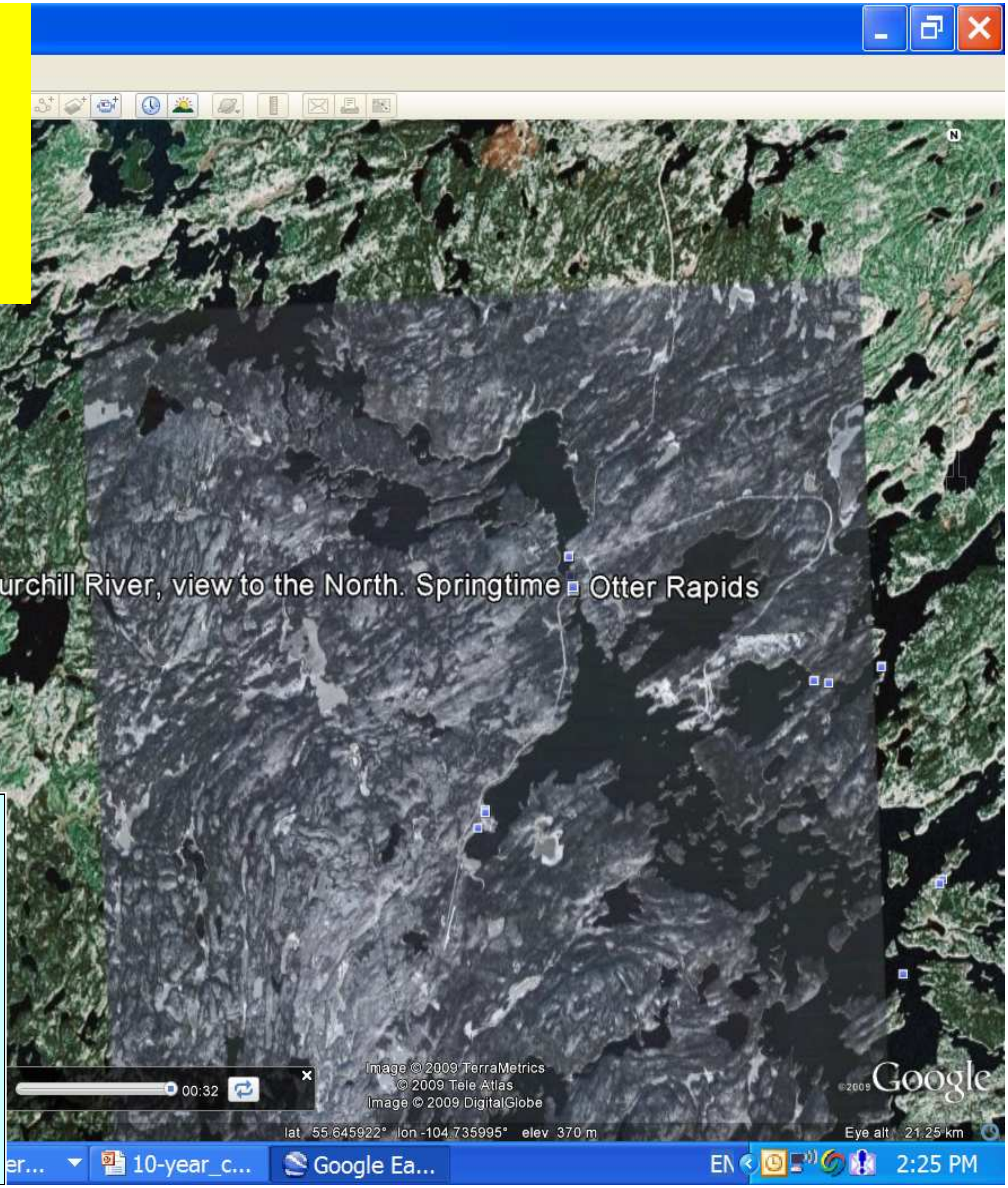
1. The Churchill River itself is generally made up of a series of lakes of various sizes; flat hydrographs

2. Scare of met stations;

3. Drainage area 119,000 km^2



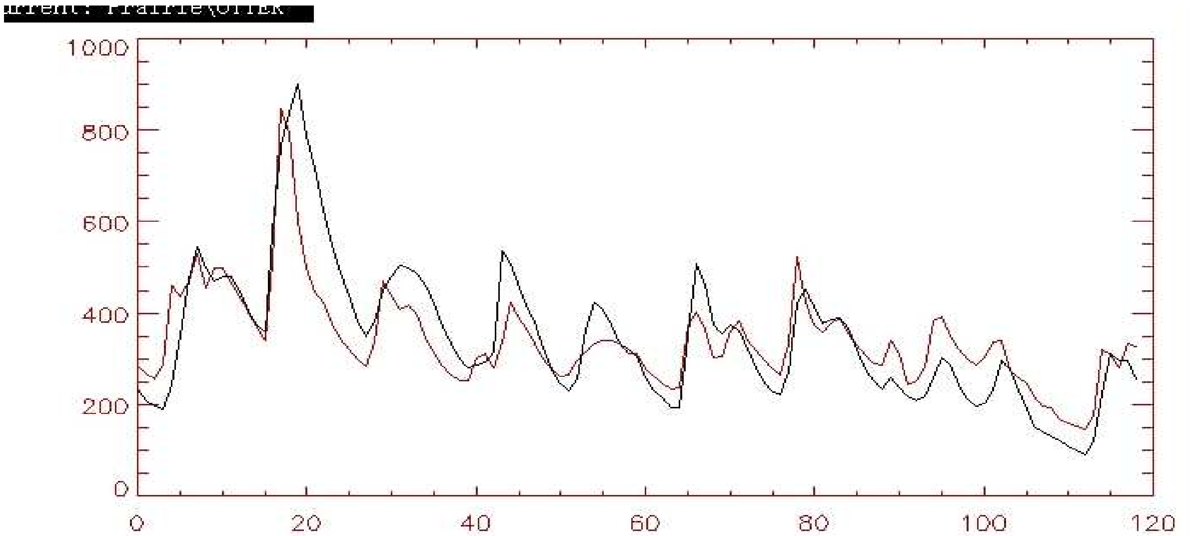




VIC parameters after and before calibration for the period 1973-1982

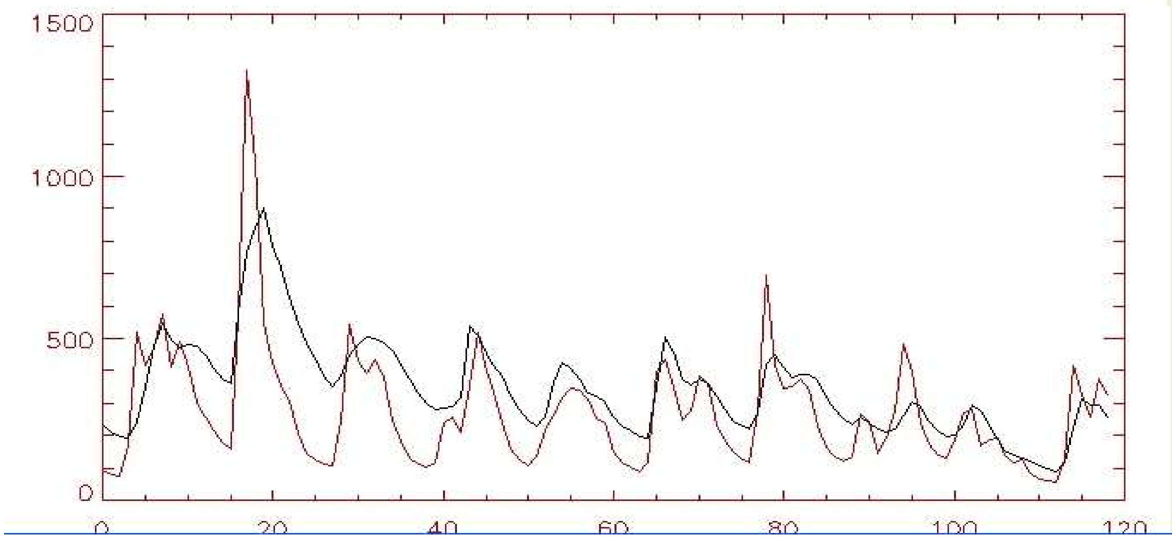
for Churchill River Above Otter Rapids

	B	Ds	Dmax	Ws	c	d1	d2	d3	error_day	Nash_day
After	0.0500	0.1940	1.5000	0.5100	2.0000	0.1000	0.6200	0.7300	-0.0339	0.6612
Before	0.0900	0.0200	2.0000	0.6000	2.0000	0.1000	0.4700	0.6300	-0.2816	-0.2250



