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EUSTACE

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EU Surface Temperature for All Corners of Earth

Deliverable D1.8

Auxiliary data to support lake influence in surface air temperature analysis

Deliverable Title	Auxiliary data to support lake influence in surface air temperature analysis	
Brief Description	In this deliverable we provide auxiliary data of lake influence on near-surface air temperature observations. Specifically, we highlight regions across the globe in which near-surface air temperatures are influenced by the presence of lakes and should thus be considered in future interpolation procedures of global air temperature products (e.g. when near-surface air temperature data are generated in the form of continuous regular grids). This report also provides a detailed analysis of the optimum methods for determining a lake region of influence, which will be beneficial for future studies.	
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1. Background

Globally, there are approximately 117 million lakes (>0.002 km^2) with a combined surface area of ~5x10^6 km^2, which is 3.7% of the Earth's non-glaciated land surface [*Verpoorter et al*., 2014]. Despite their relatively small spatial extent, lakes can have a disproportionately large influence on the climate via their influence on surface energy storage and exchange [*Dutra et al*., 2010; *Samuelsson et al*., 2010; *Thiery et a*l., 2015]. Lakes can, in turn, moderate surface air temperature (SAT) variations in their vicinity. This occurs essentially due to the effective thermal inertia of a lake on daily to monthly timescales being much greater than surrounding land surfaces. Specifically, lakes undergo distinct diel [*Woolway et al*., 2016] and seasonal [*Layden et al.,* 2015] cycles of surface temperature compared to the surrounding land areas. Lake surface water temperature (LSWT) influences surface air temperature (SAT) locally as air moves across lakes as part of the general wind field and the atmospheric boundary layer is modified by heat and moisture exchanges that are different to those in surrounding land areas [*Woolway et al*., 2017]. This temperature modification is complex, depending on wind stress, wind direction, fetch, orography, and interactions affecting surface wind stress arising from the thermal contrast between lake and surrounding land [*Desai et al*., 2009]. Overall, lakes of sufficient extent tend to moderate daily SAT anomalies on longer than daily time scales, since lakes integrate daily heat fluxes over time.

The impact of lakes on local, regional, and global climate has been investigated previously [*Samuelsson et al.,* 2010; *Balsamo et al*., 2012; *Thiery et al*., 2015]. At a global scale, General Circulation Model (GCM) simulations demonstrate an average annual cooling influence of lakes on SAT but also highlight important regional and seasonal effects [*Bonan*, 1995]. For example, *Bonan* [1995] investigated the influence of lakes on the global climate using a lake parameterisation scheme within a GCM simulation, which demonstrated that SATs in the 'with' and 'without' lake model runs were statistically different, and that the presence of lakes had a considerable influence on the climate in the lake-rich region of northwest Canada, the Great Lakes region of North America, and the lake region of East Africa. Similar results were reported by *Balsamo et al.,* [2012], who investigated the influence of sub-grid lakes (i.e. those that occupy less than 50% of a grid-box) on SAT globally. Specifically, using ECMWF's Integrated Forecasting System (IFS), driven with ERA-Interim reanalyses, *Balsamo et al.,* [2012] demonstrated that the inclusion of lakes had a considerable influence on SAT predictions for numerous regions from around the world, and that the lake influence was not restricted to the air directly above any lake but could also be observed several tens of kilometres from the lake location. Regional Climate Model (RCM) studies have been performed at higher spatial resolution, thereby emphasizing better the lake-atmosphere interplay at the local scale [*Samuelsson et al.,* 2010; *Thiery et al*., 2015]. For example, *Samuelsson et al*., [2010] investigated the impact of lakes on the European climate by analysing two 30-year RCM simulations. Specifically, a simulation where all lakes in the model domain were replaced by a representative land surface was compared to a simulation where the effects of lakes were accounted for via the use of the freshwater lake model, FLake [*Mironov et al*., 2010], coupled to the RCM. These results demonstrated that lakes induced a warming effect on the European climate in all seasons, being highest in autumn and winter, and in some regions a warming effect in excess of 1°C was reported. In the African Great Lakes region, *Thiery et al*., [2015] investigated the impact of lakes on the regional climate in the same way. *Thiery et al*., [2015] demonstrated that three major African Great Lakes (Albert, Tanganyika, Victoria) cool the annual near-surface air by up to 0.9°C, on average.

In climate research, near-surface air temperature data are commonly generated in the form of continuous regular grids, allowing data to be used for regional or global climate monitoring as well as for comparisons with the outputs from Numerical Weather Prediction (NWP) and climate models. Interpolation or averaging procedures (e.g. simple aggregation of data in grid boxes) are therefore commonly used to transform observational point data to values representative for grid cells of regular size and distance. A variety of interpolation methods can be used to derive continuous SAT data based on point observations [*Li and Heap,* 2008]. In cases of relatively coarse grid sizes [*Smith et al*., 2008; *Hansen et al*., 2010; *Morice et al*., 2012; *Rohde et al*., 2013], which typically cover monthly values at 5° spatial resolution, with a high number of observations per grid cell, simple averaging techniques are sufficient. However, for relatively fine grids, such as daily SAT at 0.25°, as generated by EUSTACE from 1850, the SAT at a given location has to be estimated on the basis of information from surrounding data points. A widely used deterministic interpolation approach for near-surface air temperature is the inverse distance weighting method, in which the information of nearby station data is used to determine the SAT at a certain target coordinate, expecting a decrease of influence with increasing distance (i.e. stations situated further away will have less influence). However, other interpolation methods, such as those involving probabilistic elements, are also commonly used (e.g. kriging). In addition, the influence of local characteristics, which can influence SAT, such as altitude, surrounding vegetation, and topography, are also often included in the interpolation procedure [*Brinckmann et al.,* 2016]. However, **the presence of lakes has not yet been used to inform global surface air temperature data sets,** despite the known influence of lakes on nearby SAT and the numerous studies that have demonstrated the added value of resolving individual lakes and realistically representing LSWTs in NWP and climate models. To address this research gap, we present a simulation-driven analysis of information quantifying the region of influence (ROI) of lakes on SAT at daily timescales, which can be used in future analyses to improve the interpolation of SAT observations and thus provide more realistic SAT reconstructions globally, in particular in regions where lakes are abundant.

