Lake model in OpenIFS

Margarita Choulga, **PhD**

ECMWF,
Research Department
margarita.choulga@ecmwf.int

Photo from https://en.wikipedia.org

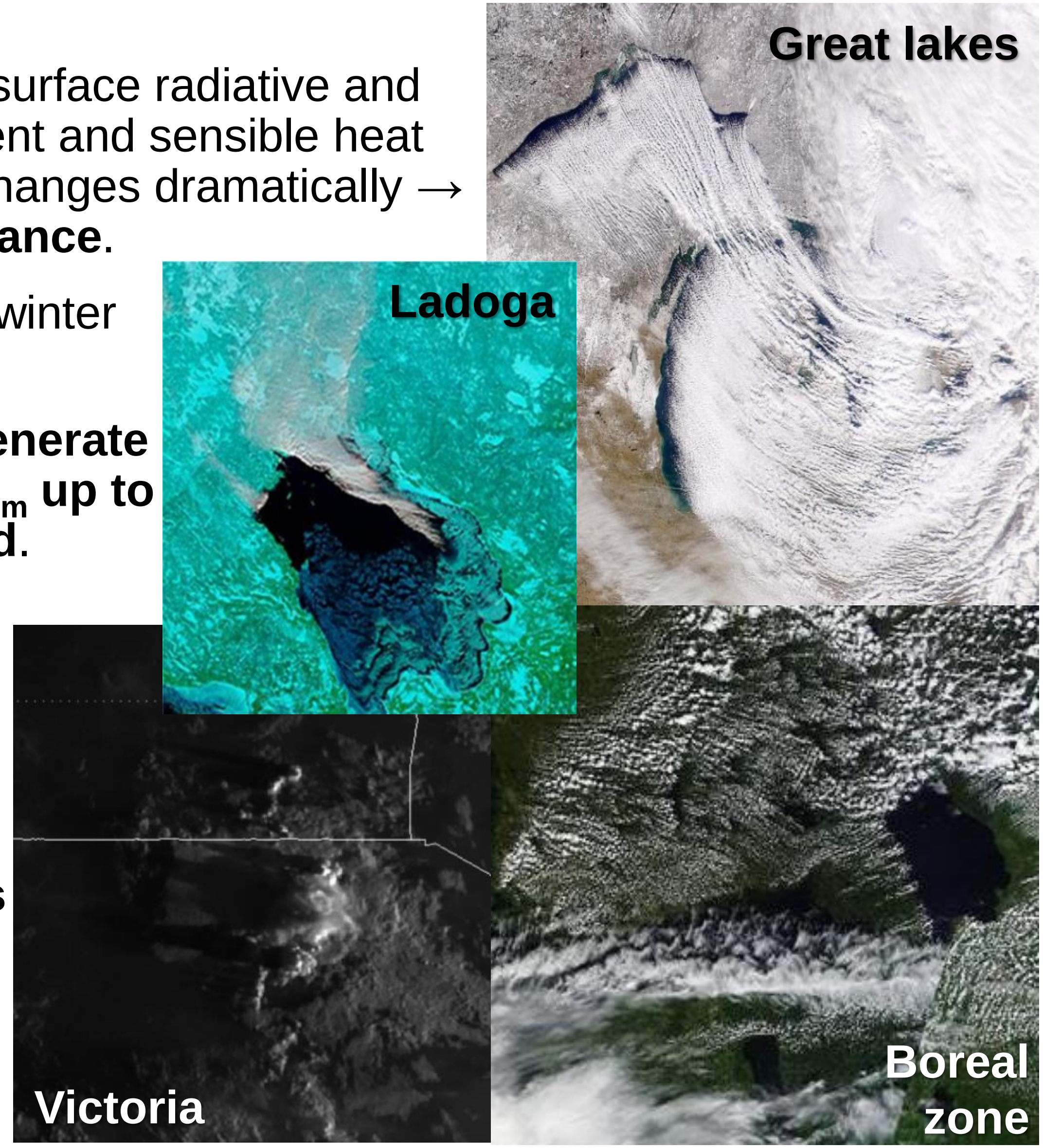
Thanks to:
Gianpaolo Balsamo,
and Souhail Boussetta

Introduction: lakes & their numbers

- **Lake** – a significant **volume of water**, which occupies a depression in the land and has **no** direct **connection with** the **sea**.
- Inland water bodies are often referred to as **lakes** when the **lateral movement** of the water is **negligible**, and as **rivers** when there is a **sizeable lateral transport**. Here, term “lakes” is used in the broad sense of **any inland water body** which lateral movement of water is neglected (i.e. lakes, reservoirs, rivers and coastal waters), although a clear separation is often complex and varies in time.
- **Globally lakes** occupy about **3.7 %** of the land surface (Borre, 2014; Verpoorter et al., 2014).
- According to the latest calculations the **total number** of lakes with a water surface area not less than 0.002 km^2, is **117 million** (excluding Greenland and Antarctica), and their **combined area** is about **5 million km^2** (excluding the Caspian Sea) (Borre, 2014; Verpoorter et al., 2014).
- **Lakes are distributed very unevenly**. **Most** lakes are situated in **Boreal and Arctic** climate **zones 45-75 °N** (Borre, 2014), namely in Canada, the Scandinavian Peninsula, Finland and Northern Russia and Siberia.

Lakes influence local weather climate

- *During freezing/melting*: lake surface radiative and conductive properties and latent and sensible heat released to the atmosphere changes dramatically → **different surface energy balance**.
- *Great lakes (USA)*: **intensify** winter **snowstorms**.
- *Lake Ladoga (Russia)*: can **generate low clouds → increase in T_{2m} up to 10 °C in** neighbouring **Finland**.
- *Boreal zone (50-70 °N)*: usually cause a **decrease of summer precipitation**.
- *Lake Victoria (Africa)*: **generates** night convection with intensive **thunderstorms → death of thousands** of fisherman **every year**.



Lakes can have global influence

- **Lakes** can also **influence global climate** by affecting the **carbon cycle** (Tranvik et al., 2009) and **methane CH_4 emissions** (Stepanenko et al., 2016).

- **Small shallow thermokarst lakes** located at Boreal and Arctic latitudes in the permafrost thaw area are rich in nutrients, which affect the **carbon dioxide CO_2 budget** (Walter et al., 2006; Walter et al., 2007; Stepanenko et al., 2012).

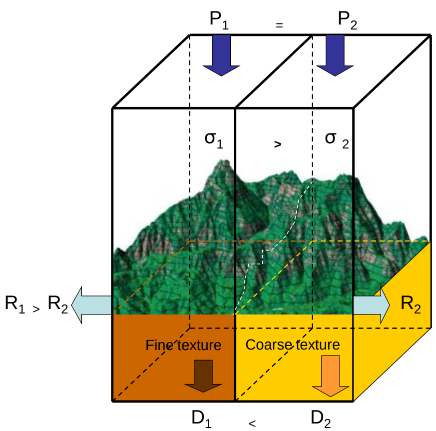
- **Small shallow** type of **lake** is most common (representing **~77 %** of the lakes **globally**), in general has a small surface area (0.002-0.01 km^2) and a **big surface-to-volume ratio** →
- important as carbon dioxide **CO_2** and methane **CH_4 degassing** takes place **through** the lake's **surface** (Borre, 2014; Verpoorter et al., 2014).

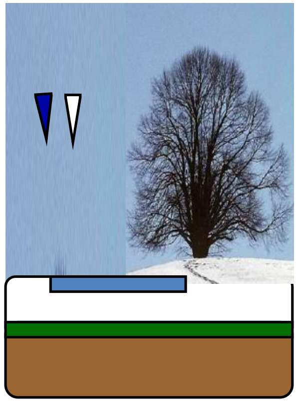
Lake parameterization in NWP

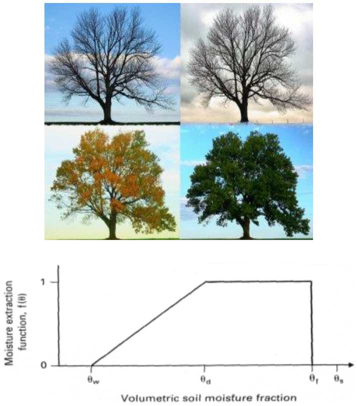
- The **effect of lakes** is handled in Numerical Weather Prediction (NWP) and climate models through **parametrization**, which **needs** information on the **locations** of the lakes and their **morphological characteristics**.
- In **global models** lakes are necessary to correctly represent **surface boundary conditions** in NWP systems (forecast + data assimilation):
  - albedo (e.g. freezing lakes);
  - thermal capacity (linked to water mass);
  - evaporation (linked to water temperature, wind, surface roughness);
  - soil moisture realism.
- The **lake schemes** for NWP need to be **simple & fast**. Constraints:
  - **reduced set of equations** that can represent lake daily/seasonal/inter-annual variability;
  - **simplified hydrology**, as lake full hydrology is too sophisticated to be fully represented in current global climate models at 9-200 km resolution;
  - **reduced set of parameters** and variables that can be initialized also on global domain (e.g. by satellite observations);
  - **numerically stable** and **physically sound** at all latitudes.
- The **main target** of lake parameterization in NWP is to **reproduce** lake **surface water temperatures** (and therefore evaporation rates).

