Predicting lake surface temperature dynamics

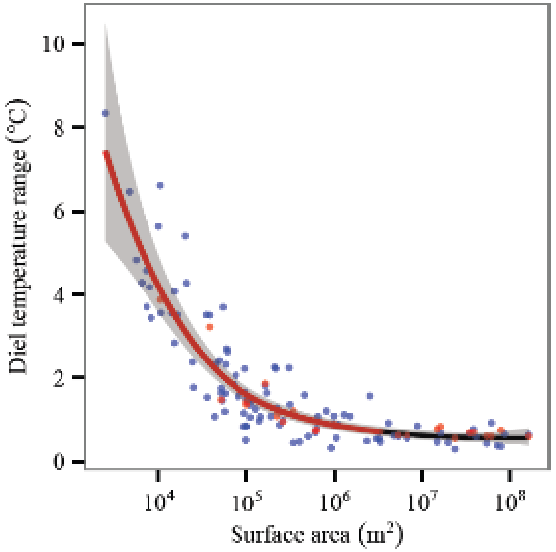
Stephen Maberly, Ian Jones & Steve Thackeray | Centre for Ecology & Hydrology
Ruth O'Donnell, Claire Miller & Marion Scott | University of Glasgow
Iestyn Woolway & Christopher Merchant | University of Reading
Mark Cutler & Eirini Politi | University of Dundee
Andrew Tyler | University of Stirling

Introduction

- **Temperature is a key environmental variable controlling, *inter alia*:**
  - Gas solubility
  - Rate of chemical processes
  - Lake stratification
  - Organism size
  - Food web interactions
  - Phenology
  - Element stoichiometry
  - Metabolic balance
  - Greenhouse gas emissions
  - Species distribution & biogeography

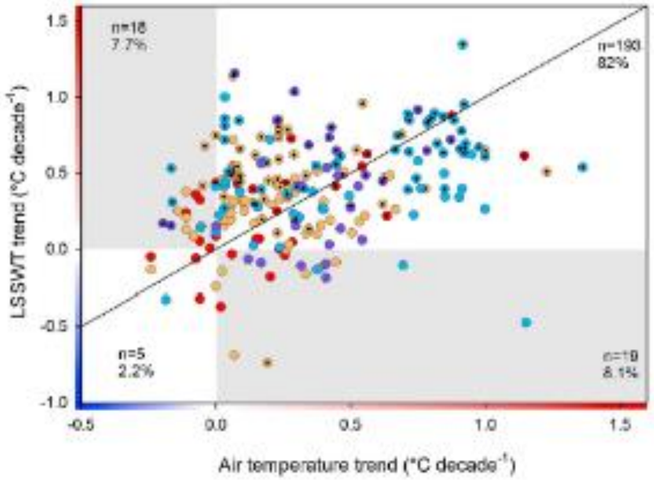
Lake Surface Water Temperature (LSWT) dynamics

Diel (100 lakes)
Sensor networks
Woolway et al. (2016)

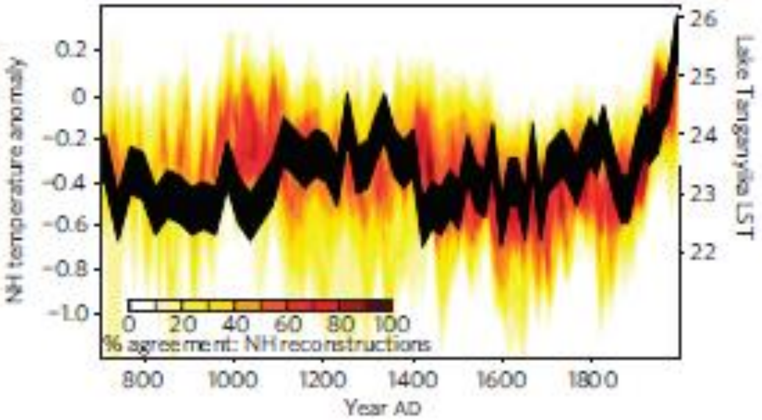


Seasonal & Geographic

Decadal (246 lakes in summer)
Direct plus satellites
O'Reilly et al. (2015)



Centennial (1 lake)
Palaeo
Tierney et al. (2010)



- Woolway et al. (2016). *PLoS ONE*
- O'Reilly et al. (2015). *Geophysical Research Letters*
- Tierney et al. (2010). *Nature Geoscience*

Centre for Ecology & Hydrology NATURAL ENVIRONMENT RESEARCH COUNCIL · University of Dundee · University of Glasgow · PML Plymouth Marine Laboratory · University of Reading · UNIVERSITY of STIRLING

Procedure

Data from ArcLake v3.0 for 732 lakes from 1996 to 2011 (16 years) (Reading)

Bi-monthly data
b-spline smoothing &
K-means clustering
FPCA & QDA to allocate smooth curves to groups
(Glasgow)