2. Aims and Objectives

To determine regions of lake influence globally we follow a two-step approach:

1. Determine optimum methods for deriving regions of lake influence on nearby SAT for one case study site, Lake Victoria, East Africa. This involves evaluating the usefulness of two separate modelling experiments to predict a lake region of influence (see details below).
2. Use the optimum methods, as determined in (1), for computing regions of lake influence on SAT globally.

The two modelling experiments evaluated in this investigation (i.e. in point 1 above) for determining a region of lake influence vary in complexity. The first modelling experiment investigates solely the influence of high-resolution LSWT variability on nearby SAT. Specifically, we propose that if high-resolution variations in LSWT have a considerable influence on nearby SAT it should be possible to determine a lake ROI by comparing two separate model runs, one with prescribed climatological LSWT and the other with prescribed high-resolution LSWT observations. If substantial differences were calculated between the SAT of these simulations, it would demonstrate that the high-resolution variability in LSWT has a substantial influence on SAT compared to the climatology. However, if minimal differences were observed between these simulations, it would either suggest the lake had no influence on the nearby SAT or that the high-resolution variability in LSWT is too similar to the climatological values to impose an influence on SAT and a more sophisticated model experiment is needed to determine a lake ROI. The second modelling experiment investigates the influence of the lake presence on SAT variability, which involves performing two model runs, one with SAT simulated by an RCM with prescribed high-resolution LSWT observations and the other where the lake is replaced by representative land pixels. Thus, whilst the first model experiment concentrates on the influence of highly variable LSWT on nearby SAT, the second model experiment investigates the influence of the lake presence on the regional climate. As we know from previous studies, lakes can impose a large influence on nearby SAT. Thus, whichever of the above model experiments also identifies a region of lake influence on nearby SAT in Lake Victoria, will be used in the global experiment of regions of lake influence. Specifically, from these model experiments (as described above) we will select the optimum method for detecting a lake ROI, which could be used globally. The above objectives will be used to provide a global map of regions of lake influence on SAT, which can then be used to inform future SAT analyses. This includes providing information on the regions near lakes in which SAT has been modified by the lake presence, by ≥0.1°C, and thus should be considered in any infilling method.

3. Regional climate modelling of Lake Victoria

3.1 Influence of high-resolution lake variability

To investigate the influence of high-resolution LSWT variability on SAT we compare two separate model runs, both using HadGEM3-RA, a regional atmospheric model based on the atmospheric component of the Earth System Model developed by the UK Met Office Hadley Centre, i.e. HadGEM3. Specifically, two separate modelling experiments, using HadGEM3-RA, are used to discern the influence of LSWT variability on regional SAT in East Africa. The set-up and implementation of the two models discussed are identical, apart from differences in the driving LSWT data. The first of these models uses monthly climatological LSWT (herein denoted as the 'Climatol LSWT' run), whereas the second model uses daily LSWT (herein denoted as the 'Daily LSWT' run). Here we provide further information on the model set-up, validation, and the calculated differences in SAT between model experiments.

3.1.1 Model set-up

Both the Climatol and Daily runs are driven by the same ERA-Interim reanalysis data, used as input for the initial atmospheric conditions. For sea surface temperature (SST) information over the Indian Ocean, which is within the model domain, both the Climatol and Daily runs use SSTs from the Reynolds dataset of daily high resolution blended analyses for SST (Reynolds et al., 2007). This dataset has a spatial grid resolution of 0.25º and has been interpolated on to the RCM grid using bi-linear interpolation. With regards to LSWT, the

'Climatol' run represents Lake Victoria as an inland sea point with surface temperatures provided by a monthly climatology of night time temperatures from the ARC-Lake dataset (ATSR2 and AATSR; MacCallum and Merchant, 2012). The 'Climatol' run spans the period 1981-2012. The 'Daily' run also uses the ARC-Lake data for LSWT but daily observations are used instead of the monthly climatology. The Daily LSWT run spans the period 1995-2012, which is shorter than the Climatol run due to the length of the ATSR2/AATSR datasets used for LSWTs. A comparison of the LSWTs used in both the Climatol and Daily LSWT running across one annual cycle can be seen in Figure 1. Differences between the two datasets are a few tenths of 1°C across much of the lake. However, because of the higher spatial and temporal resolution LSWT data used in the Daily run, we would expect this to provide a more realistic representation of Lake Victoria surface conditions as compared to the climatology.

3.1.2 Model validation

For quality assurance, we have performed some basic validation of large-scale dynamics for the Daily LSWT run, to ensure consistency with both the Climatol LSWT run and the ERA-Interim driving data. This validation was performed prior to the model simulations completing, and therefore only compares model output data from June 1995 – August 2008. Figure 2 compares 1.5 m air temperature across the Climatol and Daily LSWT runs, as well as the driving ERA-Interim data. Seasonal average comparisons are performed for four seasons within the annual cycle: March-April-May (MAM), June-July-August (JJA), September-October-November (SON) and December-January-February (DJF). It can be seen in Figure 2 that near-surface air temperatures are consistent with the driving ERA-Interim data for both the Daily and Climatol LSWT model runs, for all seasons in the annual cycle.

3.1.3 Preliminary Analysis

As a preliminary step towards assessing the effect of varying Lake Victoria surface temperatures on regional climate dynamics, a comparison between the two model simulations has been performed. Comparison of the mean, minimum and maximum 1.5m air temperature between the Climatol and Daily runs for the region surrounding Lake Victoria (Figs 3 and 4) illustrates that the differences in simulated near-surface air temperature are minimal and within the magnitude expected from the internal variability of the model; there is little variability in this diagnostic between different seasons (not shown).

