

АНАЛИЗ ЛЕДОВОЙ ОБСТАНОВКИ КРУПНЫХ ПРЕСНОВОДНЫХ ОЗЕР ПО ДАННЫМ SMOS

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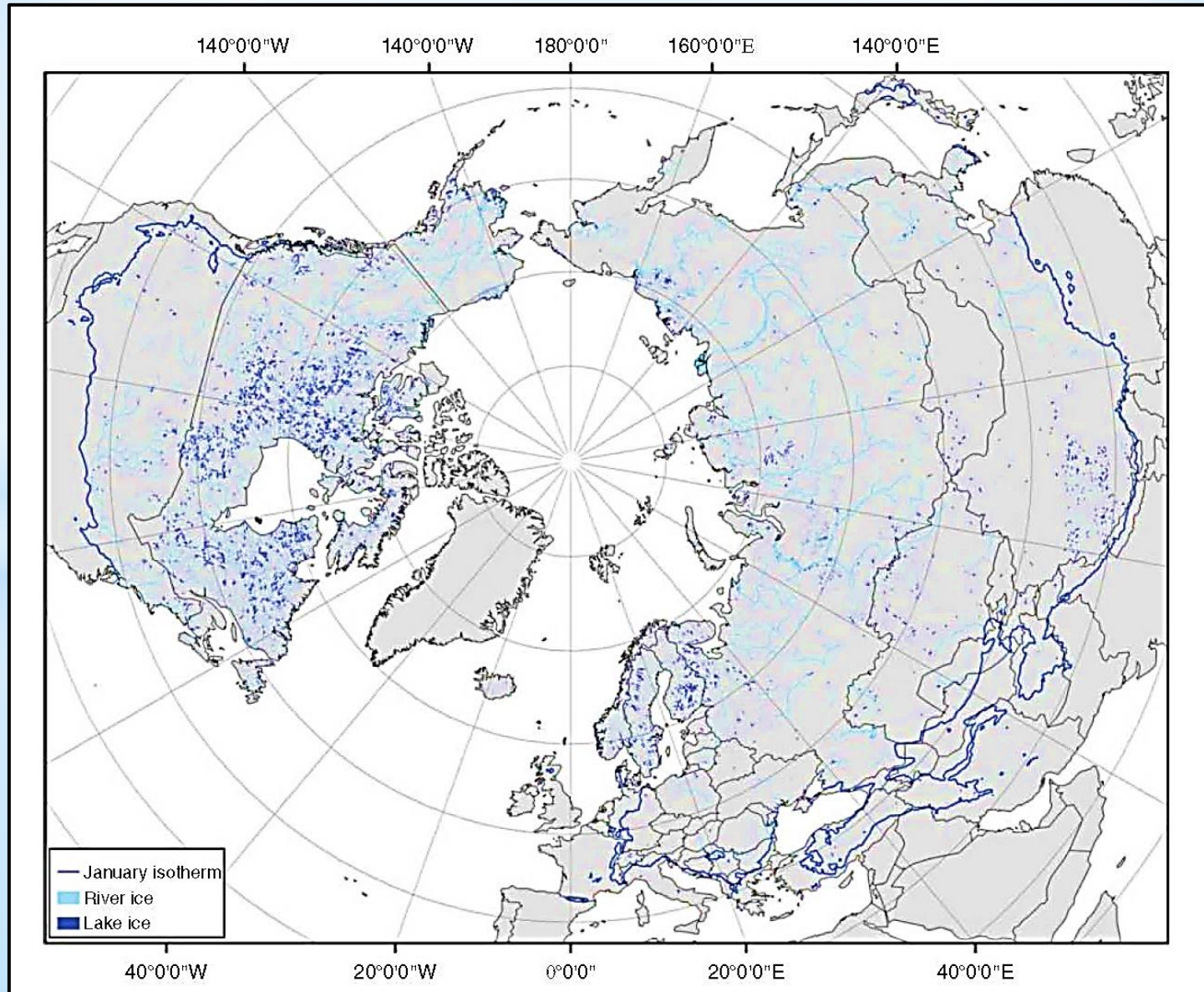
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ПРЕСНОВОДНЫЙ ЛЕД

$$S = 1.7 \times 10^6 \text{ км}^2 \approx S_{\text{Гренландии}}$$

$$V = 1.6 \times 10^3 \text{ км}^3$$

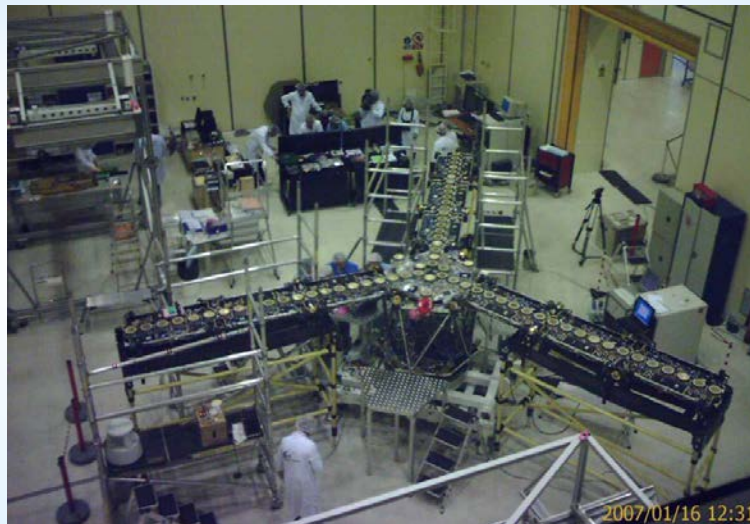


SMOS (Soil Moisture and Ocean Salinity)



MIRAS (Microwave Imaging Radiometer using Aperture Synthesis)

$$f = 1.4 \text{ ГГц}$$
$$\theta = 10^\circ \div 65^\circ$$



Продукт

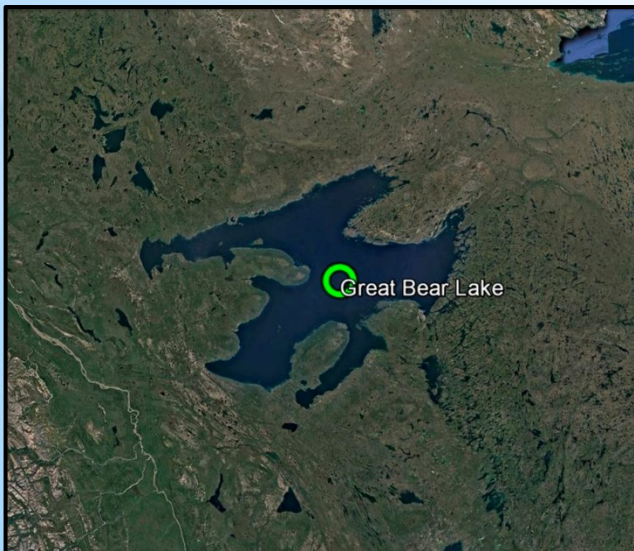
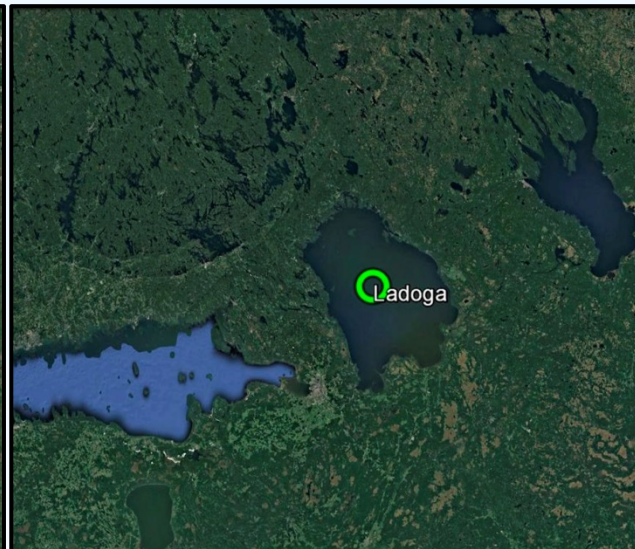
L1C SMOS v.620

