Frozen Ground Modeling Advances

Victor I. Koren,

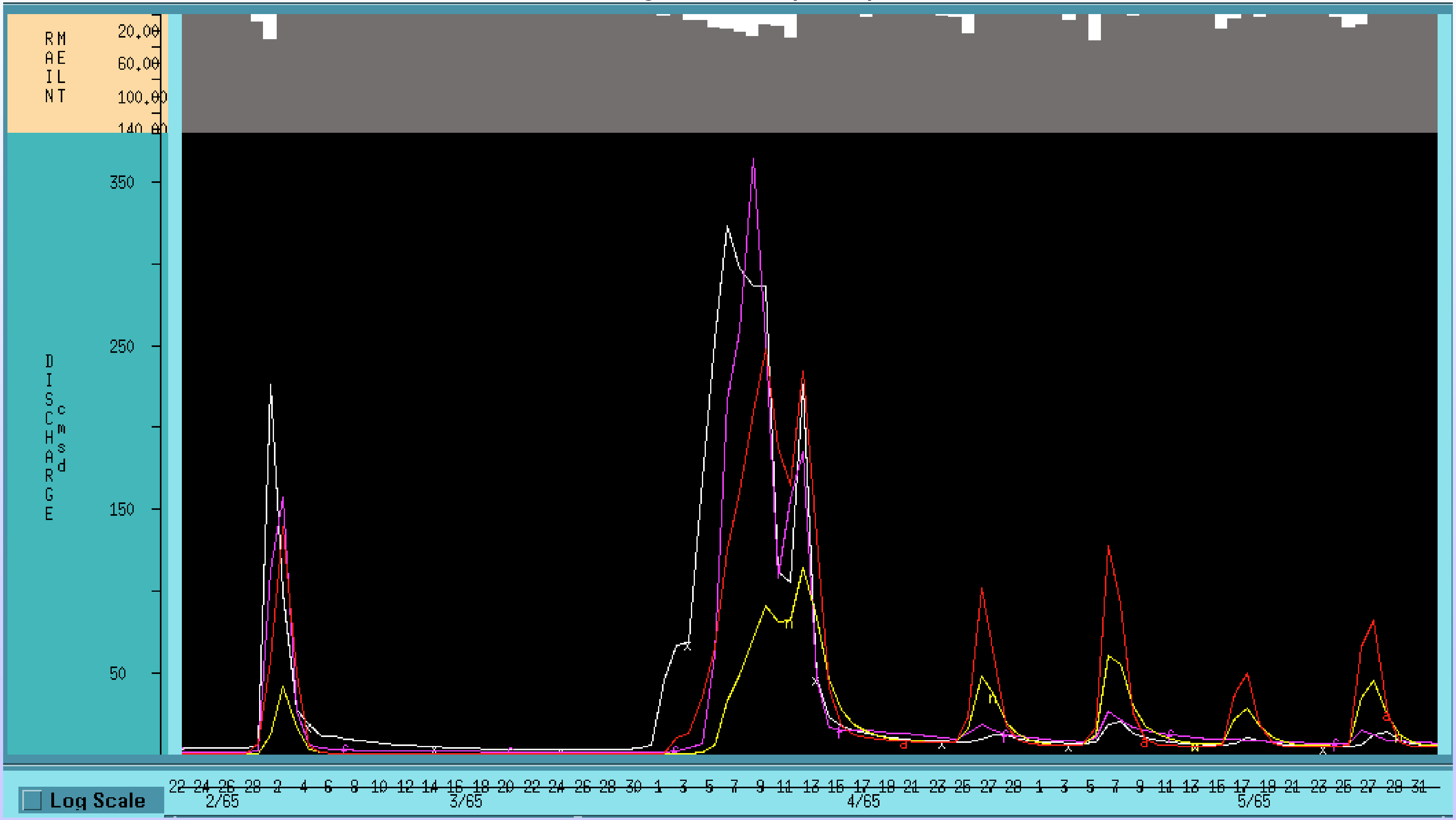
Office of Hydrologic Development, NOAA, National Weather Service, USA
Victor.Koren@noaa.gov

OUTLINE

- Importance of frozen ground processes
- Frozen ground parameterization for watershed modeling
- Test results
  - Soil moisture and temperature at selected sites
  - Runoff simulation at watershed scale
- Summary and future work