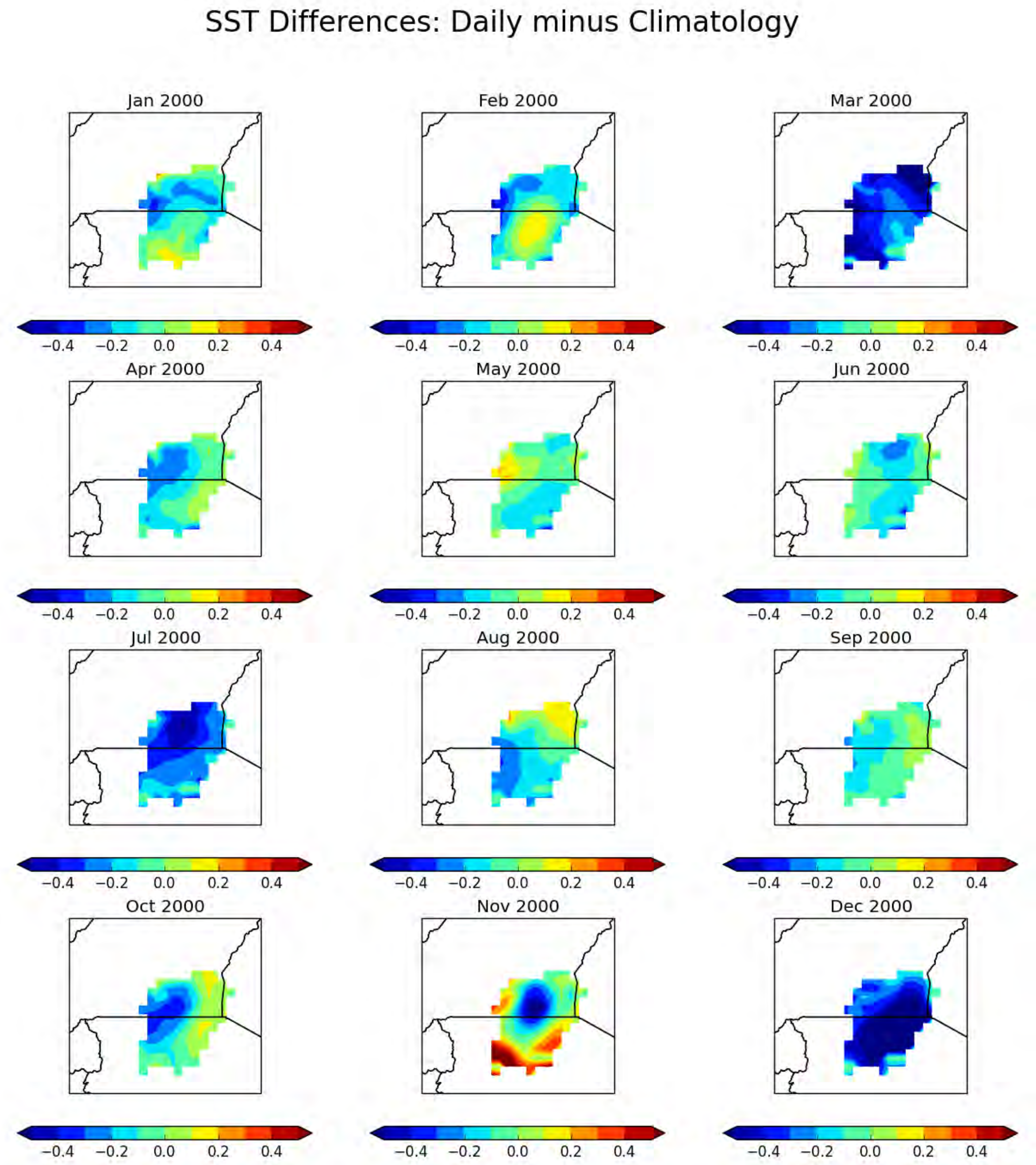

Figure 1. A comparison of Lake Victoria lake surface water temperatures °C across the annual cycle in the year 2000. Differences between the prescribed LSWT in the Daily minus Climatol LSWT model runs.

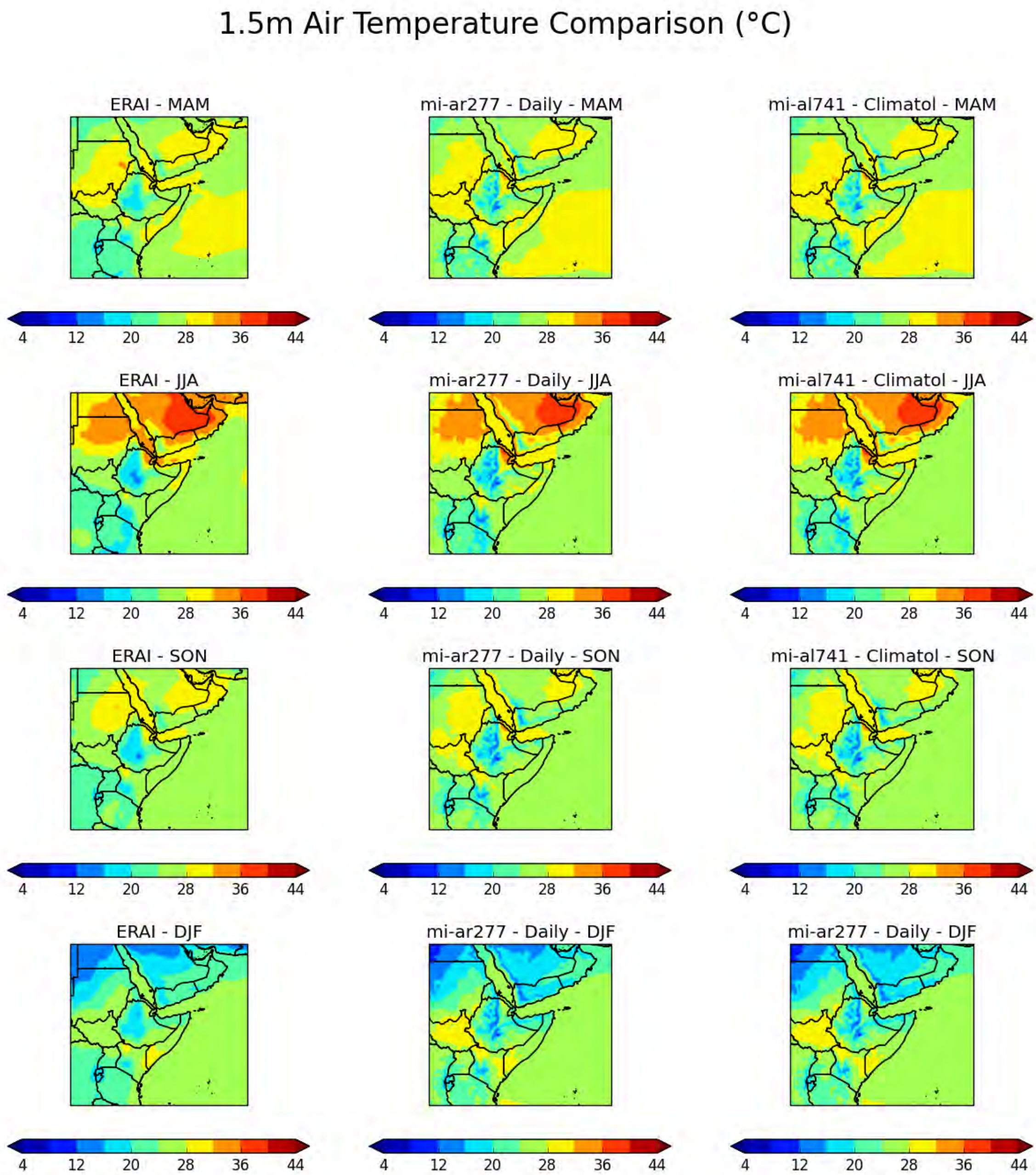

Figure 2. Seasonal average 1.5 m air temperature (°C) for MAM (top row), JJA (second row), SON (third row) and DJF (bottom row), across the ERA-Interim driving data (left column), the Daily LSWT run (middle column) and the Climatol LSWT run (right column).