$T_B^h, T_B^v, \Delta T = 5 \text{ К}$

$l = 15 \text{ км}$

$\theta = 42.5^\circ$

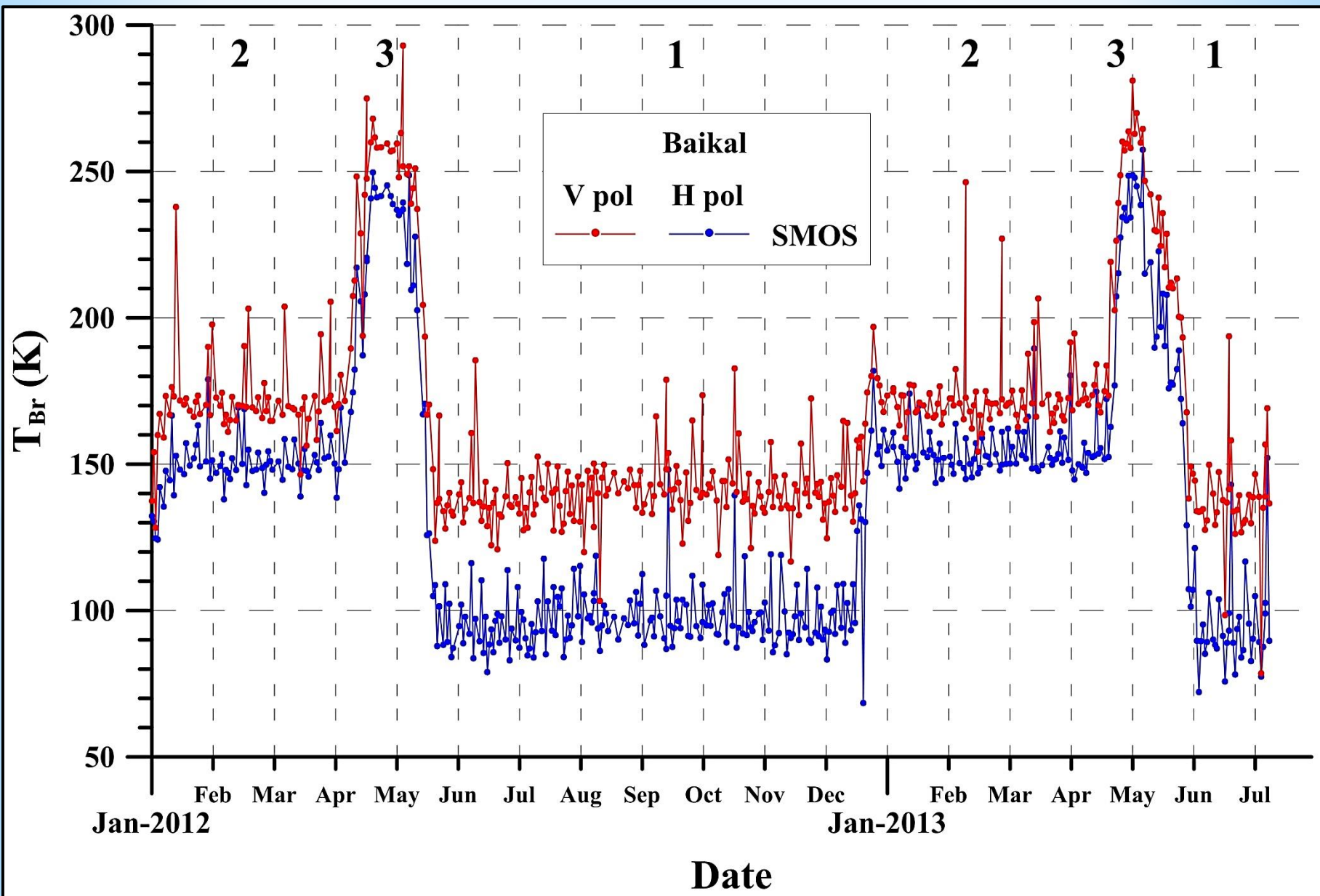
ИССЛЕДУЕМЫЕ ОЗЕРА



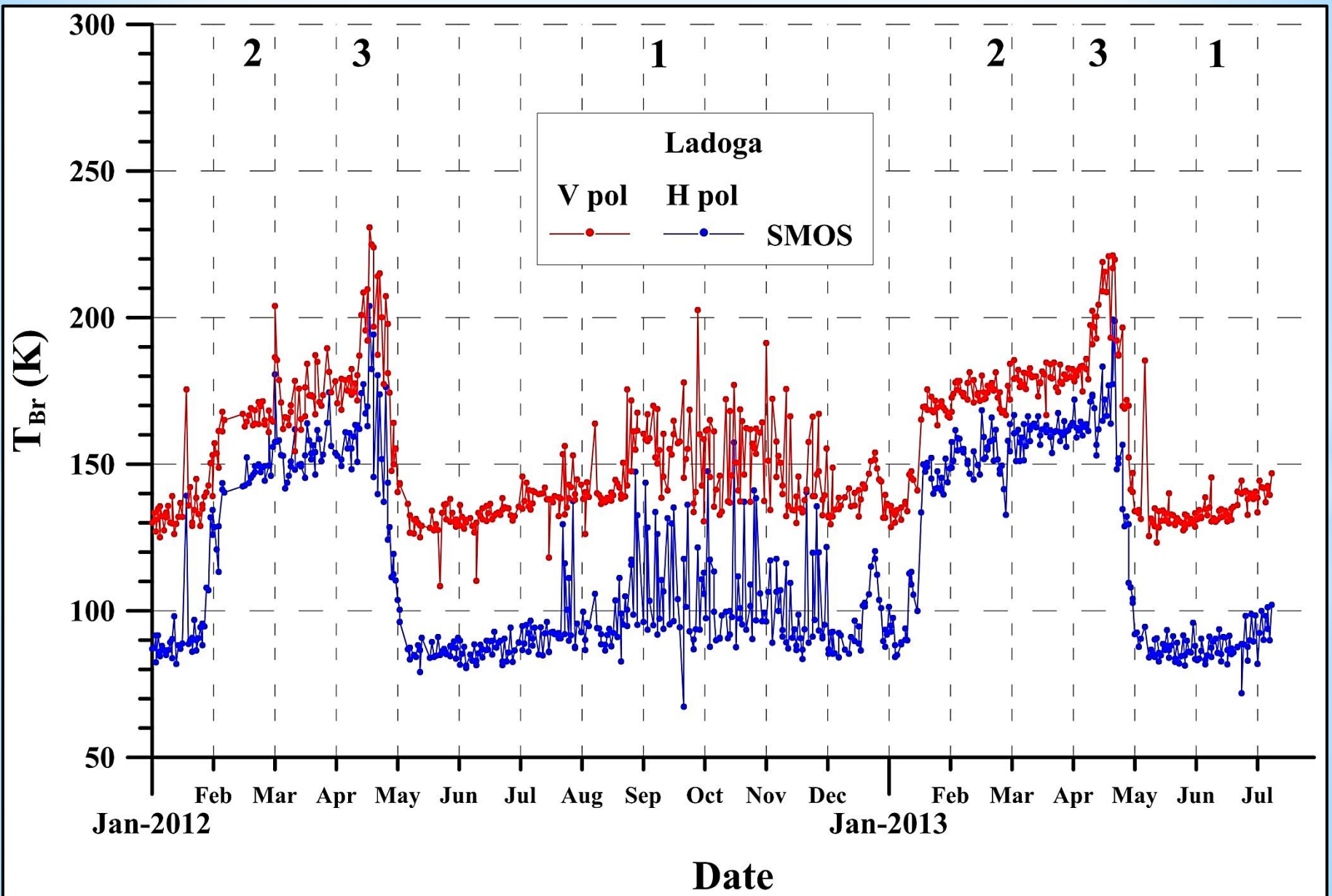
Lake Name	Region	Latitude	Longitude
Baikal	Southern Siberia, Russia	54.17° N	108.91° E
Ladoga	Northwestern Russia	60.88° N	31.37° E
Huron	Great Lakes of North America	44.56° N	82.41° W
Great Slave	Northwest Territories of Canada	61.28° N	114.80° W
Great Bear	Northwest Territories of Canada	65.97° N	120.57° W