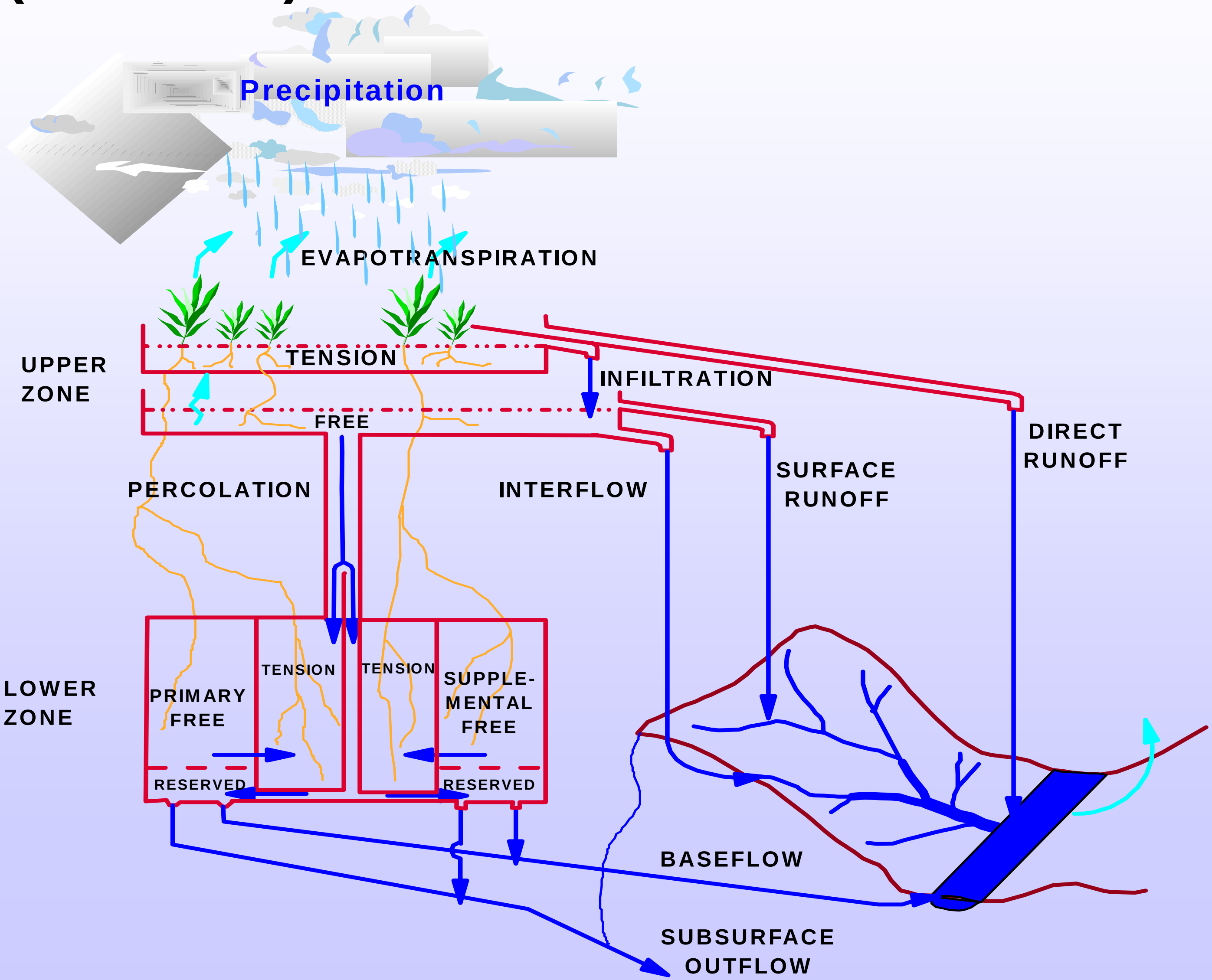
Importance of Frozen Ground on Runoff Dynamics

Observed (white) and Simulated Hydrographs, Root River, MN: with frozen ground (purple), w/o frozen ground calibrated (yellow) and adjusted (red).



Frozen Ground Formulation

Storage-type Sacramento Soil Moisture Accounting Model (SAC-SMA) that calculates soil moisture fluxes



Frozen Ground Formulation (cont.)

Layer-integrated form of the diffusion equation to calculate heat fluxes

- Basic heat flux equation integrated over selected soil layers

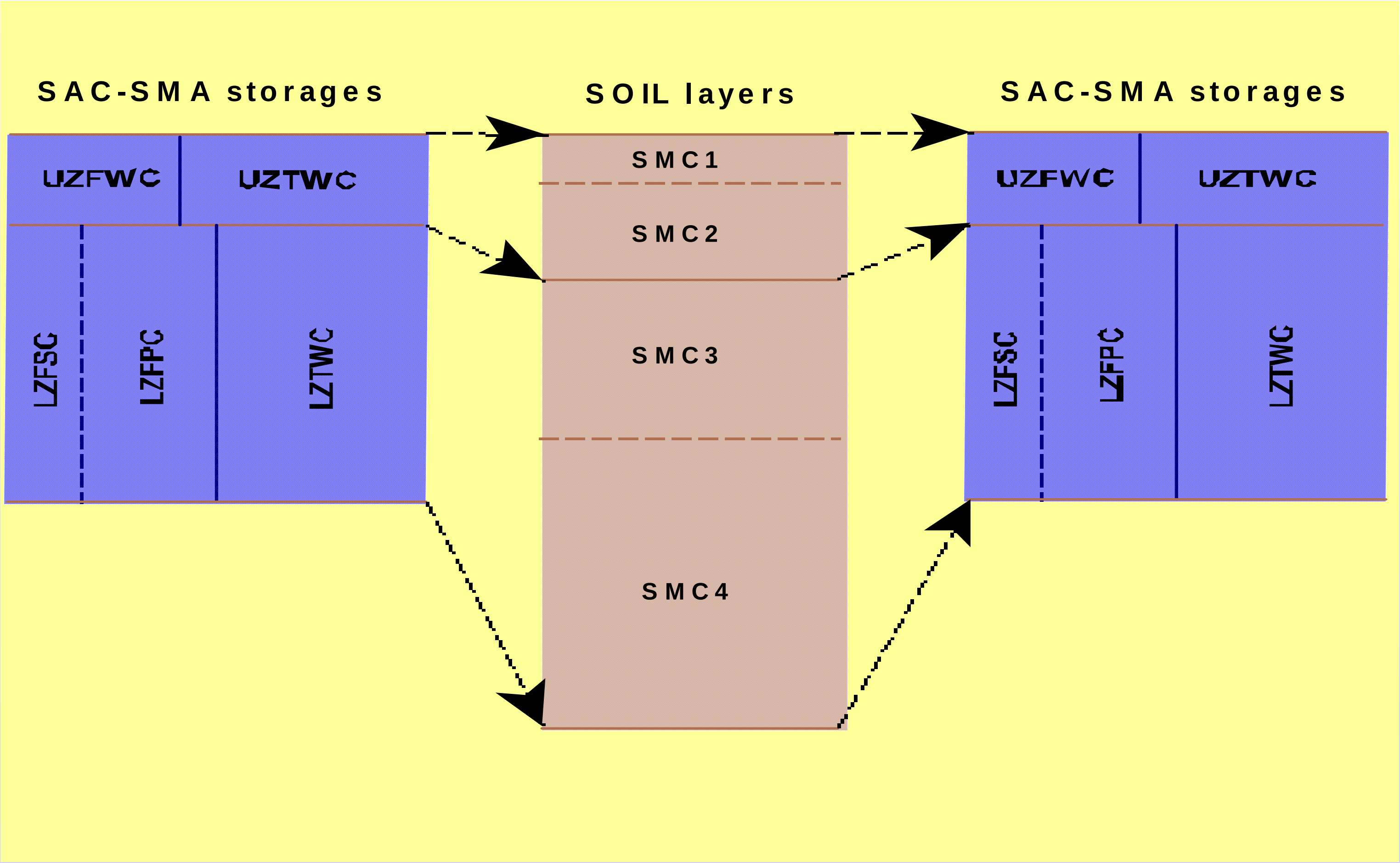
$$c\Delta z_i \frac{\partial T_i}{\partial t} = (K\frac{\partial T}{\partial z})_{z_{i+1}} - (K\frac{\partial T}{\partial t})_{z_i} + \rho L \Delta z_i \frac{\partial(\Theta_i - \Theta_{ice,i})}{\partial t}$$