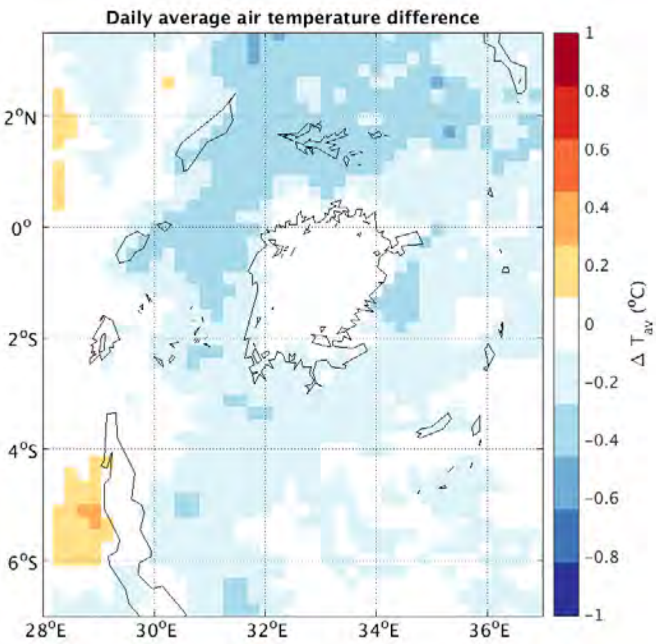

Figure 3. Annual average of daily average 1.5 m air temperature difference between Climatol LSWT and Daily LSWT run

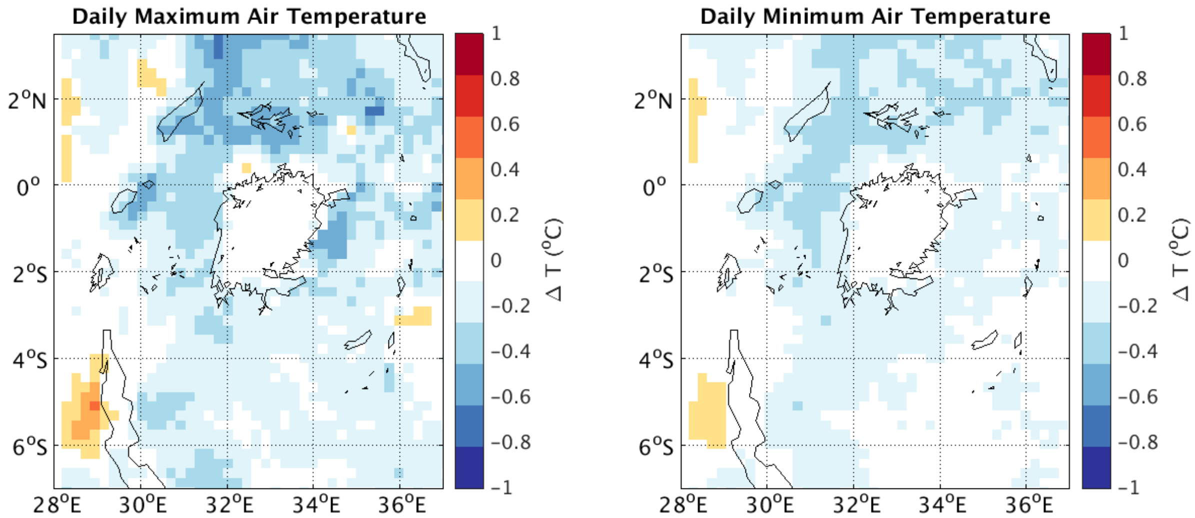

Figure 4. Annual average of daily maximum (left) and minimum (right) 1.5 m air temperature difference (daily minus climatological) (°C) between Climatol LSWT and Daily LSWT run

3.1.4 Comparison with other model experiments

Our model experiments, using HadGEM3-RA, demonstrate a negligible influence of high-resolution LSWT variability on the regional climate (i.e. SAT) of Lake Victoria. However, previous studies (as described in Section 1) have identified a considerable influence of lakes on their surroundings. This suggests that the modelling approach followed may not be suitable to capture the lake effect on regional SAT and determine a lake ROI, in particular when LSWT variability is relatively small (e.g. the within-year variability in LSWT in tropical lakes is relatively small, in the order of a few °C).

3.2 Influence of lake presence

To investigate the impact of the presence of lakes on the regional climate we use the Consortium for Small-Scale Modeling model in climate mode (COSMO-CLM) coupled to the Freshwater Lake model (FLake) and Community Land Model (CLM), which was used to dynamically downscale a simulation from the African Coordinated Regional Downscaling Experiment (CORDEX-Africa) to 7-km grid spacing.

Models involved are:

- COSMO-CLM = Consortium for Small-scale Modeling-Community Land Model
  - To investigate the influence of the African Great Lakes on the climate, we use the 3-D, non-hydrostatic regional climate model, COSMO-CLM (version 4.8). A detailed description of the model system dynamics, numeric and physical parameterizations can be found in the model documentation (e.g. http://www.cosmo-model.org).
- FLake = Freshwater Lake model
  - As a one-dimensional lake model embedded in COSMO-CLM, FLake computes the evolution of a lake column temperature profile and the integral energy budgets of its different layers. A detailed description of FLake is provided by Mironov et al. (2010).

Here we compare simulated SAT for simulations in which (i) Lake Victoria (and other African Great Lakes) is a resolved feature of the landscape and (ii) Lake Victoria is replaced by representative land pixels from within 50 km of the lake (Fig 5).