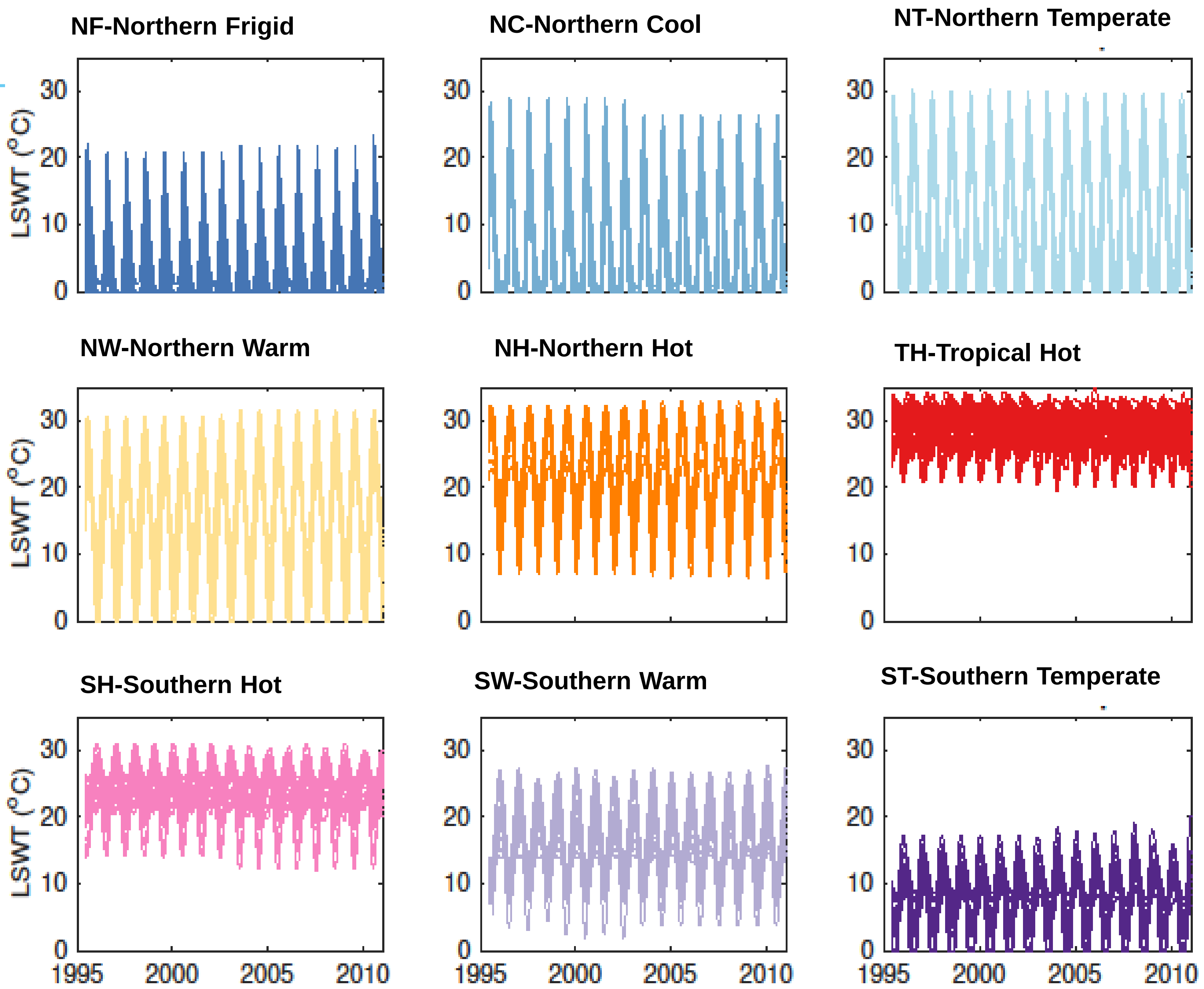
Global data on lake characteristics & weather (Dundee)

LSWT temperature modelling using FLake, & ERA-interim data or climate change scenarios (Reading & CEH)

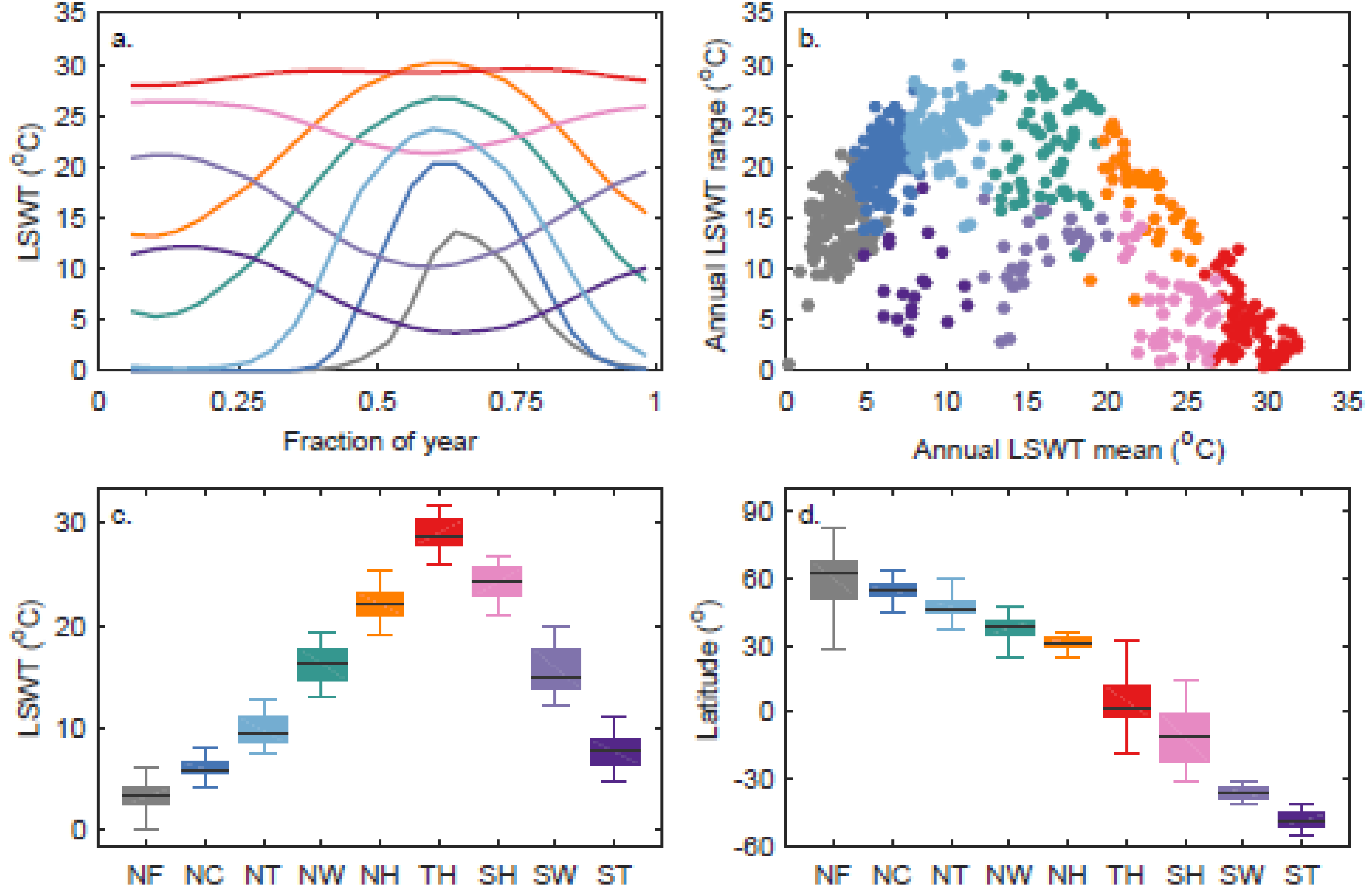
Seasonal LSWT patterns at a global scale, attribution of causes and forecast of change (CEH)