- Unfrozen soil moisture content is estimated as a function of soil temperature, *T*, and total moisture, Θ, and ice, Θ_{ice}, contents

$$\frac{g\Psi_s}{L_f}(1 + c_k\Theta_{ice})^2(\frac{\Theta - \Theta_{ice}}{\Theta_s})^b - \frac{T}{T + 273.16} = 0$$

Frozen Ground Formulation (cont.)

- **Transformation of storage-type liquid and solid soil moisture states into soil profile states, and vice versa**



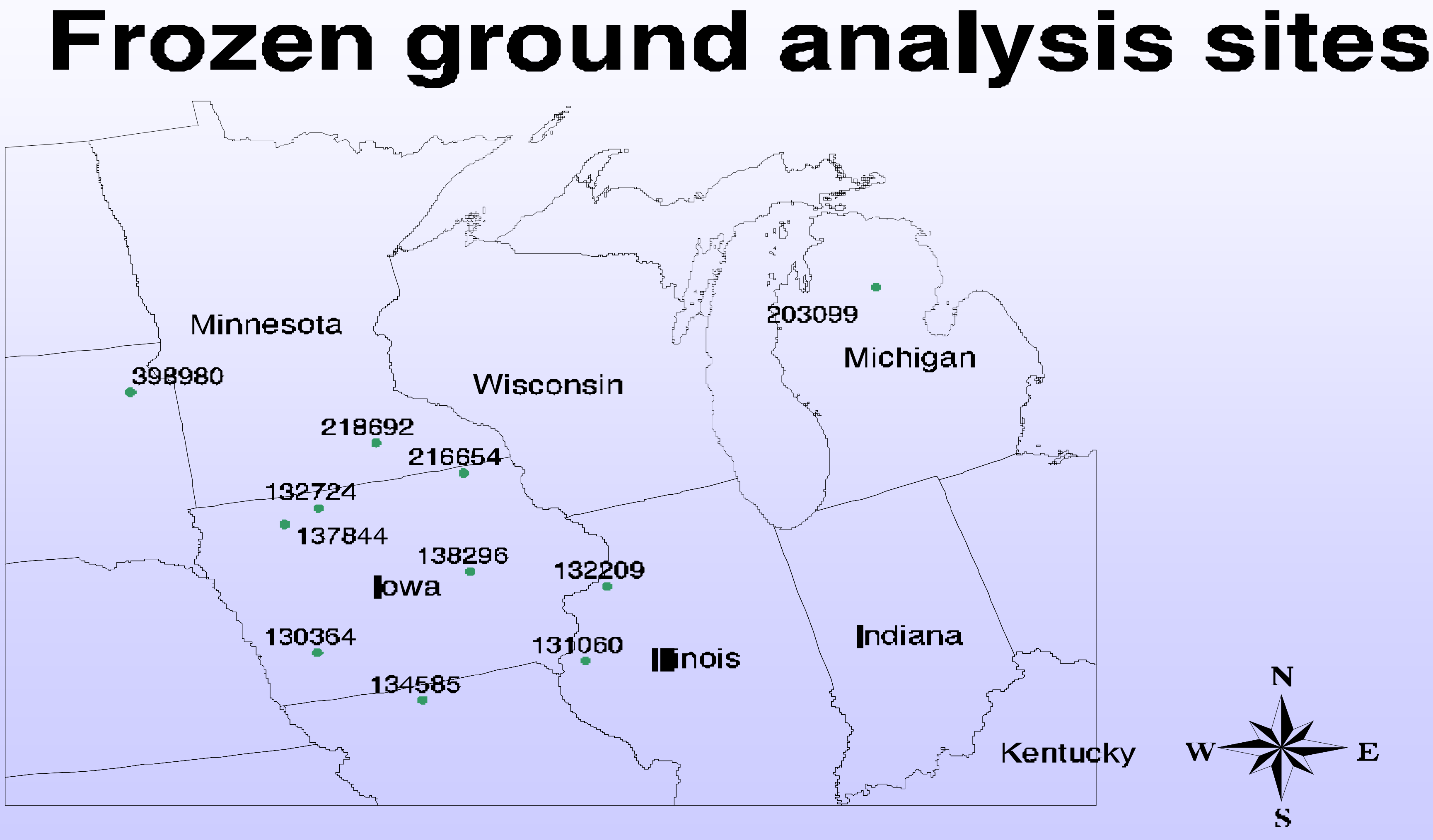
Frozen Ground Formulation (cont.)

