2nd Workshop on Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling
SMHI, Norrköping, September 15-17 2010

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LakeMIP: the effects of mixing parameterizations and interaction with bottom sediments in a shallow lake

Questions

- Are explicit sediment parameterization important in shallow lakes modeling?
- How different turbulent mixing concepts “perform” for these lakes?

Expected answers

- Sediments are important since the heat capacity of water column is relatively small
- Shallow lakes are well-mixed and do not need sophisticated turbulence closure to be used

Kossenblatter Lake (Germany)

- Shallow (mean depth 2 m, max 5 m)
- Very turbid (extinction coef. ~7 m^{-1})
- Size 168 hectares

Observational data
(Lindenberg Meteorological Observatory - Richard Aßmann Observatory)

Parameters and sampling frequency

- Conventional meteorological variables (10min)
- Radiation (10 min)
- Turbulent fluxes (30 min)
- Water temperature (10 min)

The set of models

Lake model	The type of model	Soil scheme	Source
“Completely-mixed”	One-layer model	No	-
FLake	Two-layer model	Yes	Mironov et al. 2010
Hostetler	Multilayer model	Yes	Hostetler et al., 1993
MINLAKE96	Multilayer model	Yes	Fang and Stefan, 1996
LAKE	Multilayer, K-ε model	Yes	Stepanenko and Lykosov, 2005
Simstrat	Multilayer, K-ε model	No	Goudsmit et al., 2002
LAKEoneD	Multilayer, K-ε model	No	Jöhnk and Umlauf, 2001

"Completely-mixed" model

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k_T \frac{\partial T}{\partial z} - \frac{\partial S}{\partial z}$$

$$\rho c_p \frac{\partial \overline{T}}{\partial t} = \frac{\left. \left(-k_T \frac{\partial T}{\partial t} + S \right) \right|_{z=h}^{z=0}}{h} = \frac{1}{h}\left(F_0 + S_0 - F_b - S_b\right)$$

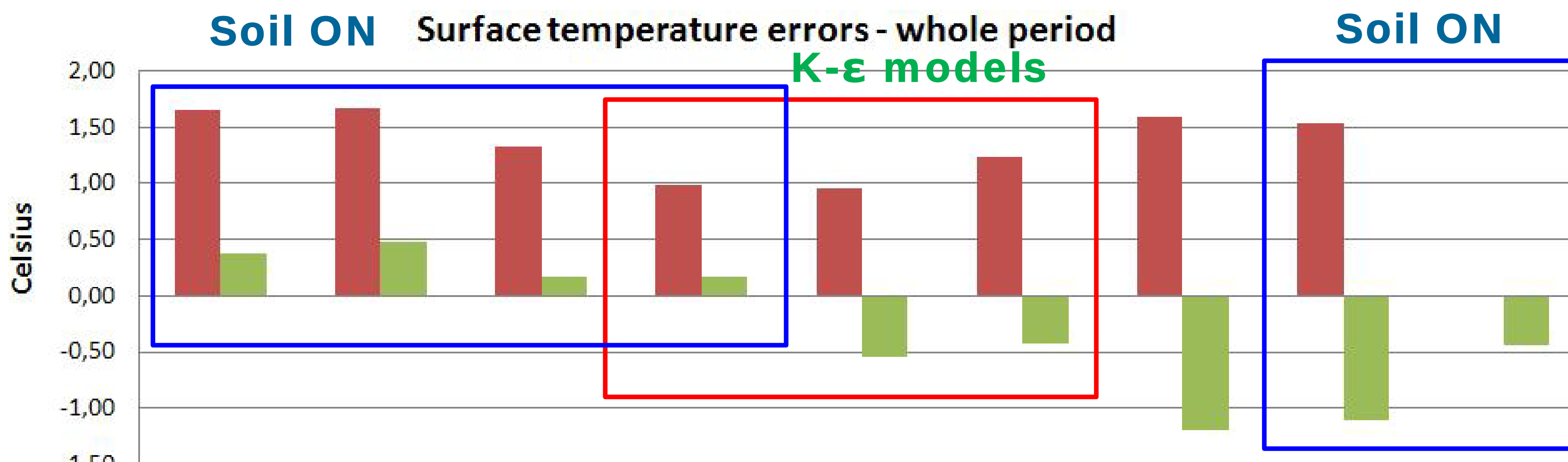
Assumes complete mixing,

$F_b = 0$ additionally neglects heat flux through sediments

Setup of numerical experiments

- warm season of 2003 (1 May–11 November)
- depths: local(1.2m), mean(2m) and maximal (5m)
- extinction coef. ~7 m^{-1} (Secchi disk 0.24 m)
- Timestep <10 min, MINLAKE96 – 24 h
- “native” surface flux schemes
- test for surface schemes decoupled from lake models
- zero heat flux at the bottom or explicit soil treatment if available

Surface temperature errors for the whole period



	FLake_passive_sediments	FLake_active_sediments	Hostetler	LAKE	Simstrat	LAKEoneD	complete-mixed	complete-mixed with bottom flux from LAKE	MINLAKE
RMSE	1,65	1,67	1,33	0,99	0,95	1,24	1,60	1,53	
d(MEAN)	0,38	0,48	0,17	0,16	-0,54	-0,43	-1,21	-1,11	-0,45

For the entire period models demonstrate comparable error values, with slightly lower RMSEs for K-ε models.
The exception is complete-mixed model that has significant bias.

