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METEOROLOGY

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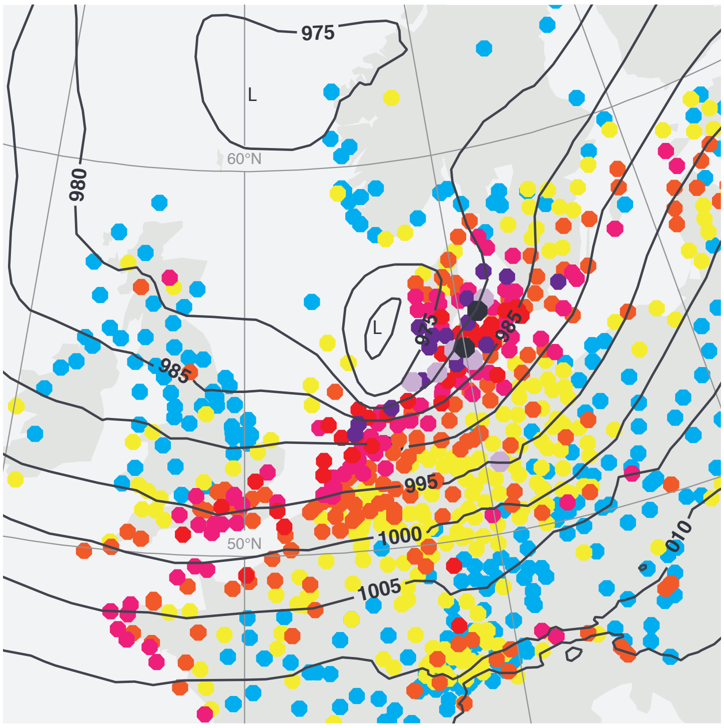


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# Interactive lakes in the Integrated Forecasting System

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Lakes are an important component of the land surface – they can influence the weather on local to regional scales. Their characteristics differ substantially from the surrounding land primarily due to the differences in albedo, roughness and heat storage. However, until recently they have been neglected in most numerical weather prediction (NWP) models.

Research aimed at introducing lakes into the operational NWP models at ECMWF has started by first considering medium-complexity schemes that can satisfy the constraint of having a low computational cost. FLake (*Mironov et al.*, 2010), a freshwater lake scheme, is a particularly appropriate choice of scheme as it predicts the vertical temperature structure and mixing conditions in lakes of various depths on time scales from a few hours to a few years, while maintaining a relatively low number of prognostic fields (7 in total). The model is intended for use as a lake parametrization scheme in NWP, climate modelling and other prediction systems for environmental applications. FLake has been implemented in the operational regional weather forecast model of Deutscher Wetterdienst (the German weather service) and used for research at several meteorological services across Europe including Météo-France, UK Met Office and Swedish Meteorological and Hydrological Institute.

FLake has been assessed for implementation in the atmospheric model of ECMWF's Integrated Forecasting System (IFS) using a set of preparatory studies: first in an offline experimental framework by *Dutra et al.* (2010) and *Balsamo et al*. (2010), and then extended to a fully-coupled lake-atmosphere simulations by Balsamo et al. (2012). More recently the possibility of treating sub-grid lakes using the land surface tiling methodology has been considered. With this approach each grid box is divided into fractions of different types of land use represented by the tiles. *Manrique Suñén et al*. (2013) have assessed the merits and limitations of the tiling methodology when there are contrasting surfaces by using field observations from a Finnish pine forest (Hyytiälä) and a small nearby lake (Valkea-Kotinen). The surface energy budgets are shown in Figure 1 as observed at the sites and simulated by the IFS land surface scheme extended with a lake tile (from FLake). These results show that the land surface model is able to characterize the main difference between the two sites.

The capacity of treating sub-grid water bodies within each model grid-box is thus important for providing more accurate boundary conditions to the atmosphere. Consequently, the lake model has been configured to allow the coupling of both resolved and sub-grid lakes (those that occupy less than 50% of a grid-box) to the IFS atmospheric model.

The set of preparatory actions to introduce the lakes in the Integrated Forecasting System at ECMWF covers the areas: (a) preparation of the ancillary datasets (lake cover and lake depth), (b) preparation of the lake initial conditions over the past 35 years and (c) evaluation of the impact of including lakes in several operational configurations and a variety of spatial resolutions.