- **Modification of hydraulic soil properties due to the ice content (W_{ice})**

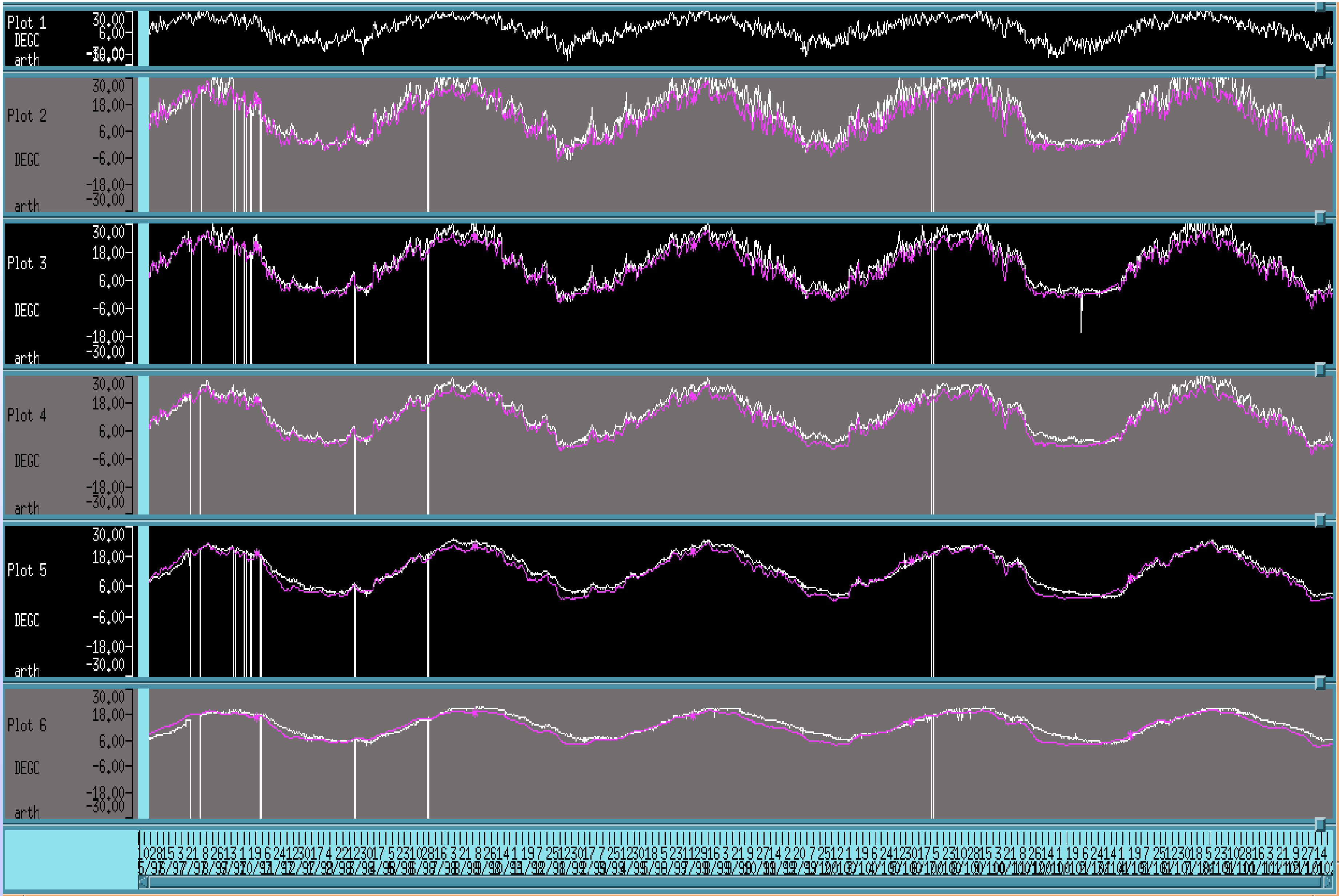
$$K_{ice} = K\,[1 + (a/S_o)]W_{ice}]^{-2} \approx K\,(1 + 8W_{ice})^{-2}$$

- K_{ice} and K are hydraulic conductivities under frozen and non-frozen conditions,
- a/S_o is an increase in the specific surface of solid particles

Soil Temperature Test Results



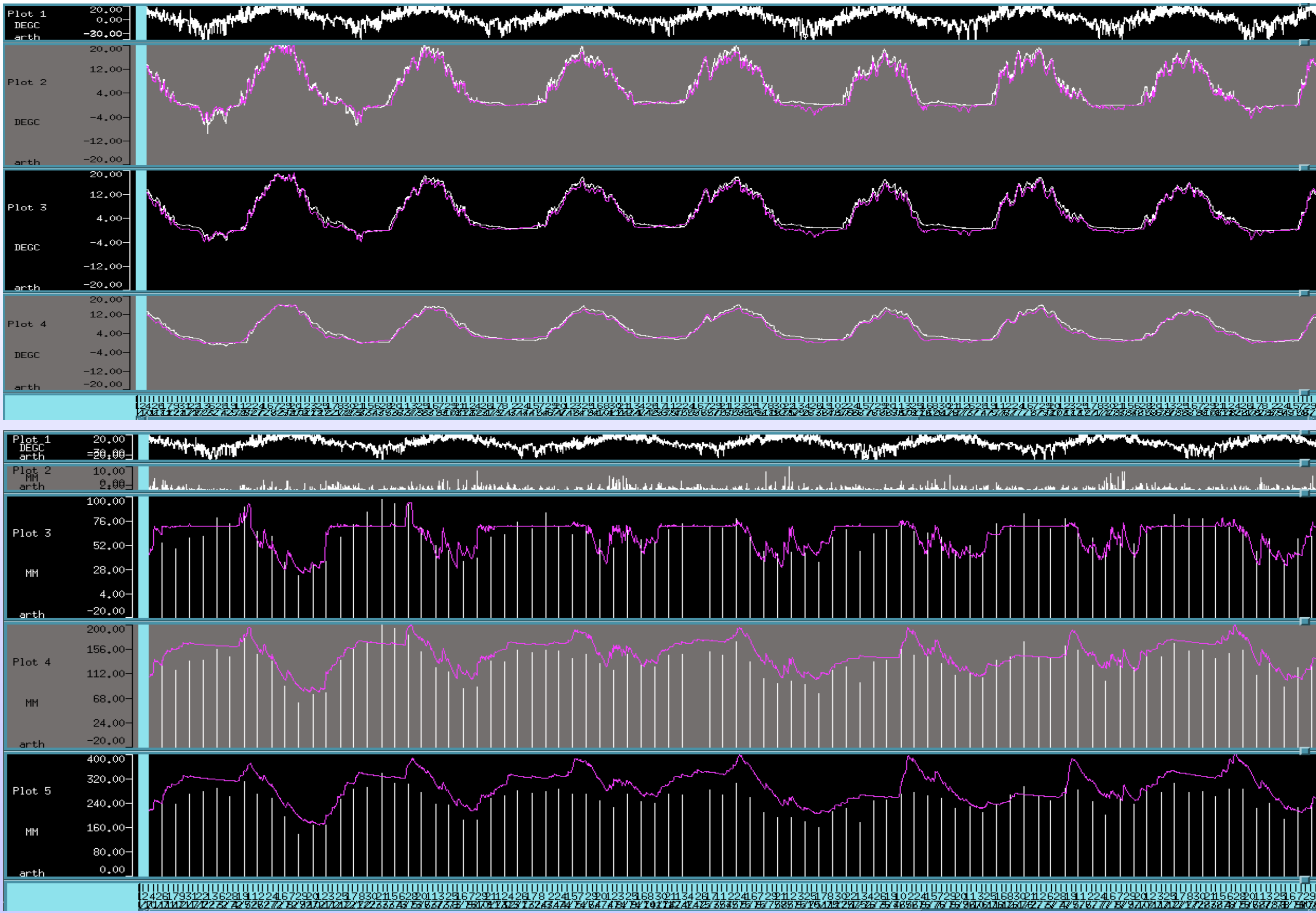
Observed (white) and simulated (red) soil temperature at 5, 10, 20, 50 & 100cm.
Atlantic Site, IA, USA, 1997-2000.