Two periods

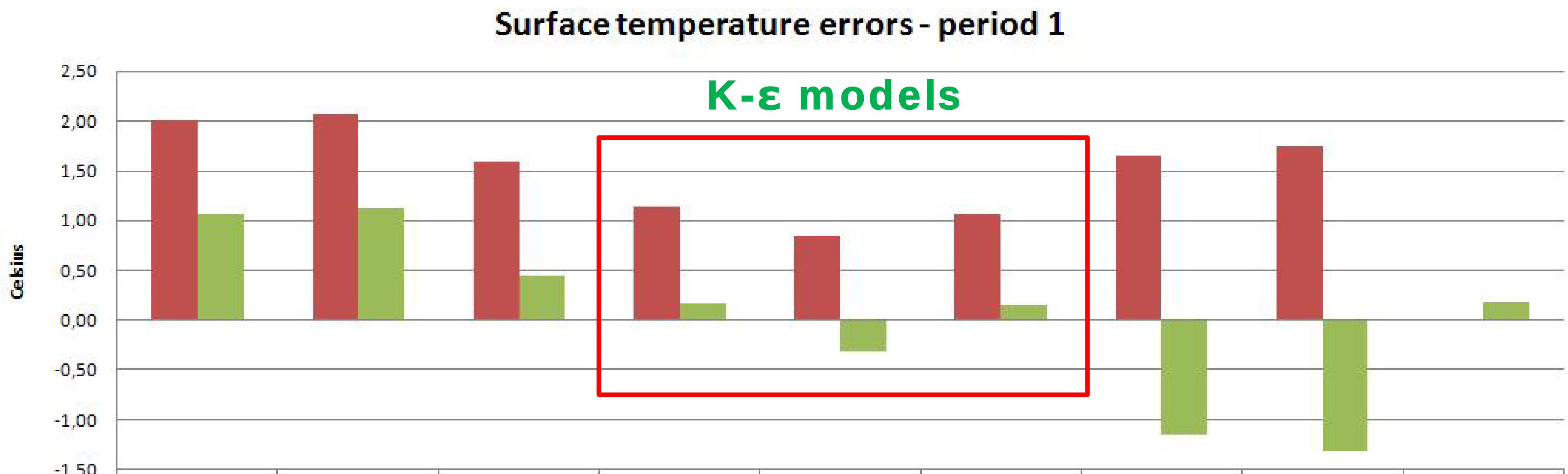
- **Temperature rise period** (summer, *stable stratification*):

  1 May – 10 August

- **Temperature decrease period** (late summer, autumn, *unstable stratification*)

  10 August – 10 November

Surface temperature errors for temperature rise period

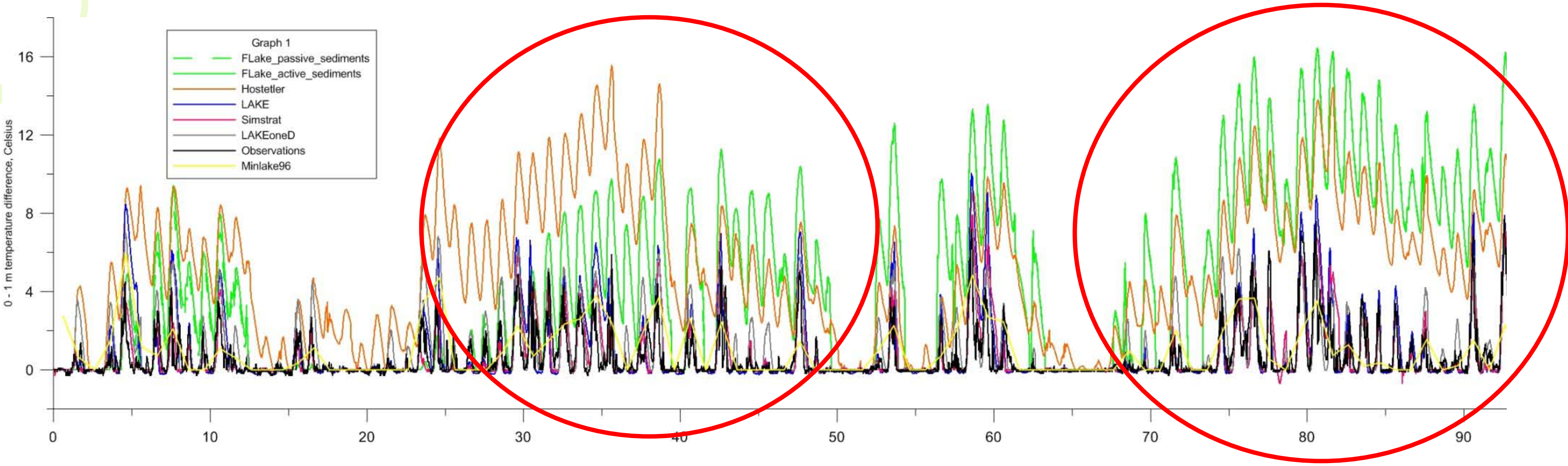


	FLake_passive_sediments	FLake_active_sediments	Hostetler	LAKE	Simstrat	LAKEoneD	complete-mixed	complete-mixed with bottom flux from LAKE	MINLAKE
RMSE	2,01	2,07	1,59	1,14	0,85	1,06	1,65	1,74	
d(MEAN)	1,06	1,13	0,44	0,17	-0,30	0,15	-1,15	-1,32	0,19