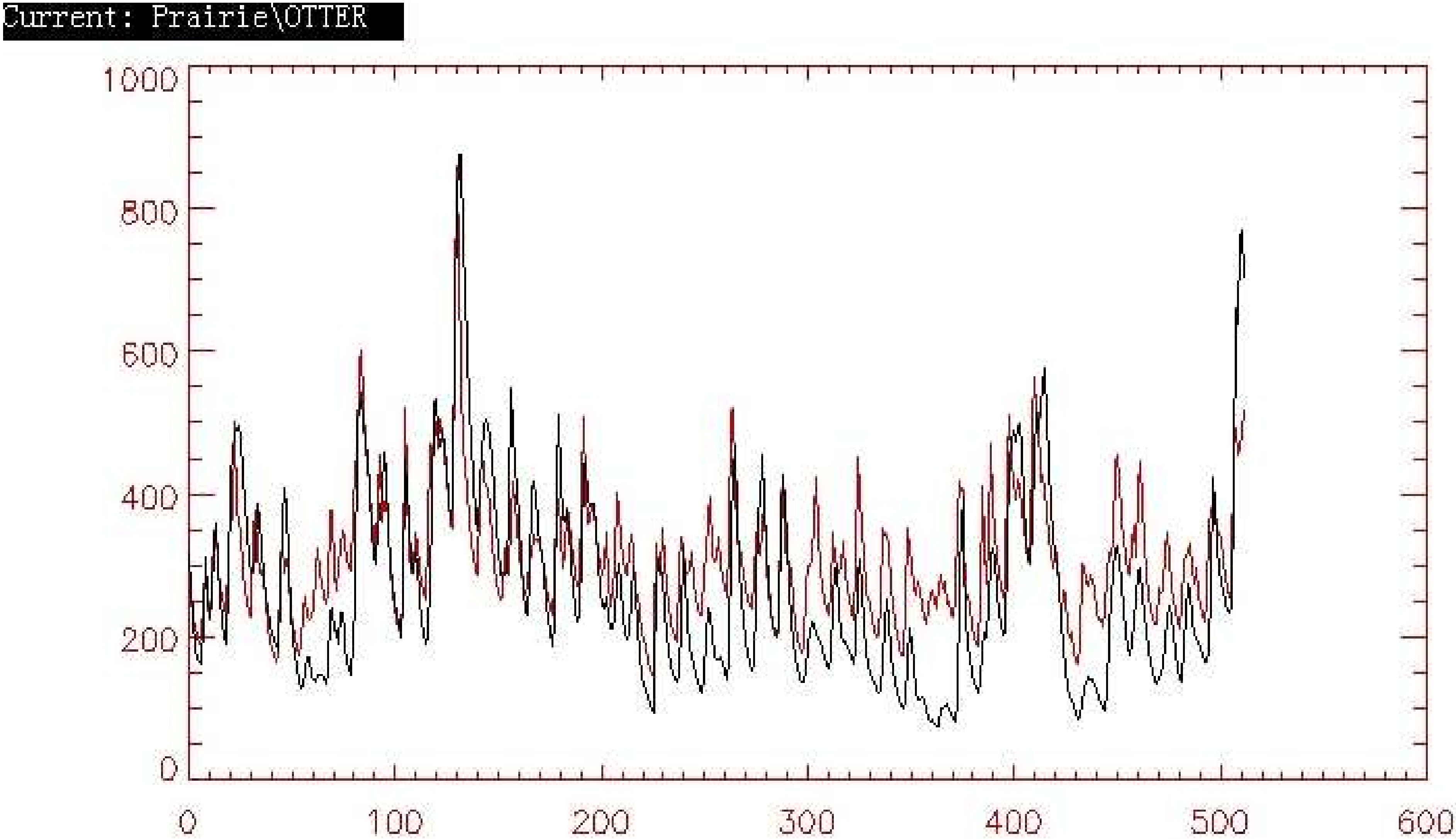
After calibration

Nash_month = 0.67
Relative error = 3%



Before calibration

Nash_month = 0.017
Relative error = -20%



The validation result for the period 1963-2005

Nash_month = 0.52

Relative error = 16%

Comparison of simulated and observed soil moisture anomalies from 6 Alberta sites

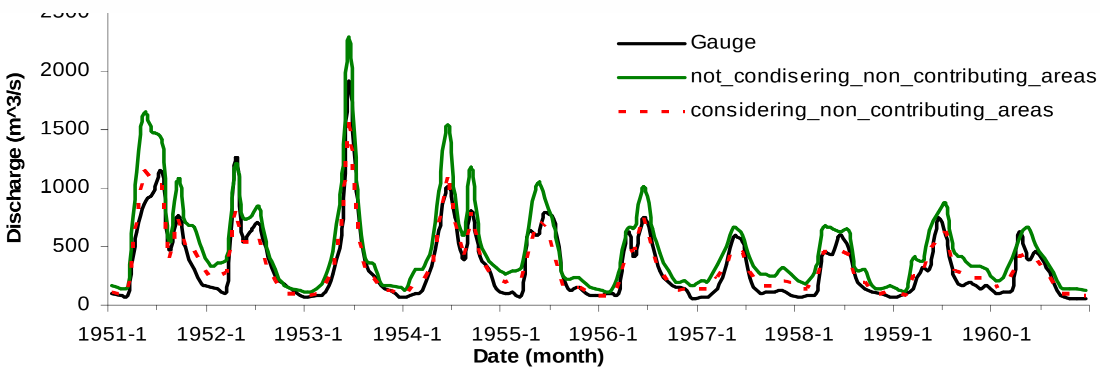
Site	Annual Precip. (mm)	Site Lat. (°N)	Site Long. (°W)	VIC grid Lat. (°N)	VIC grid Long. (°W)	Correlation coefficient (r) 0-20 cm	Correlation coefficient (r) 20-100 cm	Correlation coefficient (r) 0-100 cm
Fortremillion	364	58.38	116.04	58.38	116.13	0.17	-0.09	0.09
Beaver Lodge	337	55.20	119.40	55.16	119.38	0.44	0.56	0.59
Lacombe	451	52.45	113.76	52.38	113.88	0.45	0.61	0.58
Stavely	513	50.18	113.88	50.16	113.88	0.34	0.58	0.56
Lethbridge	359	49.63	112.80	49.63	112.88	0.67	0.65	0.69
Onefour	335	49.12	110.47	49.13	110.38	0.48	0.10	0.22

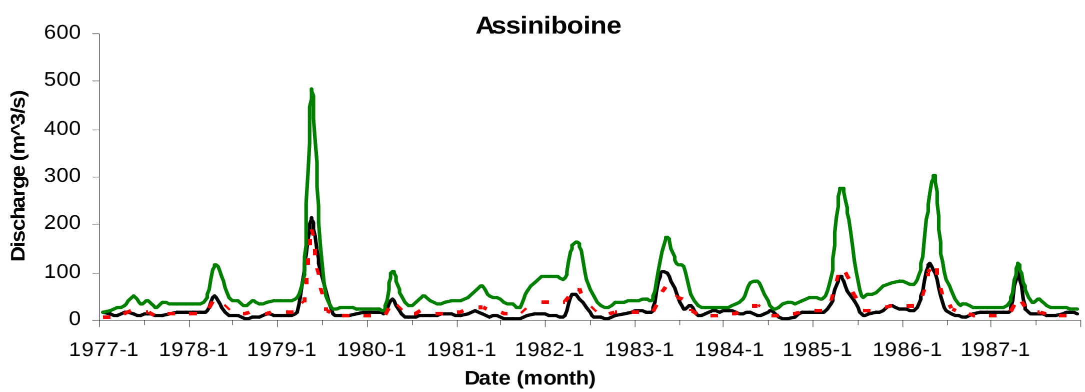
Please note: the simulated soil moisture represents the average situation of a 0.25º × 0.25º gird box. VIC is not specifically calibrated for any of these 6 grid points. Instead, we use the calibrated values for the 7 simulation regions of the Prairies in our soil moisture simulations.

Comparison results at the Onefour site

Study of non-contributing drainage area effect on runoff generation

	Catchment	Station	Drainage Area (km^2)		Period	With non-contributing area		Without non-contributing area	
			Total	Effective		E_r (%)	E_c	E_r (%)	E_c
8	Athabasca	McMurray	133000	131000	66-75	14.0	0.81	14.3	0.80
9	North Sask.	Princealbert	131000	72300	91-00	0.9	0.80	53.4	-0.45
10	South Sask.	Saskatoon	141000	88100	51-60	3.1	0.91	47.5	0.54
11	Assiniboine	Brandon	93700	36500	77-87	5.3	0.77	163.2	-2.23





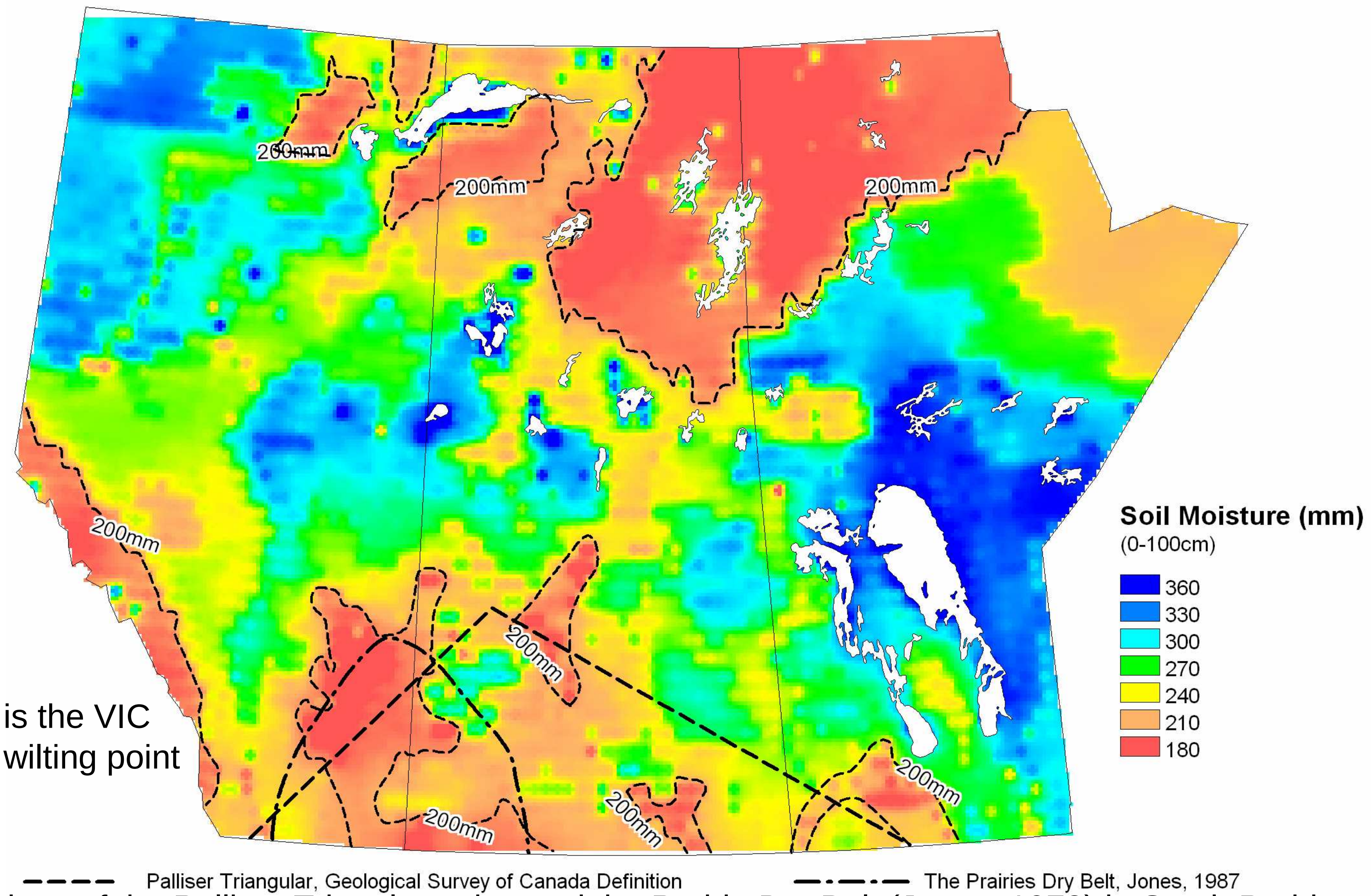
By incorporating **non-contributing drainage areas** into runoff calculations (red dashed-lines) could substantially improve the ability of hydrological models to simulate surface and sub-surface runoff in regions where the wetland is a dominant feature of land covers.