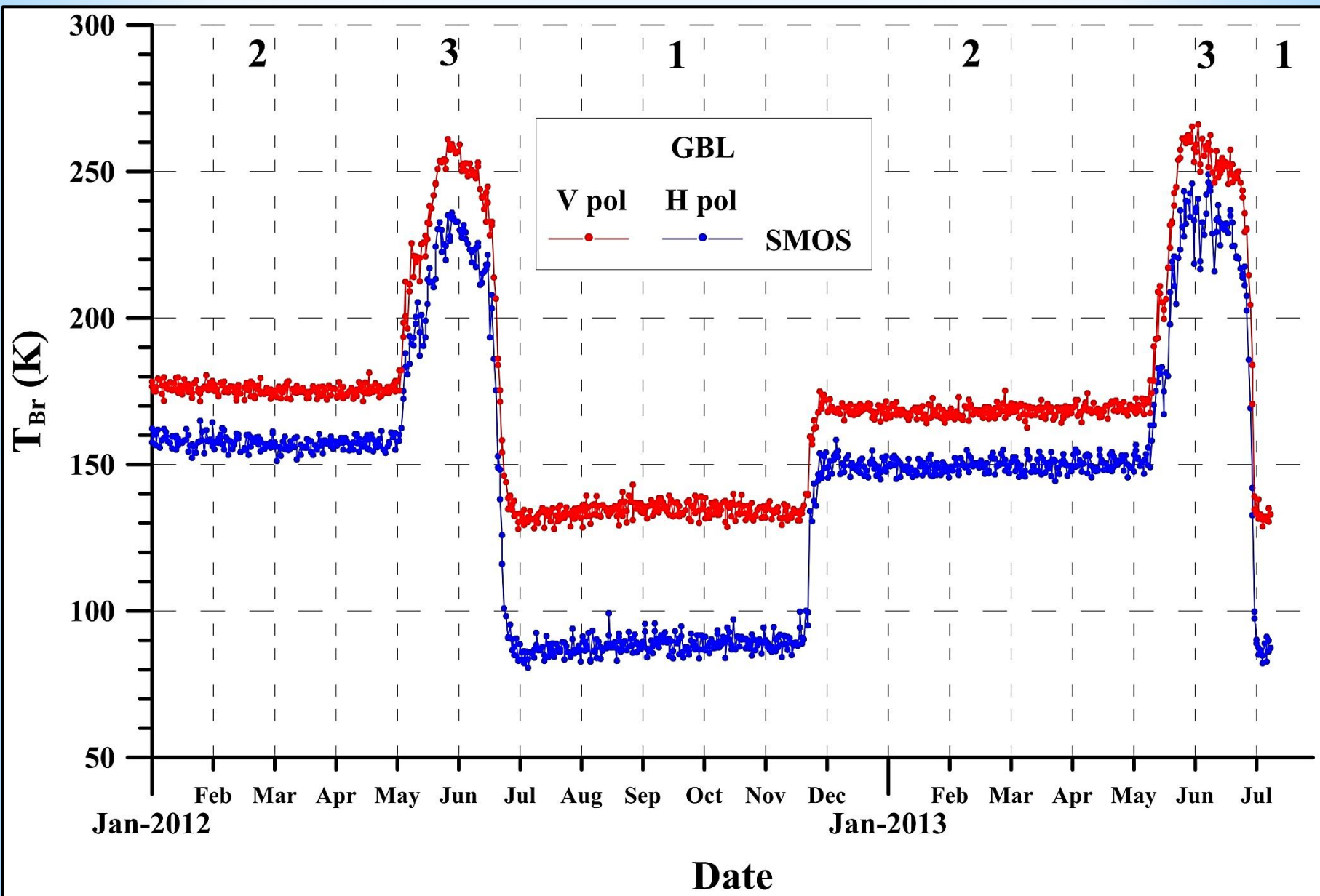
Байкал



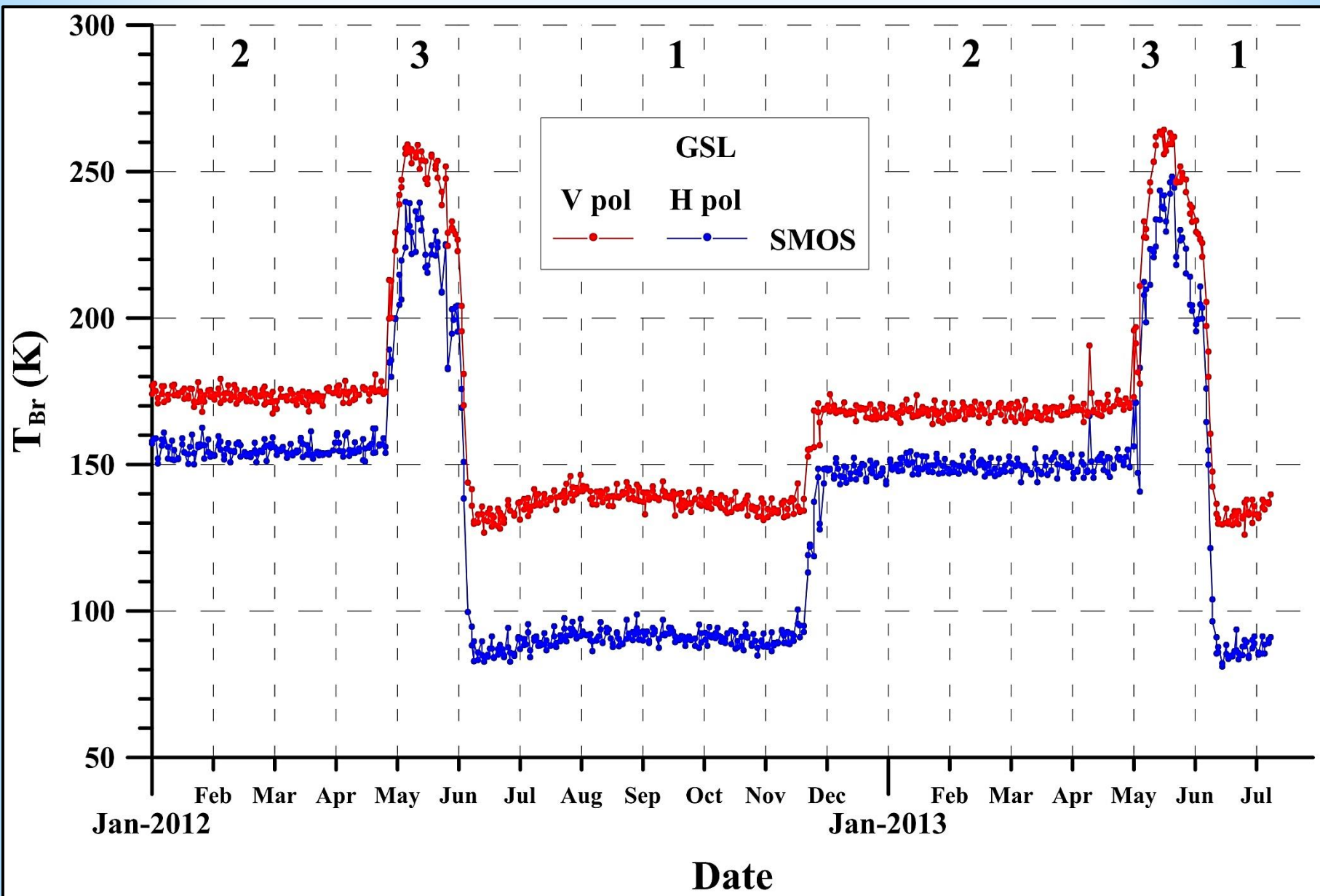
Ладожское озеро



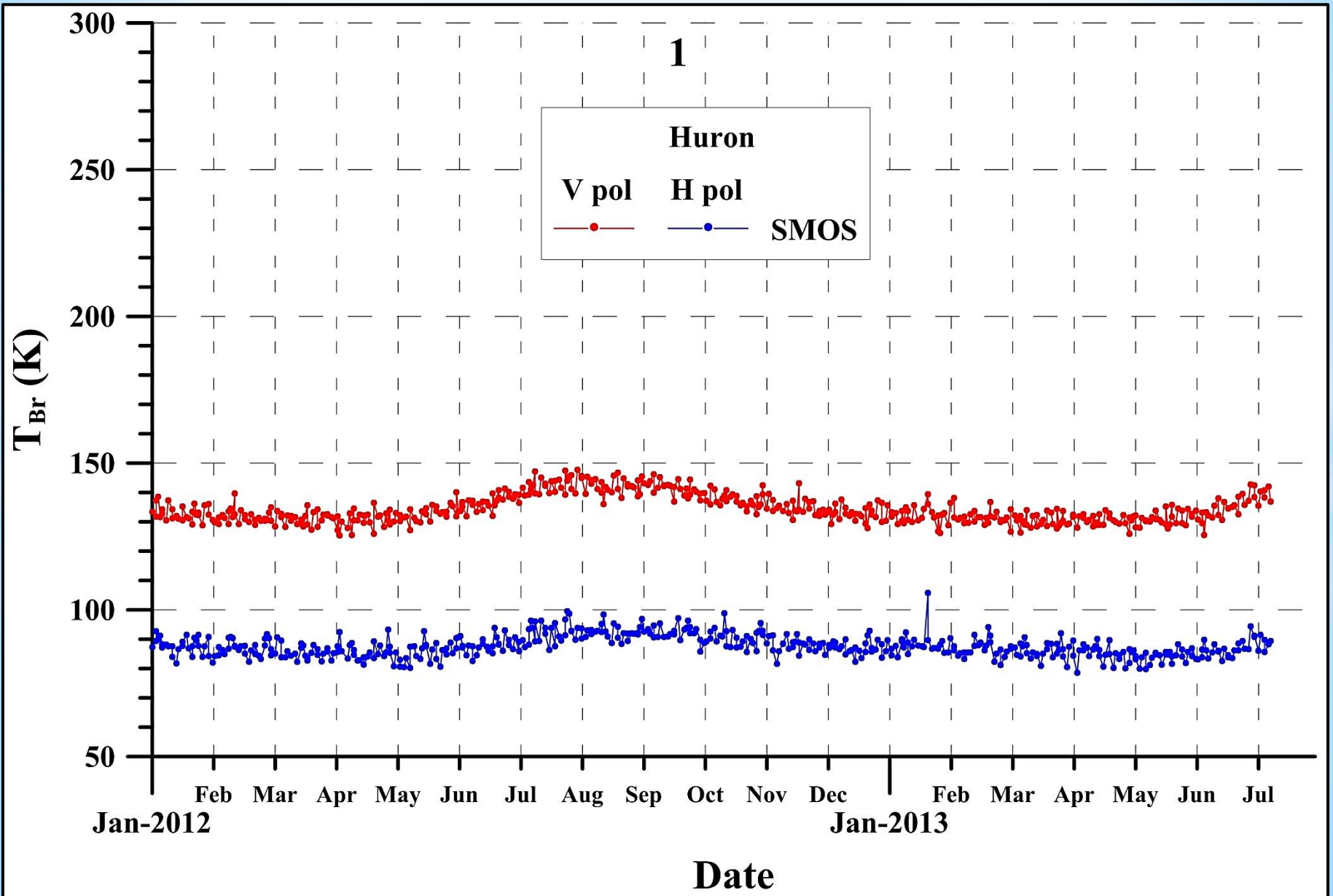
Большое Медвежье озеро



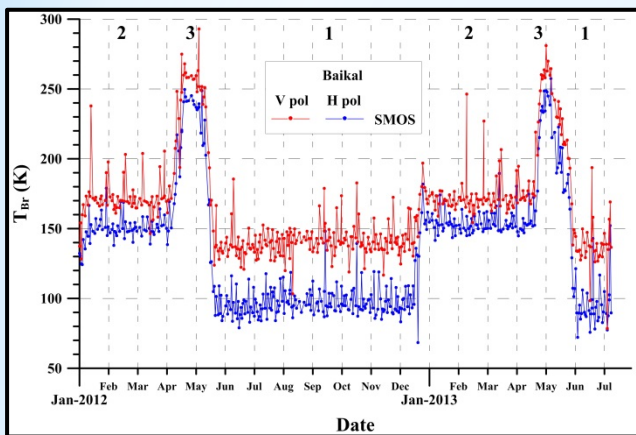
Большое Невольничье озеро



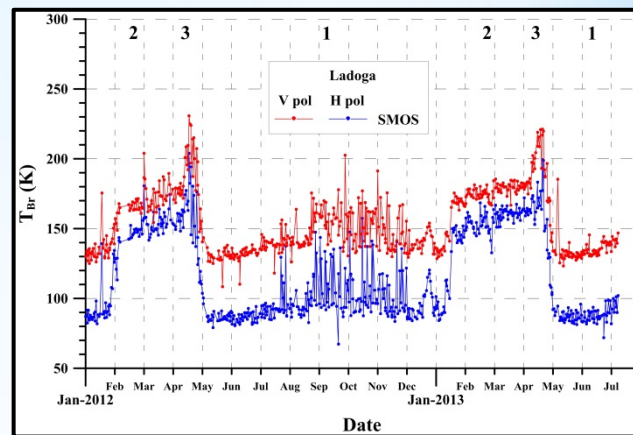
Озеро Гурон



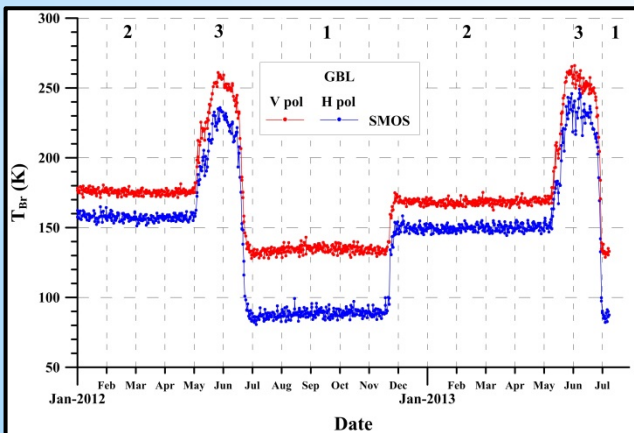
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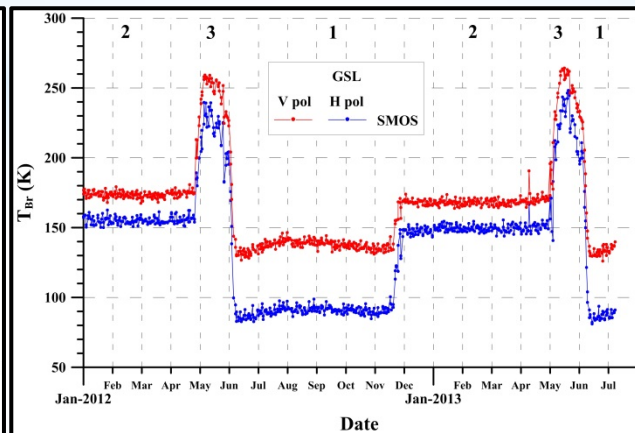
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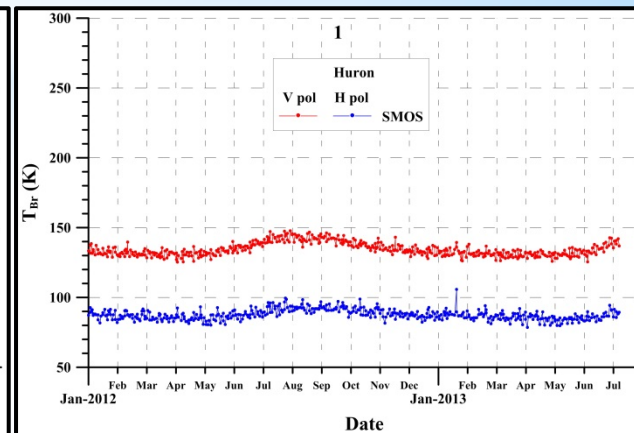
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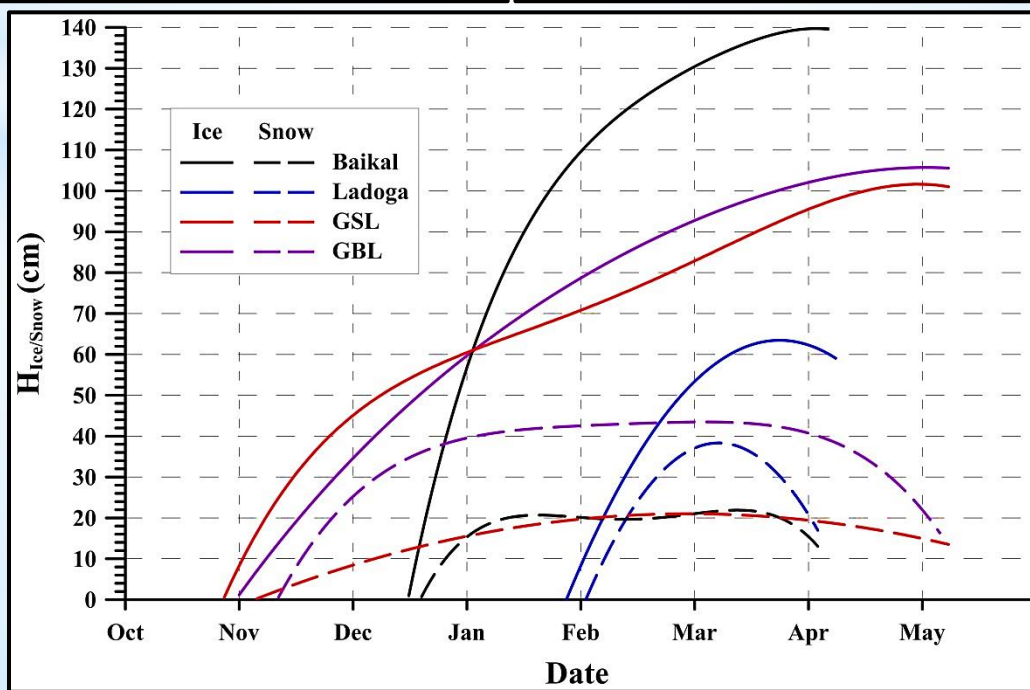
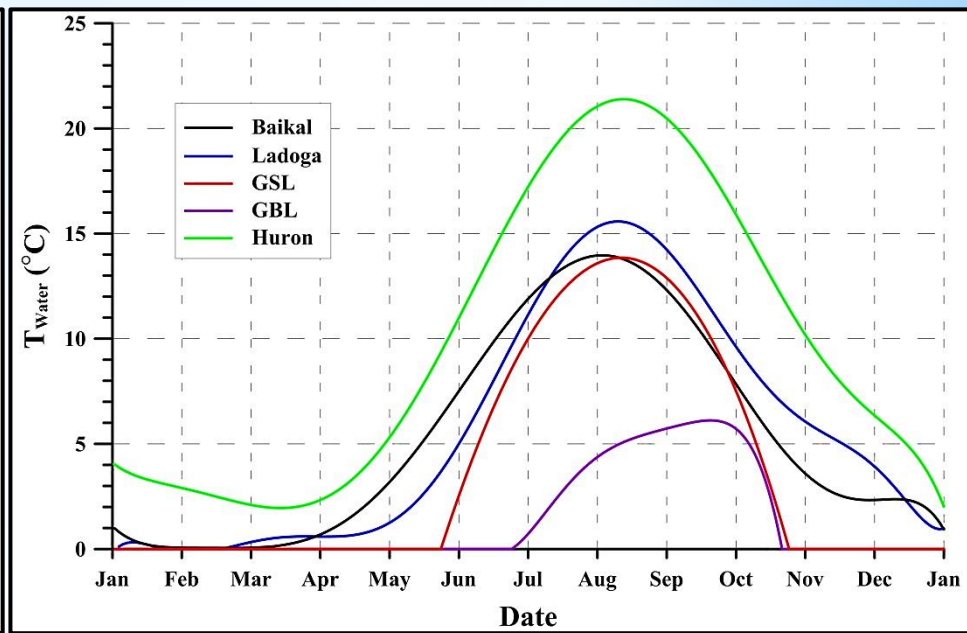
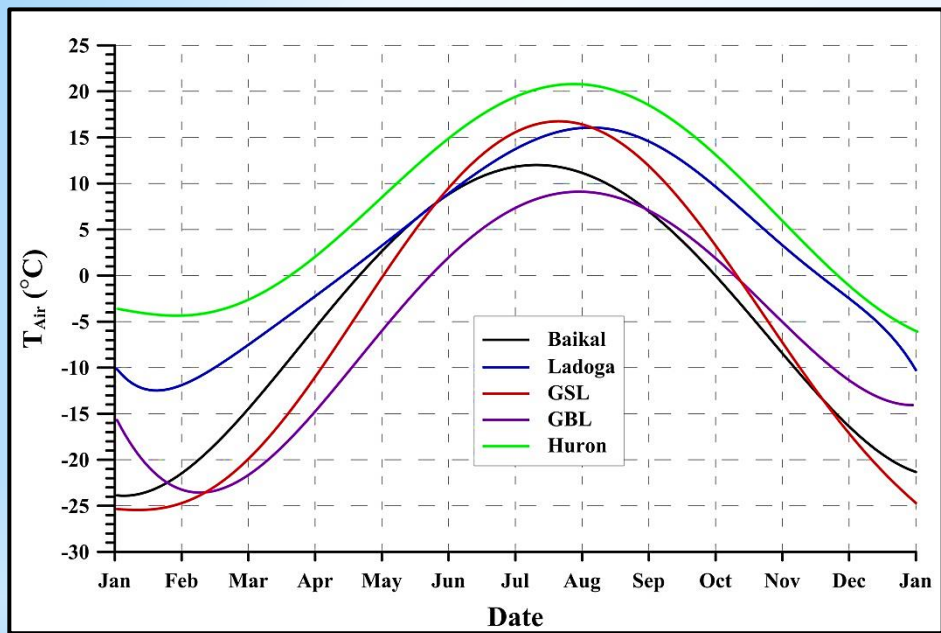
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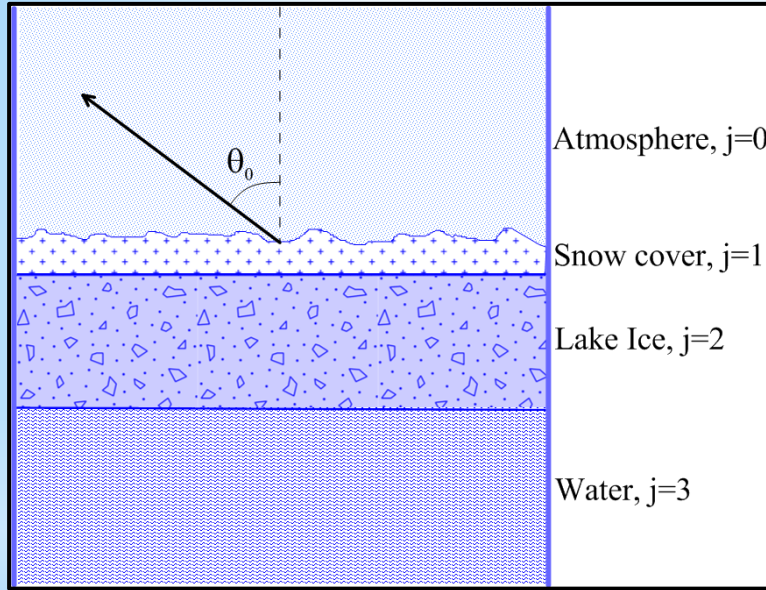
Озеро Гурон



Климатические и гляциологические данные



Модель микроволнового излучения пресноводного озера



$$T_{Br}^v = \sum_{j=1}^2 \frac{T_j |W_j|^2}{|1 - r_j^- r_j^+ \exp(2i\psi_j)|^2} \times [(1 - \exp(-2 \operatorname{Im} \psi_j)) (1 + |r_j^- \exp(i\psi_j)|^2)] +$$