Coherent clusters

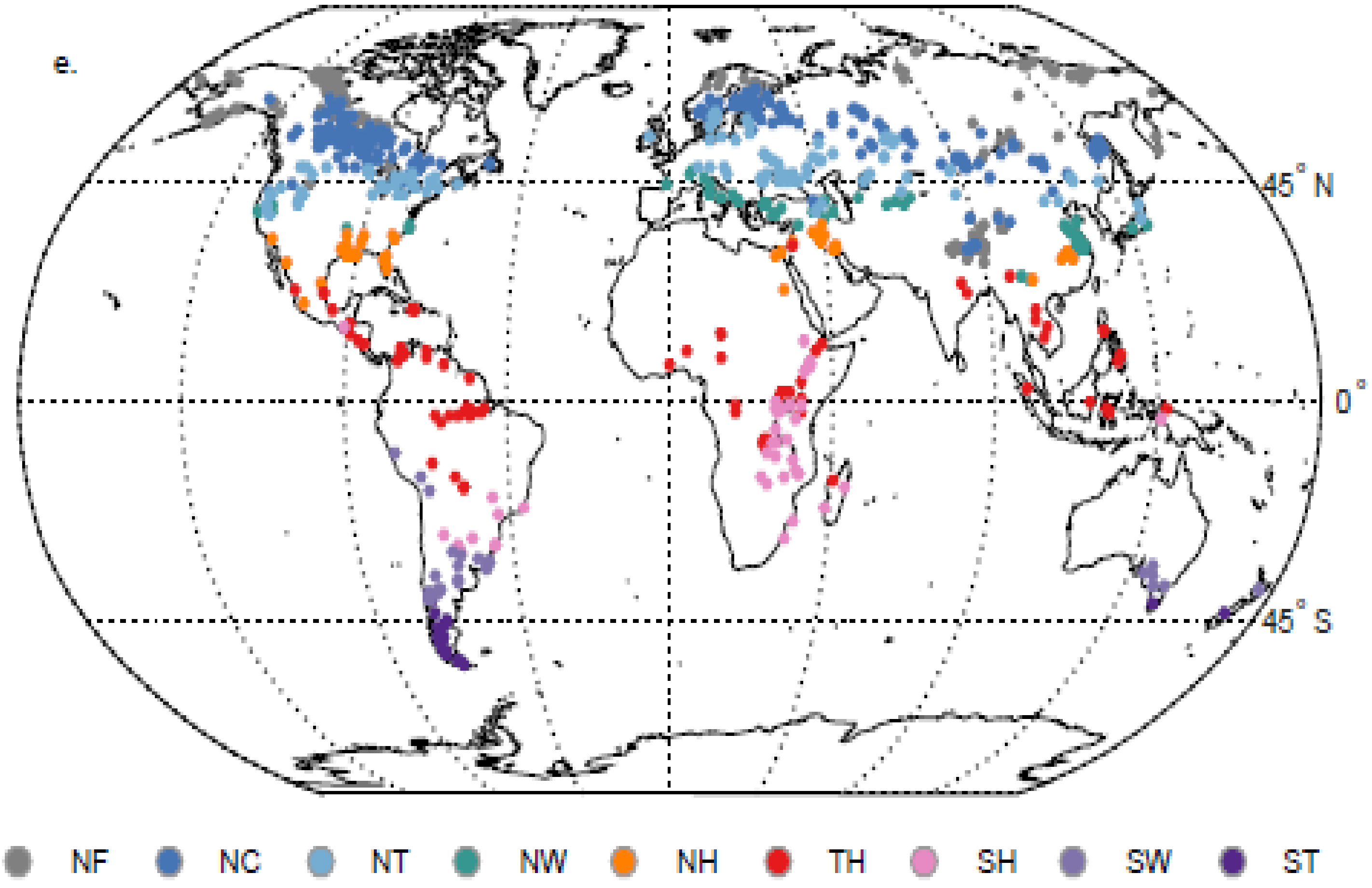
- Smooth curves allocated to groups using Functional Principal Components Analysis (FPCA) and Quadratic Discriminant Analysis (QDA)
- 96% of the 732 lakes correctly allocated