The response of short-range weather forecast for near-surface temperature to the representation of lakes is examined in a set of forecast experiments covering one full year with FLake activated and in two analysis experiments covering two-months in winter and summer.

It has been found that the impact of sub-grid lakes is beneficial in reducing forecast error over the northern territories of Canada and over Scandinavia, particularly in spring and summer seasons. This is mainly attributed to the heat storage effect of the lakes, which delays the seasonal temperature cycle.

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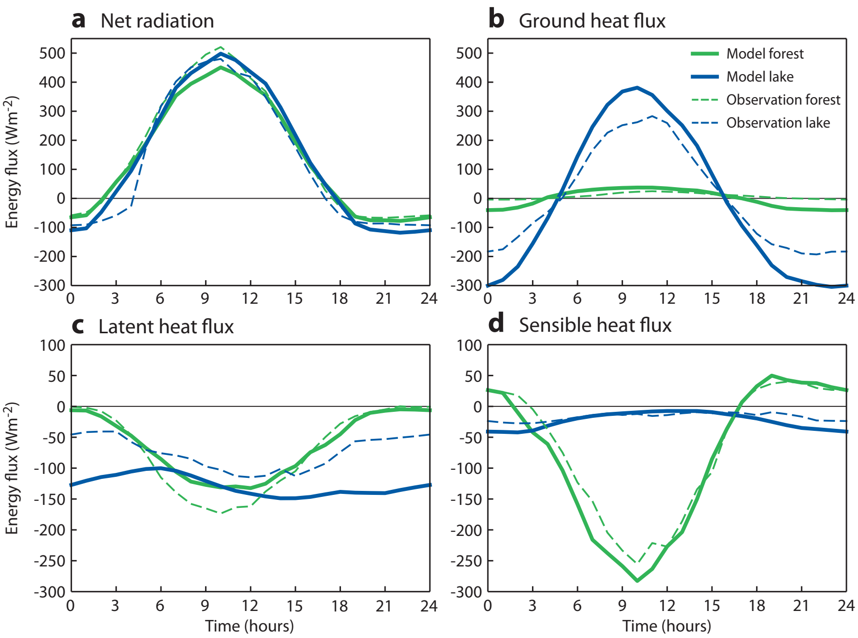


**Figure 1** Mean diurnal cycle of energy fluxes for July over a Finnish lake and a near-by forest measured by eddy-covariance and simulated by the lake and forest tiles of the IFS land surface scheme.

## FLake implementation at ECMWF

FLake is suitable for NWP and climate modelling due to its accuracy and low computational cost. It is based on a two-layer representation of the time-evolving temperature profile and on the budgets of heat and kinetic energy. For more information see Box A.

Global fields for lake cover and lake depth, as well as initial conditions for the lake physical state, have been derived in order to start the forecast experiments.

In the version of FLake used with the IFS atmospheric model the constant spatial fields of lake cover and lake depth are derived as follows.

- ***Lake cover.*** The lake cover is provided by data from the US Department of Agriculture - Global Land Cover Characteristics (GLCC) – see Figure 2.
- ***Lake depth.*** This variable is only available for a few lakes and it represents a real challenge for remote sensing. Use was made of the compilation of lake depths provided by Kourzeneva et al. (2010) supplemented by data about the Caspian Sea. The lake depth data was then merged with ocean depth data so that the performance of FLake could be assessed for coastal regions – see Figure 3.

Lakes constitute a new modelling component, with a set of new prognostic variables (i.e. mixed layer temperature and depth, bottom and average temperature, shape factor, and lake ice temperature and depth). So a way has to be found of setting up of initial conditions needed to initialize the IFS high-resolution forecast – see Box B.