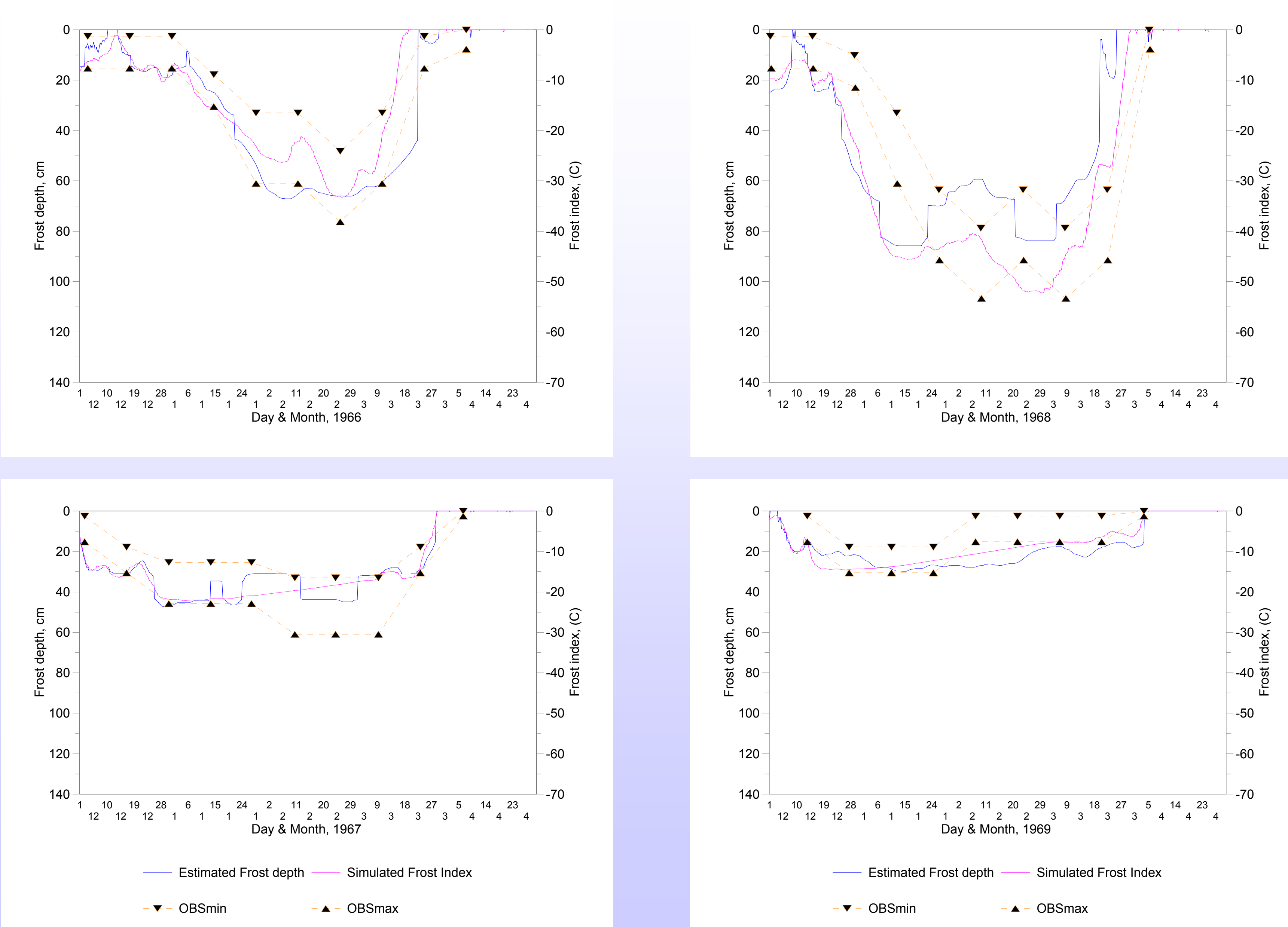
Accuracy statistics for soil temperature simulated over Northern part of the US