Comparison results at the outlets of the South Saskatchewan and Assiniboine catchments

5. Applications of VIC soil moistures

56-yr (1950-2005) average of soil moisture (top 1-m) over the Prairies

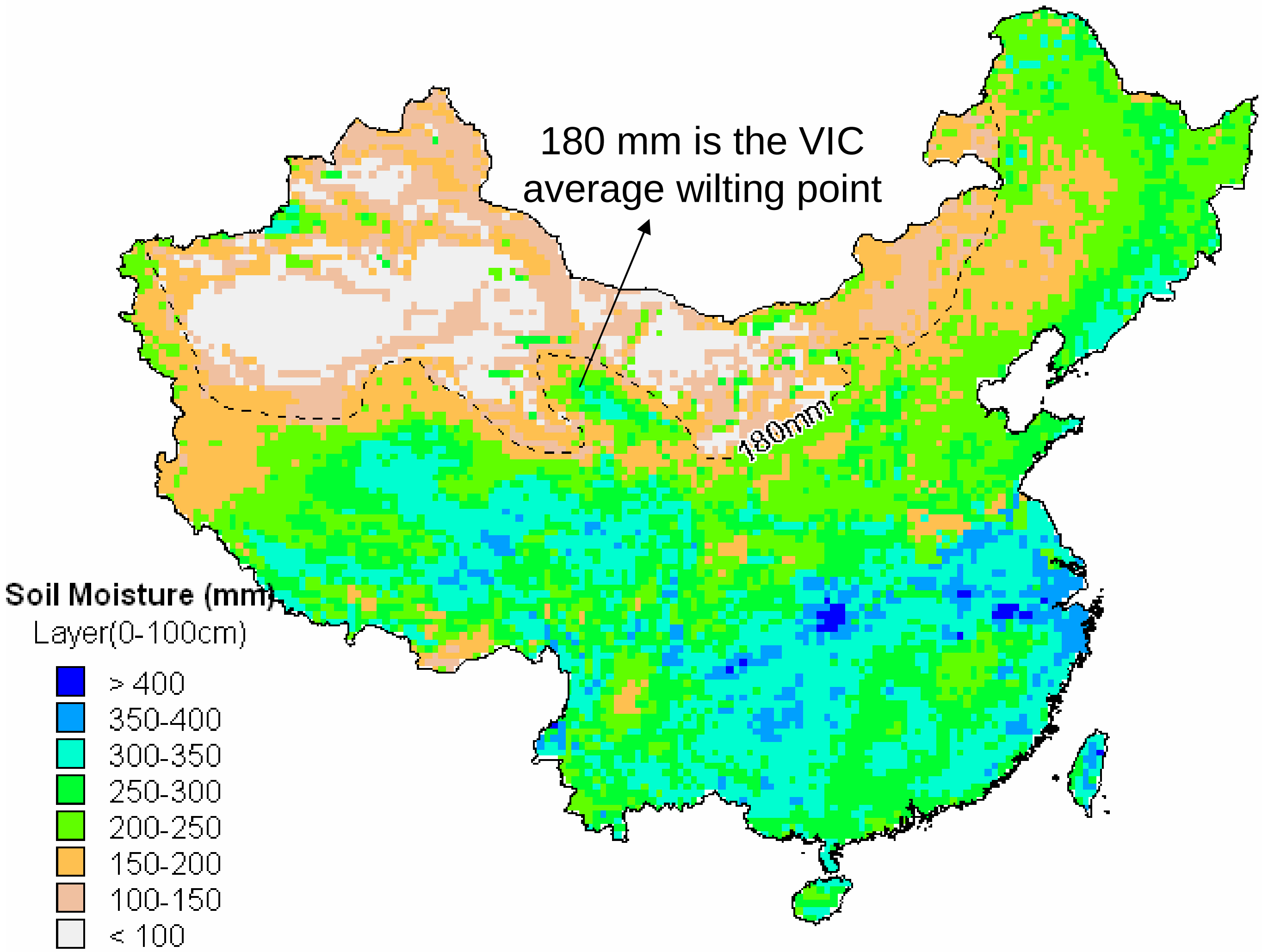
with the 200 mm soil moisture contour, showing modeled very dry areas



200 mm is the VIC average wilting point

Identifications of the Palliser Triangle region and the Prairie Dry Belt (Jones, 1978) in South Prairies.

Another example of VIC 35-yr soil moisture climatology (1971-2005) over China

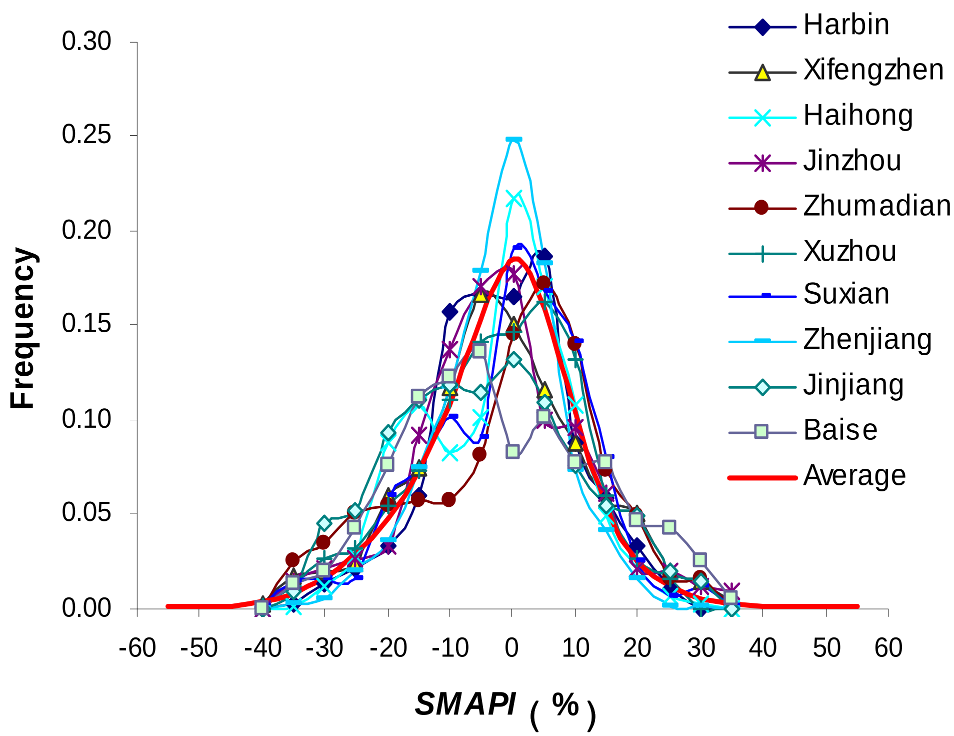


We compare qualitatively the simulated 35-yr average of the top 1-m soil moisture with an official chart of dry and wet zones in China. The simulated 180 mm soil moisture contour is in close agreement with the dry and wet zones division of the chart (page 98 in the China Flood and Drought Disaster; 1997).

Soil Moisture Anomaly Percentage Index (SMAPI)

$$SMAPI = \frac{\theta - \bar{\theta}}{\bar{\theta}} \times 100\%$$

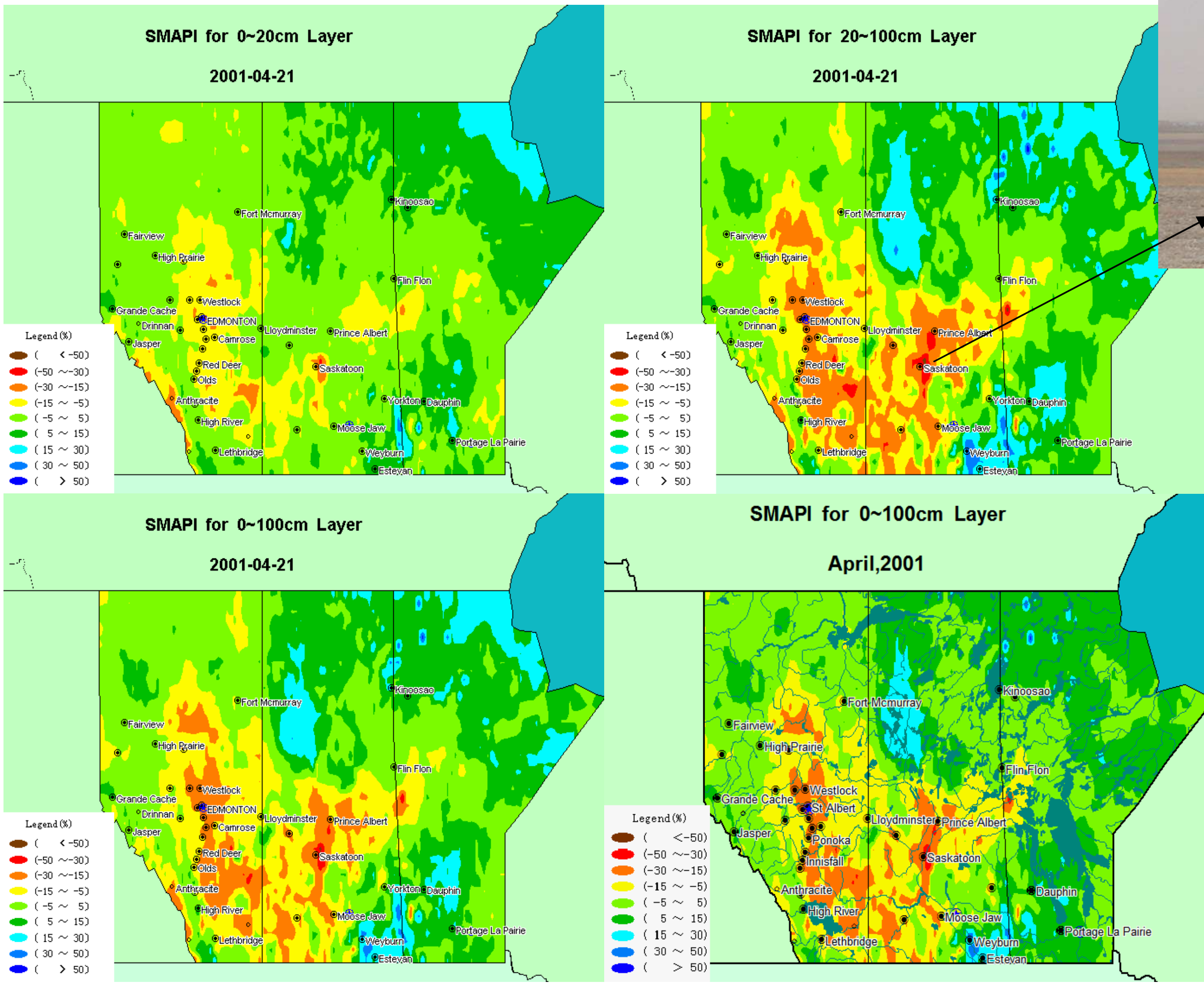
- The soil moisture climatology reflects local characteristics and mirrors the hydro-meteorological phenomena of a region;
- The concept of relative soil wetness for use in measuring drought severity
- The study of Quiring and Papakryiakou (2003) indicates that the Z-index is best suited for predicting yield. The Z-index is a measure of the monthly soil moisture anomaly