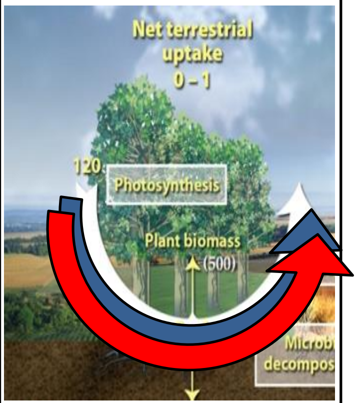
ECMWF surface model status (ERA5 setup)
and its evolution since ERA-Interim surface scheme

Implementation dates				
2007/11	**2009/03-09**	**2010/11 2011/11**	**2012/06**	**2015/05**
Hydrology-TESSEL Balsamo et al. (2009) Van den Hurk and Viterbo (2003) ➢ Global Soil Texture (FAO) ➢ New hydraulic properties ➢ Variable Infiltration capacity & surface runoff revision	**NEW SNOW** Dutra et al. (2010) ➢ Revised snow density ➢ Liquid water reservoir ➢ Revision of Albedo and sub-grid snow cover	**NEW LAI** Boussetta et al. (2013) ➢ New satellite-based Leaf-Area-Index **SOIL Evaporation** Balsamo et al. (2011), Albergel et al. (2012)	**H_2O / E / CO_2** Boussetta et al. 2013 Agusti-Panareda et al. 2015 ➢ Integration of Carbon/ Energy/ Water	**FLake** Mironov et al (2010), Dutra et al. (2010), Balsamo et al. (2012, 2010) ➢ Extra tile (9) to for sub-grid lakes and ice ➢ LW tiling (Dutra)



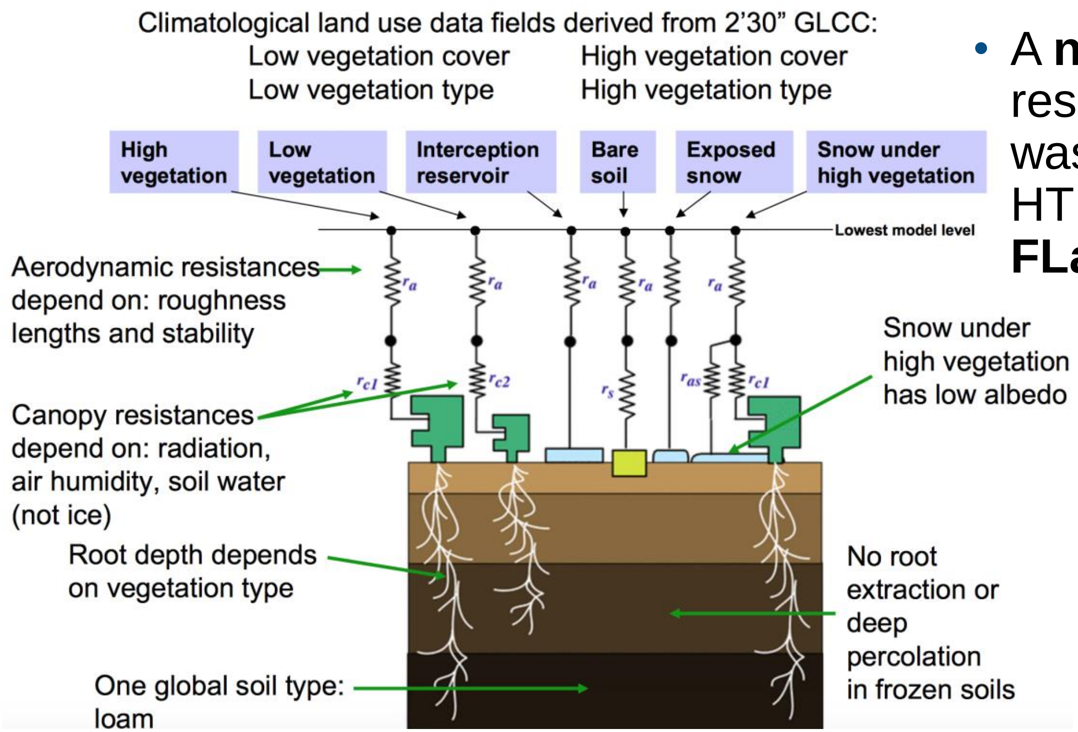






Tiling scheme

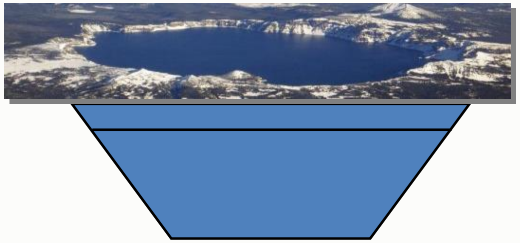
- To represent **surface heterogeneity**, the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (**HTESSEL**) is used (Balsamo et al., 2012; IFS Documentation, 2017).
- HTESSEL computes **surface turbulent fluxes** (of heat, moisture and momentum) and **skin temperature** over different tiles (vegetation, bare soil, snow, interception and water) and then calculates an **area-weighted average** for the grid-box to **couple with** the **atmosphere**.



- A **new tile**, representing lakes, reservoirs, rivers and coastal waters, was introduced (Dutra et al., 2010) in HTESSEL in **2015** by including the **FLake model** (Mironov et al., 2006).

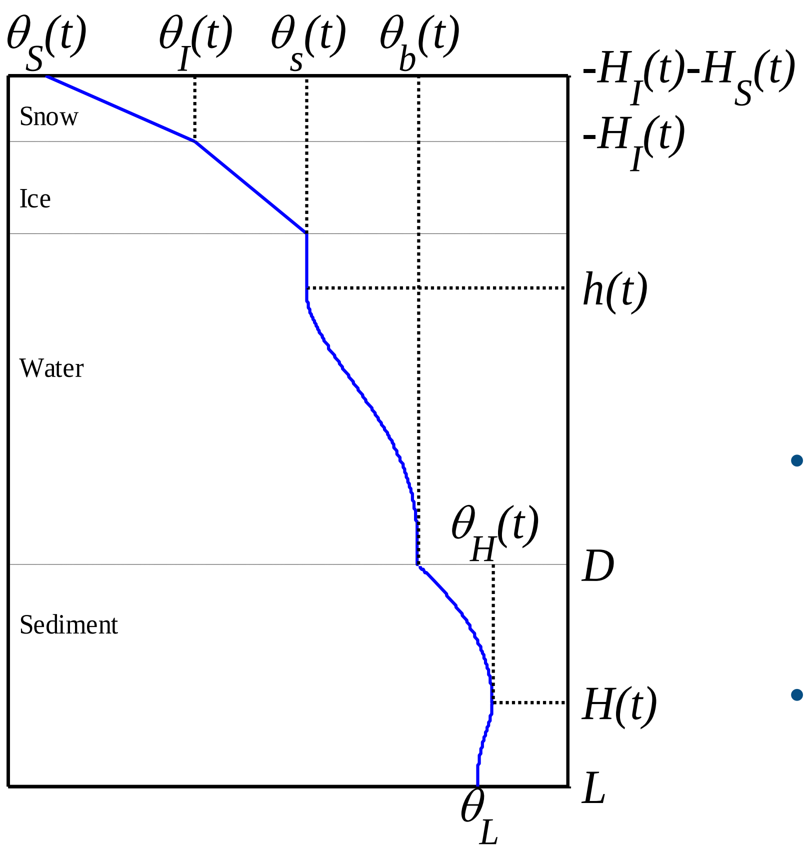
Balsamo et al. (2010, 2012, 2013)
Dutra et al. (2010)
Mironov et al (2010)

Lake tile (9)
accounts sub-grid lakes



FLake model: description

- The Fresh-water Lake model **FLake** (Mironov, 2008; Mironov et al., 2012) only accurately represents **fresh-water lakes**.



- FLake is a **one-dimensional** model, which uses an **assumed shape for** the lake **temperature profile** including the **mixed layer** (uniform distribution of temperature) and the **thermocline** (its upper boundary located at the mixed layer bottom, and the lower boundary at the lake bottom). The model also contains an *ice module, a snow module* and a *bottom sediments module*.