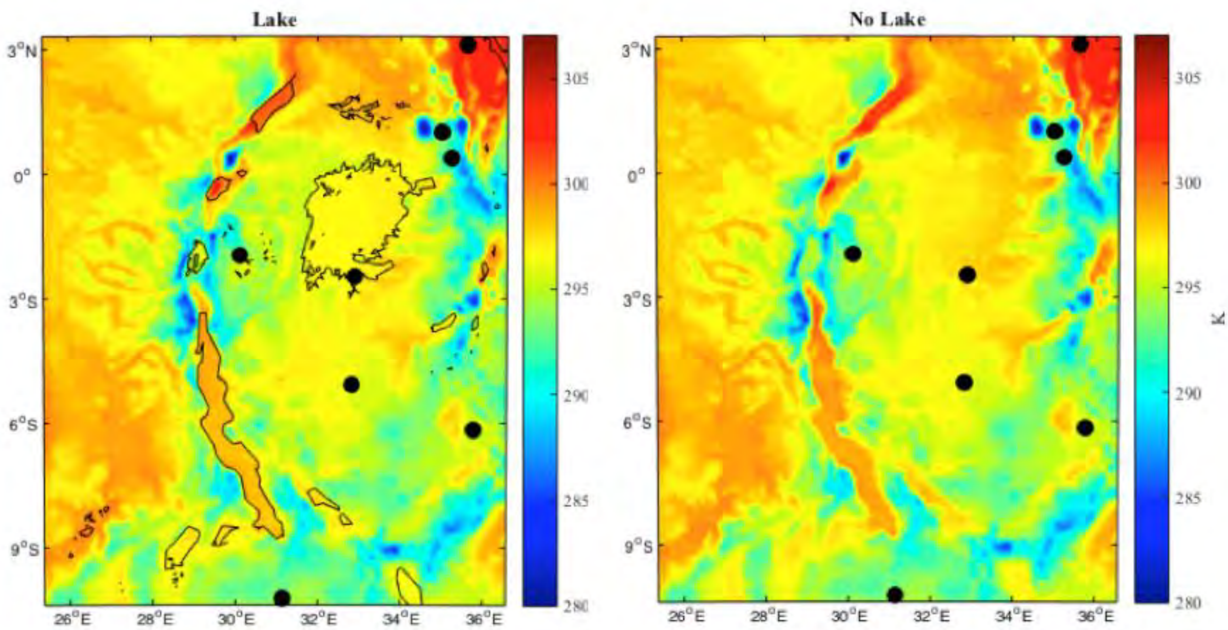

Figure 5. Model with (left) and without (right) lake presence. Nearby SAT observation locations are shown with black markers.

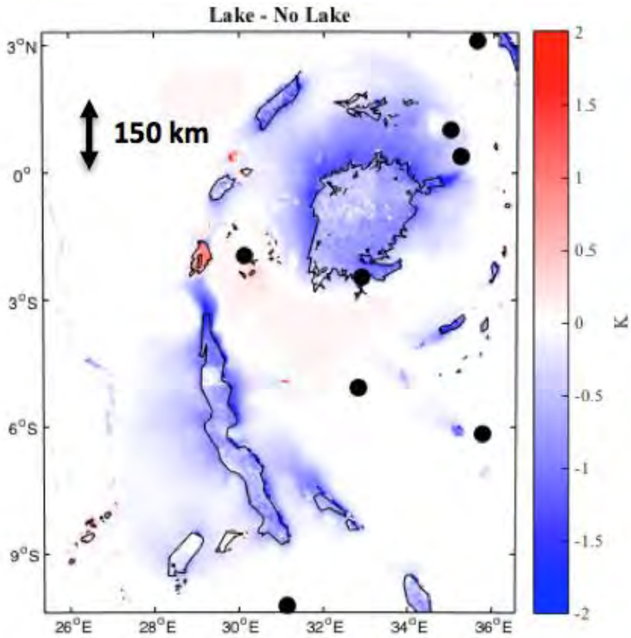

Figure 6. Annual average (day and night) difference in SAT (ºC) between simulations with and without lake presence in the regional climate model. Nearby SAT observation locations are shown with black markers.

In this case, we observe a considerable influence of Lake Victoria (and other African Great Lakes) on the regional climate of East Africa. In particular we calculate that Lake Victoria can influence SATs by 1°C or more in locations up to 150km from the lake location (Fig. 6).

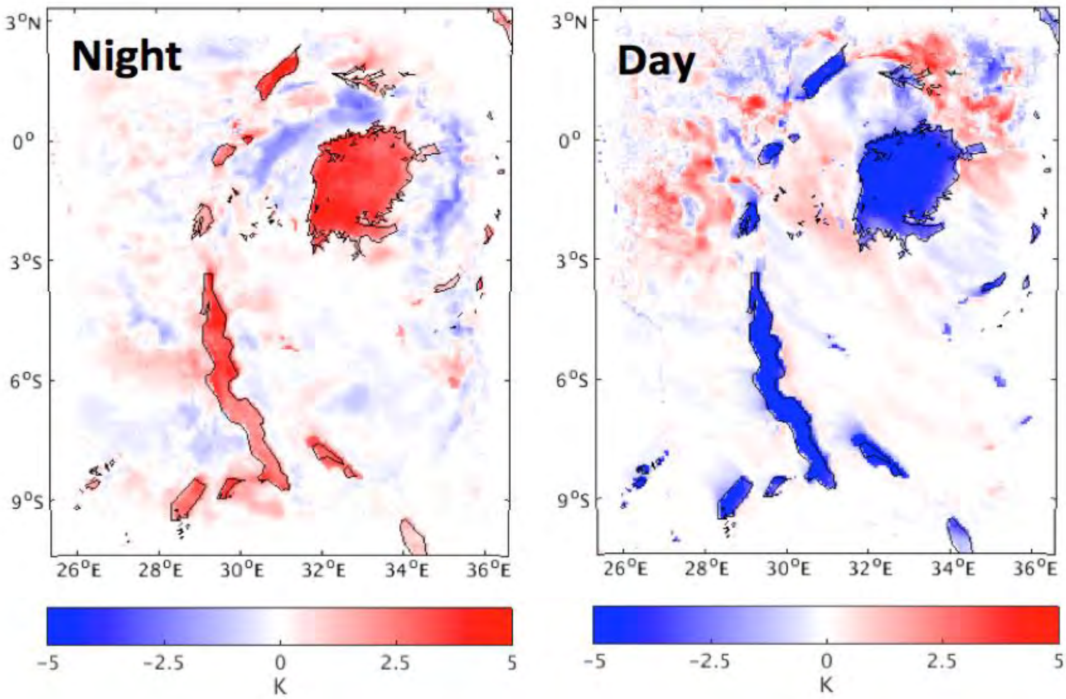

Figure 7. Comparison of lake influence on near surface air temperature during the day and night, used as a proxy for daily maximum and minimum temperatures, respectively.