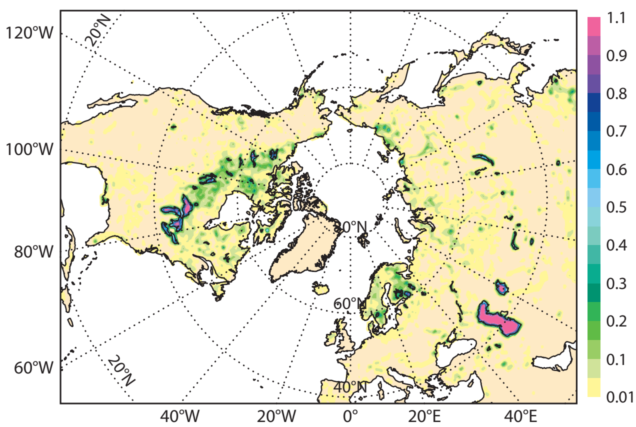


**Figure 2** Lake Cover as a fraction of a gridbox as provided by the GLCC land-cover map. Lakes are only included if they occupy more than 1% of a grid box.

## FLake in the IFS atmospheric model

A

The structure of the stratified layer between the upper mixed-layer and the lake bottom, the thermocline, is described using the concept of self-similarity (assumed shape) of the temperature-depth curve. The same concept is used to describe the temperature structure of the lake ice. A new lake tile (unit land cover characteristic) based on FLake has been introduced in the IFS land surface scheme, HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land), for research purposes and has been validated in global offline simulations. In the IFS implementation of FLake the surface fluxes of heat, moisture and momentum are computed by the HTESSEL routines. For the time being snow over lakes is not allowed and there is no representation of the bottom sediment interaction with the water columns.

The prognostic variables included in FLake are: mixed-layer temperature, mixed-layer depth, bottom temperature, mean temperature of the water column, shape factor (with respect to the temperature profile in the thermocline), temperature at the ice upper surface, and ice thickness. There is no water balance equation; the lake depth and the lake surface area (or fractional cover) are the two main ancillary fields input to the model and are kept constant in time.

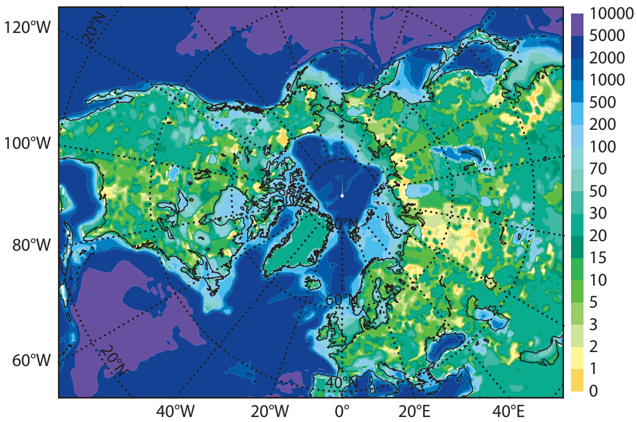


**Figure 3** The merged product consisting of lake and ocean depths. For lakes a default value of 25 m was assumed for inland grid points where there was no information. Also minimum and maximum values of 1 m and 60 m were set. The ocean depths were taken from ETOPO1 a global relief model of Earth's surface that integrates land topography and ocean bathymetry produced by NOAA's National Geophysical Data Centre.

## Verification of FLake output

FLake simulations have been carried out based on the 'lake-planet' configuration – it is assumed each surface grid-box is entirely covered by a lake with the specified lake depth. The main advantage of this configuration is the ease of interpolation to all model grids and resolutions from the GLCC lake cover dataset (which is expected to be updated in the near future).

The realism and accuracy of the FLake results were assessed in terms of lake temperature and ice formation and compared with satellite-based observations (MODIS) at 4 km resolution.

The period between 2001 and 2008 is used for validation. The comparison between model and observations is shown in Figure 4 in terms of annual mean lake temperature. The results are largely unbiased. The largest differences between lake-planet and MODIS surface temperatures are found over the Caspian Sea and the southern regions of the North-American Great Lakes (positive bias) and over Norwegian lakes (negative bias). These results are consistent with the intrinsic limitations of FLake over deep waters (not shown).

The Interactive Multisensor Snow and Ice Mapping System (IMS) (*Helfrich et al.*, 2007) was used to validate the ice formation and break-up dates in the lake-planet simulations. An overall 10-day bias in ice duration is comparable to errors for snow duration over land (not shown). Therefore, these results are considered satisfactory. They highlight, however, the importance of incorporating ice information into operational NWP. An extract of the long-term evolution of lake temperature and lake ice depth for Ladoga Lake is illustrated in Figure 5. This shows the variability in summer maximum temperature (with up to 4°C differences) and the span in ice cover duration.