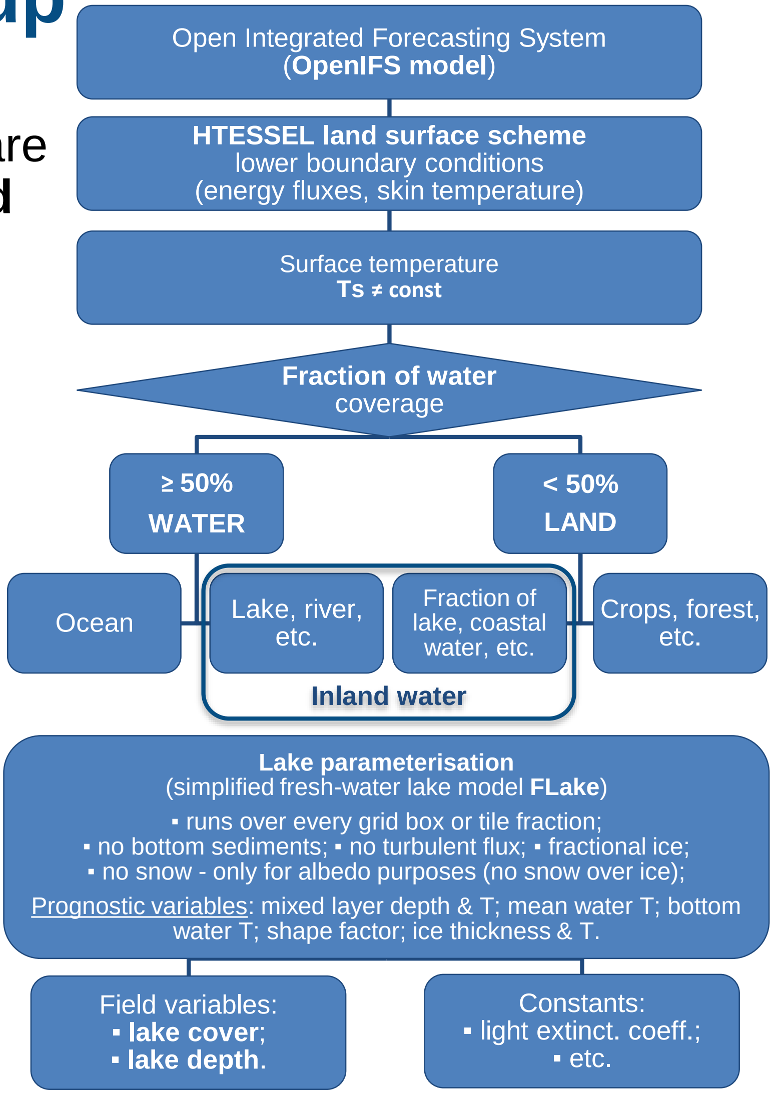
- FLake **requires** the **lake location and depth**, and lake *initial conditions*. ***Depth is the most important*** external parameter that FLake uses.

- FLake is a **computationally efficient shallow-water** model (it solves a number of ordinary differential equations) that incorporates most of the essential physics.

- FLake web page includes an **Online FLake** version at *http://lakemodel.net*.

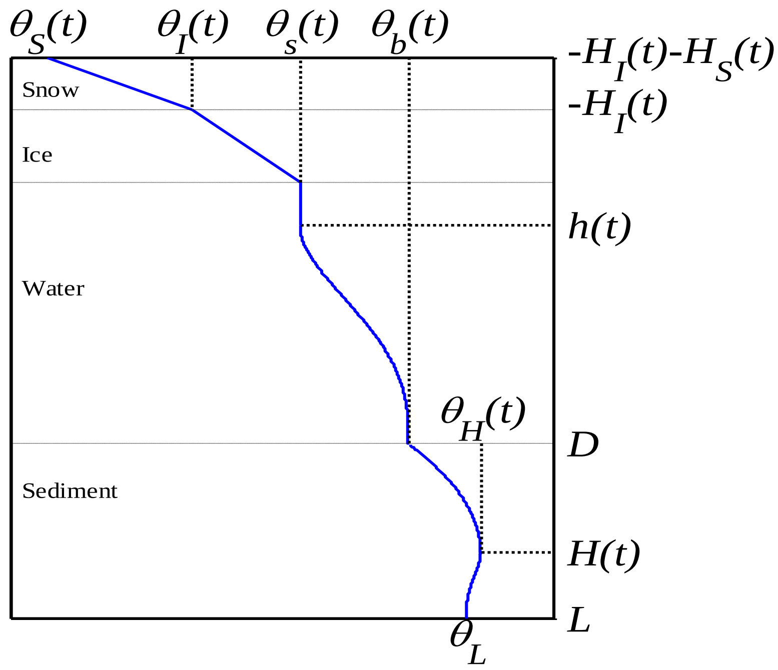
FLake model: OpenIFS setup

- **FLake** runs **on each** surface **grid-point**, whether the simulation results in this point are used later or not (resulting **fields** are **stored** in the **MARS** archive).
- FLake **runs** with **no bottom sediment** and **snow modules** (snow accumulation over ice is not allowed and snow parameters are used only for albedo purposes).
- Lake **ice** can be **fractional** within a grid-box with inland water: **10 cm** of ice = 100% of a grid-box or tile is **covered with ice**; **0 cm** of ice = 100% of the grid-box is covered by **water**; linear interpolation in between) (Manrique-Sunen et al., 2013).
- The **water balance equation** is **not included for lakes** and the lake **depth** and surface **area** are kept **constant** in time (IFS Documentation, 2017).



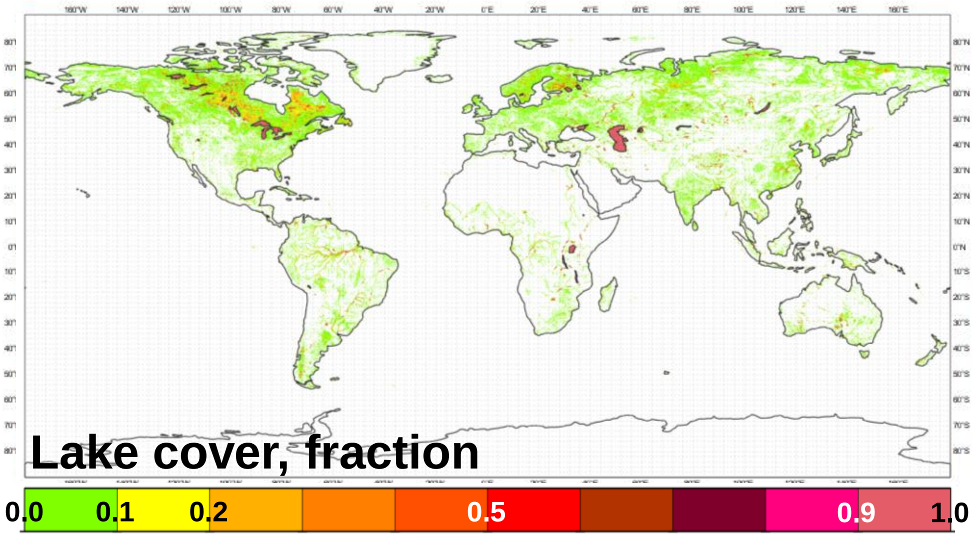
- FLake also requires **fractional** lake **cover** and lake **depth** (preferably bathymetry; should be accurate and up-to-date, **global & continuous**). (**no missing values!**)

FLake model: prognostic variables in MARS archive



GRIB short name	GRIB code	Full name
LMLT	8.228	Lake **mixed-layer temperature** (K)
LMLD	9.228	Lake **mixed-layer thickness** (m)
LBLT	10.228	**Temperature** at the water-**bottom** sediment interface (K)
LTLT	11.228	Lake **water column** mean **temperature** (K)
LSHF	12.228	Lake **shape factor** with respect to the temperature profile in the thermocline (dimensionless)
LICT	13.228	**Temperature** at the lake snow-**ice** or air-ice interface (K) (single level field)
LICD	14.228	Lake **ice thickness** (m)

FLake model: global input fields

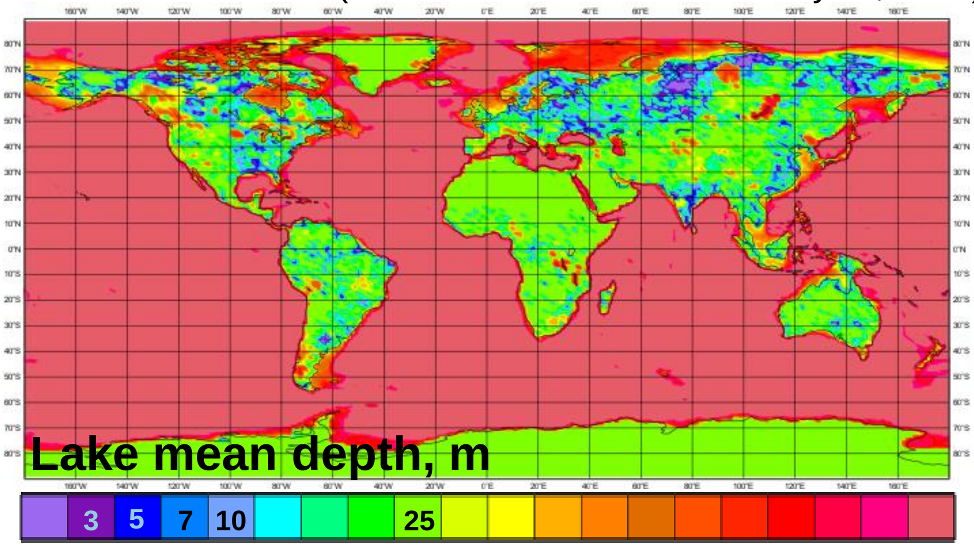


Lake cover (fraction) [CL / 26] - static field with **fraction** of lakes in every grid box. Values between **0** - **no lake** and **1** - **fully covered with lake**. CL is consistent with land-sea mask. Global field consists of:

- *60°S to 85°N* - **GlobCover 2006** [300m]
- *Antarctica* - Radarsat Antarctic Mapping Project Digital Elevation Model Version 2 (**RAMP2**) (Liu et al., 2015) [1 km]
- *Arctic* - north of 85 °N **no land** is assumed

"Depth of a lake is the main parameter to which model is sensitive…"
(Kourzeneva E. and Braskavsky D., 2006)

Lake depth, m	1- 7	Annual cycle amplitude changes for 1 K when depth changes for	1 m
	7-16		2 m
	16-40		3 m



Lake depth (m) [DL / 7.228] - static field with **mean depth** value in each grid box in order to **ease** the **interoperability of** lake **output at diverse** spatial **resolutions** where the ratio of resolved/unresolved lakes and coastal water varies. Global field consists of:

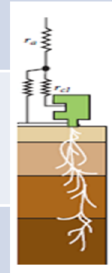
- *Over land*
  - ✓ lake mean depth – **GLDBv1** (in-situ ~13'000) [~1km]
  - ✓ bathymetry – **ETOPO1** [~2km] (Great lakes, Azov sea), **Calaveri** [~4km] (Caspian sea)
  - ✓ default = **25 m**
- *Over ocean* – **ETOPO1** [~2km]

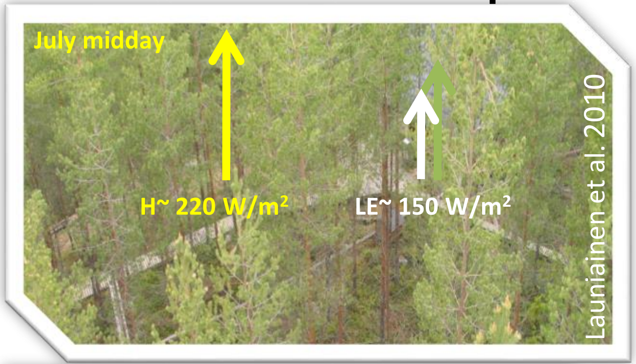
Introducing FLake under the tiling approach

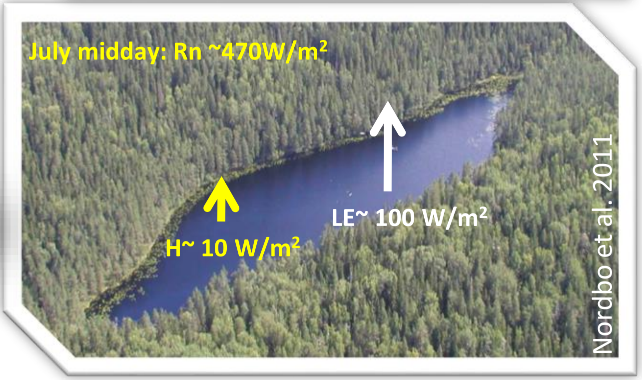
(Manrique-Suñén et al., 2013)

Southern Finland, stations are ~80 km apart

In-situ data

Hyytiala forest	Location: 61°51’N, 24°17’E	
	Scots pine forest with lingonberry, blueberry and mosses underneath	
	Canopy height in 2006: 16.5 m	
Lake Valkea-Kotinen	Location: 61°51’N, 24°17’E	
	Small boreal lake surrounded by tall forest – strong channelling of flow along the lake	
	Area: 0.041 km^2, elongated shape	
	Depth: mean = 2.5 m, max = 6.5 m	





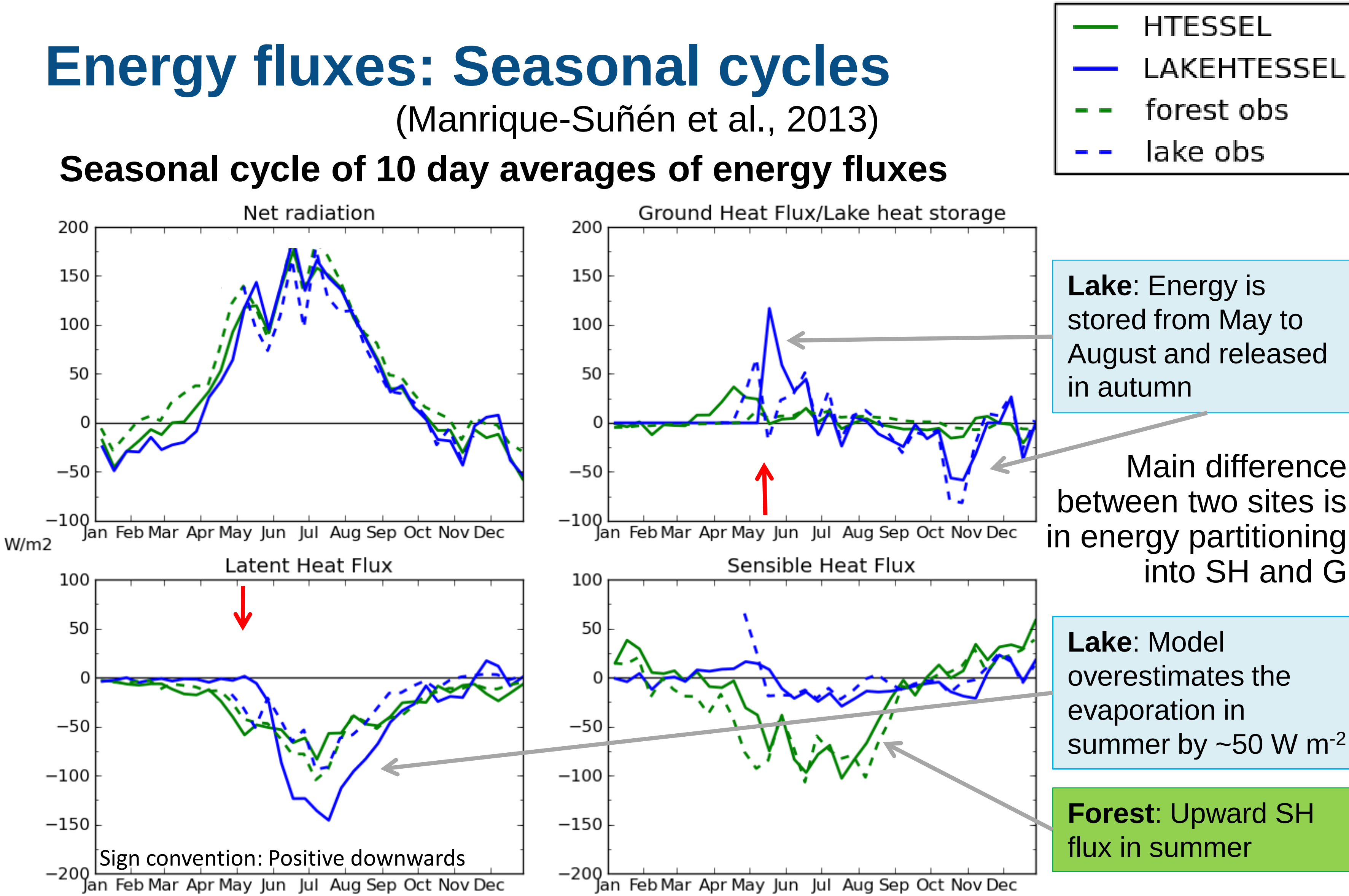
Model data

Surface off-line experiments single column (**no feedback** from **surface to atmosphere**)	**ERA-Interim** atmospheric forcing (~80 km), lakes not resolved
IFS model CY43R1, site characteristics from the nearest model grid point	**~9 km** horizontal **resolution** (Tco1279)
Length: January-December 2006	Prior cyclic yearly 3 time **spin up**

Energy fluxes: Seasonal cycles

(Manrique-Suñén et al., 2013)