$$+ 4 \frac{\operatorname{Im} \psi_j}{\operatorname{Re} \psi_j} \operatorname{Re}(r_j^- \exp(i\psi_j)) \operatorname{Im}(\exp(i\psi_j)) \times \left[\frac{|k_{z_j}|^2 - k_x^2}{|k_j|^2} \right] \frac{\operatorname{Re} Z_j}{\operatorname{Re} Z_0} + T_3 |W_3|^2 \frac{\operatorname{Re} Z_3}{\operatorname{Re} Z_0}$$

$$T_{Br}^h = \sum_{j=1}^2 \frac{T_j |W_j|^2}{|1 - r_j^- r_j^+ \exp(2i\psi_j)|^2} \times [(1 - \exp(-2 \operatorname{Im} \psi_j)) (1 + |r_j^- \exp(i\psi_j)|^2)] +$$

$$+ 4 \frac{\operatorname{Im} \psi_j}{\operatorname{Re} \psi_j} \operatorname{Re}(r_j^- \exp(i\psi_j)) \operatorname{Im}(\exp(i\psi_j)) \left[\frac{\operatorname{Re} Z_j}{\operatorname{Re} Z_0} + T_3 |W_3|^2 \frac{\operatorname{Re} Z_3}{\operatorname{Re} Z_0} \right]$$

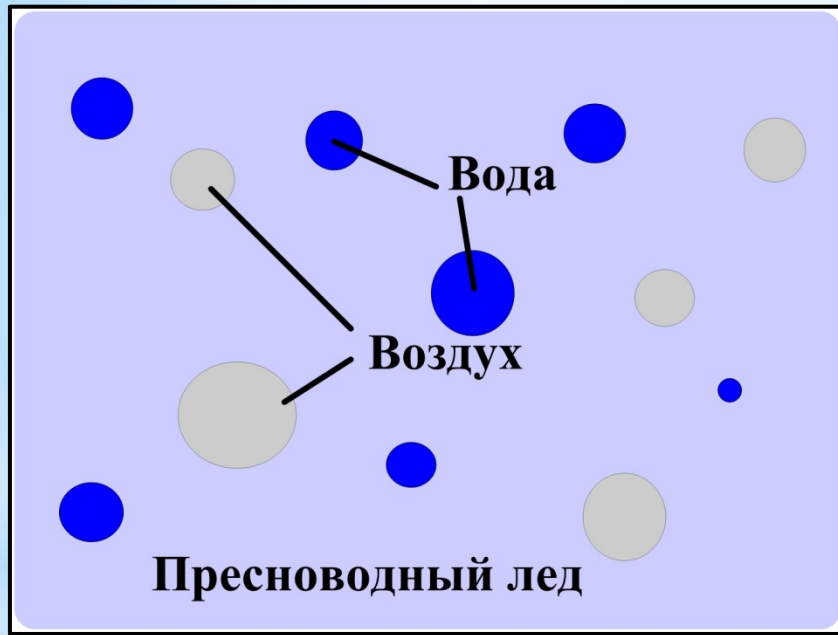
$$W_j = \prod_{m=1}^j \frac{Z_{m-1}^{in+} + Z_{m-1}}{Z_{m-1}^{in+} + Z_m} \exp(i\psi_{m-1}), \quad Z_j^{in+} = Z_j \frac{Z_{j-1}^{in+} - iZ_j \operatorname{tg} \psi_j}{Z_j - iZ_{j-1}^{in+} \operatorname{tg} \psi_j}, \quad Z_j^{in-} = Z_j \frac{Z_{j+1}^{in-} - iZ_j \operatorname{tg} \psi_j}{Z_j - iZ_{j+1}^{in-} \operatorname{tg} \psi_j}$$

$$\psi_j = k_{z_j} h_j, \quad k_{z_j} = k_j \cos \theta_j, \quad k_x = k_0 \sin \theta_0, \quad k_j = \frac{2\pi \sqrt{\varepsilon_j}}{\lambda}, \quad \cos \theta_j = \sqrt{\frac{\varepsilon_j - \varepsilon_0 \sin^2 \theta_0}{\varepsilon_j}}$$