In general, Lake Victoria induces a warming effect (in particular on the atmosphere directly above the lake) on the climate during the evening and a cooling effect during the day (Fig. 7). In particular, the lake warms slower than the land during the day, as a result of its large thermal inertia, resulting in the lake being cooler than its surroundings. This can not only influence SAT directly above the lake but also influence SAT further afield. Specifically, as the lake absorbs heat during the day, the air directly above the lake is cooled, resulting in denser air, and forming a cell of relatively high pressure over the lake surface (Fig. 8). As the sun warms the land, the air above becomes less dense, thus inducing relatively low pressure. The regional pressure gradient that emerges pushes winds inland off the lake, resulting in a cooling of the surrounding land region (Fig. 8).

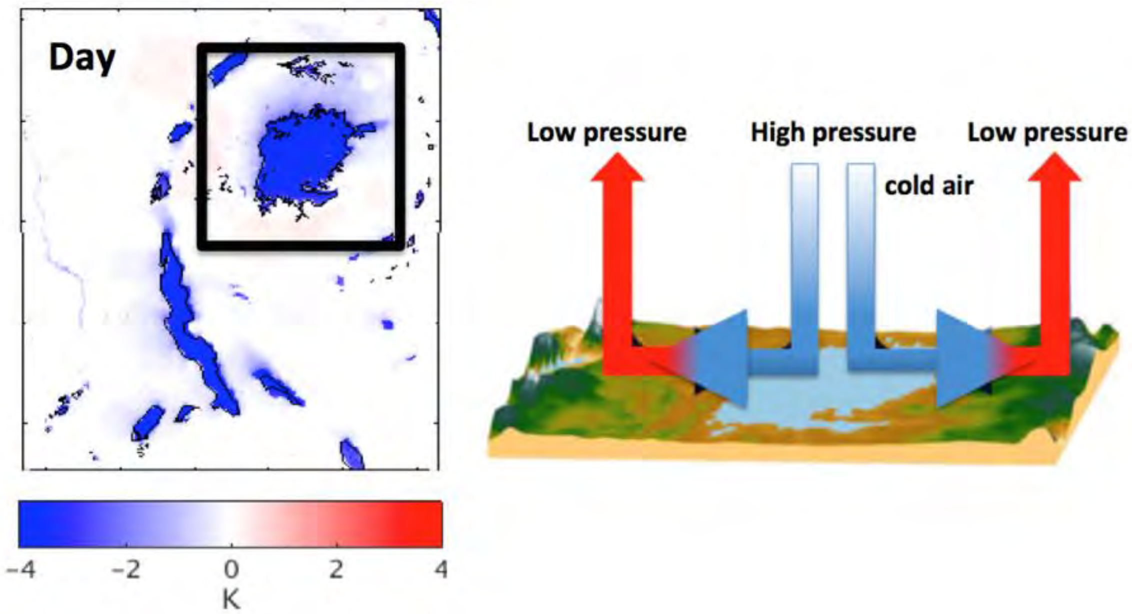

Figure 8. Annually averaged lake influence on daytime near-surface air temperature (K, left), and a graphical representation of the lake influence on atmospheric dynamics (right).

As the lake has heated substantially during the day, heat is released slowly during the evening, following a decrease in over-lake SATs and thus an increase in the air-water temperature gradient and thereby an increase in sensible heat transfer. By releasing heat, the lake increases the temperature of the overlying air, thereby increasing SAT above the lake. The influence of Lake Victoria on nearby SAT during the evening is minimal. However, some nearby regions of Lake Victoria experienced cooling during the evening which is likely a result of the lake-induced stabilization of the atmospheric column over the surrounding land (Thiery et al., 2015). On balance, Lake Victoria generally has a cooling effect on the regional climate at an annual timescale.

This study has provided important insights into what is needed to understand the influence of lakes on nearby SAT and the optimum method for detecting a lake ROI, in particular in regions where the inter-annual daily variability in LSWT in small. Specifically, a ‘with-lake’ minus ‘without-lake’ model study is needed. This method will be adopted in the global scale analysis that follows.

4. Global modelling of lake influence using ECMWFs IFS

We aim to evaluate the influence of lakes on near-surface air temperature at a global scale. Specifically, we aim to determine regions of lake influence on nearby SAT, to be used in infilling methods of global SAT analyses (see Section 1). In this global scale analysis, we will use ECMWF's Integrated Forecasting System (IFS) to investigate the impact of lakes on nearby SAT by comparing a global simulation that resolves lakes and explicitly computes LSWT to a simulation without lakes, where each lake pixel is replaced by a representative land pixel. This follows the optimum method determined in Section 3 for Lake Victoria and the African Great Lakes region.

In the first global model run, lakes will be included in the model integration. For this purpose, FLake will be used to compute the surface temperature of each (sub-grid) lake globally. The surface fluxes of heat, moisture and momentum, which ultimately control the interactions between a lake and the overlying and surrounding atmosphere, were computed by the HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land) routines. The second simulation (the no-lake run) is identical to the first, but with each lake pixel replaced by a representative land pixel.

The influence of lakes on near-surface air temperature is then evaluated by comparing outputs from the 'lake' and 'no-lake' model runs, specifically evaluating how lakes influence the magnitude and variability of near-surface air temperature. Therefore, two experiments were performed with (LAKE) and without (NOLAKE) FLake activated. In the NOLAKE experiment, subgrid lakes are treated as land only and resolved lakes (i.e. those that occupy more than one model grid box) are treated as ocean with initial conditions (surface temperatures) provided by a surface temperature monthly climatology lagged by 1 month (selected to represent a typical time scale of thermal inertia). Therefore, note that large lakes (e.g. the North American Great Lakes) are not included in this analysis as they are resolved features in the IFS. The effect of the model on near-surface temperature is evaluated.

In the following discussions, the near-surface air temperature sensitivity is defined as the mean difference of LAKE compared with NOLAKE, indicating whether a warming or a cooling is produced. A verification dataset has been considered to check the accuracy of the FLake simulations in IFS. For LSWT, the ARC-Lake dataset was used (Fig. 9). The results suggest a largely unbiased simulation over the lakes considered.