Site ID	5 cm layer			20 cm layer			50 cm layer		
	RMS	%RMS	R	RMS	%RMS	R	RMS	%RMS	R
134585	3.0	23.1	0.96	2.9	19.0	0.99	2.9	20.4	0.99
130364	5.0	33.0	0.96	3.3	23.7	0.99	2.9	22.1	0.98
131060	3.3	23.8	0.96	2.5	19.0	0.97	3.0	21.1	0.97
132209	3.7	27.4	0.97	1.9	15.2	0.99	1.6	13.4	0.99
132724	4.5	38.8	0.96	2.0	21.9	0.98	2.6	25.8	0.98
138296	3.2	25.3	0.97	3.2	26.3	0.98	2.3	19.2	0.99
216654	3.9	44.0	0.97	2.4	31.2	0.98	2.4	25.2	0.99
398980	3.3	31.2	0.96	1.5	16.9	0.99	1.3	15.1	0.99
137844	8.1	51.1	0.95	5.1	36.7	0.98	3.6	29.4	0.99
203099				3.1	27.3	0.98	2.8	25.8	0.99
218692							3.3	30.9	0.99
Average	4.2	33.1	0.96	2.8	23.7	0.98	2.6	22.6	0.99

Observed (white) and simulated (red) soil temperature and moisture at 20cm, 40cm, and 80cm depths. Valdai, Russia, 1971-1978.



Observed and simulated frost depth and frost index. Root river basin, MN.



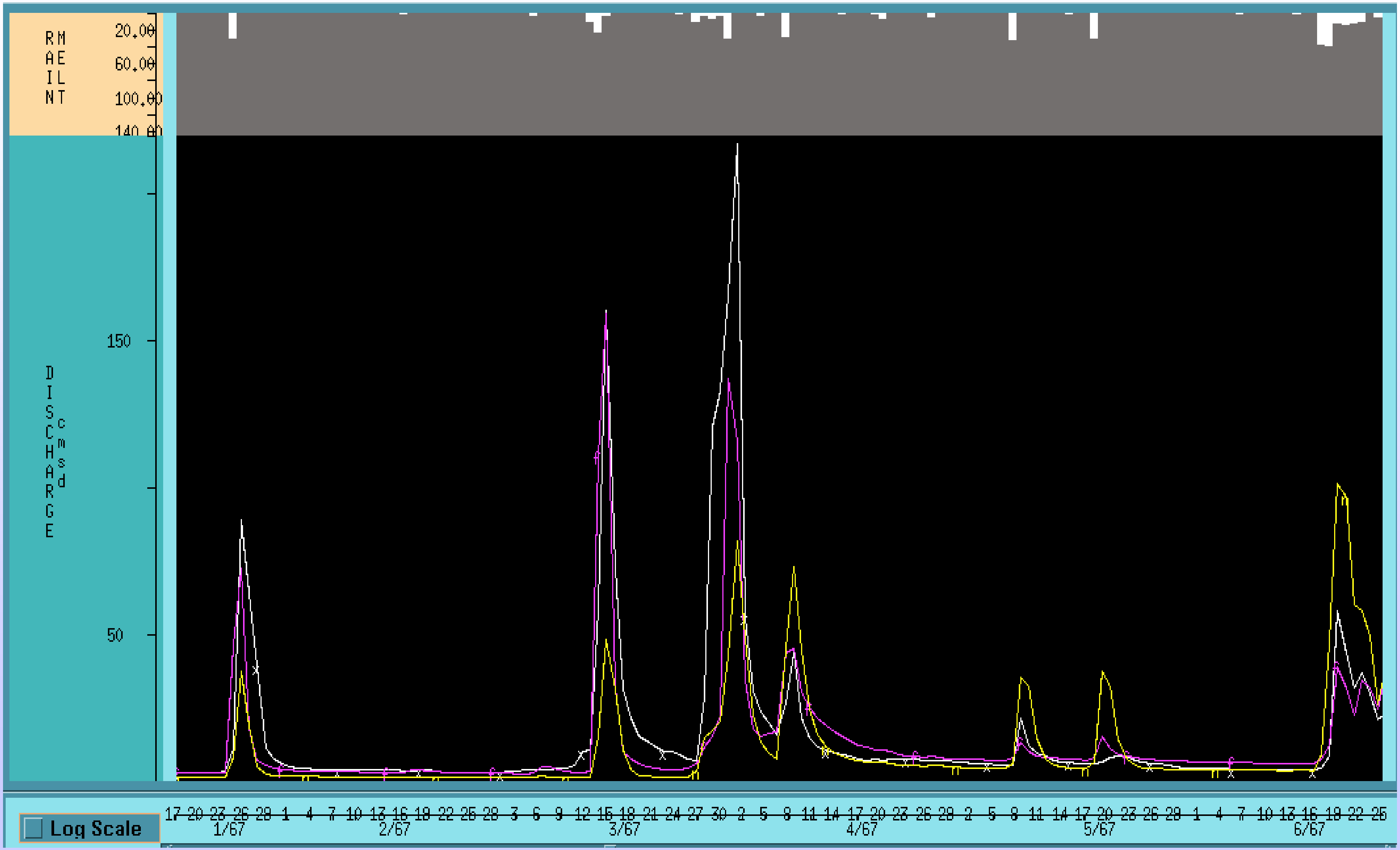
Runoff Simulation Results for Four River Basins

(the Northern US)