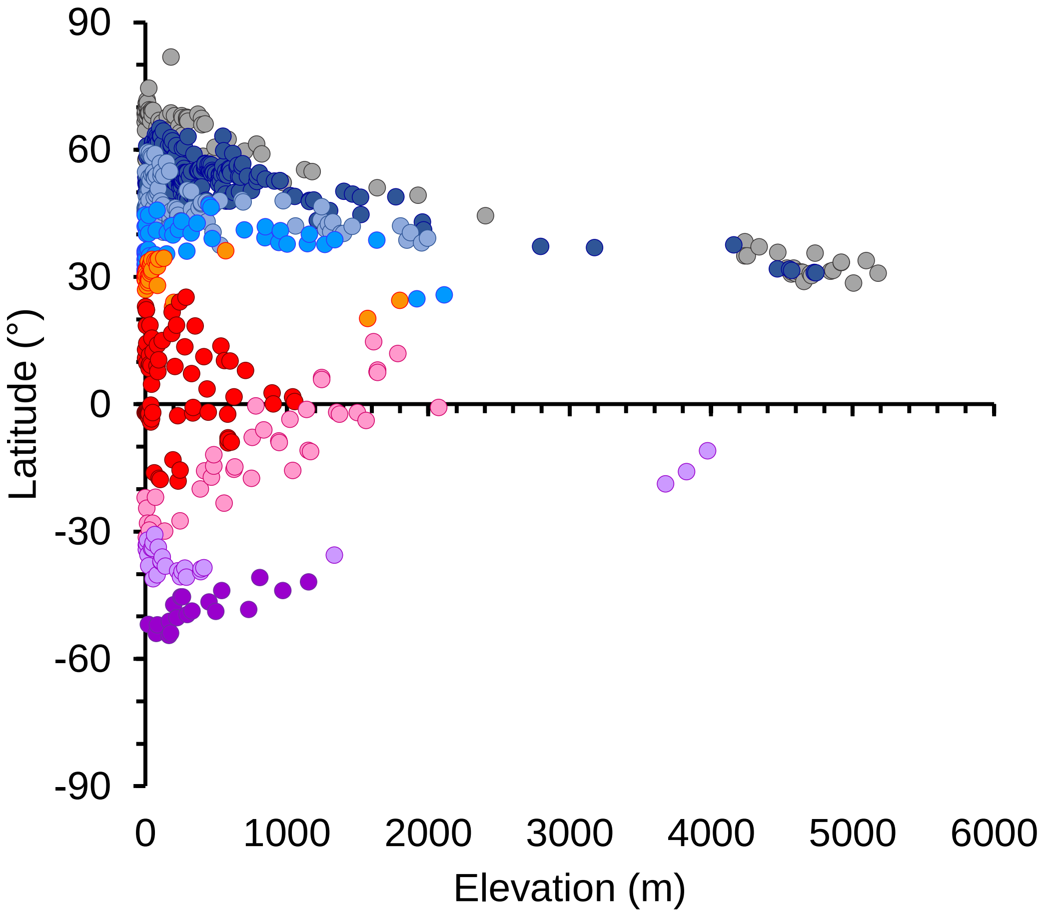


Cluster characteristics



Geography & elevation



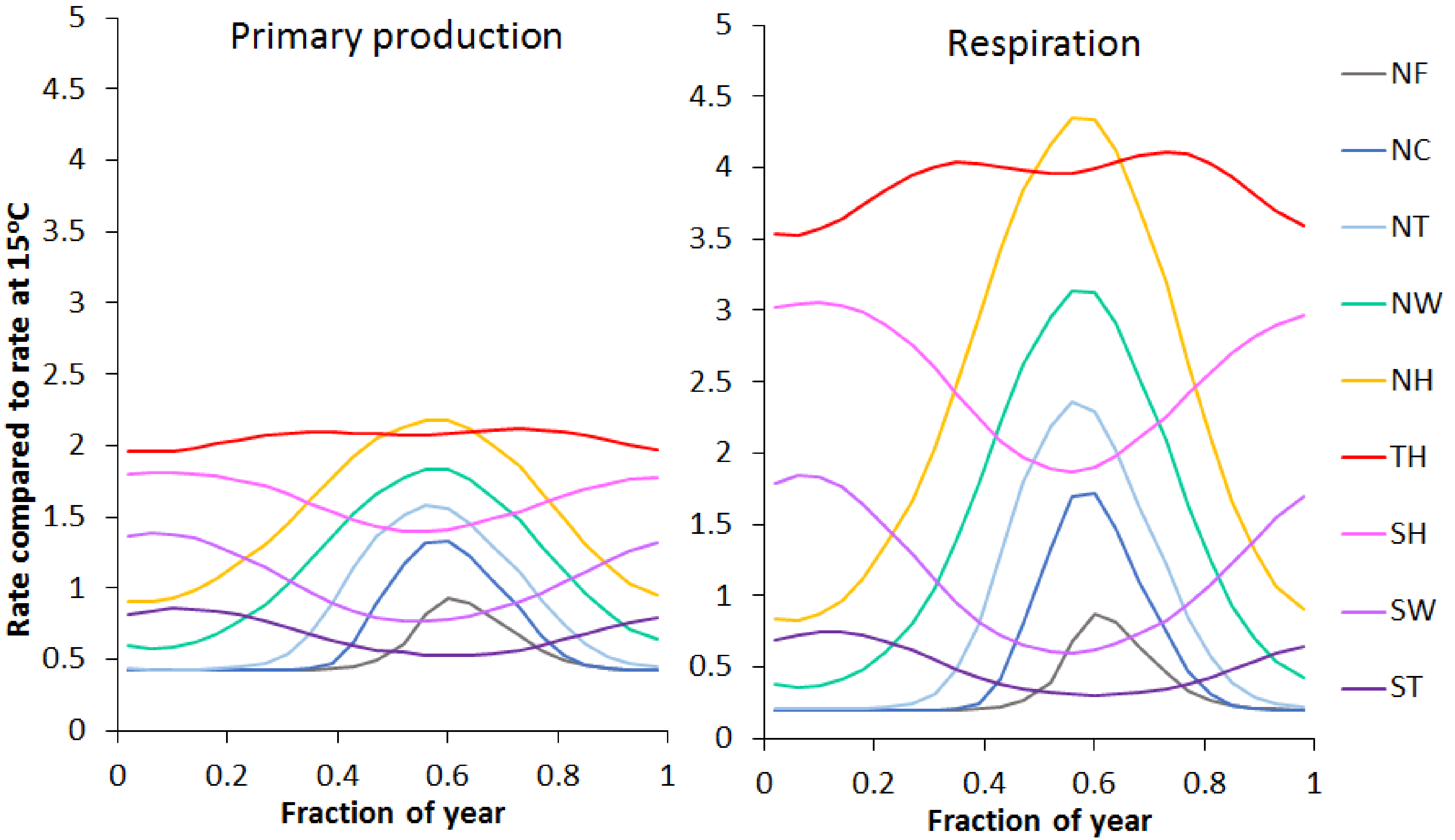


Metabolic Theory of Ecology

The Boltzmann-Arrhenius equation:

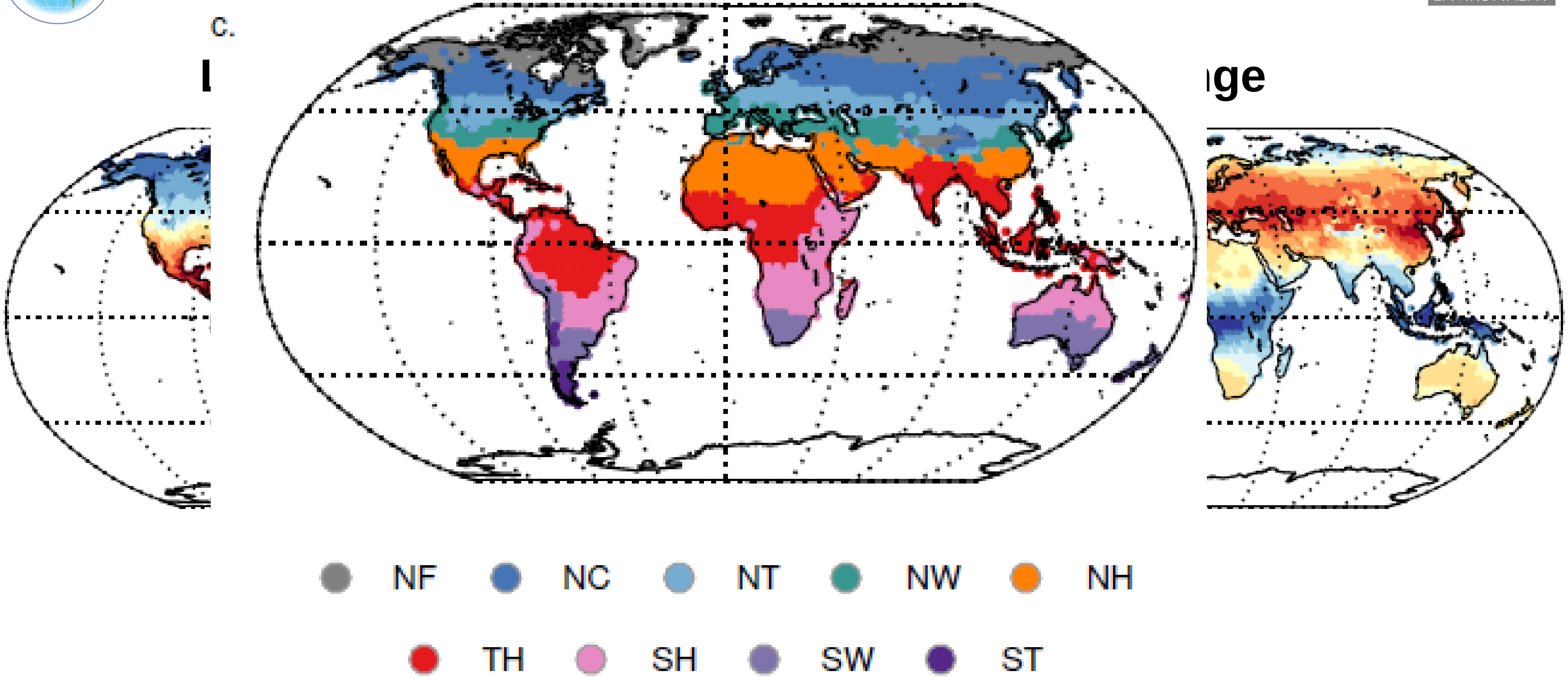
$$r = r_0 e^{-E/kT}$$

Mean E (Kraemer et al. 2016):
Primary prodn: 0.39 eV
Respiration: 0.73 eV



- Brown et al. (2004) *Ecology*
- Kraemer et al. (2016) *Global Change Biology*

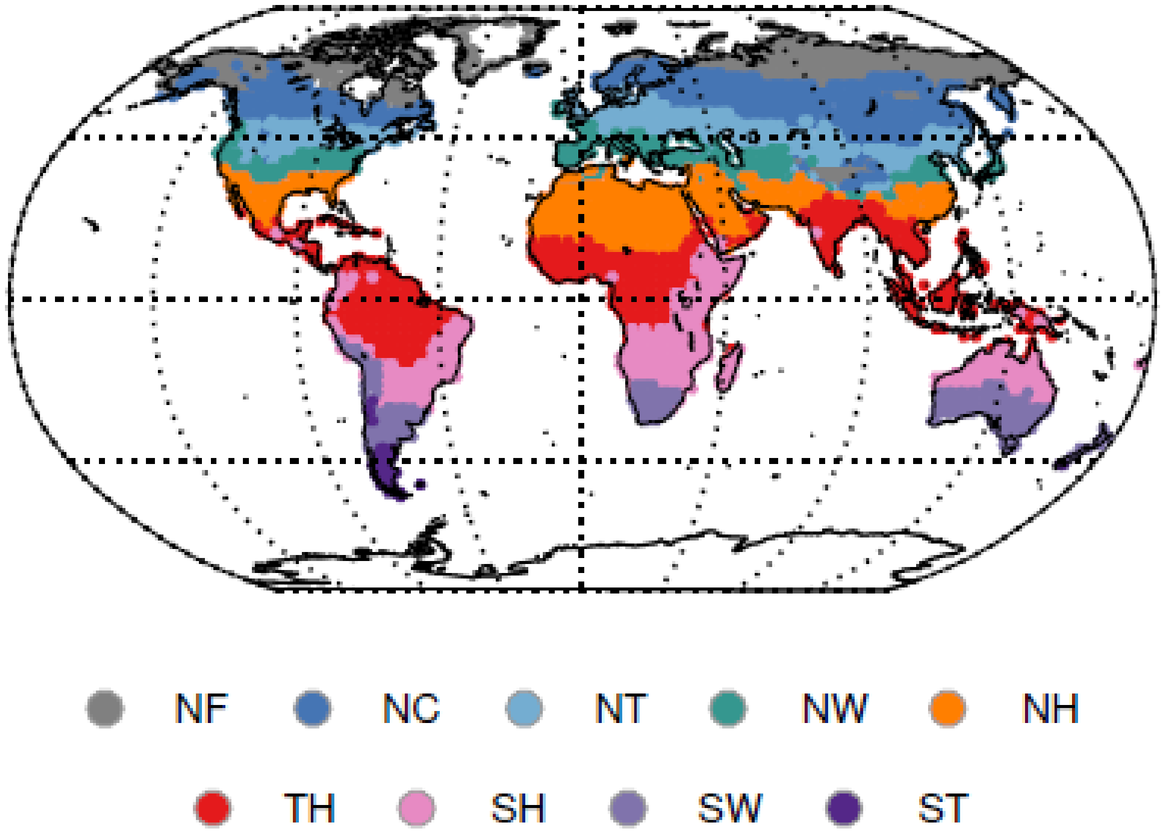
Colouring in the world

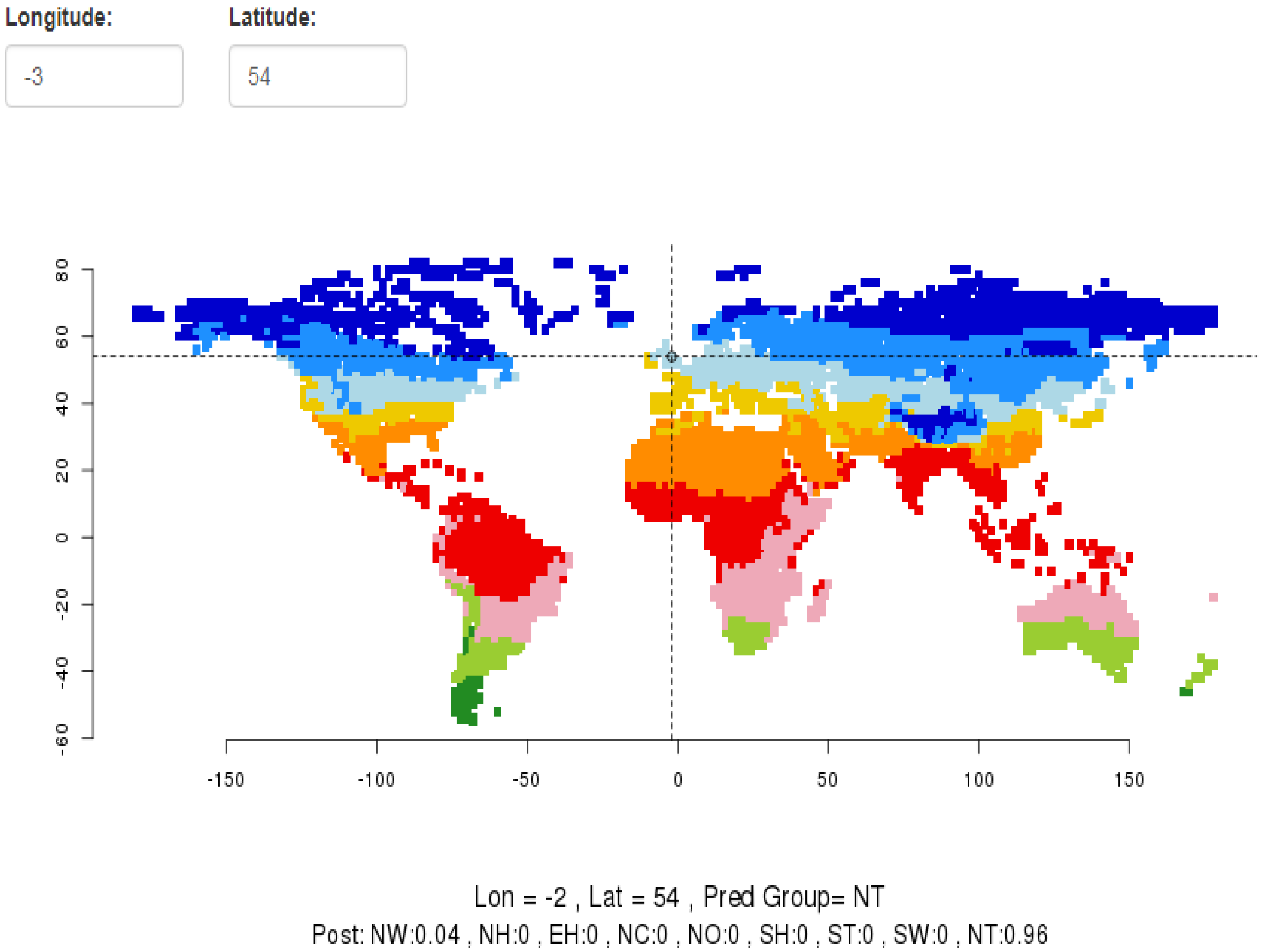


Flake model, ERA-Interim weather, ‘standard lake’ 2 degree grid

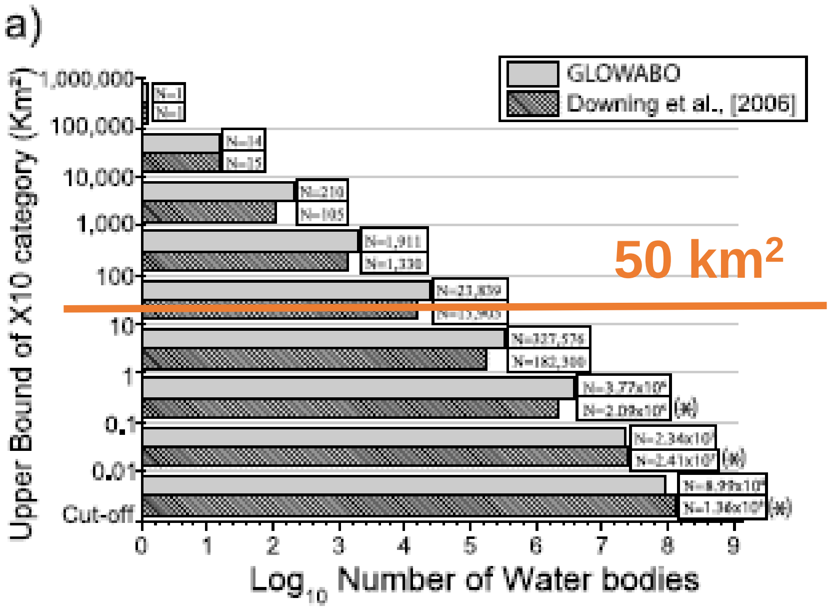
Shiny App

c.


NF
NC
NT
NW
NH
TH
SH
SW
ST


Longitude:
-3
Latitude:
54
80
60
40
20
0
-20
-40
-60
-150
-100
-50
0
50
100
150
Lon = -2 , Lat = 54 , Pred Group= NT