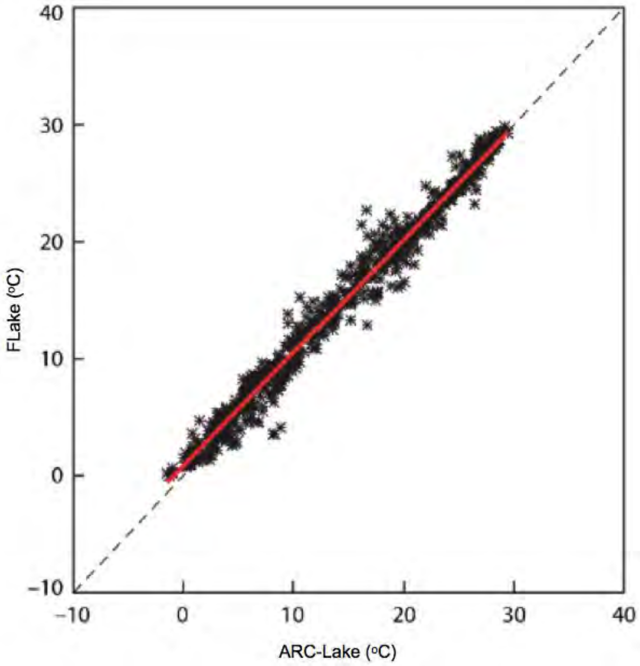

Figure 9. Comparison between the modelled lake surface water temperature (via the FLake model) and the ARC-Lake observed LSWT over grid points where the model lake fraction is >10%.

On a given day some lakes can impose a cooling influence on SAT whereas others can impose a warming influence (e.g. Fig. 10). This is particularly evident in North America where we see a mixture of cooling and warming, all of which are under 0.5°C. As expected, the influence of lakes on SAT is particularly evident in regions where lakes are abundant. On a monthly timescale, the regional influence of lakes on SAT is less scattered, as the diurnal cycles of cooling and warming that some lakes experience will cancel out to be negligible. The lake influence for a given month is still relatively minimal, generally in the order of <0.5°C in North America. In Scandinavia, one of the regions where lakes are most abundant, the lake influence on SAT is clearly evident (Fig. 11) and the direction of influence of lakes on nearby SAT can be either negative (i.e. cooling) or positive (i.e. heating) depending on the time of year. In spring, lakes generally have a cooling effect, as a result of the lakes absorbing heat following the winter ice cover period and during the onset of thermal stratification. During autumn, the lakes typically have a warming influence as lakes release a substantial amount of heat which has accumulated during the summer months. Lakes in Scandinavia have least influence on nearby SAT in summer, often much less than 0.1°C as a result of the lakes having reached thermal equilibrium with the atmosphere and thus minimal heat is exchanged at the air-water interface.

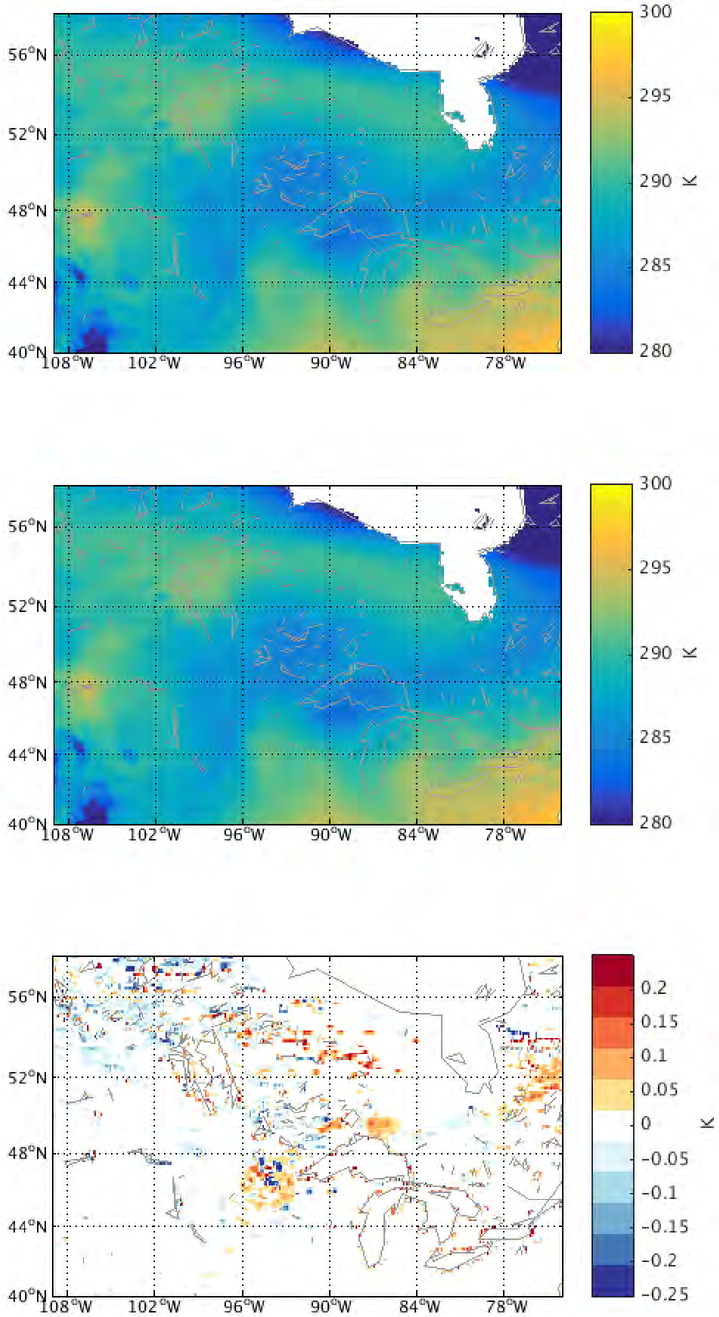

Figure 10. Comparison of with lakes (top) and without lakes (middle) model run on daily averaged near-surface air temperature in IFS, and the difference between these model runs (bottom) for one specific day: 1979-08-01 12:00.