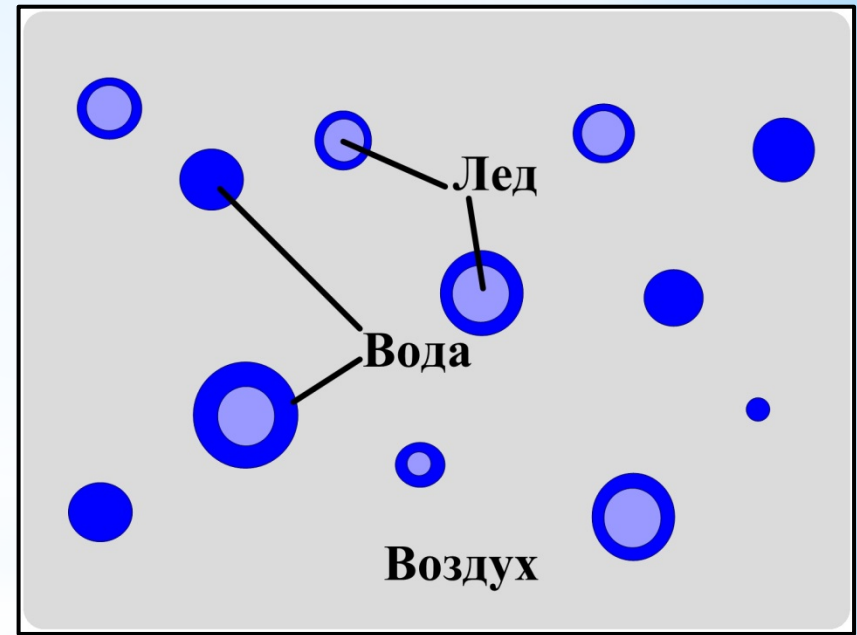
$$r_j^+ = \frac{Z_{j-1}^{in+} - Z_j}{Z_{j-1}^{in+} + Z_j}, \quad r_j^- = \frac{Z_{j+1}^{in-} - Z_j}{Z_{j+1}^{in-} + Z_j}, \quad Z_j = \begin{cases} 1 & \text{— горизонтальная поляризация} \\ \sqrt{\varepsilon_j} \cos \theta_j & \\ \cos \theta_j & \text{— вертикальная поляризация} \\ \sqrt{\varepsilon_j} & \end{cases}$$

Квазиволновая модель эффективной диэлектрической проницаемости (Quasi-wave model - QWM)

Озерный лед



Снежный покров



$$\epsilon_{eff}^{lake\ ice} = \epsilon_i \left[1 - \frac{4\pi n_a (\epsilon_a + 2\epsilon_i) \frac{\langle f_\omega \rangle_a}{k^2}}{2\epsilon_{eff} + \epsilon_a} - \frac{4\pi n_w (\epsilon_w + 2\epsilon_i) \frac{\langle f_\omega \rangle_w}{k^2}}{2\epsilon_{eff} + \epsilon_w} \right]^{-1}$$

$$\epsilon_{eff}^{snow} = \epsilon_a \left[1 - \frac{4\pi n_i (\epsilon_i^w + 2\epsilon_a) \frac{\langle f_\omega \rangle_i}{k^2}}{2\epsilon_{eff} + \epsilon_i^w} - \frac{4\pi n_w (\epsilon_w + 2\epsilon_a) \frac{\langle f_\omega \rangle_w}{k^2}}{2\epsilon_{eff} + \epsilon_w} \right]^{-1}$$

$\lambda \gg r$

модель Polder-van Santen (PVSM)

$$\epsilon_{eff}^{lake\ ice} = \epsilon_i \left[1 - \frac{3V_a (\epsilon_a - \epsilon_i)}{2\epsilon_{eff} + \epsilon_a} - \frac{3V_w (\epsilon_w - \epsilon_i)}{2\epsilon_{eff} + \epsilon_w} \right]^{-1}$$

$$\epsilon_{eff}^{snow} = \epsilon_a \left[1 - \frac{3V_i (\epsilon_i - \epsilon_a)}{2\epsilon_{eff} + \epsilon_i} - \frac{3V_w (\epsilon_w - \epsilon_a)}{2\epsilon_{eff} + \epsilon_w} \right]^{-1}$$