Post: NW:0.04 , NH:0 , EH:0 , NC:0 , NO:0 , SH:0 , ST:0 , SW:0 , NT:0.96

Does the analysis apply to small lakes?



< 1% of global lakes > 50 km^2

In situ data from 71 lakes	Area (km^2)
Average	6.3
Min	0.01
Max	47.5
Median	0.94

	In situ	
	No.	%
1st	57	**80**
2nd	12	**17**
1st + 2nd	69	**97**
Neither	2	**3**
Total	71	**100**

Verpoorter et al. (2014) *Geophysical Research Letters*

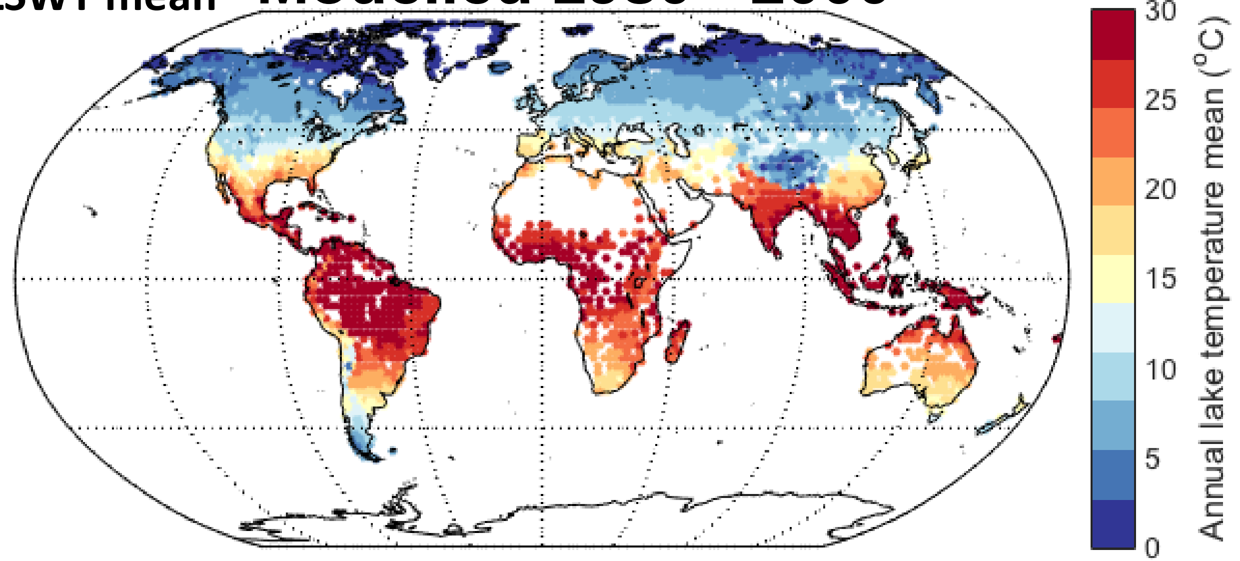
Centre for Ecology & Hydrology NATURAL ENVIRONMENT RESEARCH COUNCIL
University of Dundee
University of Glasgow
PML Plymouth Marine Laboratory
University of Reading
UNIVERSITY of STIRLING