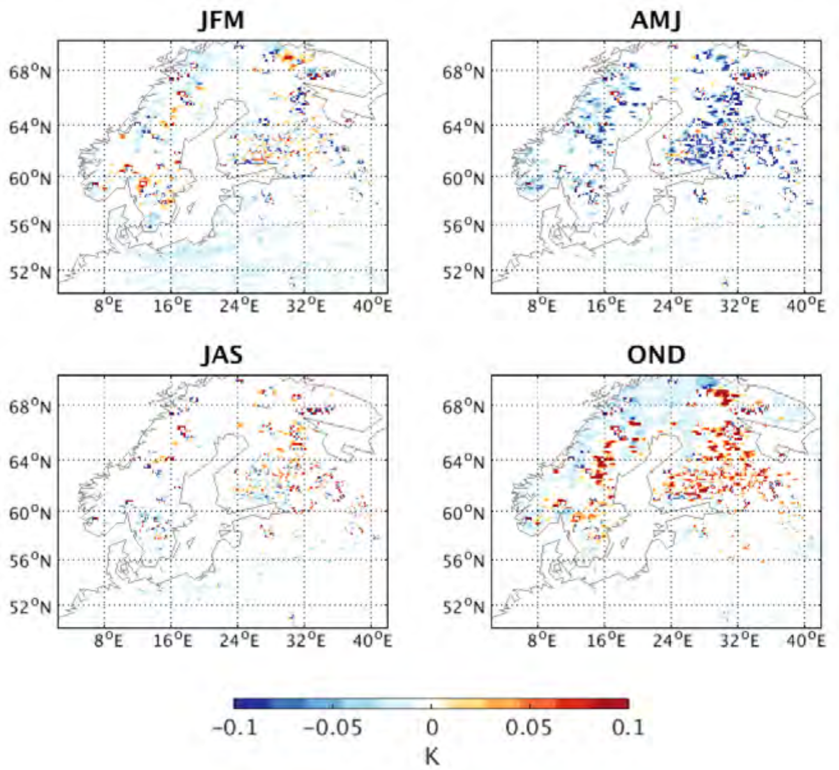

Figure 11. Difference between 'with' and 'without' lake model runs for Scandinavia.

Globally, we find that the inclusion of lakes in IFS results in a mixture of warming and cooling signals, illustrating that the influence of lakes on nearby SAT is dependent on a combination of climate, lake location, and local characteristics (Fig. 12). Thus, our results illustrate that the influence of lakes on nearby SAT can differ at regional and temporal scales. A maximum warming influence of lakes on SAT is observed in autumn with some lakes influencing local SAT by >0.5°C (e.g. in North America). In winter, the representation of lakes has a different impact depending on if the lake is frozen or ice-free. During summer, the main impact of lakes is a significant cooling of the daily maximum near-surface air temperature.

Following this analysis, we provide a global dataset of lake influence on SAT, to indicate where the presence of lakes has influenced near-surface air temperature. Different Lake ROI masks are provided for the minimum, maximum, and mean SAT lake ROI. The NetCDF file is structured as:

Variable	Units	Dimensions
Cell-centre latitudes	°N	h
Cell-centre longitudes	°E	g
Month	Month of year	d
Variable (Tmin, Tmax, Tmean)	K	g x h x d

This file contains monthly climatological SAT differences between the IFS experiments. Monthly climatologies are provided to allow for the seasonal variability in the influence of lakes on SAT.

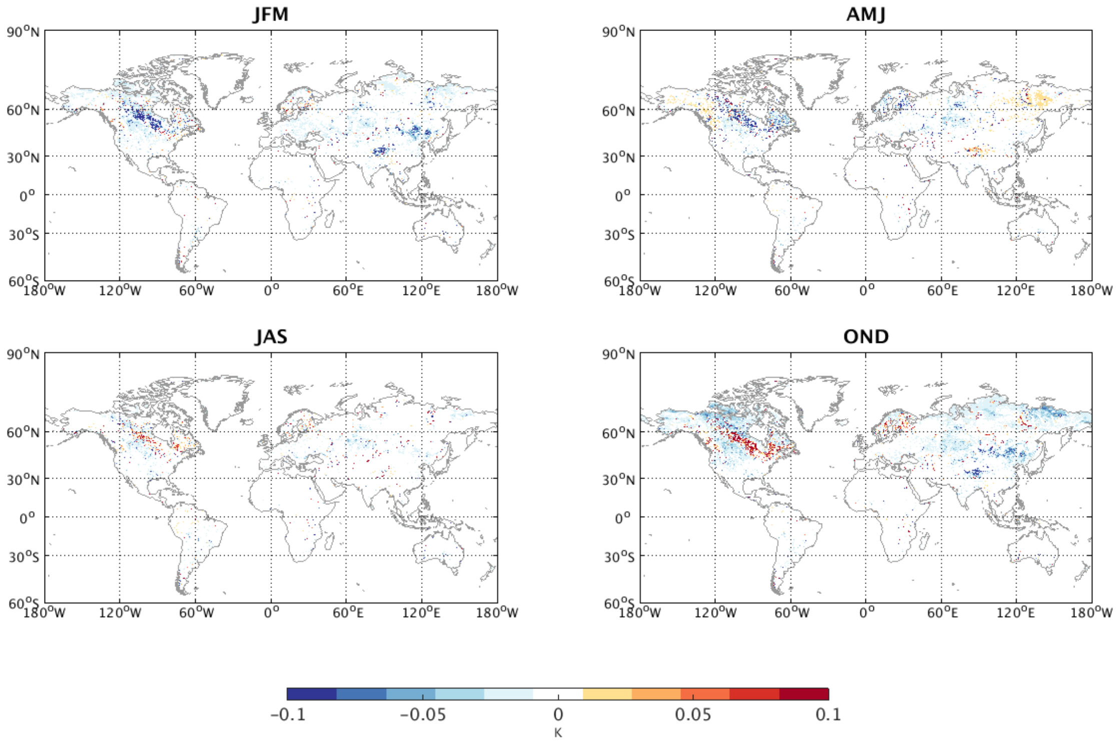

Figure 12. Difference between the model runs with and without lakes globally, shown for different seasons.

5. Lessons Learnt

In order to estimate the ROI of a lake on nearby SAT a modelling approach that compares ‘with’ and ‘without’ lake presence is necessary. Lakes can influence nearby SATs by >0.1°C in many regions globally. Thus, not accounting for lakes in global surface temperature data sets can potentially lead to erroneous estimates of SAT, especially when lakes are abundant, and they occupy a relatively large fraction of the desired grid cell. In this work we provide a global lake ROI mask which can be used in future infilling methods of global SAT analyses. Specifically, we provide a lake mask for the lake influence on minimum, maximum, and mean SAT globally.

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