Drought classifications based on SMAPI

Category	SMAPI	Average Frequency
extreme drought	≤ -50%	0.005
severe drought	-50% to -30%	0.020
moderate drought	-30% to -15%	0.100
mild drought	-15% to -5%	0.200
near normal	-5% to 5%	0.350
slightly wet	5% to 15%	0.200
moderately wet	15% to 30%	0.100
very wet	30% to 50%	0.020
extremely wet	> 50%	0.005

Reconstructing prairie drought history

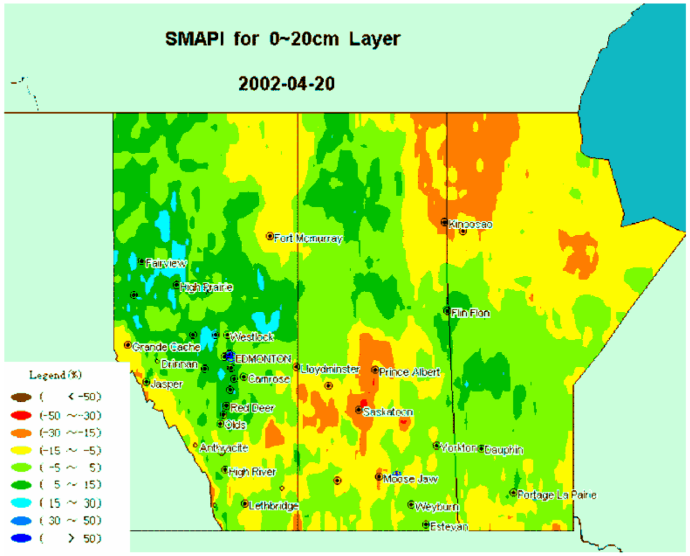


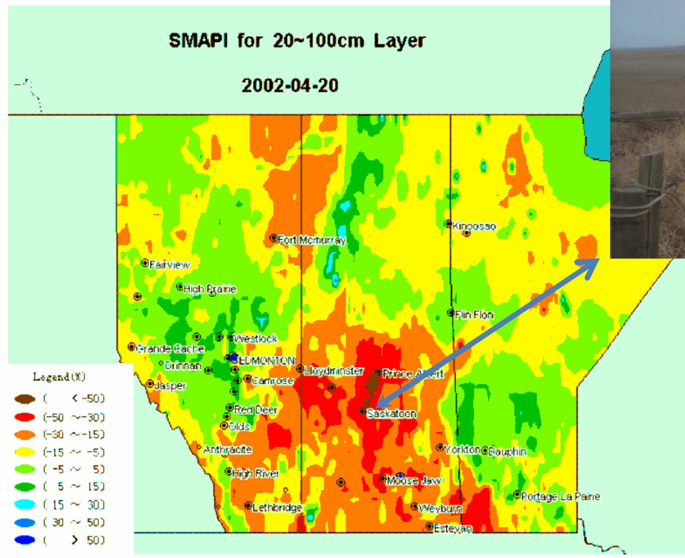
Visibility reduction due to blowing dust at Rosetown, Saskatchewan, about April 21, 2001 (photo provided courtesy of AAFC)

Example 1: daily SMAPI distributions of the three soil layers for April 21, 2001, together with the April-2001 average

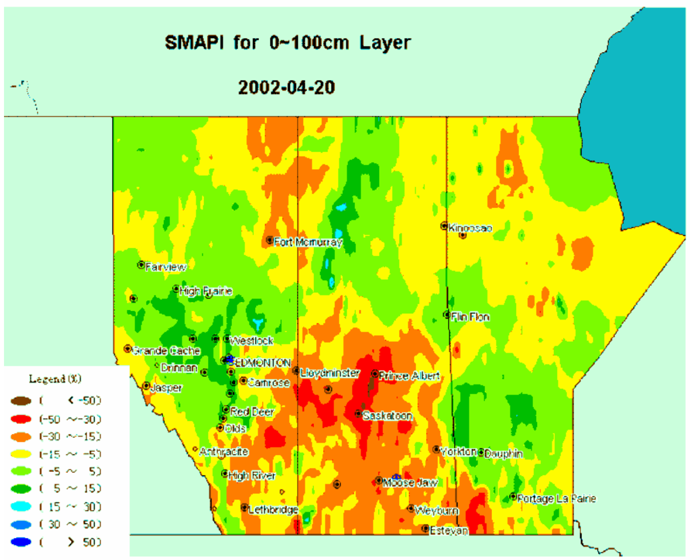
We calculate daily (monthly, seasonal and annual) SMAPI for the three soil layers (0-20 cm, 20-100 cm, and 0-100 cm) at each of the 4,393 grid points covering the Prairies from Jan.1 up to present http://www.meteo.mcgill.ca/~leiwen/vic/prairies/

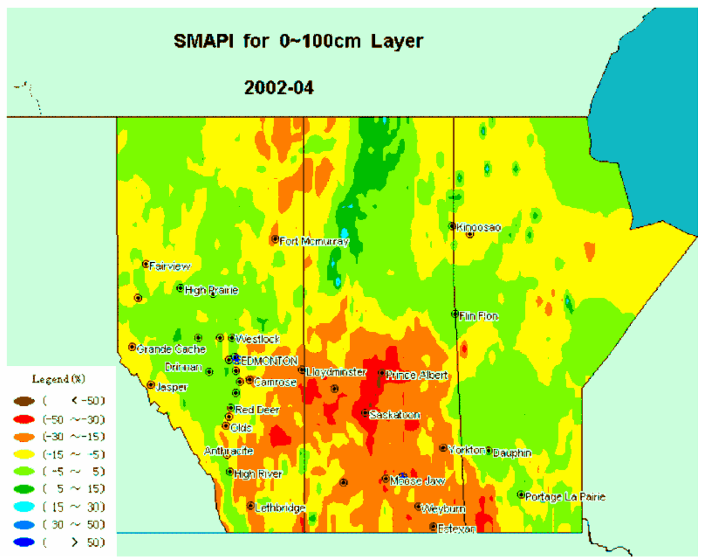
Reconstructing prairie drought history



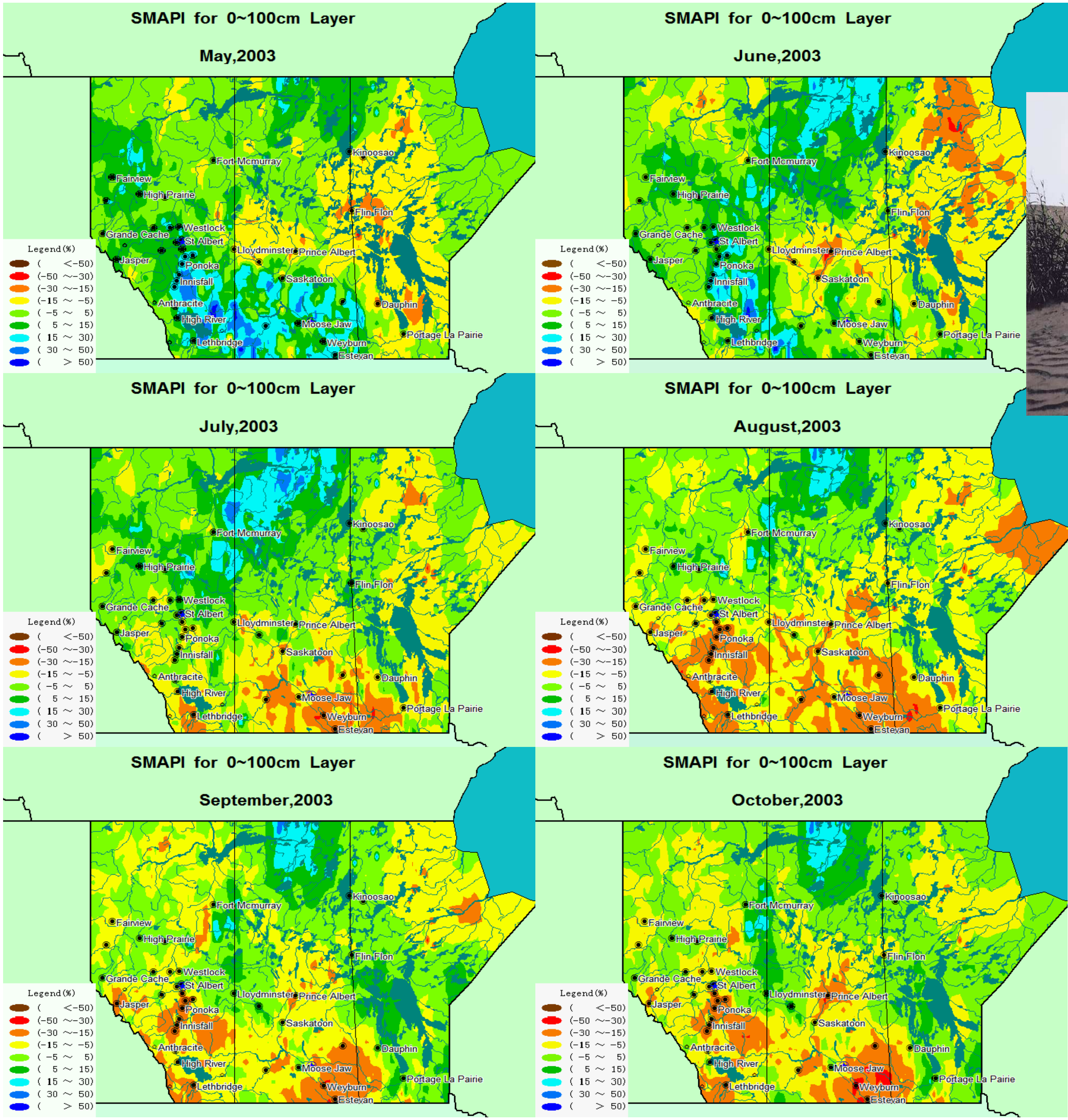


Southern Saskatchewan, April 2002; Taken from Stewart





Example 2: daily SMAPI distributions of the three soil layers for April 20, 2002, together with the April-2002 average