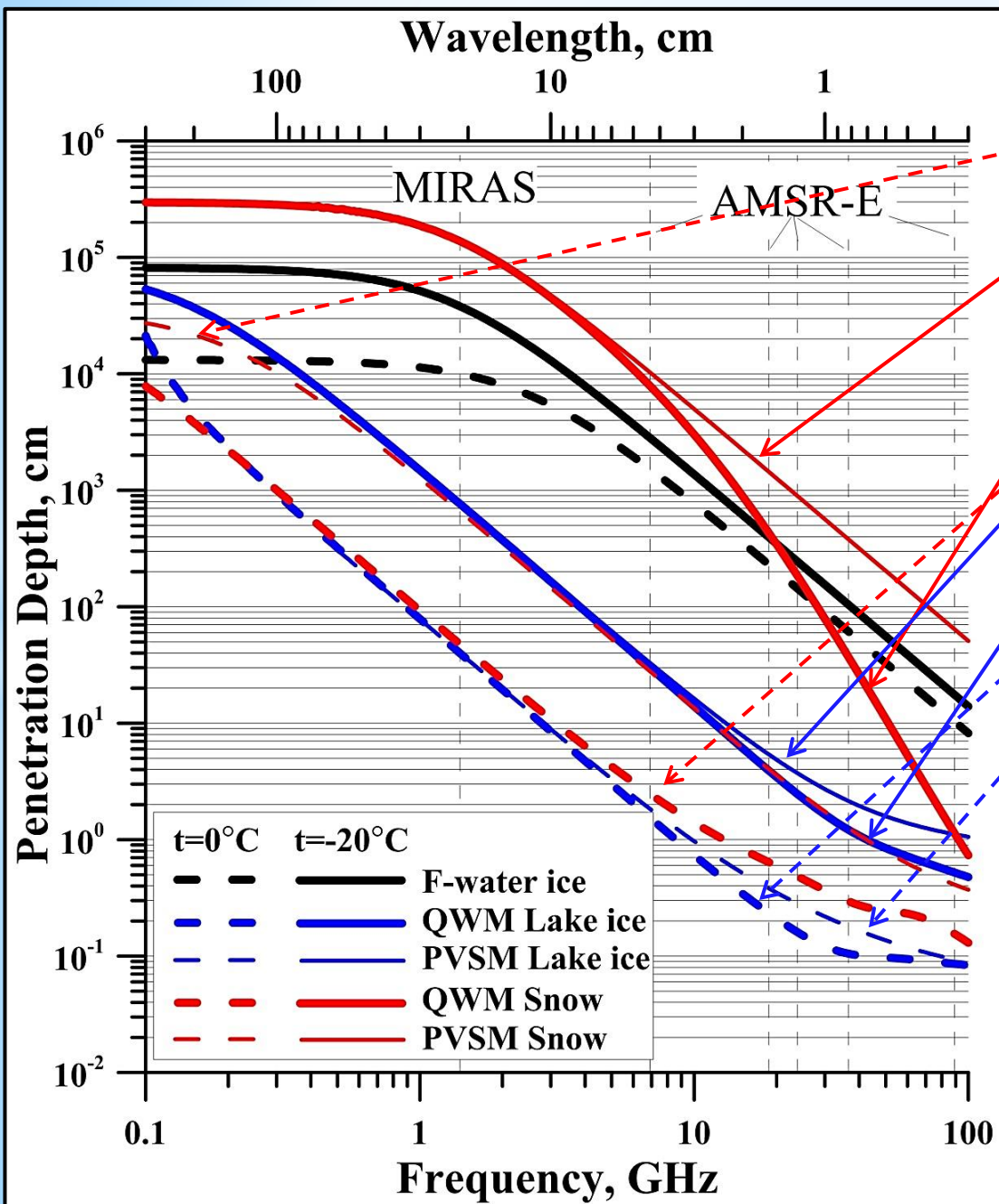
Глубина формирования излучения

Влажный снег

Сухой снег

Сухой озерный лед

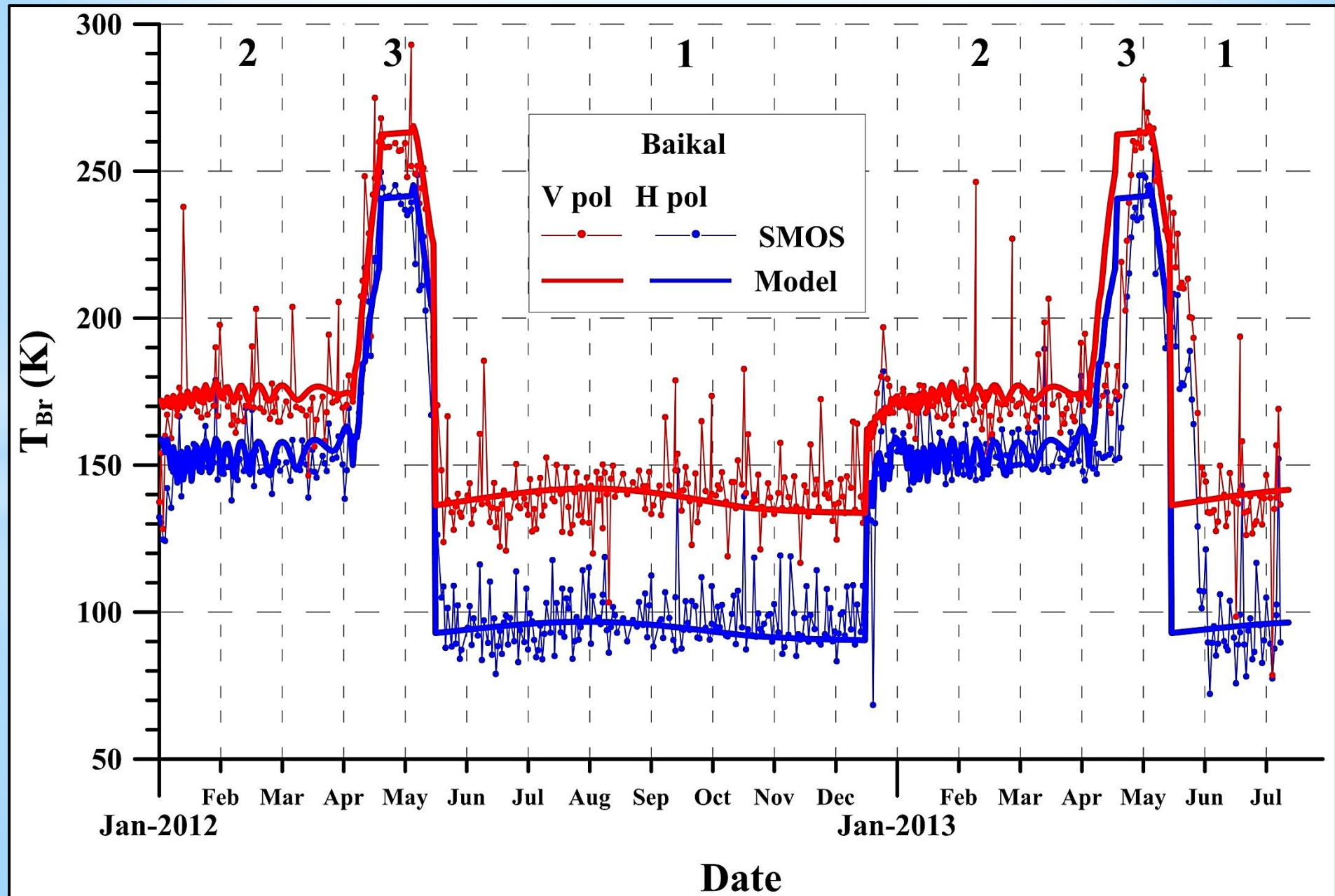
Влажный озерный лед



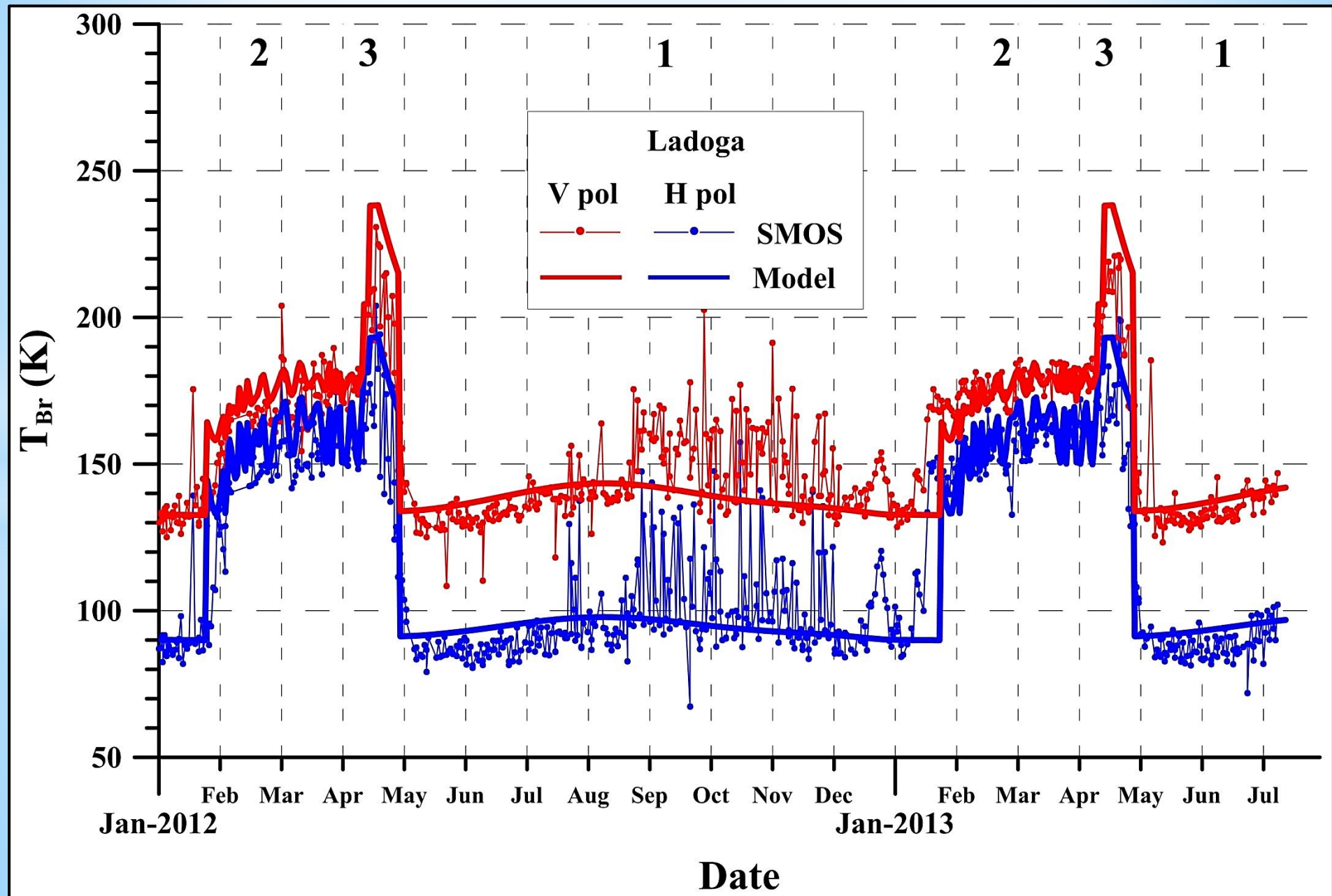
$$h_{PD} = \frac{\lambda}{4\pi \operatorname{Im}(\sqrt{\epsilon_{eff}})}$$

	t=-20° C	t=0° C
Snow cover		
dry density	0.3 g/cm ³	0.3 g/cm ³
diameter ice particle	0.04 cm	0.06 cm
volumetric wetness	0 %	9 %
Lake ice		
porosity	12 %	50 %
diameter air particle	0.1 cm	0.1 cm
volumetric wetness	3 %	25 %