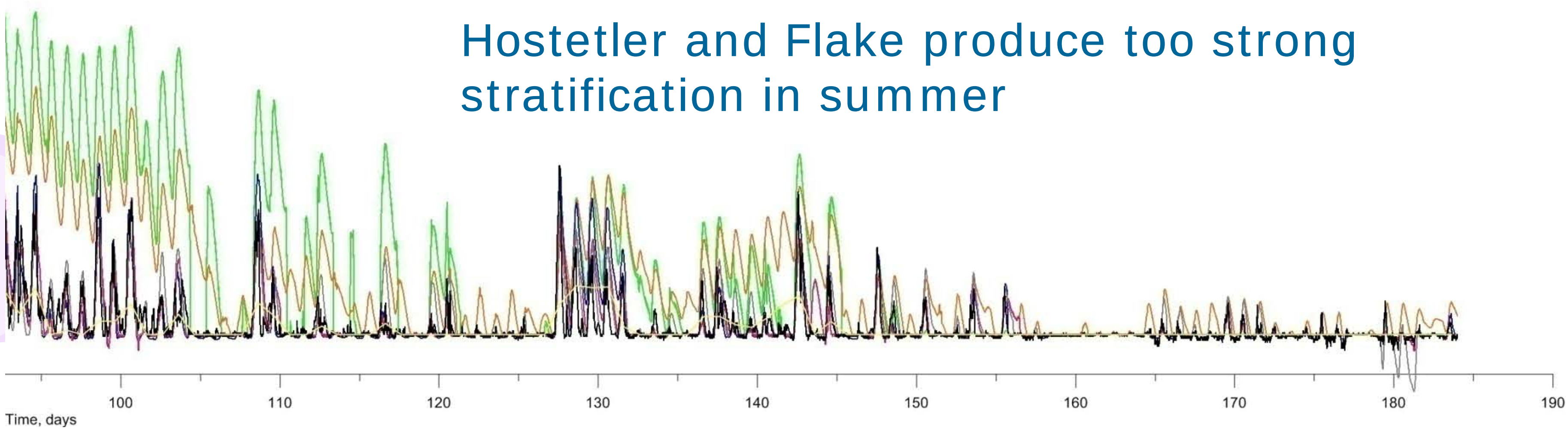
During the period of stable stratification in a lake K-ε models have less errors. Models with simpler mixing parameterizations tend to overestimate surface temperature (and stratification).

Lake stratification

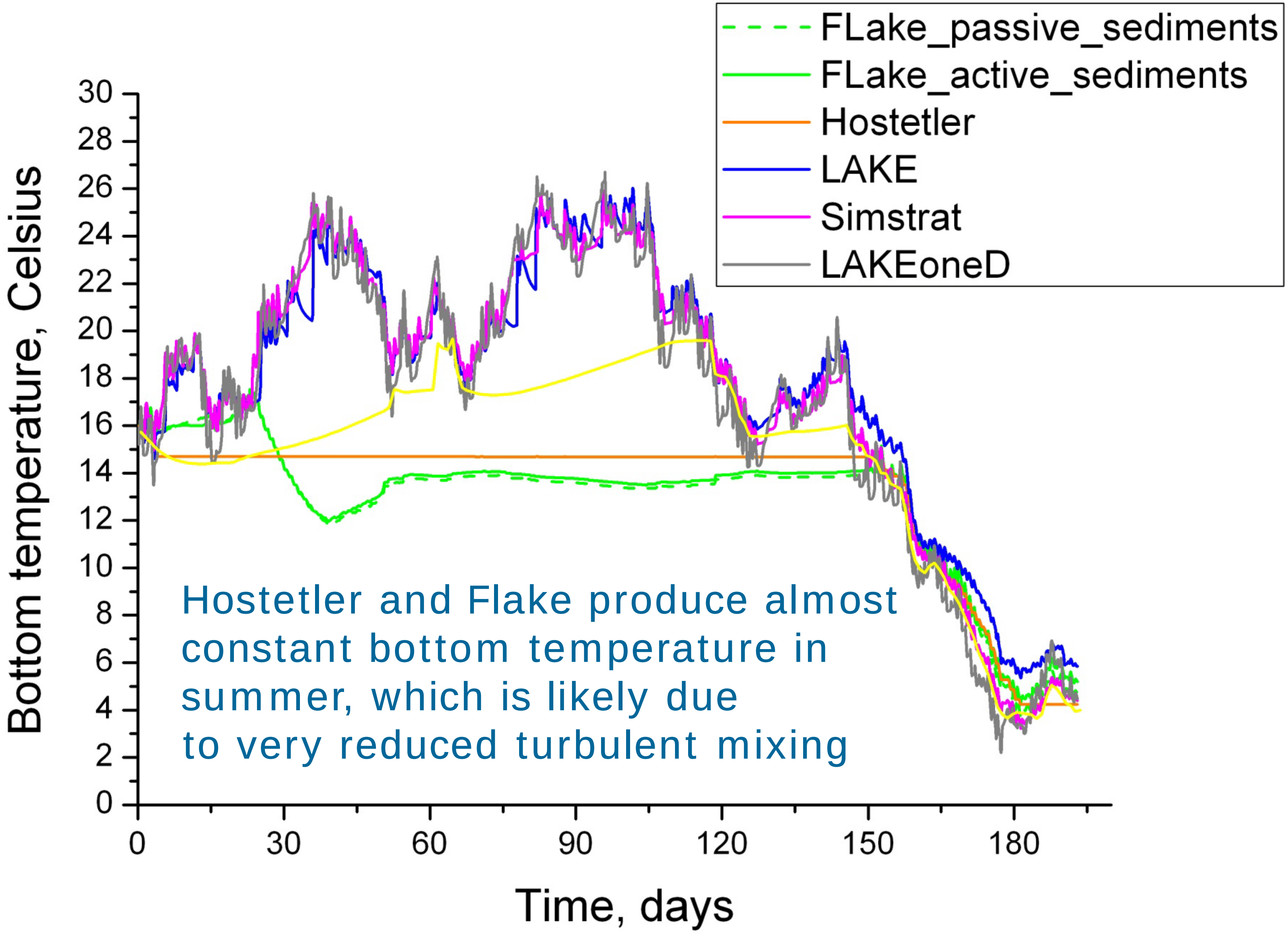
The 0 – 1 m depth temperature difference