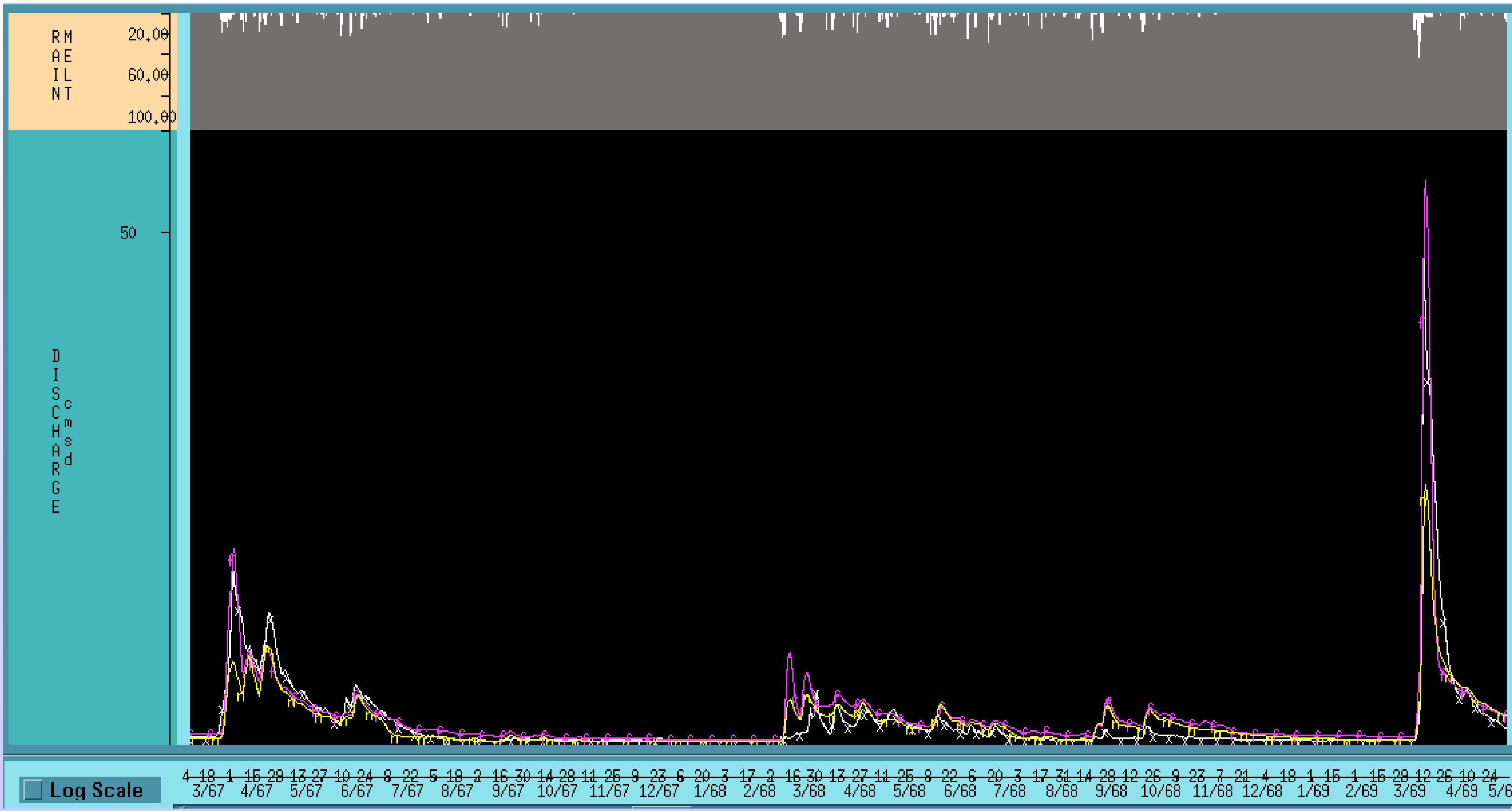
Basin ID	With new frozen ground			w/o frozen ground			With old frozen ground (RFC)		
	MSOF	DRMS	MRMS	MSOF	DRMS	MRMS	MSOF	DRMS	MRMS
LNEM5	**21.86**	**13.91**	**3.85**	28.52	16.14	5.98	24.59	15.55	4.05
GRDM5	**18.28**	**9.95**	**5.48**	20.76	11.20	6.36	21.12	11.46	6.24
MMLM5	**5.98**	**3.40**	1.59	7.02	3.90	1.98	6.03	3.46	**1.58**
HWYM5	5.24	2.67	1.66	5.62	2.92	1.68	**5.00**	**2.65**	**1.42**

Note: MSOF is a multi-scale objective function applied to observed and simulated hydrographs, in cms;
DRMS is the daily discharge root mean square error, in cms;
MRMS is the monthly discharge root mean square error, in cms;
BIAS is the overall runoff bias, in cms.

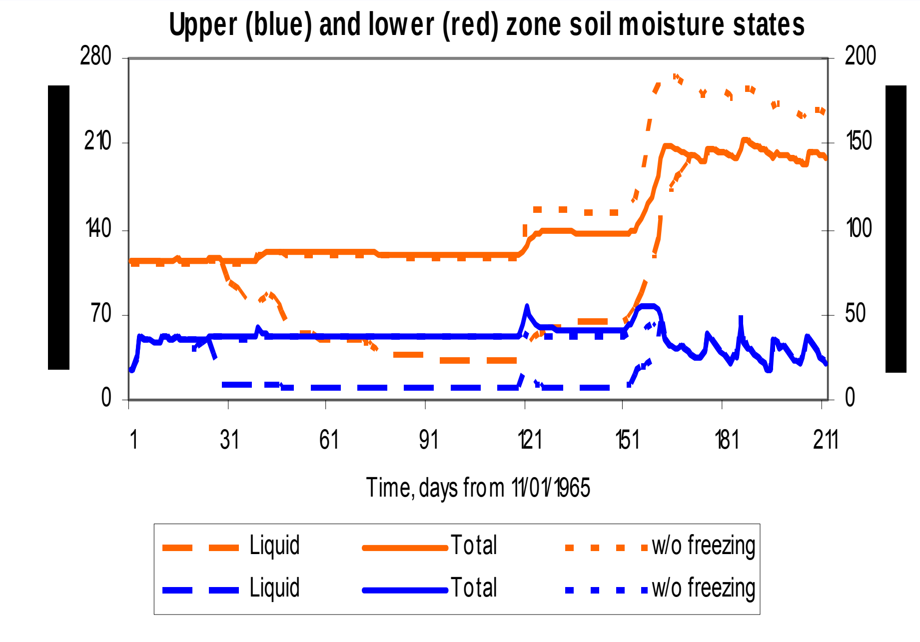
Observed (white) and Simulated Hydrographs, Root River nr Lanesboro, MN: with frozen ground (purple), w/o frozen ground (yellow)