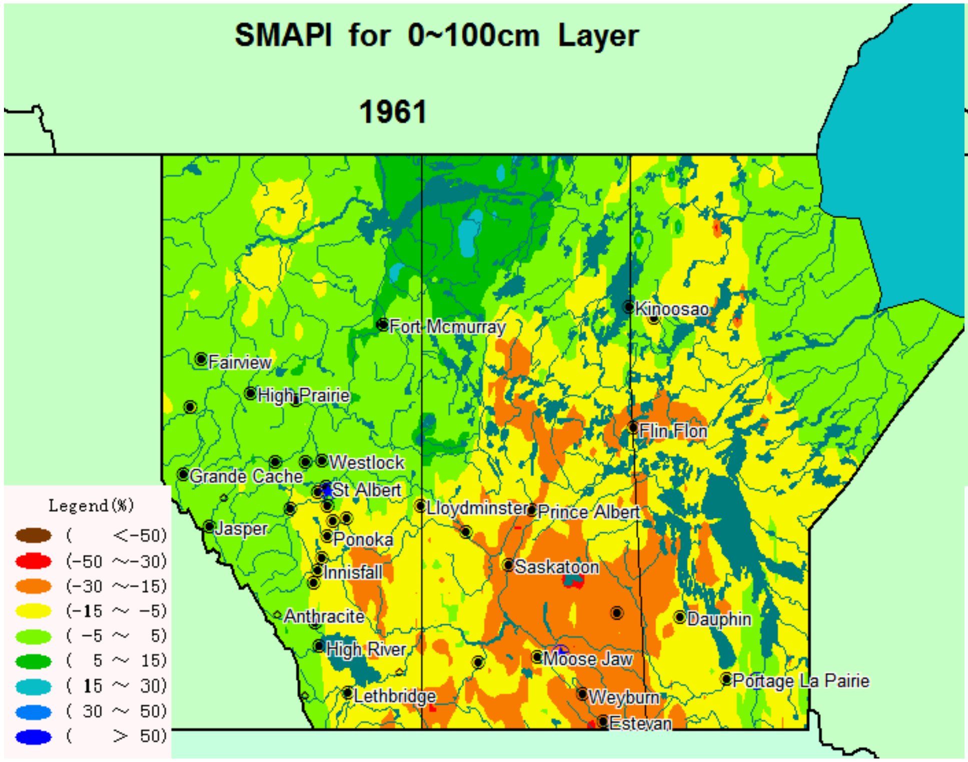


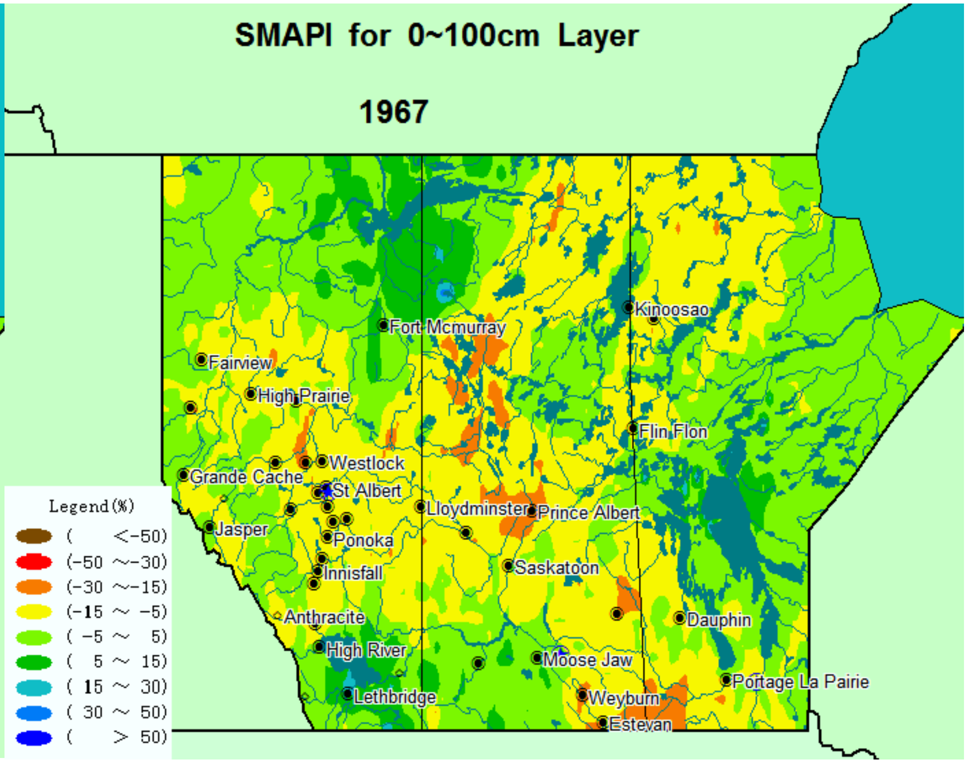
Wind erosion and dust storms caused considerable soil and much other damage in a large area south of Saskatoon, Saskatchewan, in the summer of 2003 (photo by E. Wheaton, SRC)

Example 3: monthly SMAPI distributions of July, August, September and October, 2003

Clearly showing soil conditions changed from wet to dry

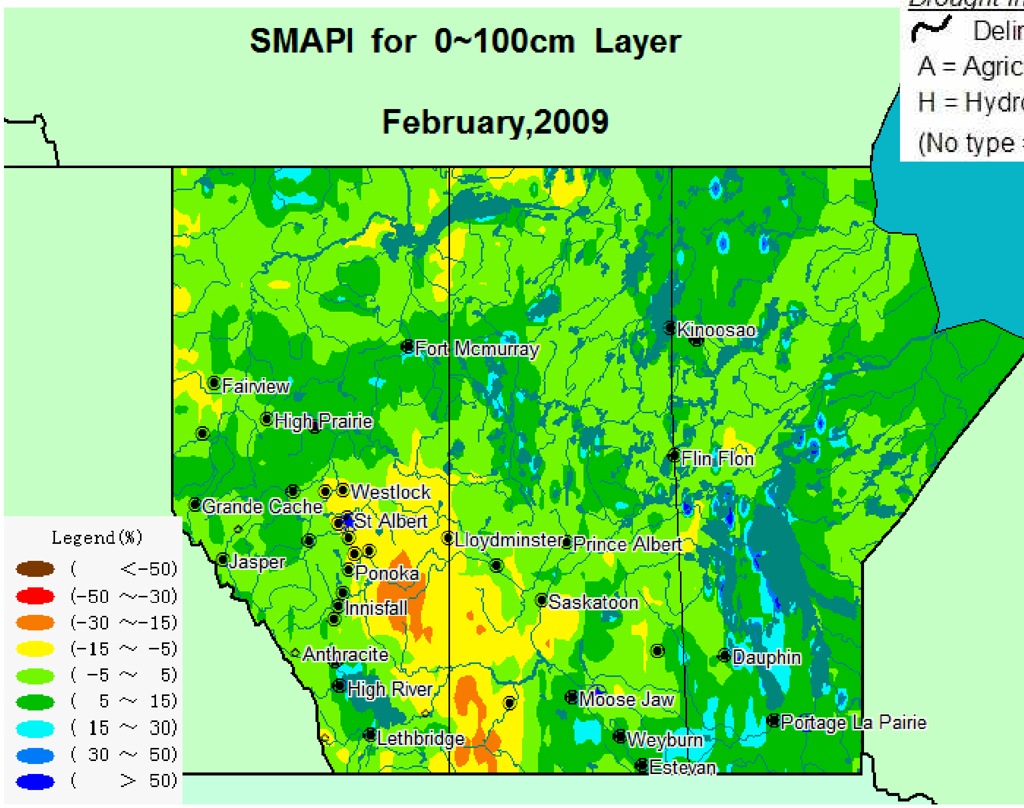
Comparing SMAPI with ‘soft’ data, e.g., media reports

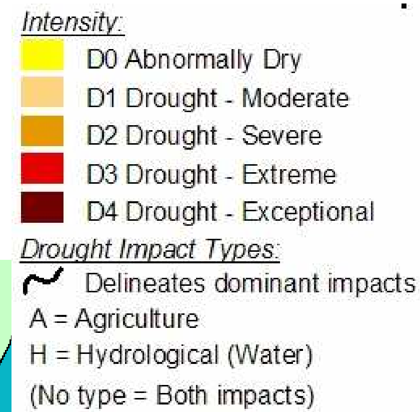


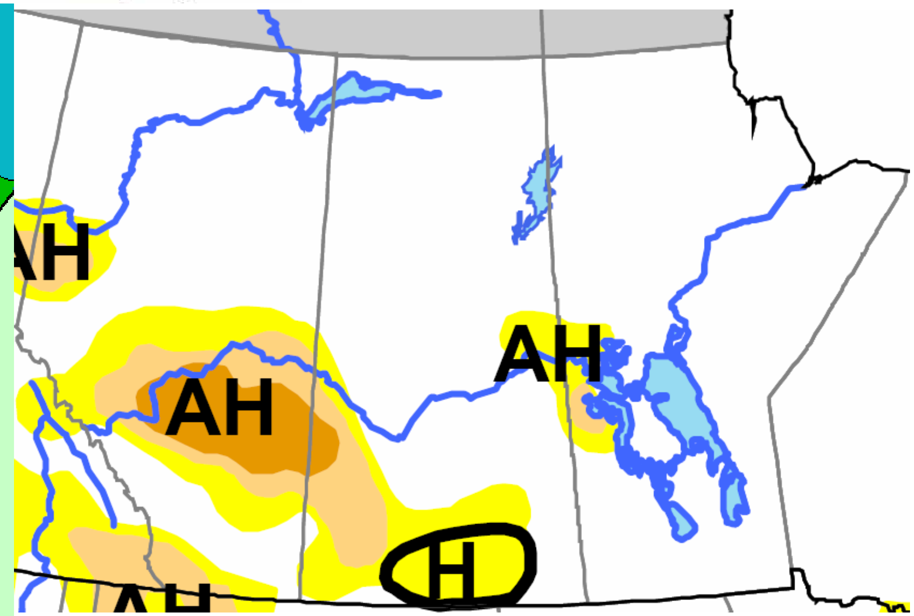


“Notable among the single-year droughts are the years 1961 and 1967, both of which were years of widespread drought on the Canadian prairies” (Madhav L. Khandekar)