Hostetler and Flake produce too strong stratification in summer

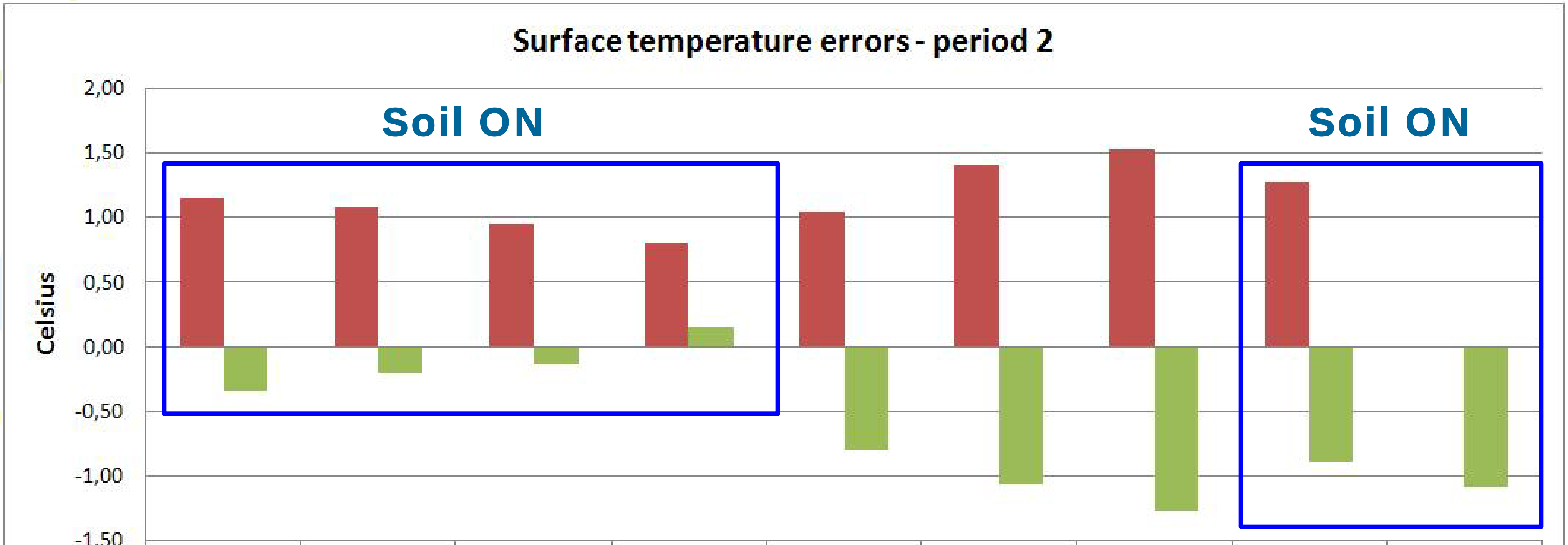


Bottom temperature



Hostetler and Flake produce almost constant bottom temperature in summer, which is likely due to very reduced turbulent mixing