Seasonal cycle of 10 day averages of energy fluxes



Lake: Energy is stored from May to August and released in autumn

Main difference between two sites is in energy partitioning into SH and G

Lake: Model overestimates the evaporation in summer by ~50 W m^{-2}

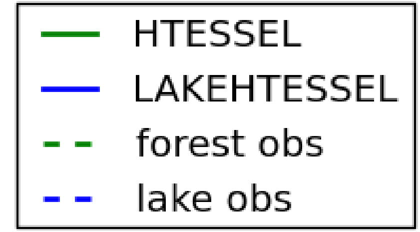
Forest: Upward SH flux in summer

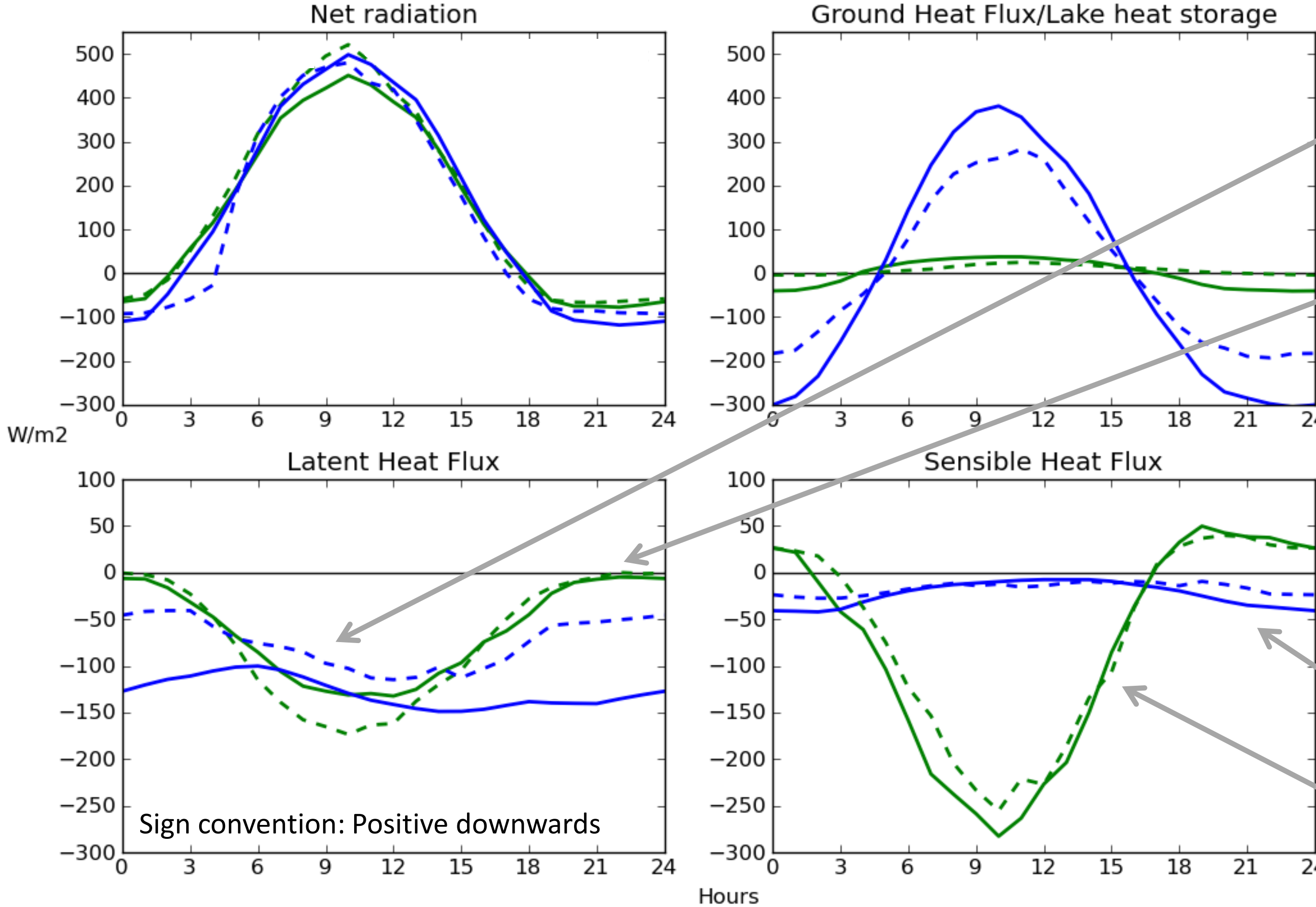
Timing of the lake's energy cycles is influenced by the ice cover break up, in the model it is delayed by 14 days → ice-initial condition will benefit from EO data constraint!

Energy fluxes: Diurnal cycles

(Manrique-Suñén et al., 2013)

Monthly diurnal cycle of energy fluxes for July





Lake LH diurnal cycle: overestimation in evaporation

Forest: evaporation is driven by vegetation → it is zero at night

Main difference between two sites is in energy partitioning into SH and G

Lake: SH maximum is at night

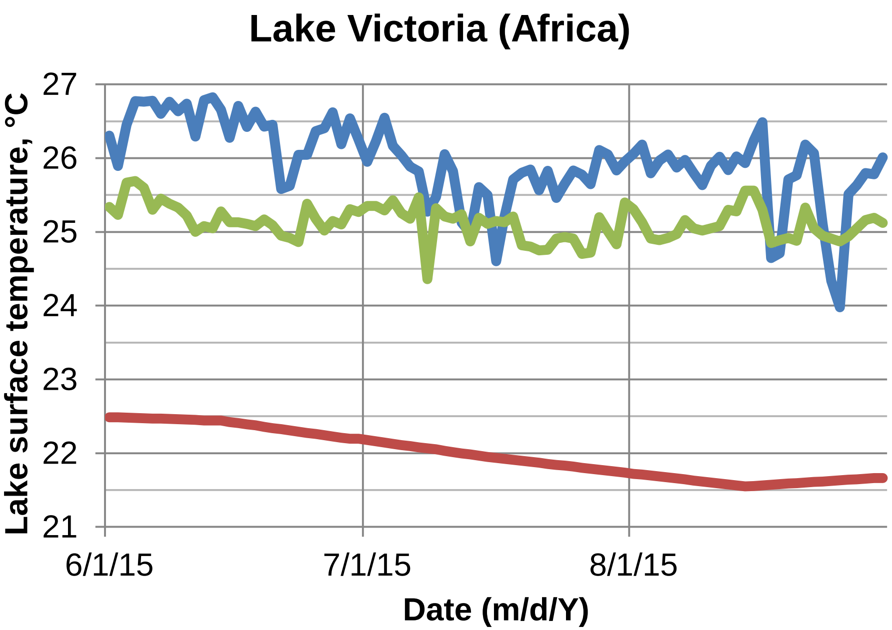
Forest: SH maximum is at midday

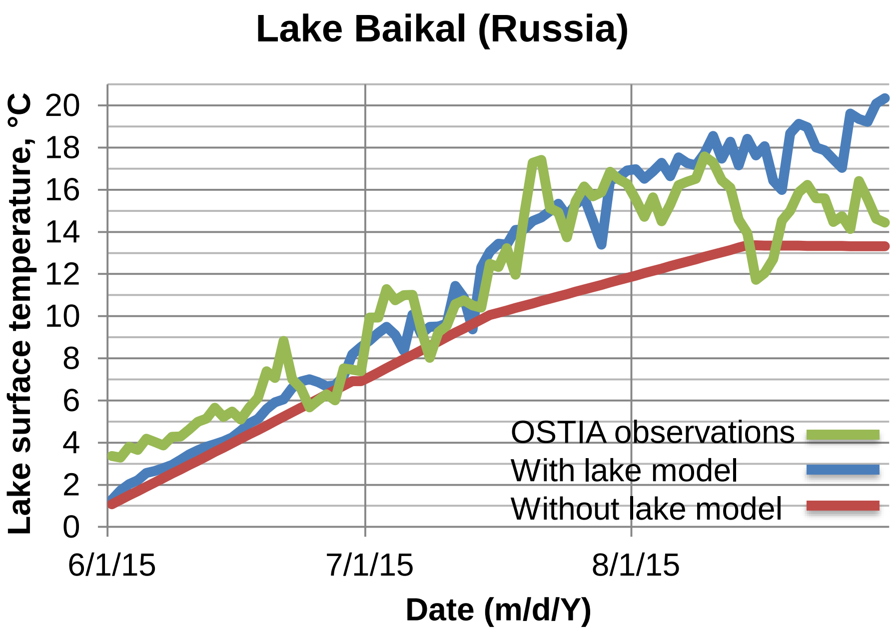
Very good representation by the model of diurnal cycles and particularities of each surface!