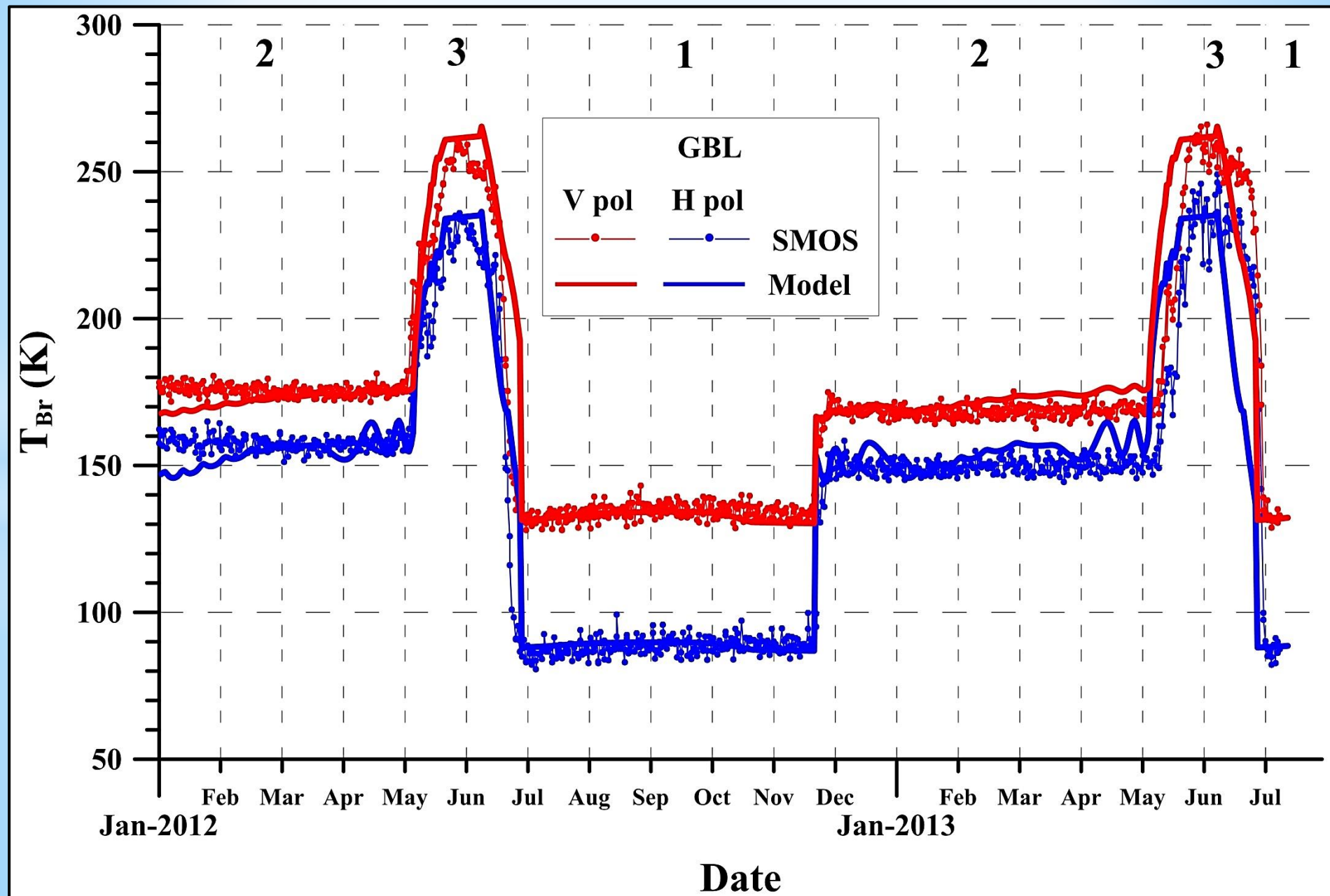
Байкал



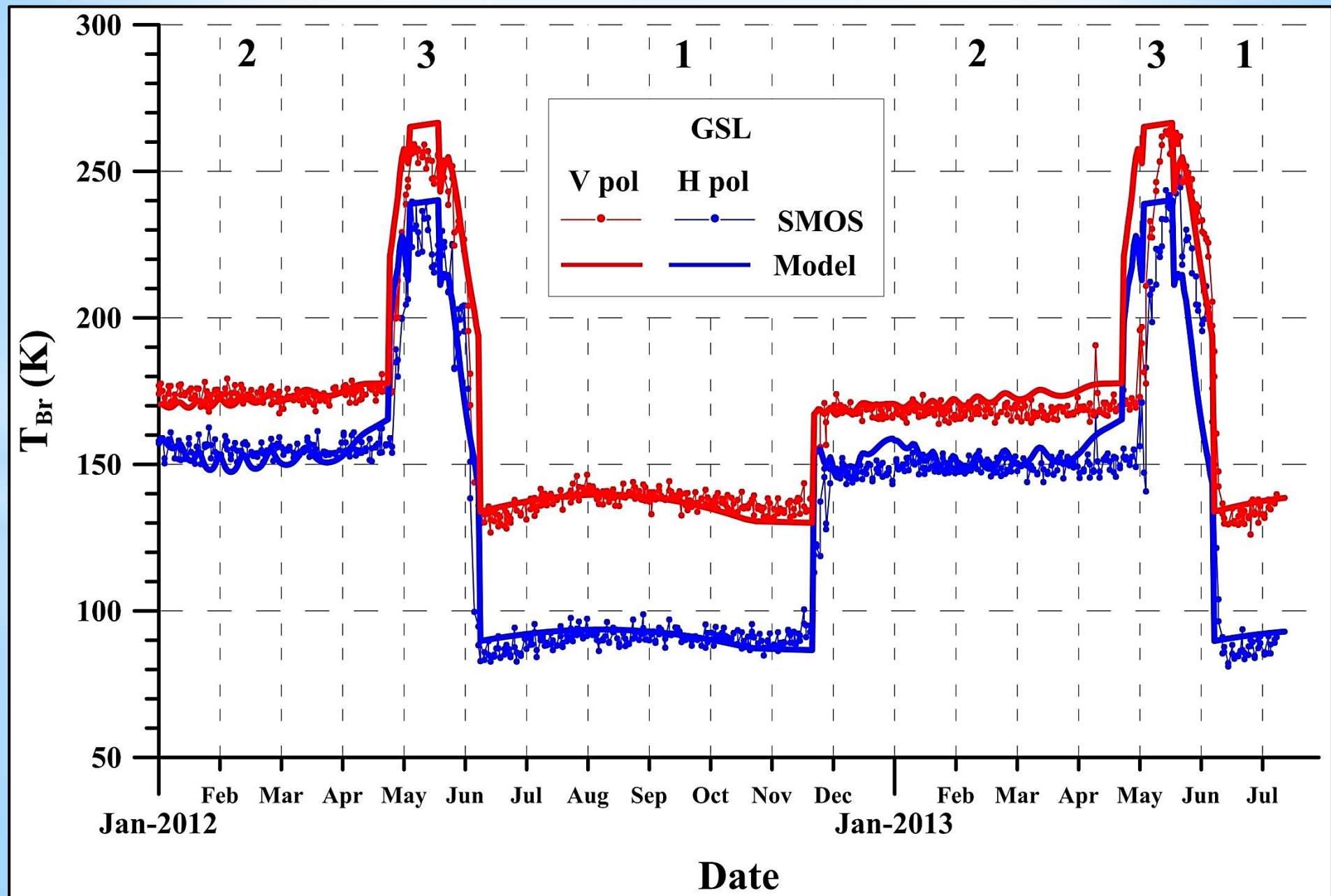
Ладога



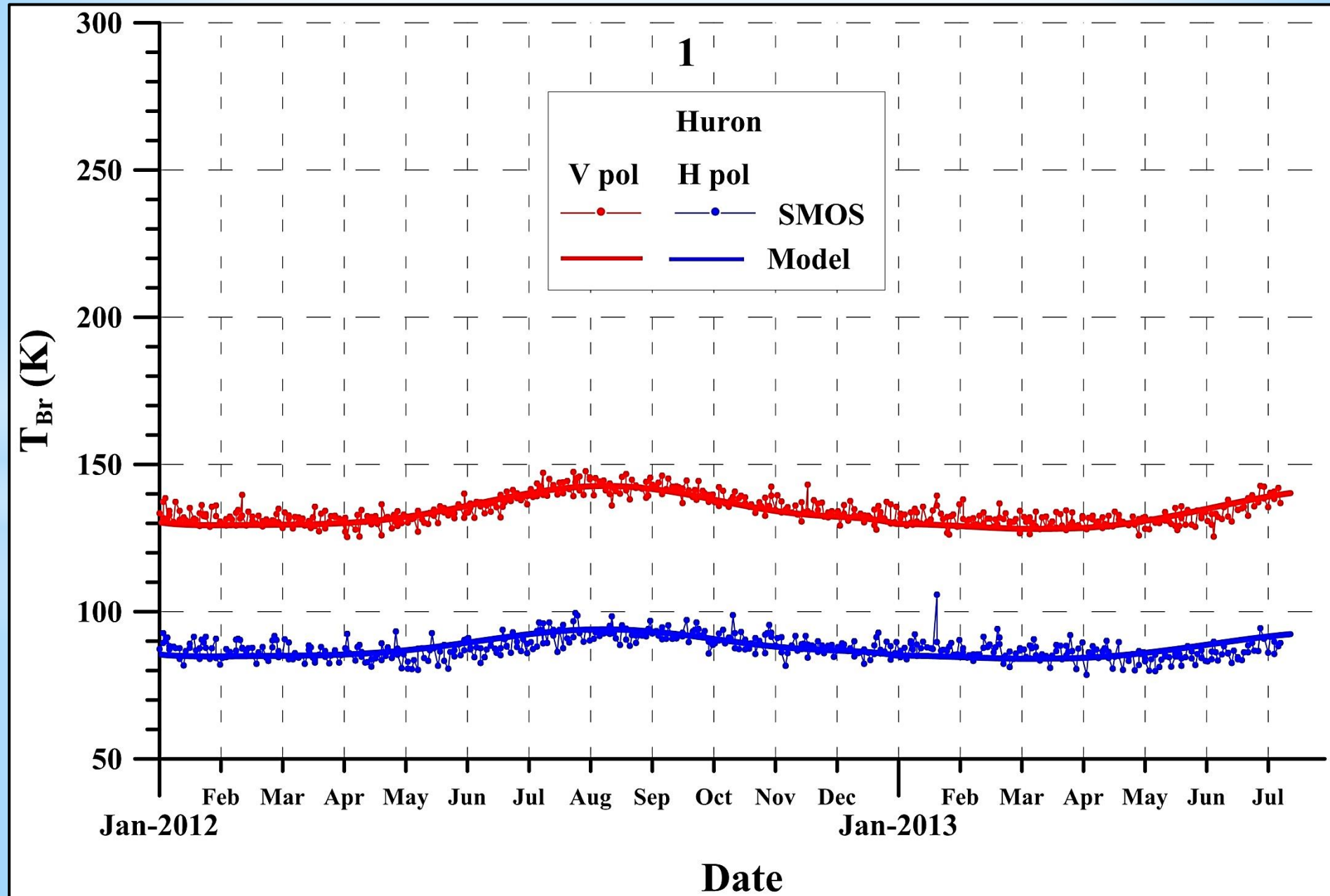
Большое Медвежье озеро



Большое Невольничье озеро



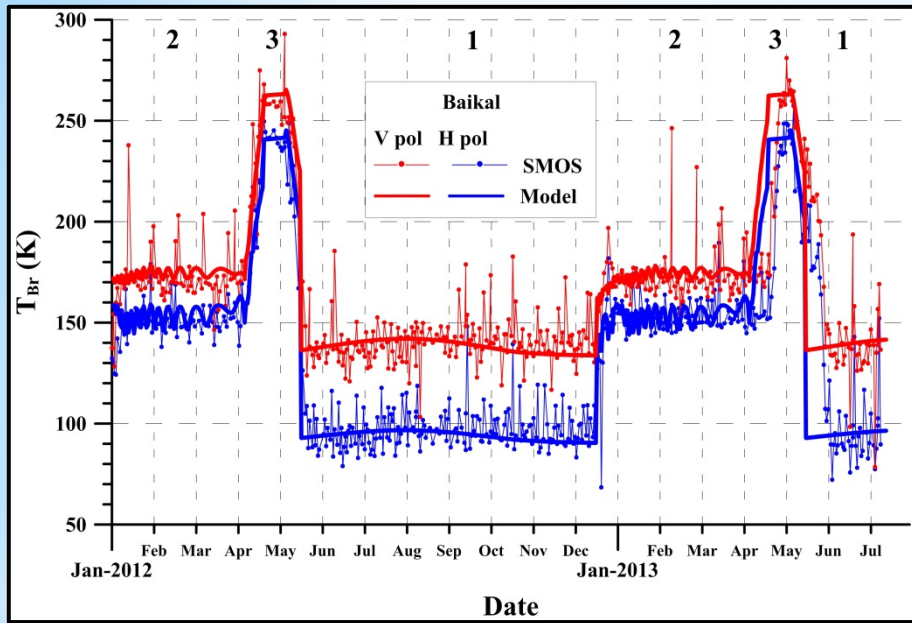
Озеро Гурон



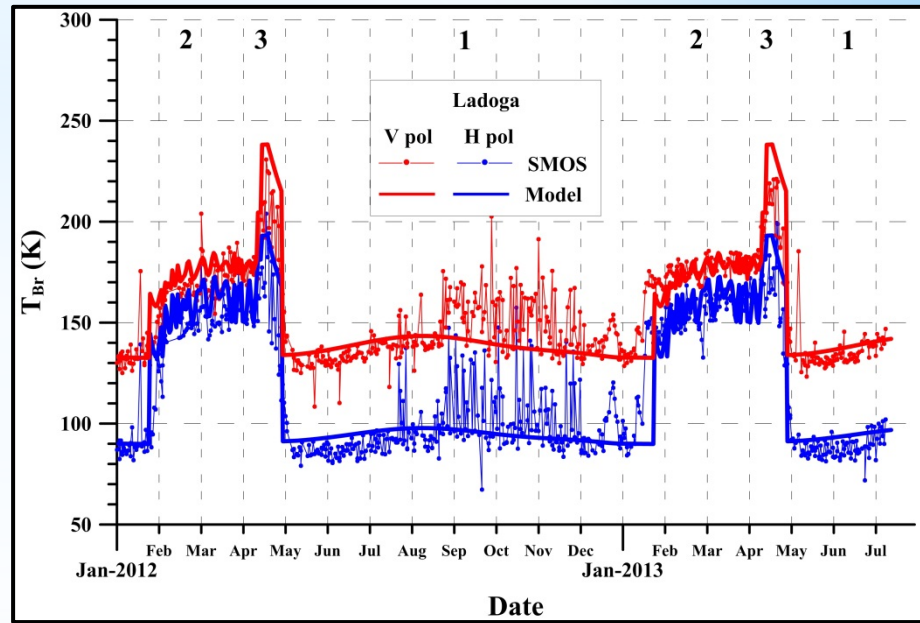
Входные параметры

Lacustrine Environment	Region 1	Region 2	Region 3
Water			
Temperature	T_{Water}	T_{Water}	T_{Water}
Lake ice			
Temperature	-	$(T_{\text{Water}} + T_{\text{Air}})/2$	0°C
Porosity	-	12-18 %	50 %
Diameter air particle	-	0.1 cm	0.1 cm
Volumetric wetness	-	3-8 %	25-50 %
Thickness	-	H_{ice}	H_{ice}
Snow cover			
Temperature	-	T_{Air}	0°C
Dry density	-	0.3 g/cm^3	0.3 g/cm^3
Diameter ice particle	-	0.04 cm	0.06 cm
Volumetric wetness	-	0 %	8-20 %
Thickness	-	H_{snow}	5-10 cm