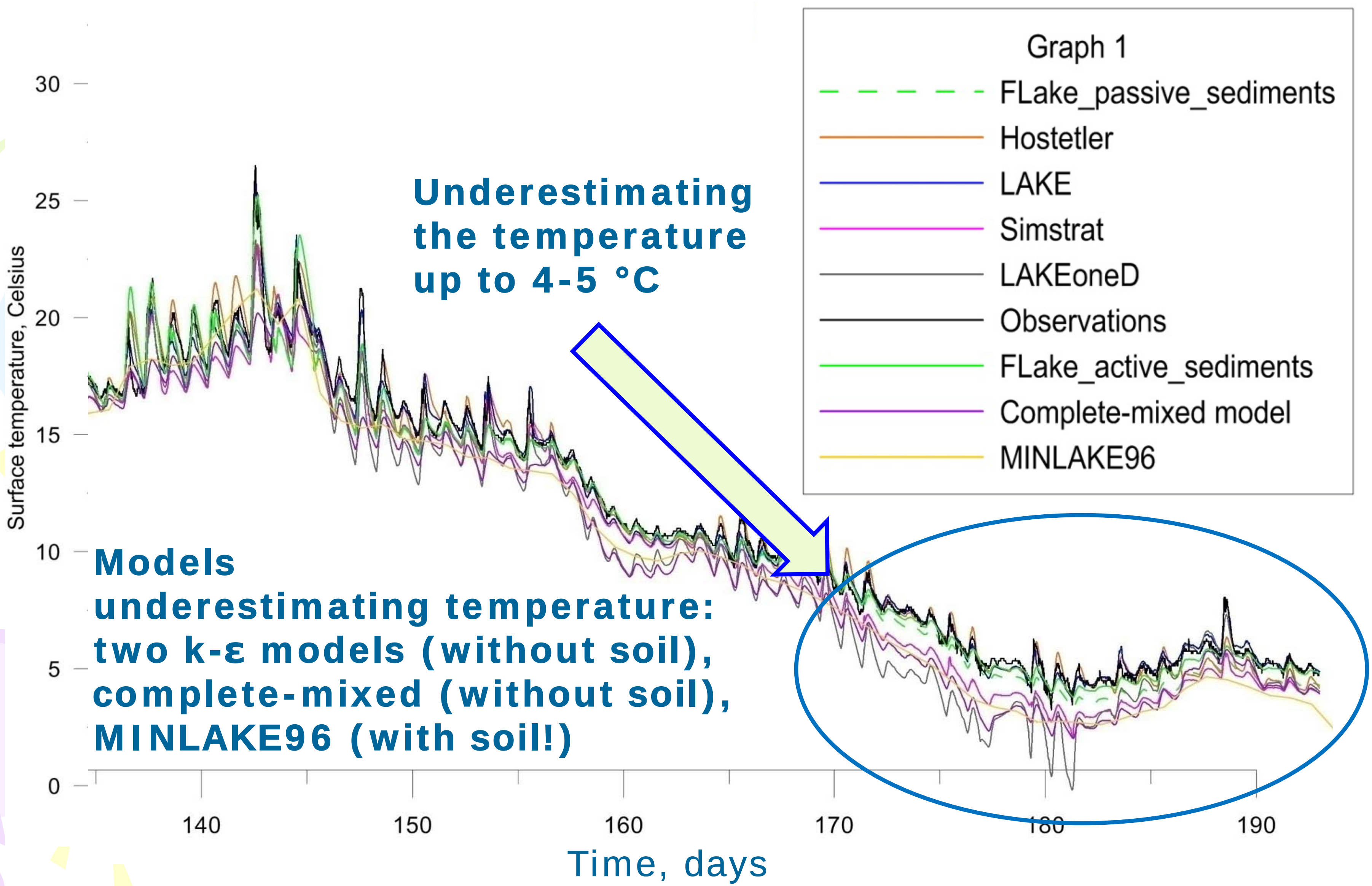
Surface temperature errors for temperature decrease period



	FLake_passive_sediments	FLake_active_sediments	Hostetler	LAKE	Simstrat	LAKEoneD	complete-mixed	complete-mixed with bottom flux from LAKE	MINLAKE
RMSE	1,15	1,09	0,96	0,80	1,05	1,41	1,54	1,28	
d(MEAN)	-0,35	-0,20	-0,13	0,16	-0,80	-1,06	-1,27	-0,88	-1,09

During fall models with explicit soil parameterization have less bias and RMSE, excluding MINLAKE96.

Surface temperature in the fall



Underestimating the temperature up to 4-5 °C

Models underestimating temperature: two k-ε models (without soil), complete-mixed (without soil), MINLAKE96 (with soil!)

Heat fluxes at the lake surface

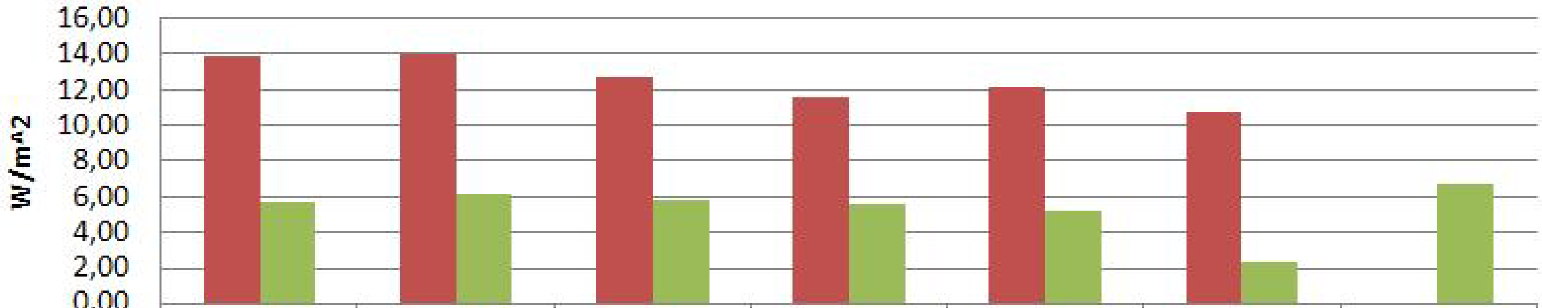
Means:

SHF = **8 W / m²**,

LHF = **67 W / m²**

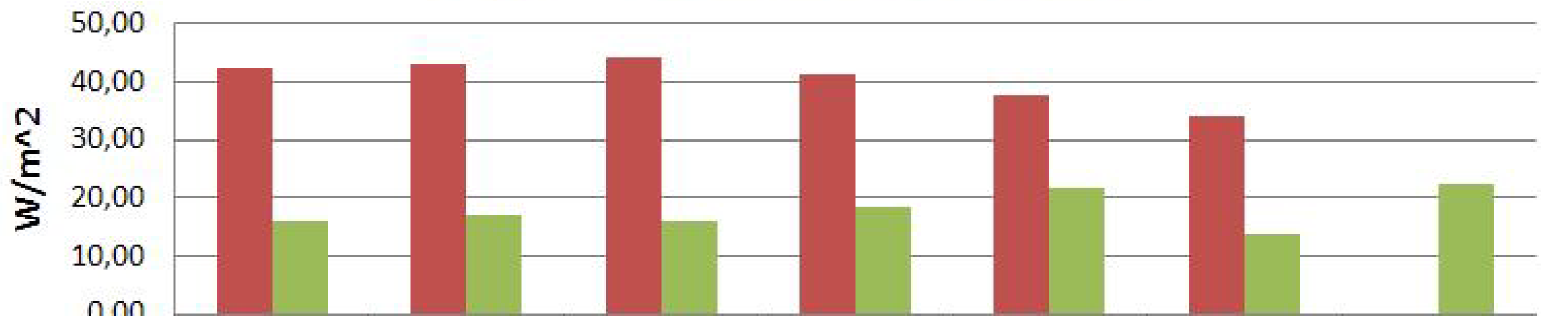
All biases are positive.

Sensible heat flux errors - whole period



	FLake_passive_sediments	FLake_active_sediments	Hostetler	LAKE	Simstrat	LAKEoneD	MINLAKE
RMSE	13,95	14,06	12,75	11,55	12,18	10,74	
d(MEAN)	5,70	6,16	5,82	5,51	5,22	2,29	6,75

Latent heat flux errors - whole period



	FLake_passive_sediments	FLake_active_sediments	Hostetler	LAKE	Simstrat	LAKEoneD	MINLAKE
RMSE	42,52	43,09	44,04	41,28	37,64	33,94	
d(MEAN)	15,96	16,96	15,99	18,35	21,72	13,84	22,33