Forecasting the effects of climate change

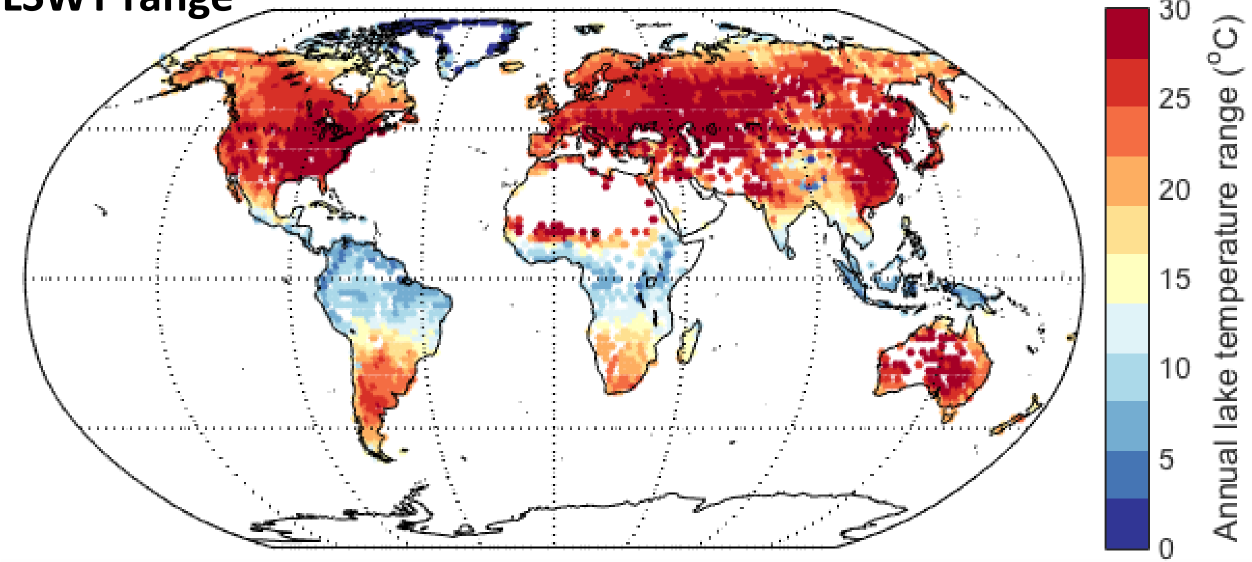
1) HydroLakes database* used to obtain the mean depth and surface area of all (1.4 million) lakes (> 0.1 km^2) globally
2) The average lake mean depth and surface area was calculated for each 2^o grid
3) These grid- averages used within FLake to simulate lake surface temperature globally
4) Four climate model projections used: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5
(the examples are from HadGEM2-ES which agrees with the other models)