Comparing SMAPI with ‘soft’ data







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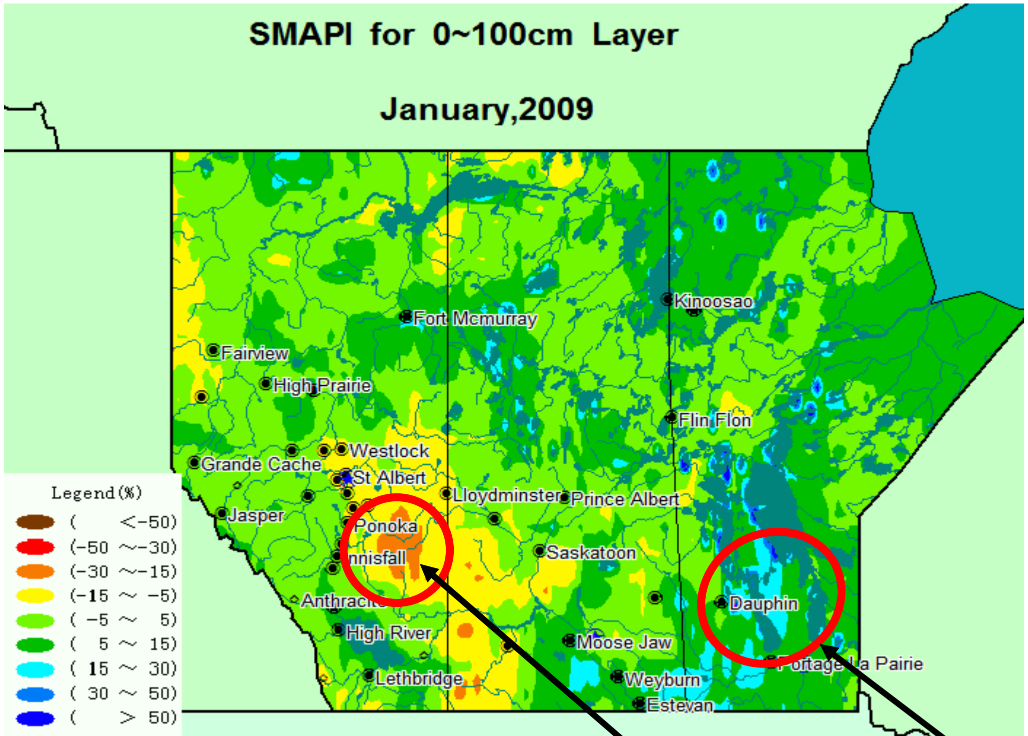
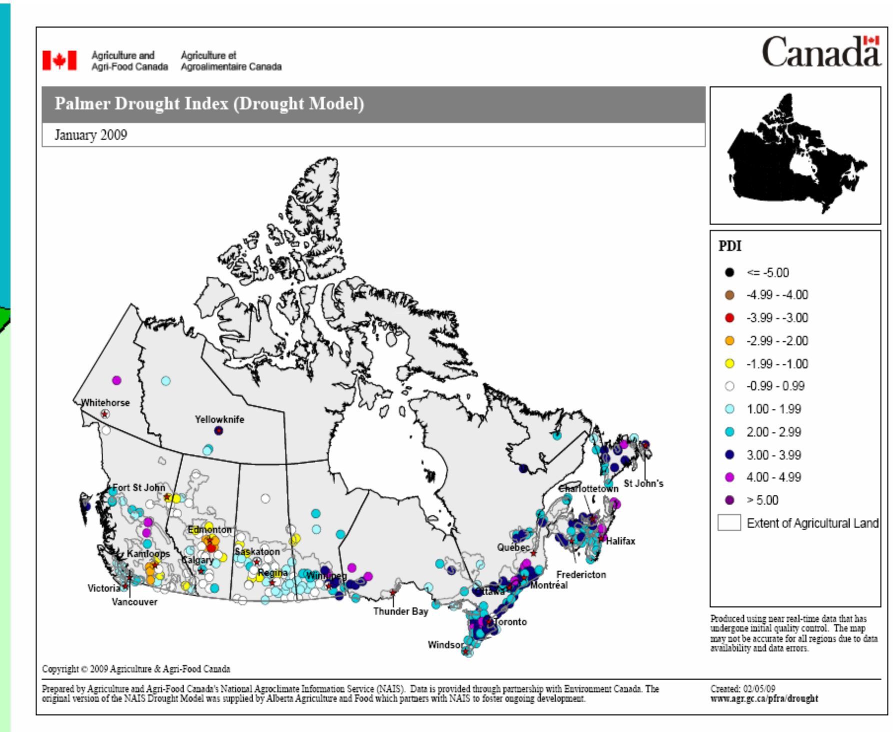
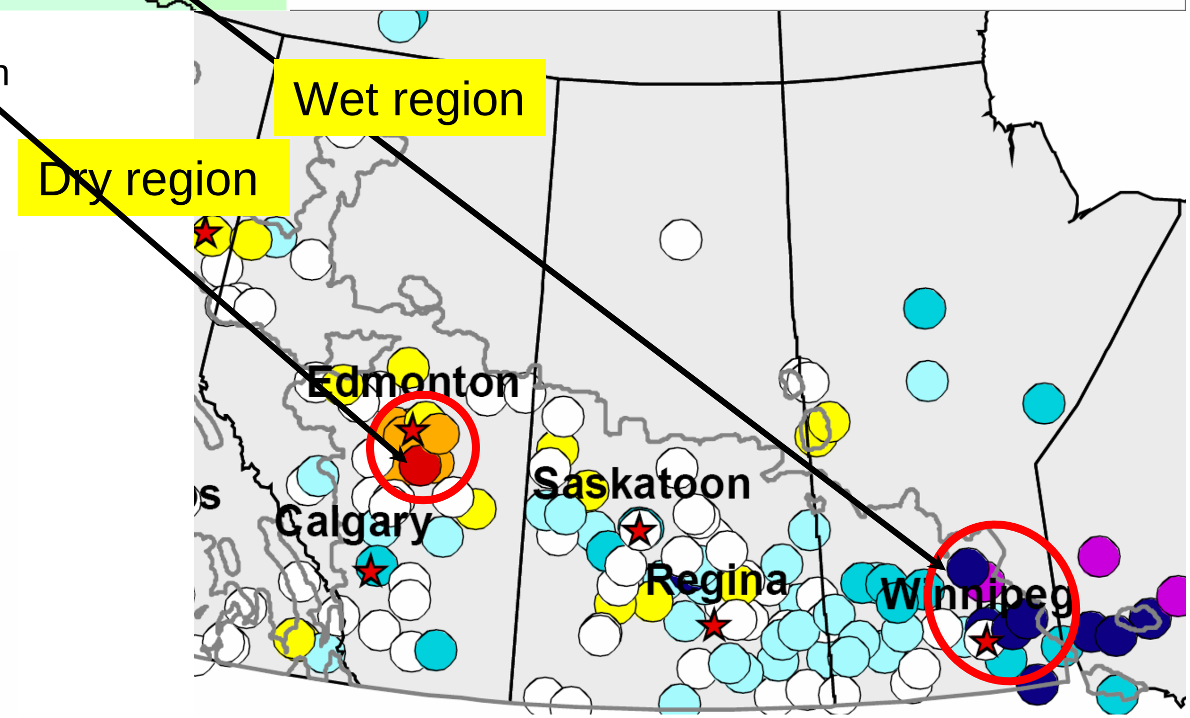
slightly wet	5% to 15%	0.200
moderately wet	15% to 30%	0.100
very wet	30% to 50%	0.020
extremely wet	> 50%	0.005

Comparison of drought indexes of soil moisture from VIC simulation and North American Drought Monitor (‘observation’). The index of VIC model is the monthly averaged value; and NADM index represents the mean of the month. This is a qualitative comparison.