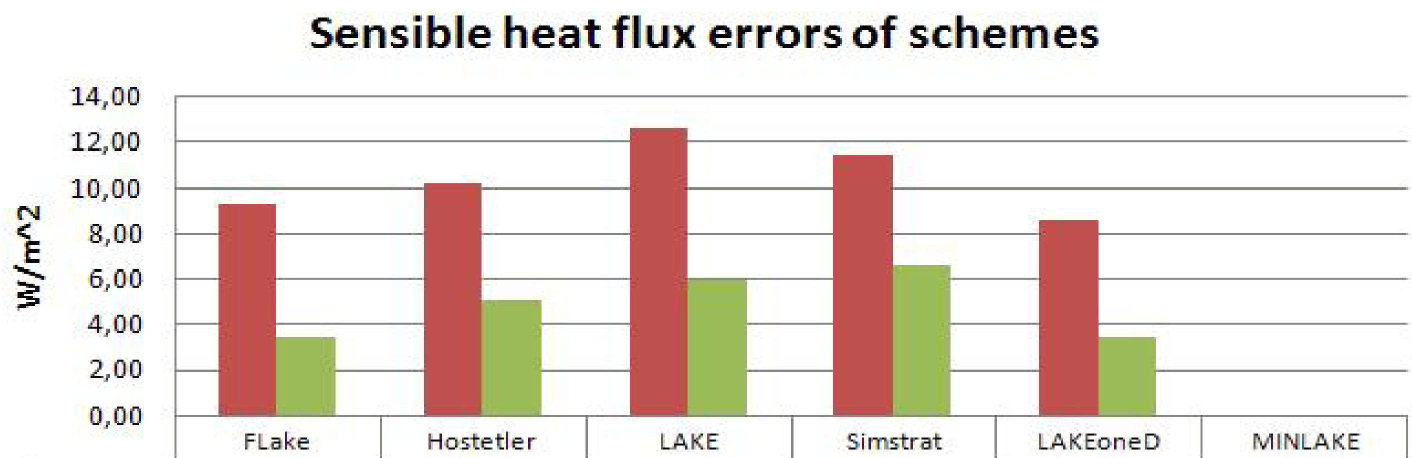
Surface flux schemes test

Surface schemes are forced by

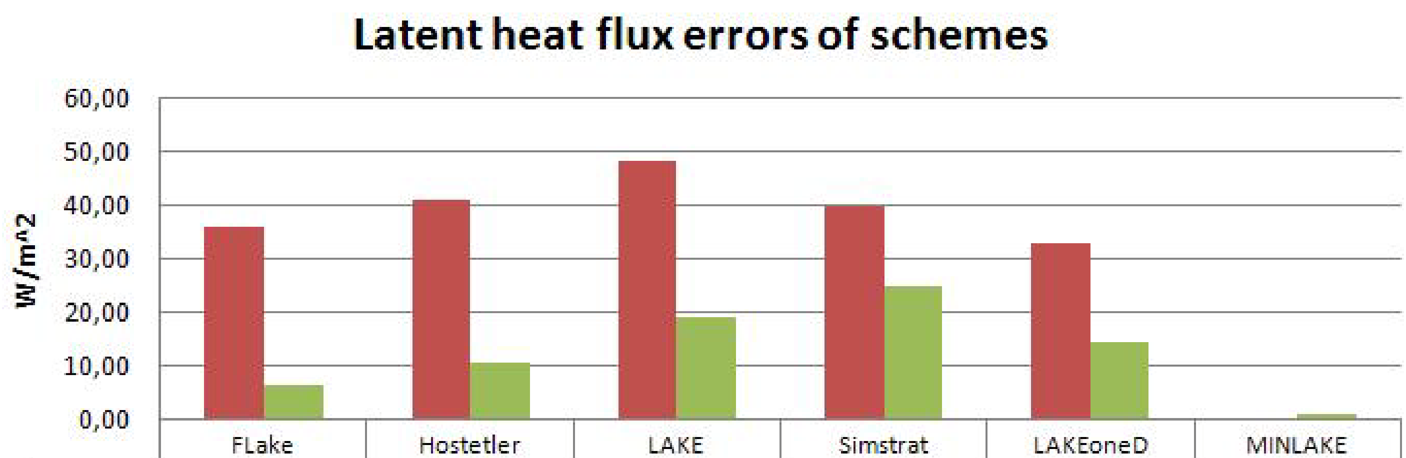
1) surface layer meteorology;

2) <u>measured</u> water surface temperature.

All biases are positive.



	FLake	Hostetler	LAKE	Simstrat	LAKEoneD	MINLAKE
RMSE	9,34	10,22	12,63	11,44	8,57	
d(MEAN)	3,46	5,04	5,94	6,63	3,47	0,02



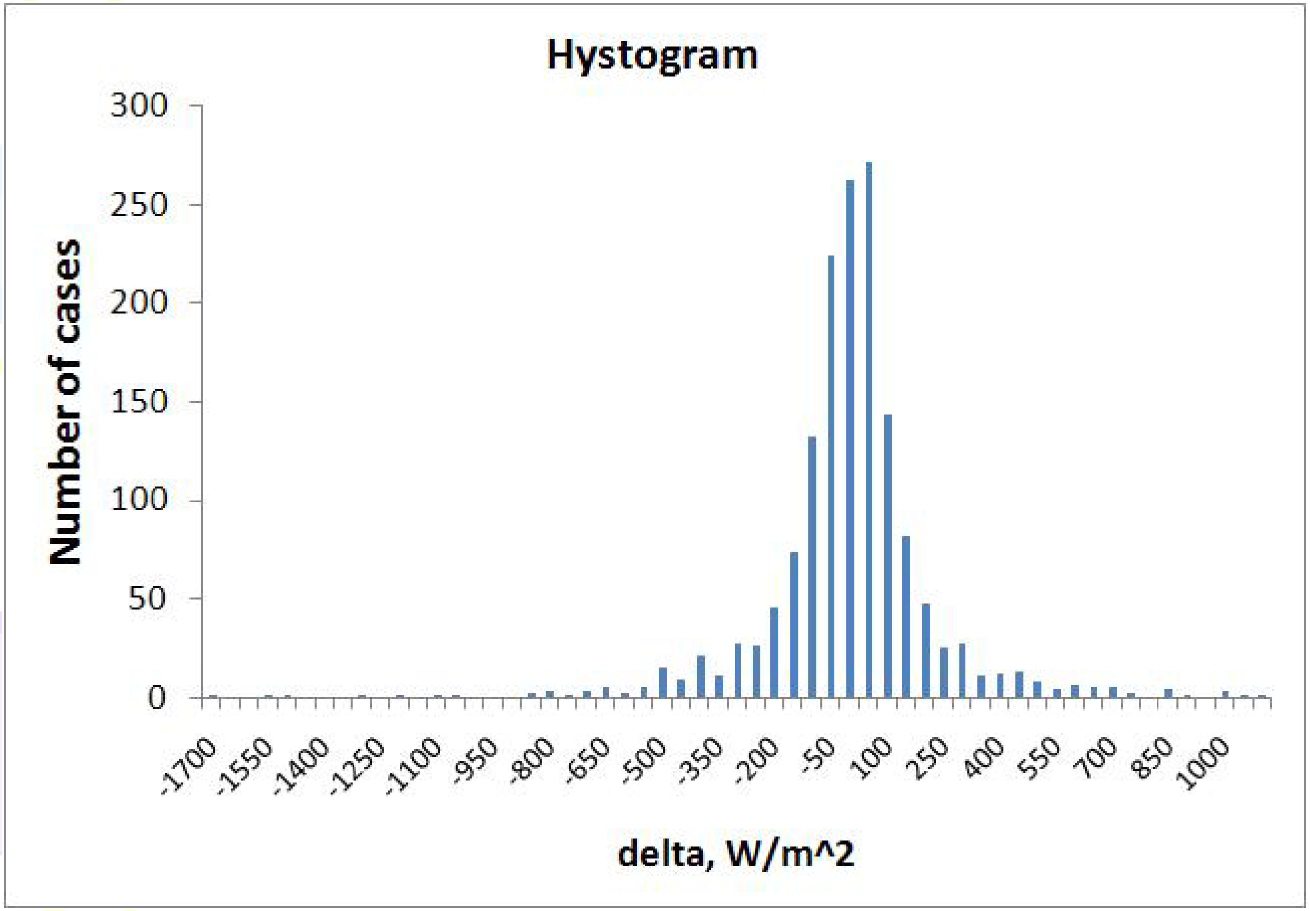
	FLake	Hostetler	LAKE	Simstrat	LAKEoneD	MINLAKE
RMSE	35,99	41,15	48,48	40,04	32,71	
d(MEAN)	6,02	10,60	19,14	24,69	14,37	0,58