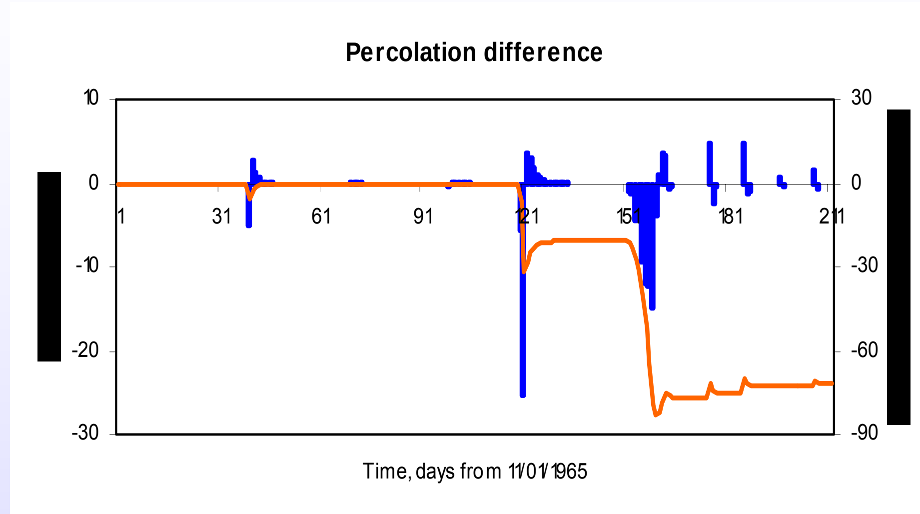


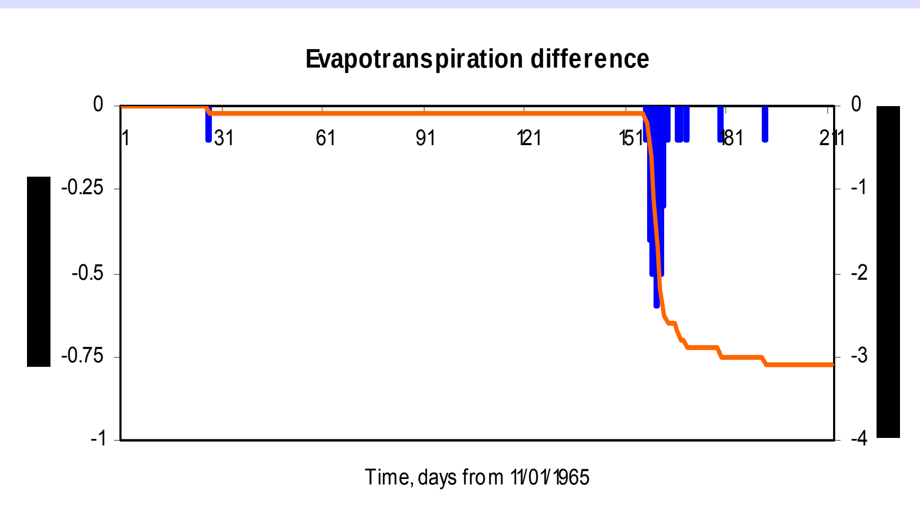
Observed (white) and Simulated Hydrographs, Buffalo River at Hawley, MN: with frozen ground (purple), w/o frozen ground (yellow)

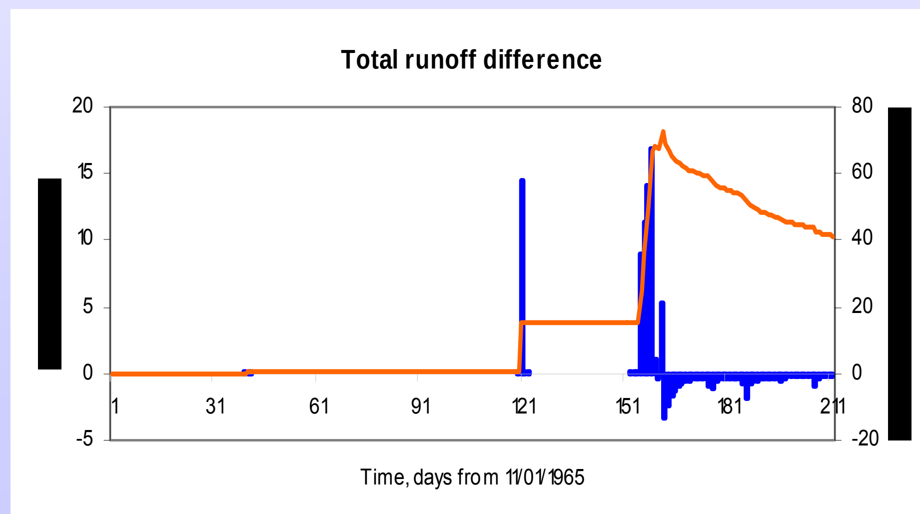


Frozen Ground Effect on Water Balance Components









SUMMARY

- **Conceptual representation of soil moisture fluxes combined with a physically-based heat transfer model provides reasonable simulations of water and heat exchanges over a soil profile.**
- **Ignoring soil moisture phase transitions can lead to significant biases of seasonal soil temperature.**
- **Physically-based modification of the hydraulic soil properties due to the ice content leads to runoff simulation improvements for both snowmelt- and rainfall-induced floods.**
- **No additional parameters were introduced to account for frozen ground effects.**
- **Spring-Summer flood analysis suggests that it is impossible to remove runoff biases consistently by parameter adjustments without introducing frozen ground physics.**

FUTURE WORK

- **Finish tests (more performance analysis and sensitivity to physical constant changes)**
- **Finalize MCP3 source code (need the HSEB help)**
- **Tests by NCRFC (and possibly OHRFC)**
- **Incorporate the combined storage-layer water-heat transfer parameterization into HL-RMS**
- **Test HL-RMS version over a large area using available soil moisture/temperature data in addition to measured runoff**