Lake surface temperature: Diurnal cycles

Large improvements:

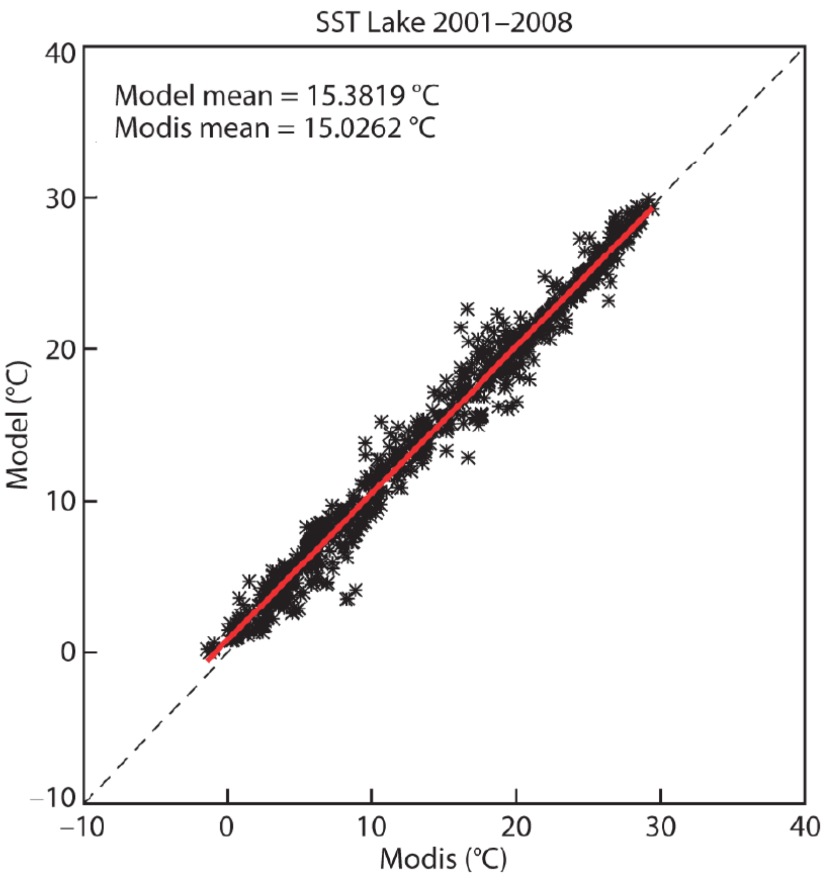
- **reducing** the lake temperature **bias for big** and **deep lakes** (e.g. Lake Victoria, Great Bear, Titicaca);
- generally more **realistic** temperature **diurnal variability**.





Lakes surface temperature: global validation

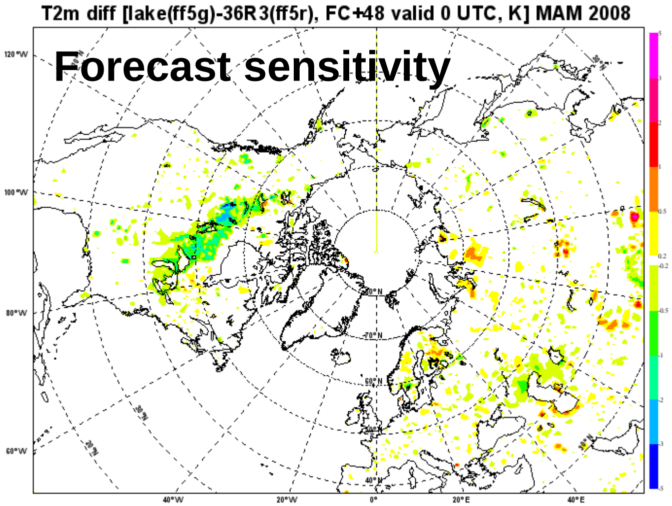
(Balsamo et al., 2012)



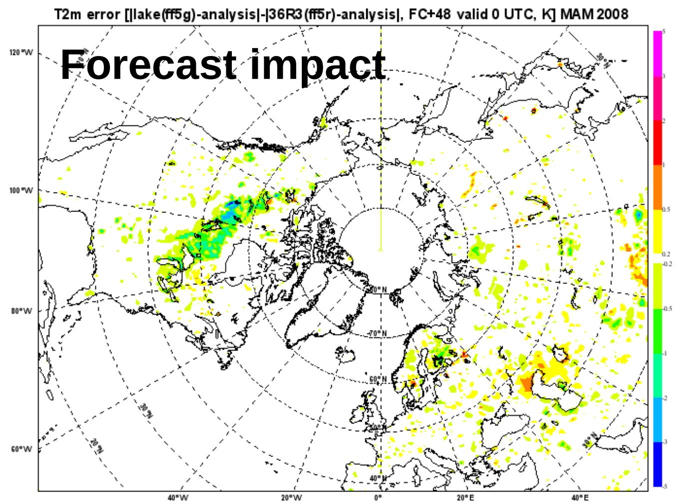
- **In-situ**: *MODIS* Terra/Aqua satellite global composite based on the Level 3 Mapped Thermal IR sea surface temperature product, which senses the *sea/lake water temperature*, *resolution ~4 km*.
- **Model**: *FLake* model driven by *ERA-Interim* 3-hourly atmospheric forcing, *resolution ~80 km*.
- **Period**: 2001.01.01-2008.12.31.
- **Comparison** in terms of annual mean surface water temperature values:
  - ✓ largely *unbiased* simulation over grid points where the model lake fraction is ≥ 10 %:
    - ❖ **good correlation** between **modelled** and **observed** annual mean R = 0.98;
    - ❖ **BIAS** (modelled – observed) is **reduced**, is < 0.3 K;
  - ✓ largest differences are found over Caspian sea and southern regions of the North-American Great Lakes (positive BIAS) and over Norwegian lakes (negative BIAS) → consistent with model intrinsic **limitations over deep waters**.

Impact of lakes in NWP forecasts

(Balsamo et al., 2012)

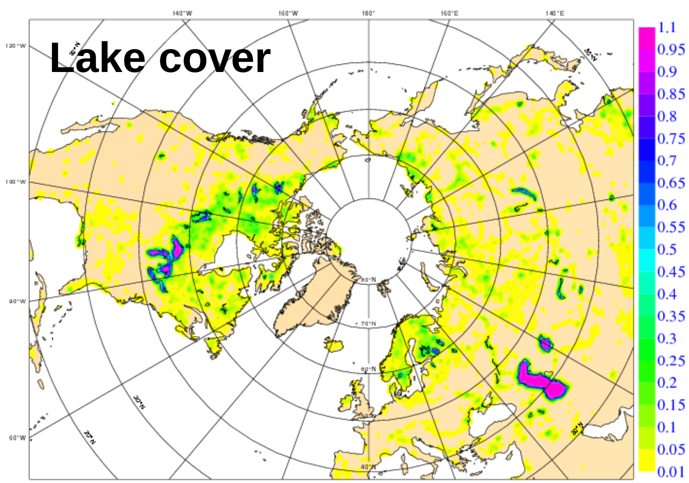


Cooling 2m temperature
Warming 2m temperature



Improves 2m temperature
Degrades 2m temperature

Here is shown **spring sensitivity** and **error impact** on **temperature** when **lake** model is **activated**.



Forecasts sensitivity and impact show **spring-cooling over lake** areas with benefit to the 2-meter temperatures forecasts (day-2, 48-hour forecast).

ERA-Interim forced runs of FLake model are used for **lake model climatology** generation, which serves as **initial conditions in forecasts experiments**.

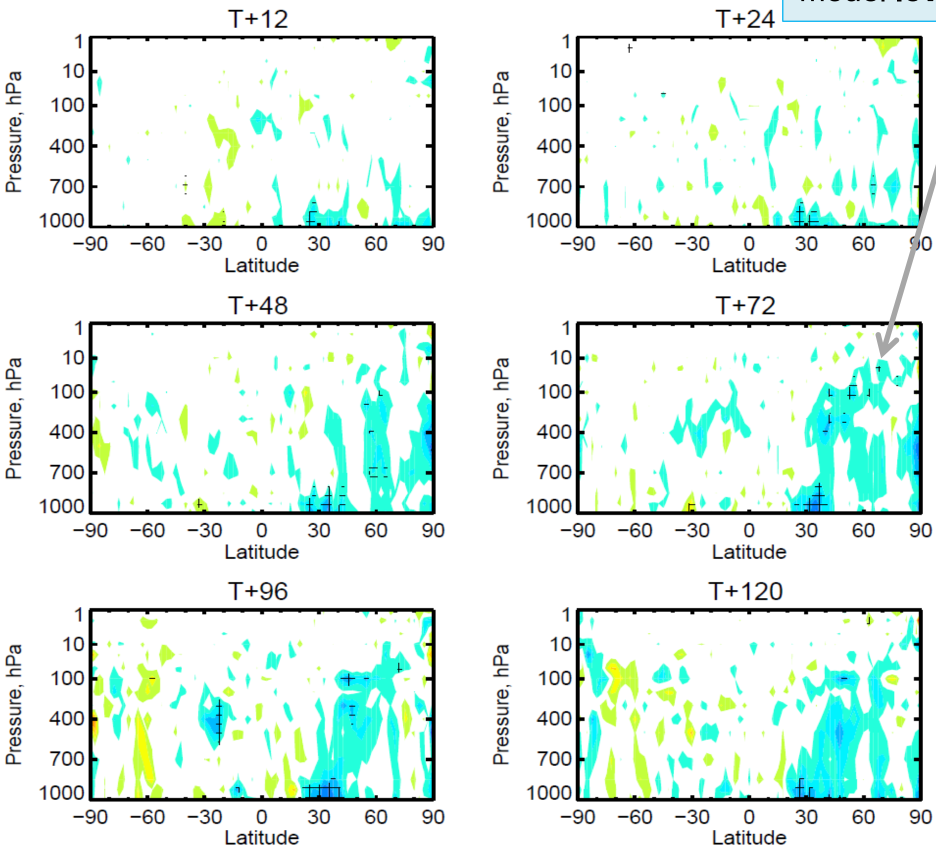
Impact of lakes in NWP analysis cycles (1)