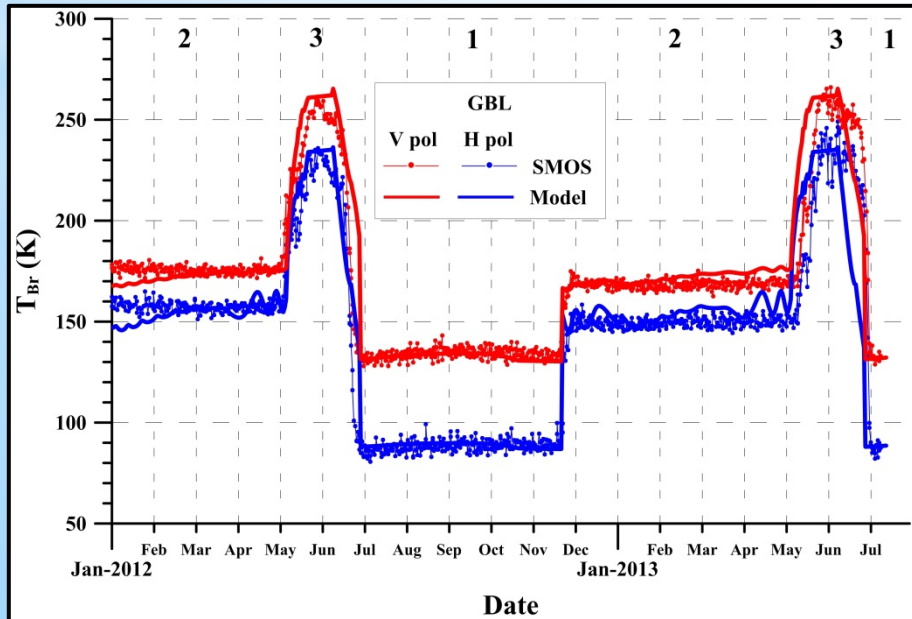
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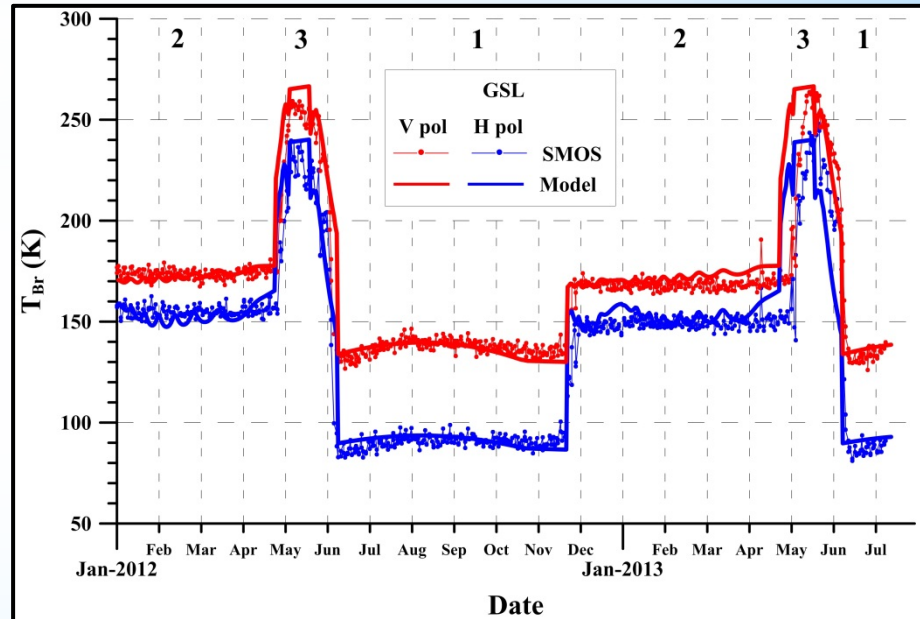
Ладожское озеро



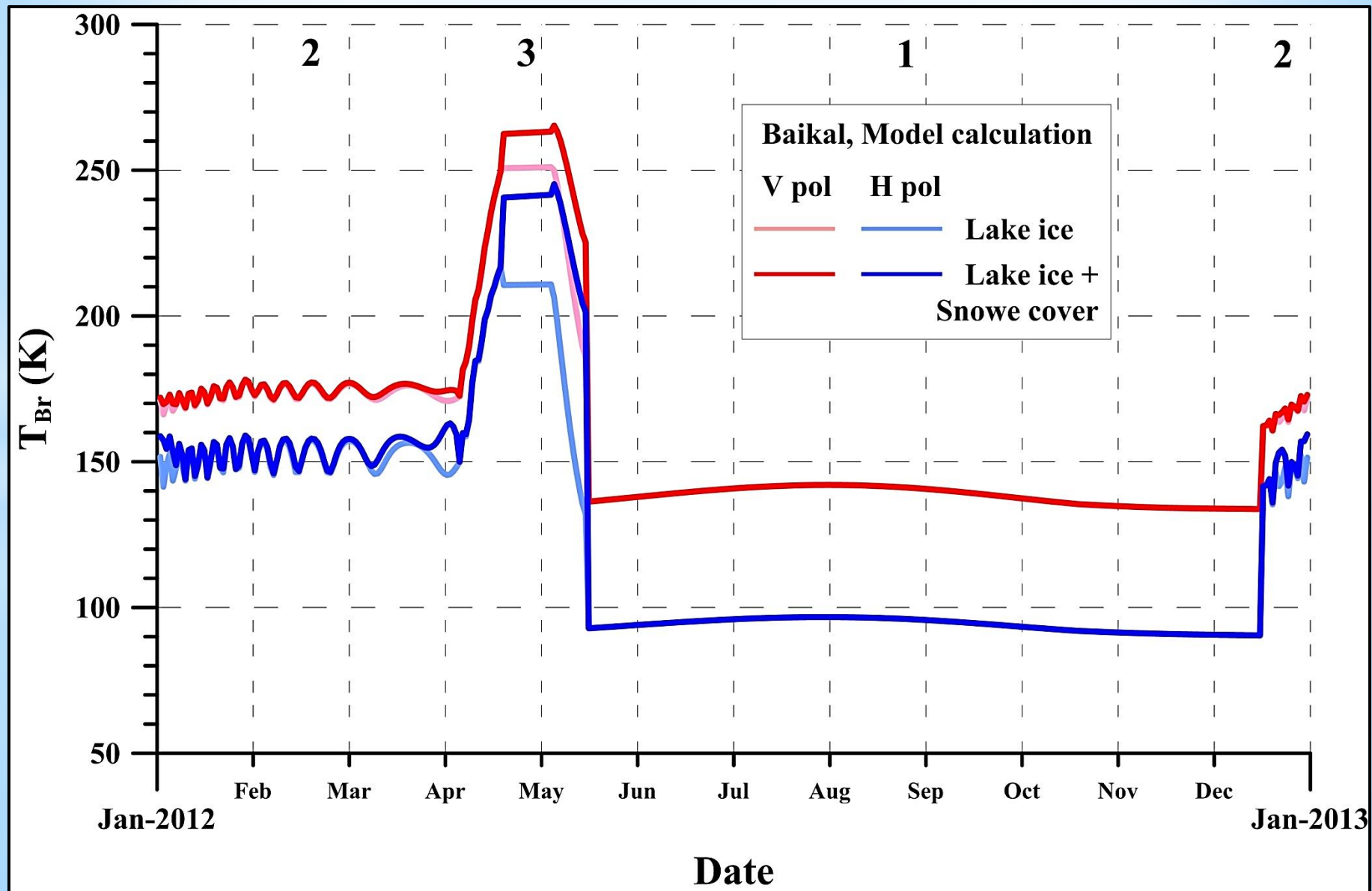
Большое Медвежье озеро



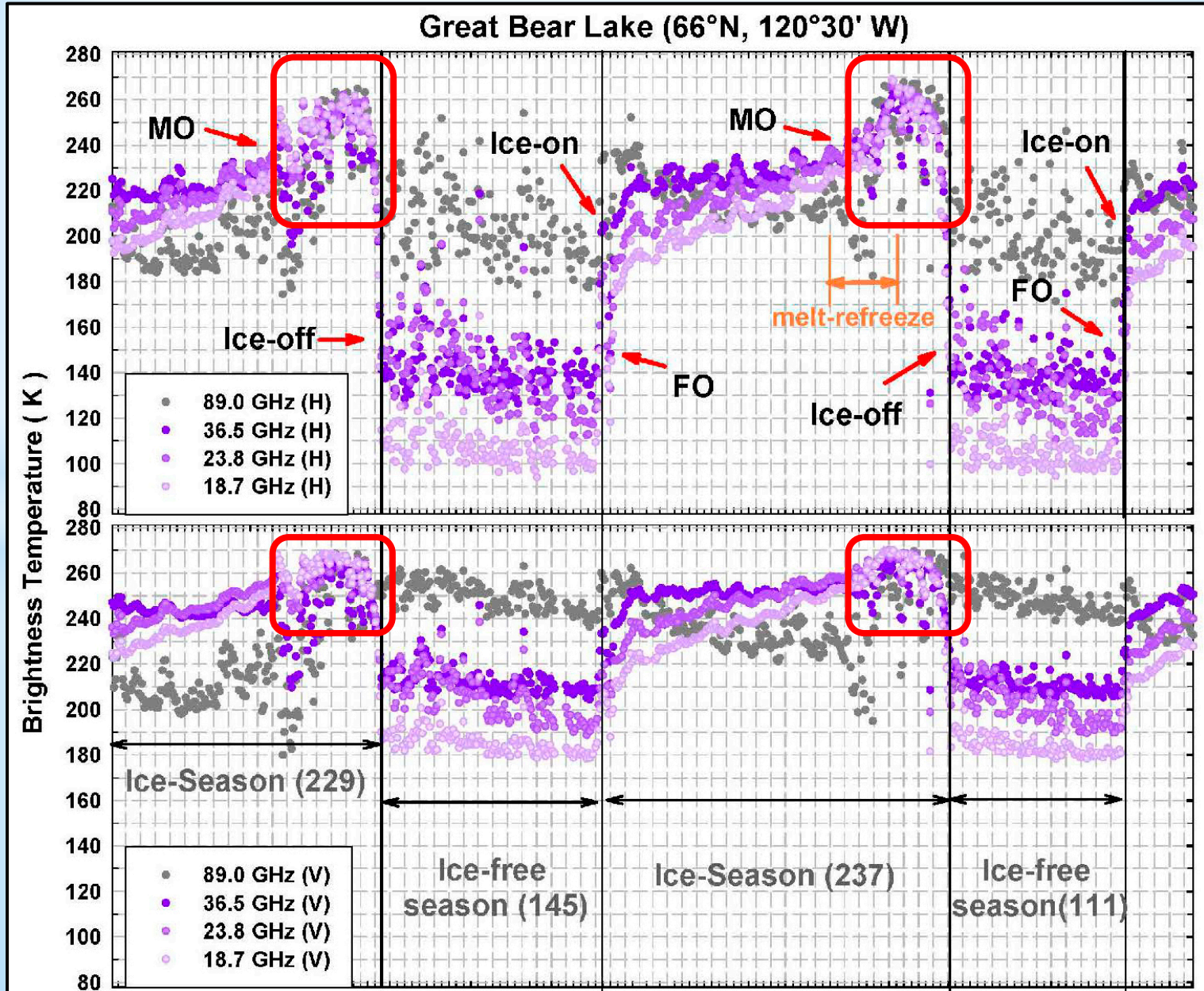
Большое Невольничье озеро



Влияние снежного покрова



Kang, K. K., Duguay, C. R., Howell, S. E. L.: Estimating ice phenology on large northern lakes from AMSR-E: algorithm development and application to Great Bear Lake and Great Slave Lake, Canada, *The Cryosphere*, 6, 235–254, <https://doi.org/10.5194/tc-6-235-2012>, 2012.



Спасибо!