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## FLake initial conditions

B

A straightforward procedure would be to initialize the model with physically reasonable fields and allow for a long spin up so that fields can reach an equilibrium state (depending on the lake depth, months to years might be necessary to reach this state). However, this is not an option due to the high computational cost of long-term integrations. In this study we used initial conditions derived from a model-based retrospective simulation of lake prognostic fields. This was achieved by carrying out a long-term offline simulation of the land surface scheme forced by the ECMWF ERA-Interim reanalysis.

Lake simulations driven by ERA-Interim meteorological forcing have been realized with a configuration named 'lake-planet'. This assumes each surface grid-box is entirely covered by a lake with the specified lake depth from the merged bathymetry product. The advantage of this configuration is that it provides continuous fields at the water-land interface and thereby allows a simpler interpolation of the simulation output and independence from the lake cover dataset (which can be subject to updates).

The lake-planet experiment consists of a 35 years off-line run (1979–present) of the FLake model driven by 3-hourly atmospheric forcing from ERA-Interim. The ECMWF N128 Gaussian grid was adopted, which has a resolution of about 80 km. The continuity of lake-planet fields permits spatial interpolation of the model climatology onto different target grids (e.g. a higher resolution grid) via standard bi-linear procedures. This procedure permits the initialization of the prognostic variables required for the lake initial conditions for past dates and is essential for the re-forecasts of past weather (that support all anomaly-based products at ECMWF).

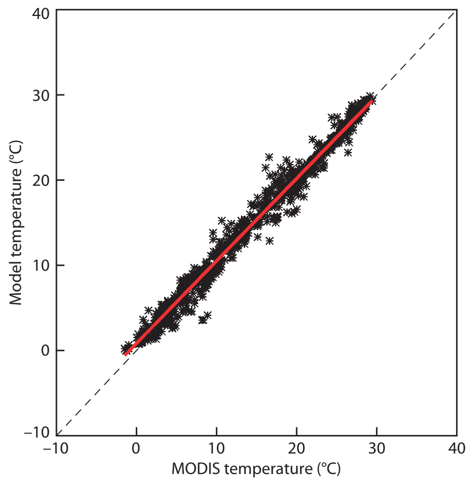


**Figure 4** Comparison between the lake-planet mixed-layer temperature simulations and the MODIS LST for 2001–2008 over grid points where the model lake fraction is greater than 10%.

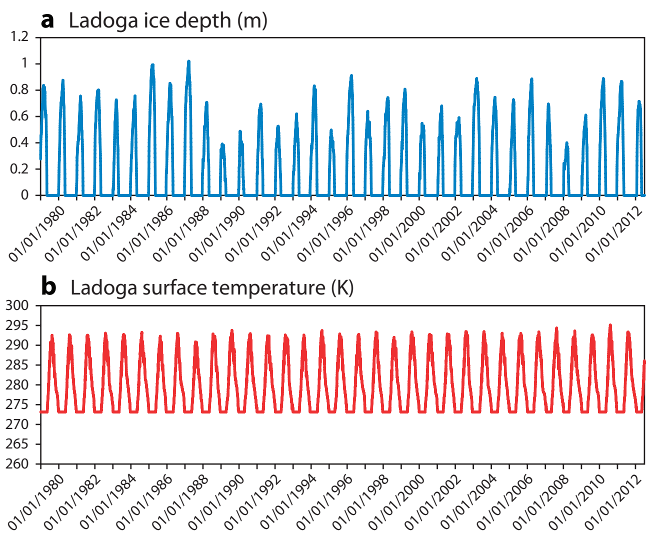


**Figure 5** Extract of the lake reanalysis forced by ERA-Interim for Ladoga Lake showing (a) the ice depth and (b) surface mixed-layer temperature during 1979–2012.