AN cycling and initialisation: temperature scores

Summer experiment

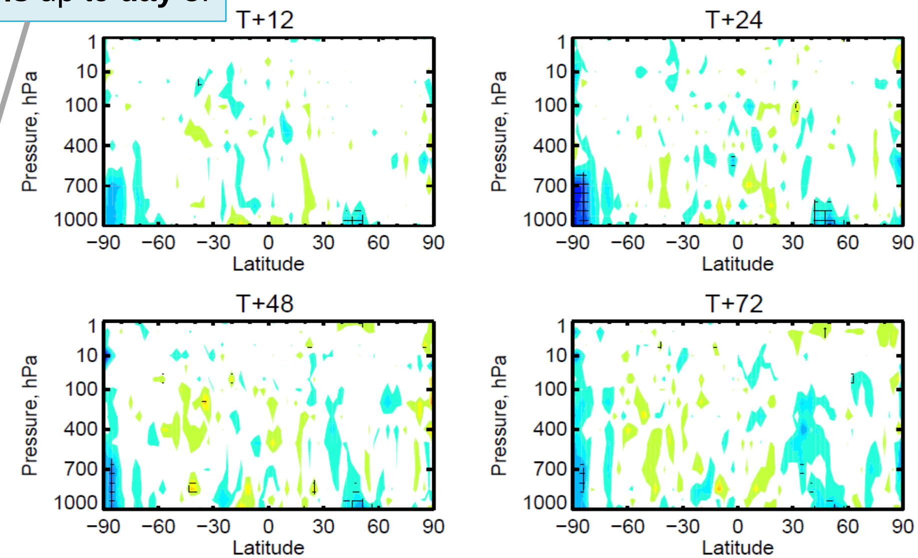
15–Jun–2013 to 5–Jul–2013

Propagation of the **positive impact** to **higher** model **levels** up to **day 5**!



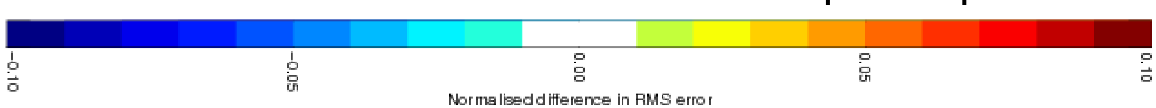
Winter experiment

1–Dec–2013 to 31–Dec–2013

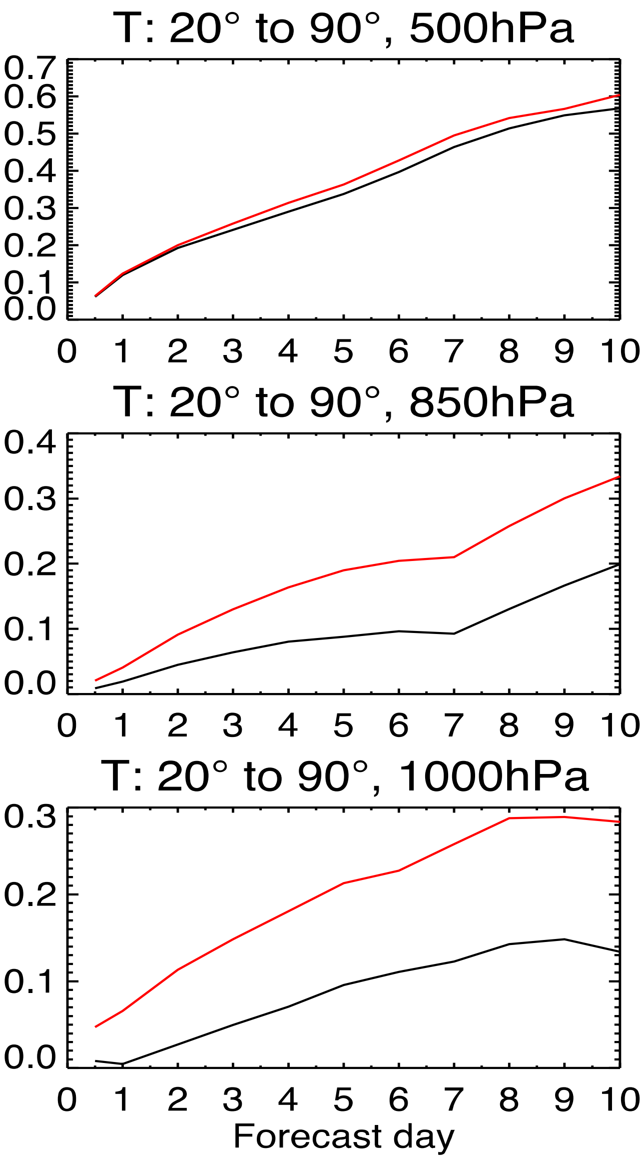


Transition period lake open water / ice covered modelling is **very challenging** and requires a **careful initialisation**.

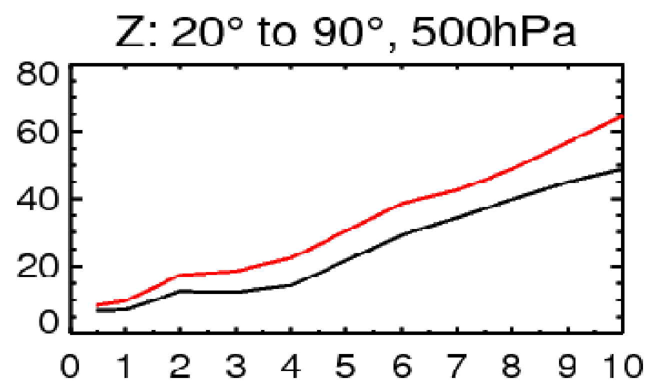
Sea-ice is probably in a **similar situation** (predictive skill is severely affected by the lack of atmospheric predictability in winter).



Impact of lakes in NWP analysis cycles (2)



- During **summer** lake **impact** is not confined to the surface layer but **propagates upwards reducing** the mean model **temperature error** over **Northern** hemisphere (e.g. at 850 hPa).
- Part of the **signal** is also **detected** in **Z500** (geopotential height at 500 hPa), which gets a lot **attention from meteorologists!**



mean error of CY40R3 with lakes

mean error of CY40R3 without lakes

Summary & Outlook

- **The ECMWF land surface scheme and its extension to lakes**
  - ✓ The introduction of subgrid lakes and coastal waters enhances the capacity of representing natural Earth surface heterogeneity.
- **Benefits of considering sub-grid lakes**
  - ✓ Each tile has its process description (no ad-hoc or effective parameters).
  - ✓ All inland water bodies considered independently from their size, shape and depth.
- **Atmospheric forecast impact**
  - ✓ The introduction of interactive lakes has beneficial impact on forecast accuracy.
  - ✓ Impact is significant and detected in Northern Hemisphere scores.
- **The verification phase**
  - ✓ Use of satellite based lake temperature and lake ice information has potential to allow a routine verification of lakes that can foster further improvements.

Thank you for your attention!