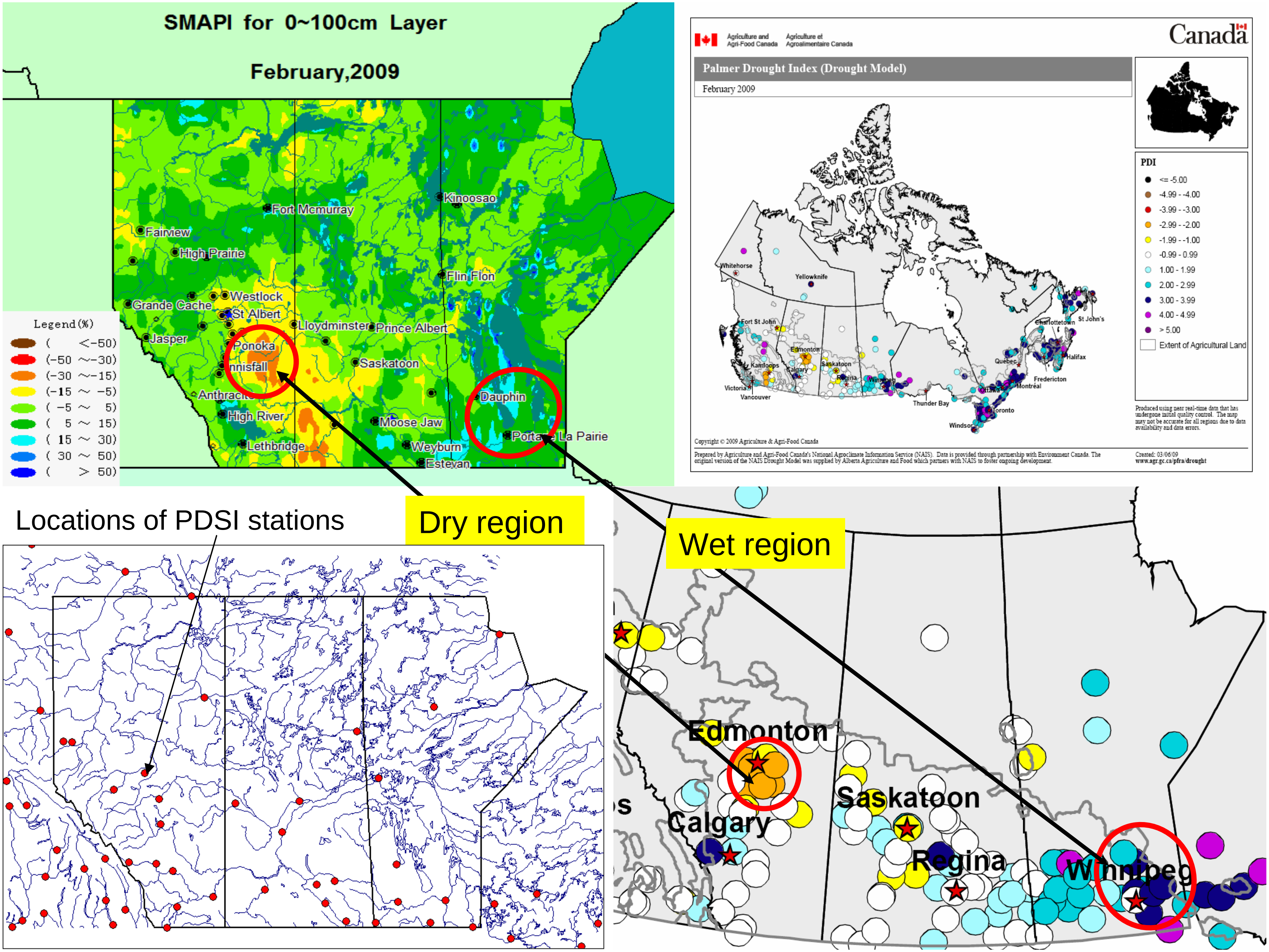


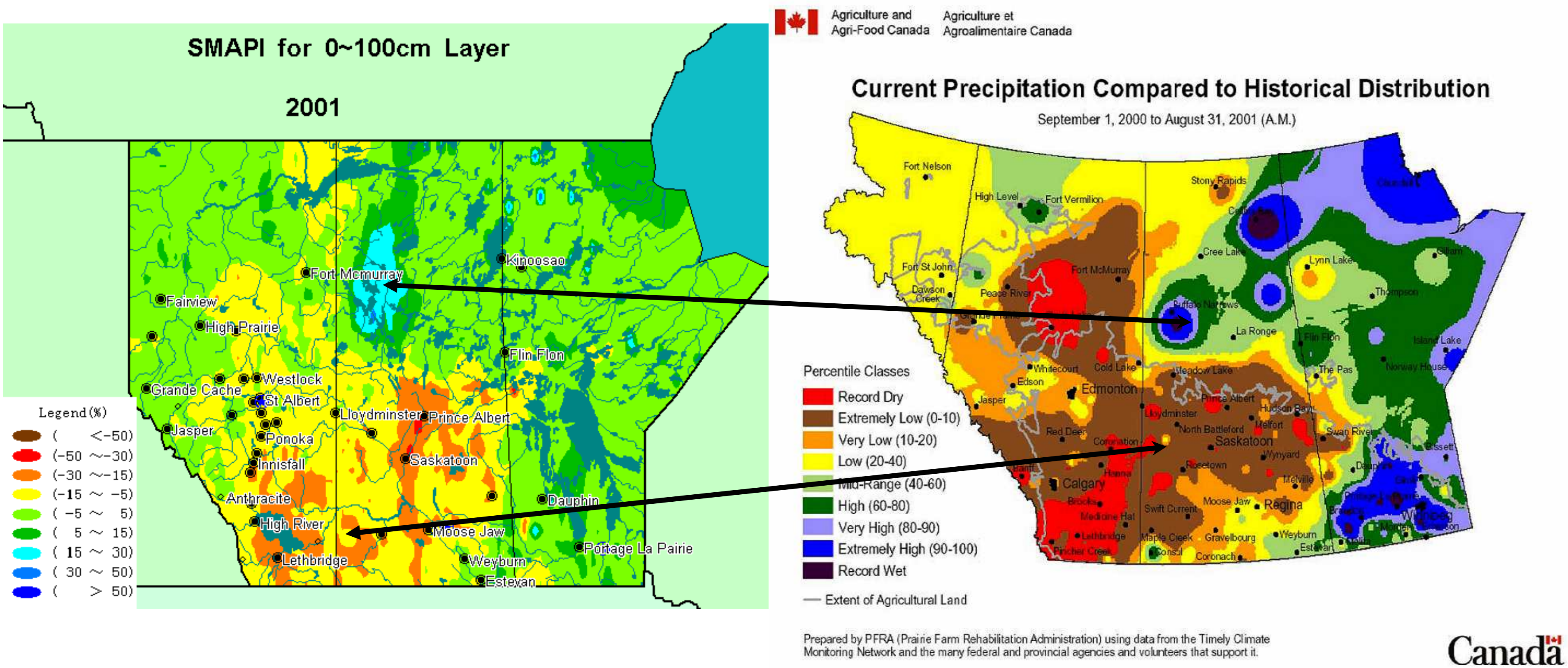




Comparison of monthly mean drought indexes of soil moisture from VIC simulation and National Drought Indice Maps of Agriculture and Agri-Food Canada ('observation').

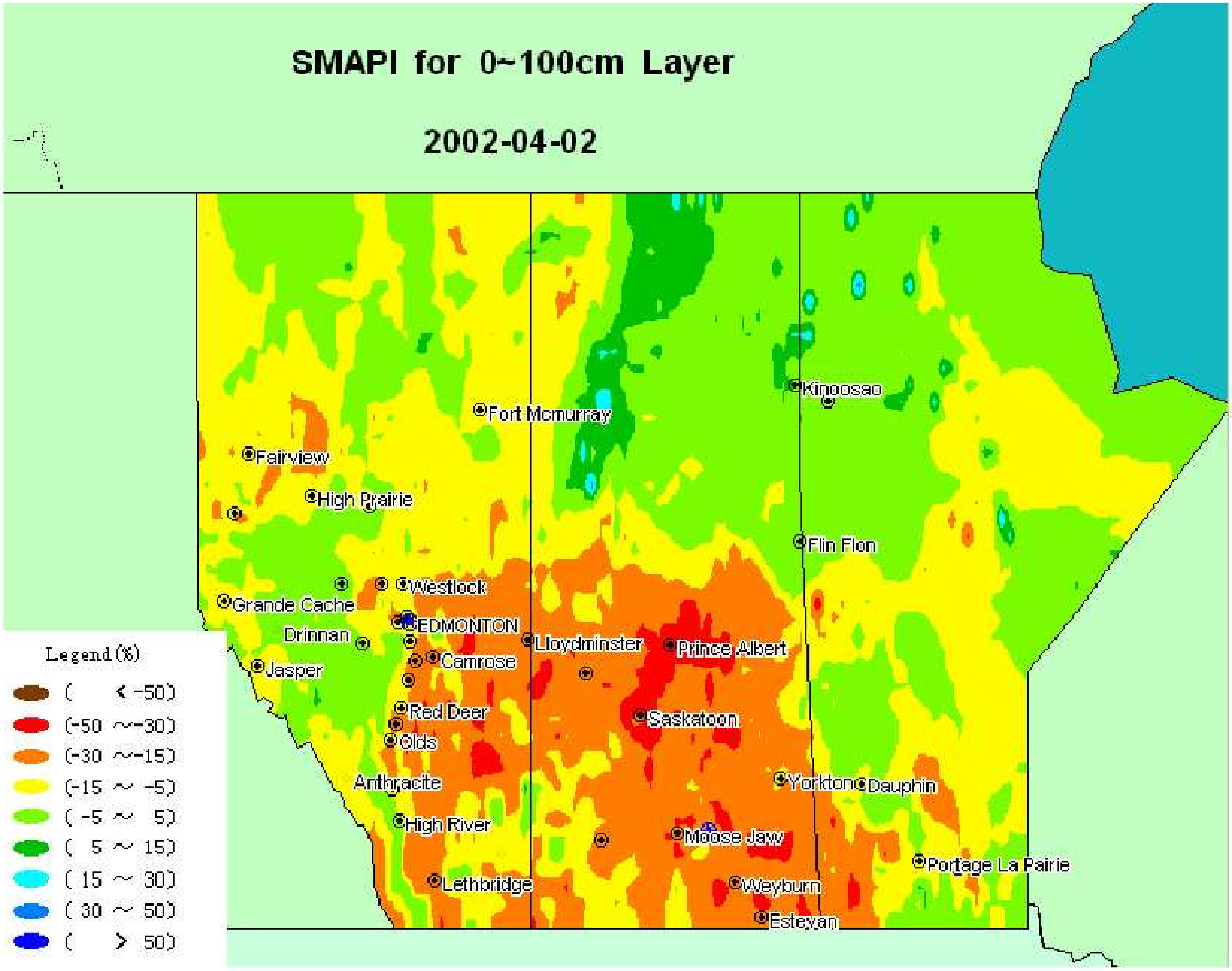
Category	SMAPI	Average Frequency
extreme drought	≤ -50%	0.005
severe drought	-50% to -30%	0.020
moderate drought	-30% to -15%	0.100
mild drought	-15% to -5%	0.200
near normal	-5% to 5%	0.350
slightly wet	5% to 15%	0.200
moderately wet	15% to 30%	0.100
very wet	30% to 50%	0.020
extremely wet	> 50%	0.005


SMAPI for 0~100cm Layer
February,2009
Legend(%)
(<-50)
(-50 ~-30)
(-30 ~-15)
(-15 ~ -5)
(-5 ~ 5)
(5 ~ 15)
(15 ~ 30)
(30 ~ 50)
(> 50)
Fort Mcmurray
Kinoosao
Fairview
High Prairie
Flin Flon
Westlock
Grande Cache
St Albert
Lloydminster
Prince Albert
Jasper
Ponoka
Saskatoon
Anthracit
High River
Moose Jaw
Dauphin
Lethbridge
Weyburn
Portage La Pairie
Estevan
Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada
Canada
Palmer Drought Index (Drought Model)
February 2009
PDI
<= -5.00
-4.99 - -4.00
-3.99 - -3.00
-2.99 - -2.00
-1.99 - -1.00
-0.99 - 0.99
1.00 - 1.99
2.00 - 2.99
3.00 - 3.99
4.00 - 4.99
> 5.00
Extent of Agricultural Land
Whitehorse
Yellowknife
Fort St John
Edmonton
Saskatoon
Kamloops
Calgary
Regina
Winnipeg
Victoria
Vancouver
Thunder Bay
Windsor
Toronto
Ottawa
Montreal
Quebec
Fredericton
Halifax
Charlottetown
St John's
Copyright © 2009 Agriculture & Agri-Food Canada
Locations of PDSI stations
Dry region
Wet region
Edmonton
Calgary
Saskatoon
Regina
Winnipeg