## Forecast experiments

Sets of 10-day forecasts covering one full year have been performed with the operational high-resolution model (version Cy36r3) at T399 spectral resolution (~50 km horizontal resolution). Two experiments were performed with Flake (LAKE) and without FLake (NOLAKE). Forecasts are run 10 days apart to cover the period from 1 January to 31 December 2008 (37 forecasts per experiment). In the NOLAKE experiment, sub-grid lakes are treated as land only and resolved lakes are treated as ocean points with initial surface temperature provided by a monthly climatology lagged by one month (to represent a typical time-scale for lakes to respond to the energy that they are receiving).

For two lakes near real-time data was used for specifying the initial temperature conditions: the Caspian Sea and the US Great Lakes.

The effect of FLake on near-surface air temperature is evaluated for the 48-hour forecasts. In the following discussion 2-metre temperature sensitivity and impact are defined as follows.

- 2-metre temperature sensitivity is the mean difference of LAKE compared to NOLAKE for the 48-hour forecast. This assesses the impact of the LAKE versus NOLAKE representation in terms of whether a warming or a cooling is produced.
- 2-metre temperature impact is the mean absolute error reduction obtained with LAKE compared to NOLAKE, and evaluated with respect to the operational analysis. This is a measure of the added skill of forecasts when lakes are taken into account.

In Figure 6 (right column) the 2-metre temperature sensitivity shows a pronounced cooling effect in spring and summer. This is due to the incoming radiation being stored in the lake (with a relatively small impact on surface temperature) rather than being used to warm the atmosphere. The heat stored during spring and summer (which resulted in an atmospheric cooling) is then released during autumn (leading to a warming of the near-surface air). An additional cooling mechanism is that lakes evaporate more than dry land, resulting in lower near-surface temperatures. This can give an overall cooling when averaged through the year.

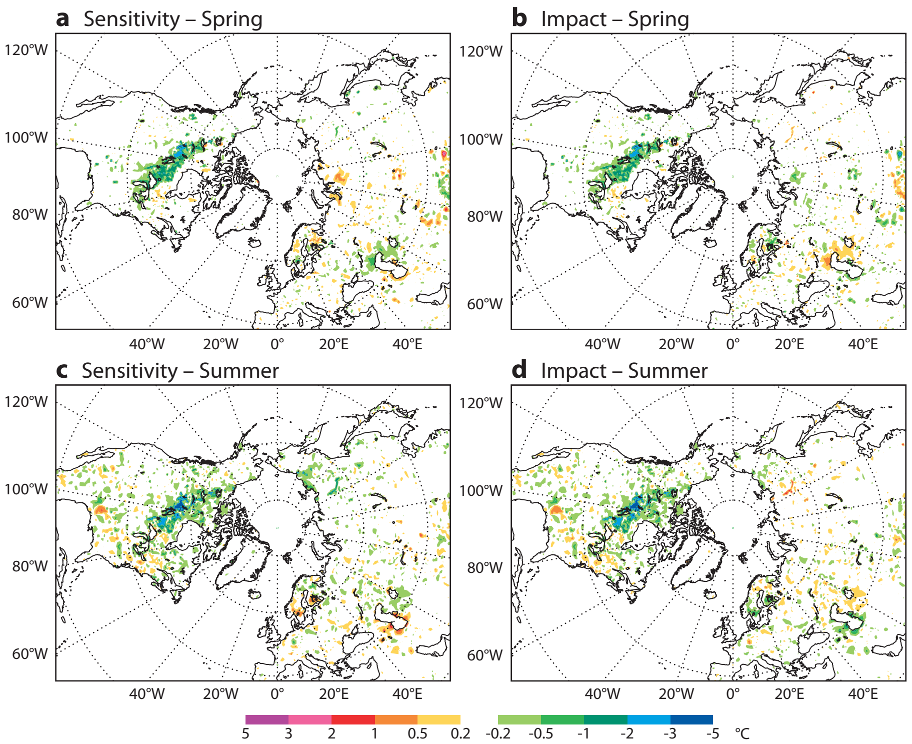


**Figure 6** (a) Sensitivity (i.e. mean difference) and (b) impact (i.e. difference of mean absolute errors) of 48-hour 2-metre temperature forecasts (valid at 00 UTC) for LAKE compared to NOLAKE simulations for spring (March, April, May). (c), (d) As (a) and (b) but for summer (June, July, August). Negative values indicate cooling, which usually translates into a forecast improvement (i.e. reduction of errors compared to the 2-metre temperature analysis).