The lake heat balance

$$\delta = \rho c_p h \frac{\partial \overline{T}}{\partial t} - \left(F_0 + S_0 - F_b - S_b\right)$$

Negligible due to high water turbidity

Mean δ -24…-26 W / m² depending on F_b = 0 or F_b taken from LAKE model

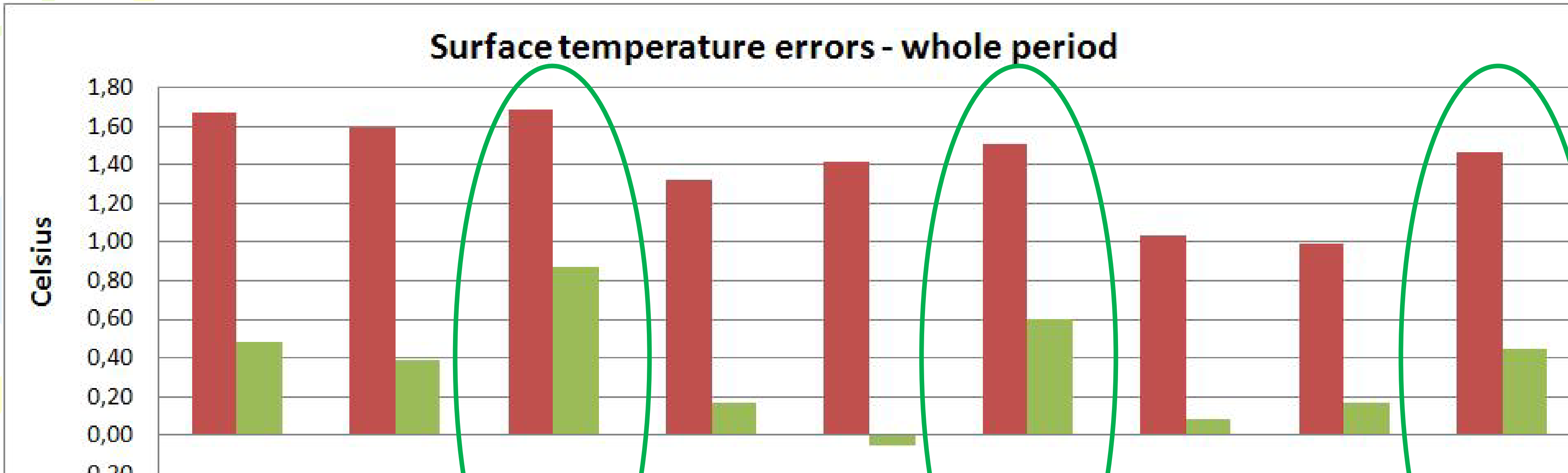


Bias of total heat flux for flux schemes

Scheme	**Bias, W / m²**
Flake	9.48
Hostetler	15.1
LAKE	25.08
Simstrat	31.32
LAKEoneD	17.84

The influence of depth on surface temperature error

Depths: local(1.2m), mean(2m) and maximal (5m)



	FLake_active_sediments	FLake_active_sediments_1.2m	FLake_active_sediments_5m	Hostetler	Hostetler_1.2m	Hostetler_5m	LAKE_1.2m	LAKE	LAKE_5m
RMSE	1,67	1,59	1,69	1,33	1,42	1,51	1,04	0,99	1,47
d(MEAN)	0,48	0,39	0,88	0,17	-0,06	0,60	0,08	0,16	0,45

Errors when using local and mean depths are close,
but with 5 m they increase due the increase of lake heat capacity

Conclusions

- Shallow and turbid lakes are likely to have significant stratification in summer calling for accurate mixing parameterization, that is crucial for reproducing deep temperatures
- Parameterization of heat exchange in soil becomes important for reproducing lake temperature during the fall
- Accurate “deep” temperatures are important for biochemical processes which rates are exponentially dependent on temperature

Errors of sensible and latent heat fluxes

The model	Sensible heat flux				Latent heat flux			
	D(MEAN)		RMSE		D(MEAN)		RMSE	
	Coupled	Decoupled	Coupled	Decoupled	Coupled	Decoupled	Coupled	Decoupled
Flake_passive	5.70	3.46	13.95	9.34	15.96	6.02	42.52	35.99
Flake_active	6.16	3.46	14.06	9.34	16.96	6.02	43.09	35.99
Hostetler	5.82	5.04	12.75	10.22	15.99	10.60	44.04	41.15
MINLAKE96	6.75	0.02	-	-	22.33	0.58	-	-
LAKE	**5.51**	5.94	**11.55**	12.63	**18.35**	19.14	**41.28**	48.48
Simstrat	**5.22**	6.63	12.18	11.44	**21.72**	24.69	**37.64**	40.04
LAKEoneD	**2.29**	3.47	10.74	8.57	**13.84**	14.37	33.94	32.71