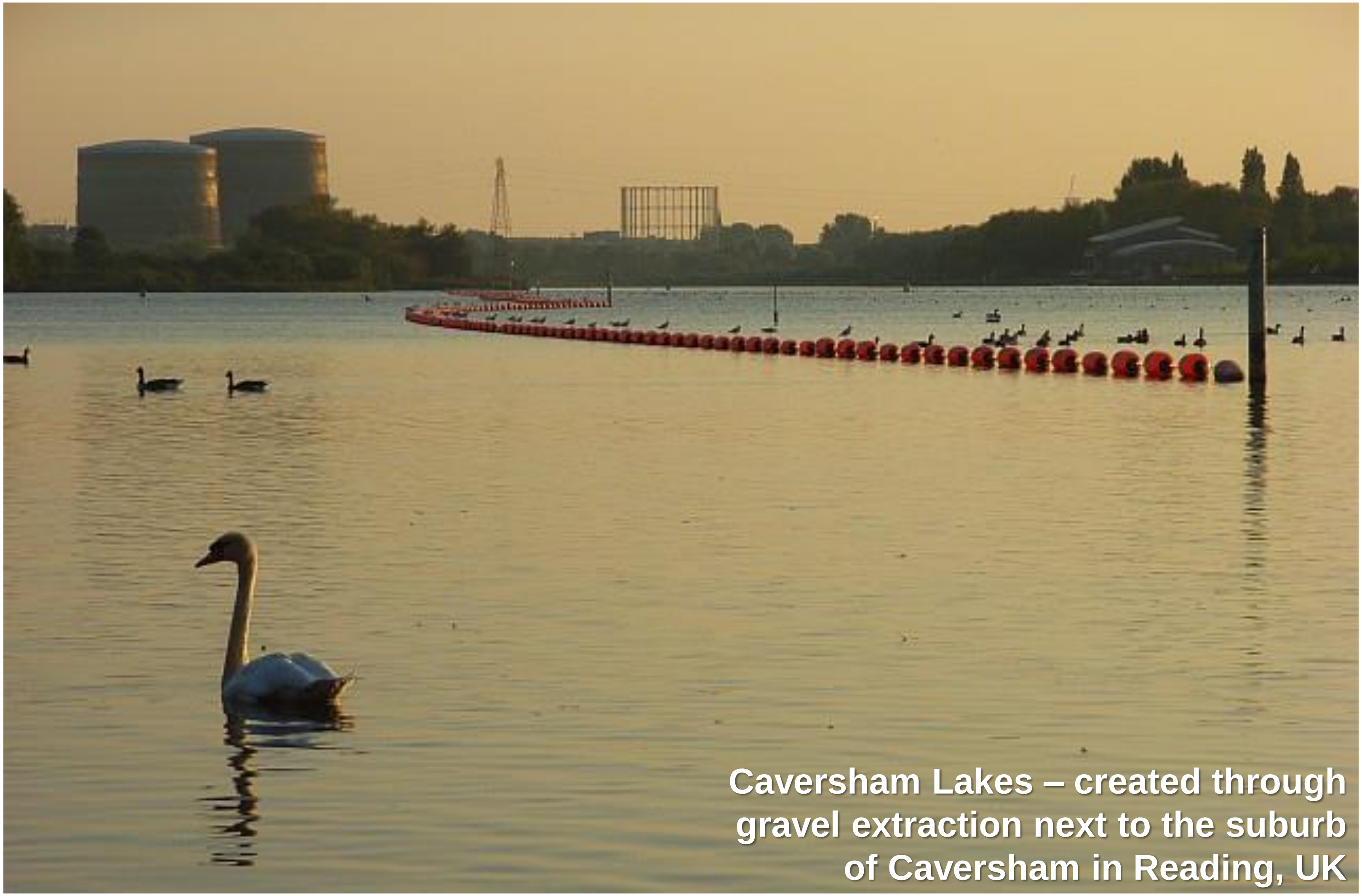


Photo from www.touropia.com

ECMWF

Lake surface temperature: point validation

Lakes verification in the first three full months June-July-August 2015 (91-days AN vs OSTIA-lake) of operations → large improvements on the majority of lakes according to the OSTIA satellite products.

Lake AFRICA	RMSE	BIAS	CORRELATION	Mean Model	Mean Obs	St.Dev. Model	St.Dev. Obs
Victoria_IFS41R1	**0.957**	**0.826**	0.491	25.665	24.849	0.554415	0.230933
Victoria_IFS40R1	3.157	-3.14	0.328	21.743	24.849	0.322463	0.230933

Lake CANADA	RMSE	BIAS	CORRELATION	Mean Model	Mean Obs	St.Dev. Model	St.Dev. Obs
Great_Bear_IFS41R1	**2.875**	**1.877**	0.927	5.225	3.368	3.87317	1.96852
Great_Bear_IFS40R1	5.401	4.598	0.894	7.916	3.368	4.45394	1.96852

Lake S. AMERICA	RMSE	BIAS	CORRELATION	Mean Model	Mean Obs	St.Dev. Model	St.Dev. Obs
Titicaca_IFS41R1	**0.611**	**-0.425**	0.822	12.322	12.742	0.739826	0.482809
Titicaca_IFS40R1	3.804	-3.789	0.752	8.995	12.742	0.463688	0.482809

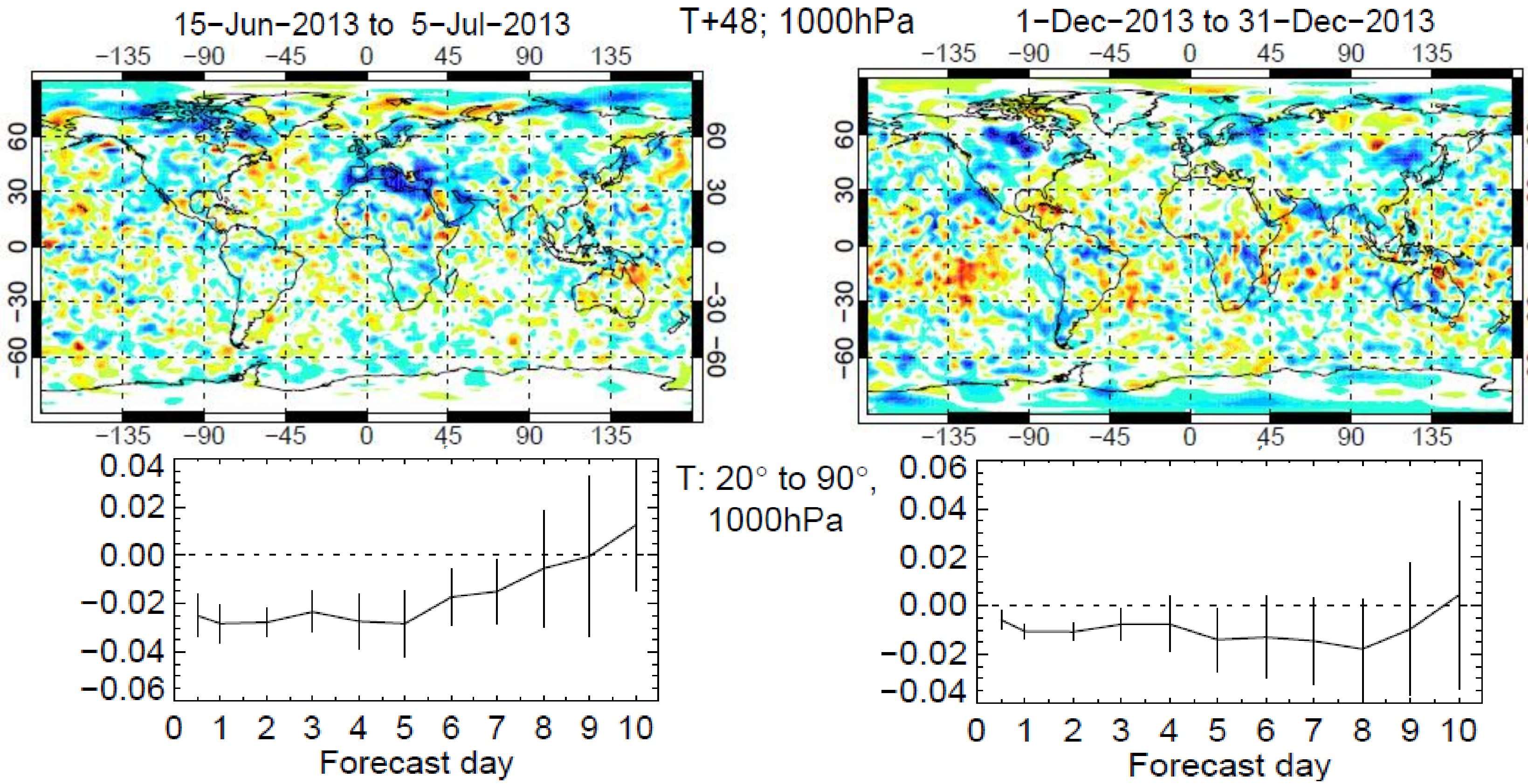
Lake EU	RMSE	BIAS	CORRELATION	Mean Model	Mean Obs	St.Dev. Model	St.Dev. Obs
Ladoga_IFS41R1	**2.45**	**2.051**	0.958	14.207	12.178	4.22985	4.60613
Ladoga_IFS40R1	1.443	-0.295	0.984	11.886	12.178	3.3881	4.60613

Lake sub-grid EU	RMSE	BIAS	CORRELATION	Mean Model	Mean Obs	St.Dev. Model	St.Dev. Obs
Haukivesi_IFS41R1	**1.706**	**-0.02**	0.807	15.188	15.207	2.24239	2.88615
Haukivesi_IFS40R1	2.915	-2.733	0.964	12.504	15.207	3.44774	2.88615

Impact of lakes in NWP analysis cycles (3)

AN cycling and initialisation: temperature scores

Summer experiment | ***Winter experiment***



- In lake and coastal water proximity 2-meter temperature forecast is improved.
- During summer there is 2-3 % of relative improvement in 1000 hPa temperature RMSE, with significance of up to 7 days.
- During winter RMSE impact is also positive and around 1 %.