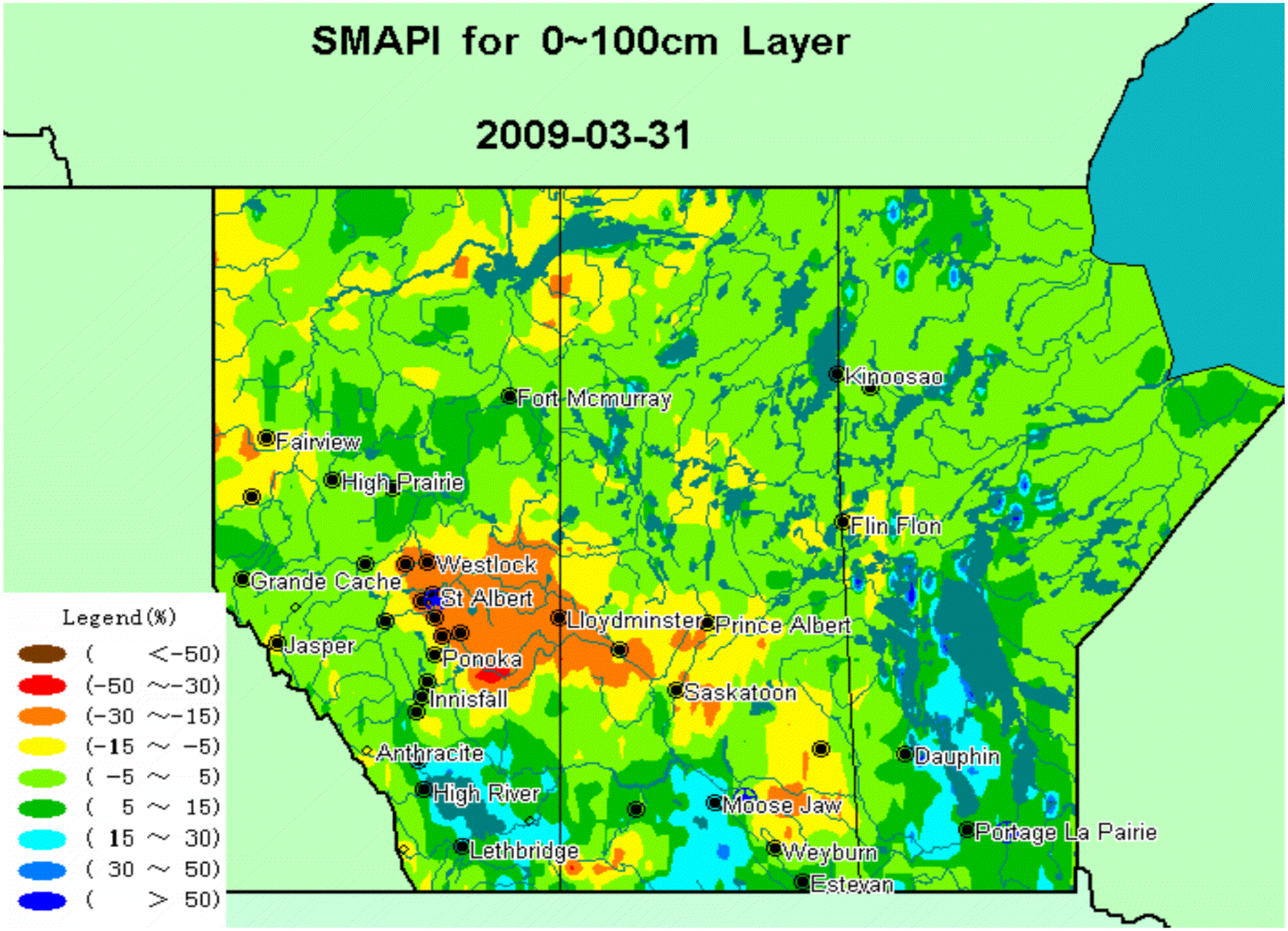


Annual average comparison of SMAPI and precipitation percentile

Re-contracted prairie droughts based on VIC daily SMAPI

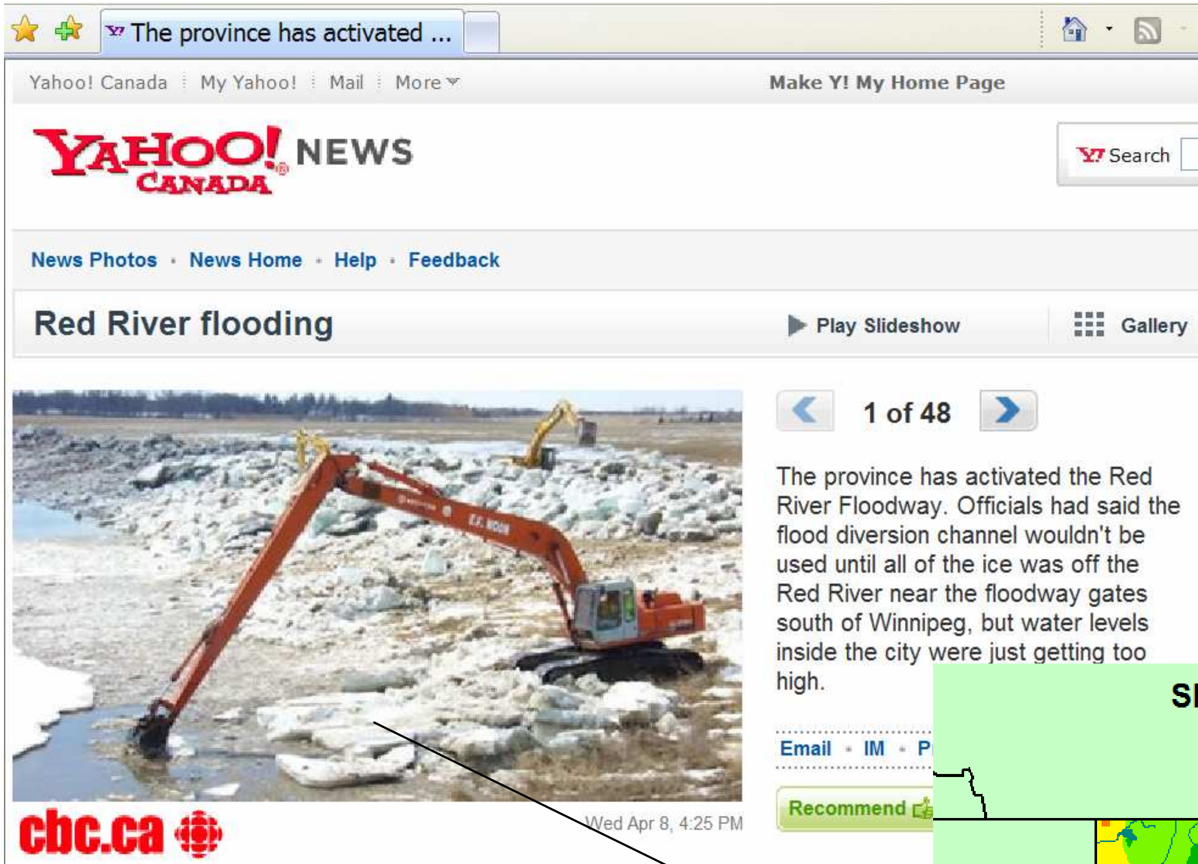


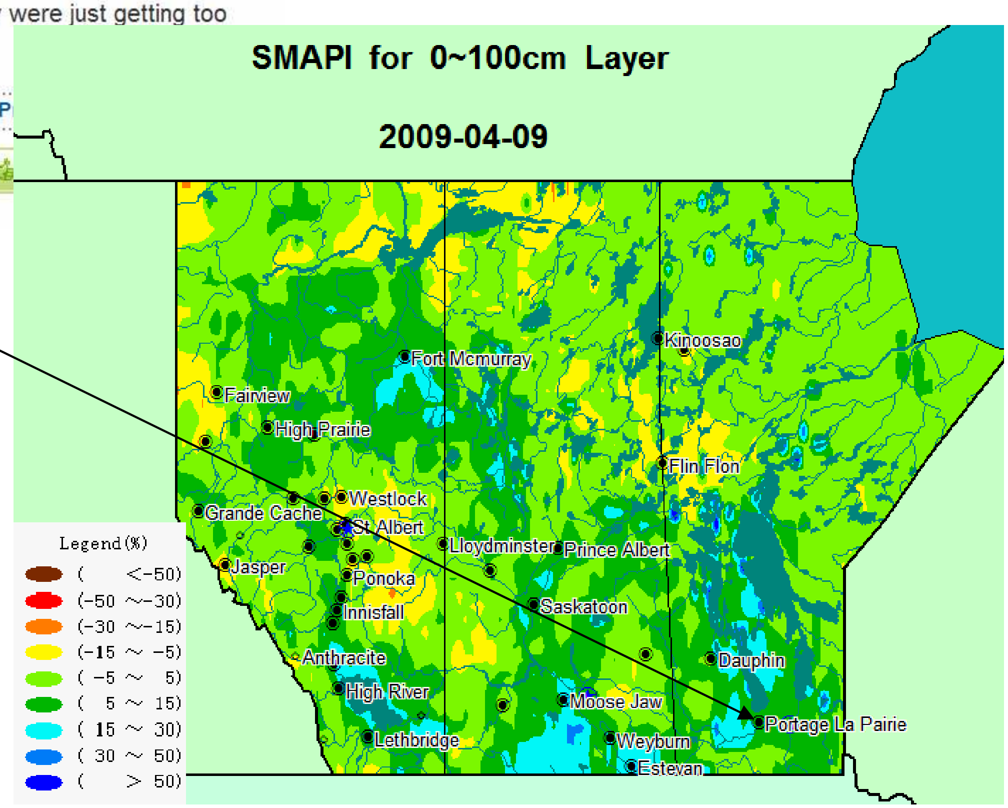
Real-time prairie drought monitoring and forecasting using VIC-based daily SMAPI



NOW!

Monitoring and forecasting prairie flooding





Thanks very much

Merci beaucoup!