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The impact of FLake on the forecasts of 2-metre temperature is shown in Figure 6 (left column) by comparison with an analysis of in-situ observations (SYNOP and METAR). A marked positive impact is obtained in spring and summer, particularly in the vicinity of North American lakes and the European large lakes.

Two data assimilation experiments for winter (January and February 2013) and summer (June and July 2012) are performed to assess the temperature forecasts for LAKE compared to NOLAKE. In both cases the forecasts are verified against their own analysis.

Figure 7 shows the results of the assimilation experiments in terms of the reduction in root-mean-square error of the forecast. Use of FLake has had a positive effect in the areas depicted by cyan/blue shading. The winter experiment shows neutral impact across the atmosphere with the exception of an area around the Great Lakes (not shown), while the summer impact is largely positive over the northern hemisphere and it is shown to propagate through the troposphere. These results reflect the better performance of FLake in predicting the surface temperatures in summer compared to the winter season when lake ice predictions are controlling the impact on the atmosphere. Overall the impact of FLake is positive and shows encouraging results for future operational implementation.

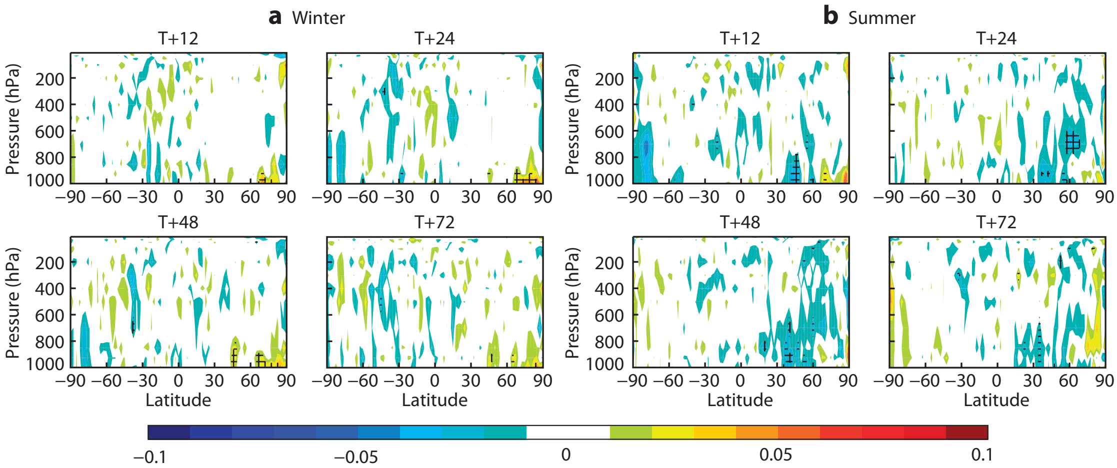


**Figure 7** Impact on the temperature forecasts for LAKE compared to NOLAKE data assimilation experiments verified against the own analysis in terms of normalised difference in root-mean-square error for (a) winter (January and February 2013), (b) summer (June and July 2012). Negative (cyan/blue) areas indicate a reduction in root-mean-square error and therefore an improvement in the forecast (dashed areas indicate 95% significance).

## Summary and outlook

The introduction of lakes via FLake in the IFS atmospheric model produces a realistic delay in seasonal evolution of temperature with a cooling in spring and summer and a warming in autumn. The forecasts that included lake-atmosphere interaction using FLake show a non-negligible impact on near-surface air temperature as a consequence of heat storage in the lakes. Less spring and summer warming is shown to be largely beneficial by significantly reducing forecast errors up to 72 hours; this improvement is particularly evident in the near-surface temperatures. A careful initialization of the lake ice is required in winter cases and this will be subject to further testing. The potential of activating FLake for land points with sub-grid shallow sea-water will be also explored to mitigate forecast biases along coastal areas and estuaries.

The interaction with the lake modelling community has been very beneficial to this work and is acknowledged together with the Nordic Networks (NetFAM, MUSCATEN) that supported the organization of three dedicated lake workshops.

## Further reading

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