*Messager et al. (2016). *Nature Communications*

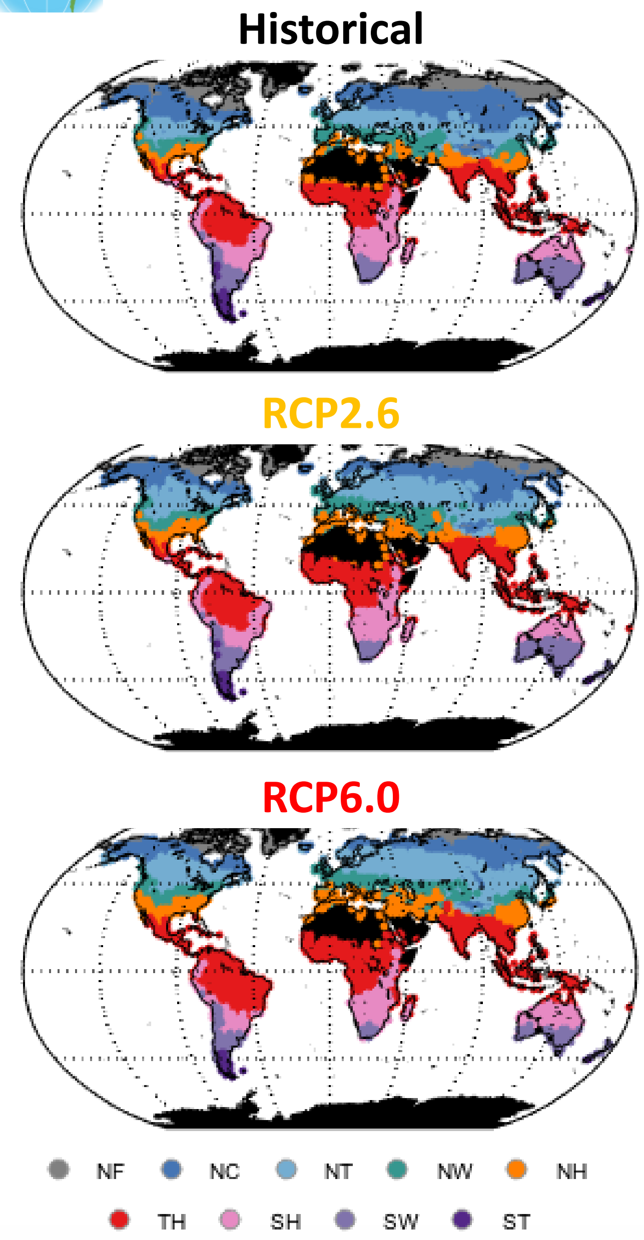
LSWT mean **Modelled 1980 - 2000**



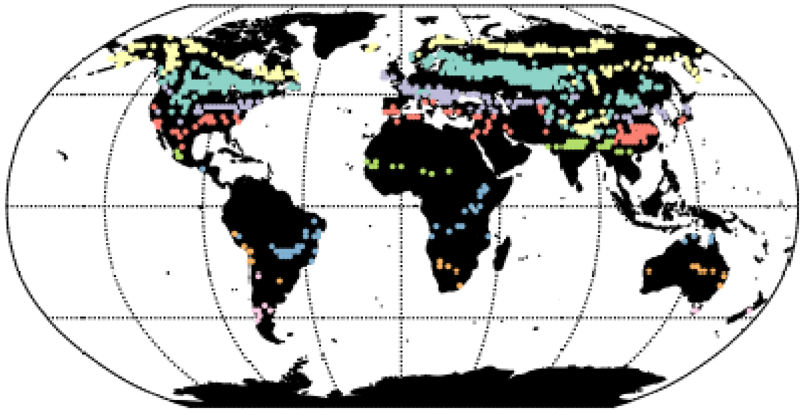
LSWT range

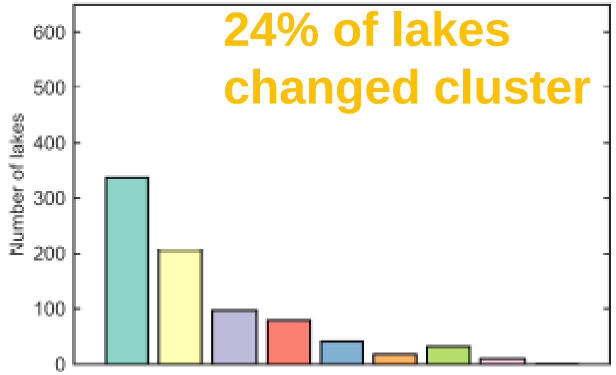


Forecasting change in cluster membership by 2100

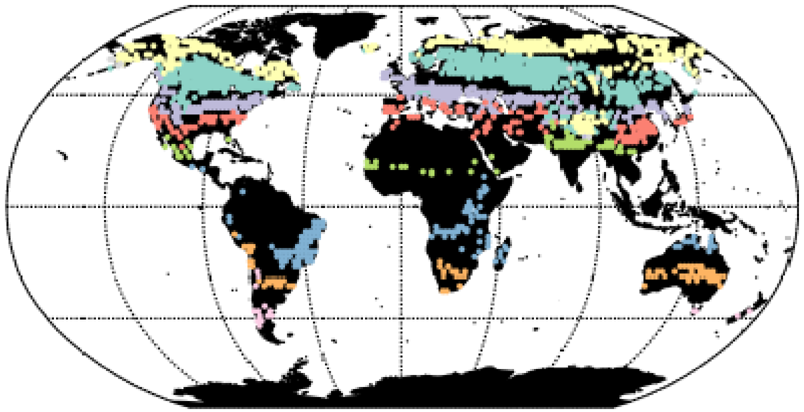


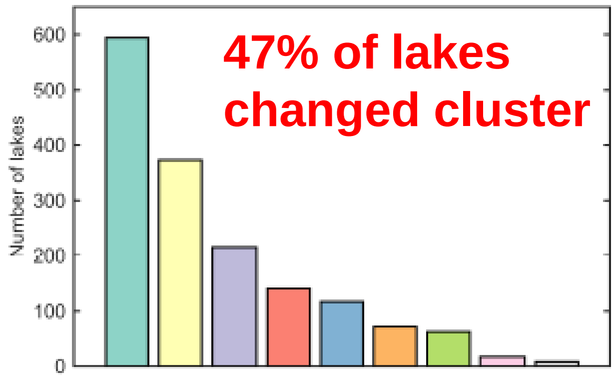
RCP2.6 *vs* historic

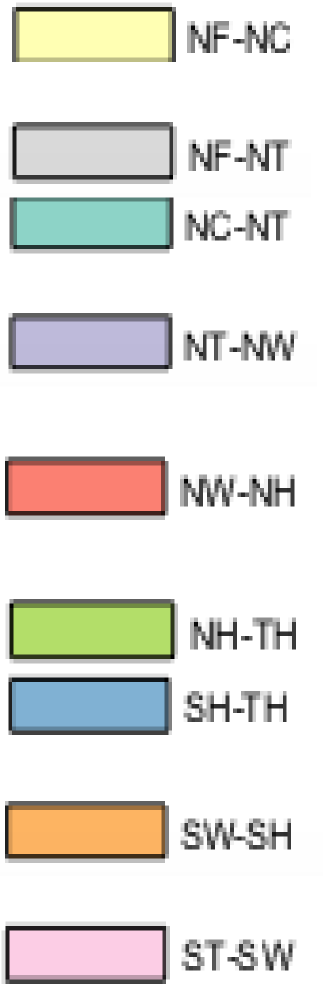




RCP6.0 *vs* historic



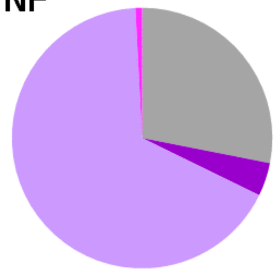
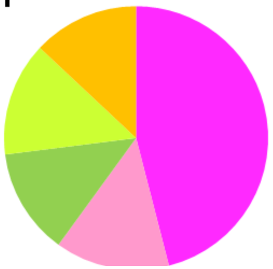
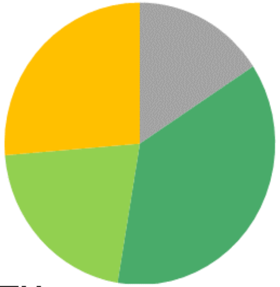
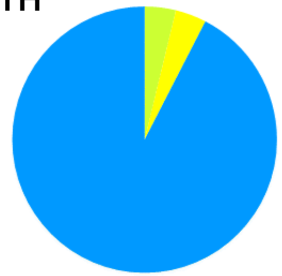




Relationship with terrestrial biomes/ climate classifications

Koppen-Geiger

Koppen-Geiger categories	NF	NC	NT	NW	NH	TH	SH	SW	ST
Polar (E)	28.1	1.6						3.4	15.8
Cold, Very cold winter (Dd)	4.1								
Cold, Cold summer (Dc)	66.9	57.4							
Cold, Warm summer (Db)	0.8	34.4	46.0	3.6					
Cold, Hot summer (Da)		0.8	14.0						
Temperate, Cold summer(Cc)									36.8
Temperate, Warm summer (Cb)		0.4	13.0	25.5	2.3		19.0	41.4	21.1
Temperate, Hot summer (Ca)			14.0	58.2	62.8	3.8	23.8	34.5	0.0
Arid, Cold (Bk)		5.3	13.0	10.9				20.7	26.3
Arid, Hot (Bh)				1.8	30.2	3.8	9.5		
Tropical (A)					4.7	92.4	47.6		
Total number of lakes	**121**	**244**	**100**	**55**	**43**	**79**	**42**	**29**	**19**
Number of Koppen-Geiger categori	**4**	**6**	**5**	**5**	**4**	**3**	**4**	**4**	**4**

NF

NT

ST

TH


Peel et al. (2007). *Hydrology and Earth System Science*

Conclusions

- Seasonal lake surface temperature dynamics vary greatly among lakes
- Annual LSWT mean and range both vary from about 1 to 30°C
- The variation is geographically coherent and can be modelled effectively
- In the future, lake temperatures will increase and cluster membership will shift towards the equator especially in the northern hemisphere
- We hope that the lake temperature clusters will be used as a classification system
- Unlike other ecosystems (marine, terrestrial) there is no coherent biome classification for inland waters, we plan to use these temperature clusters, along with other remotely sensed data, to produce lake biomes.

Thank you

Stephen Maberly
Lake Ecosystems Group
Centre for Ecology & Hydrology
Lancaster Environment Centre
Lancaster LA1 4AP UK

t +44 1524 595852
e scm@ceh.ac.uk
w www.ceh.ac.uk/staff/stephen-maberly

www.globolakes.ac.uk

@globolakes

This research was funded by the Natural Environment Research Council (NE/E009328)

NERC
SCIENCE OF THE ENVIRONMENT