# EU SURFACE TEMPERATURE FOR ALL CORNERS OF EARTH (EUSTACE)

Nick Rayner, Met Office Hadley Centre, Science Coordinator EUSTACE project, and partners

Material provided by Renate Auchmann, Yuri Brugnara, Colin Morice, Darren Ghent, Lizzie Good, John Kennedy, Kristine Madsen, Iestyn Woollway, Finn Lindgren and Janette Bessembinder

*MARCDAT-IV, 18th-22nd July 2016*

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

# EUSTACE AIMS

**EUSTACE will give publicly available daily estimates of surface air temperature since 1850 across the globe for the first time by combining surface and satellite data using novel statistical techniques.** To do this, we need to:

- Identify non-climatic discontinuities in daily weather station data, *so users can trust the changes our records show*
- Produce consistent uncertainty estimates for satellite skin temperature retrievals over all surfaces (land, ocean, ice and lakes), *so we know how far to trust the estimates everywhere*
- Understand how surface temperature measured *in situ* and by satellite relates, *to estimate air from skin temperature*
- Estimate values in areas where we have no *in situ* or satellite data, *so users can have daily information here*

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

Universität Bern
Oeschger Centre Climate Change Research

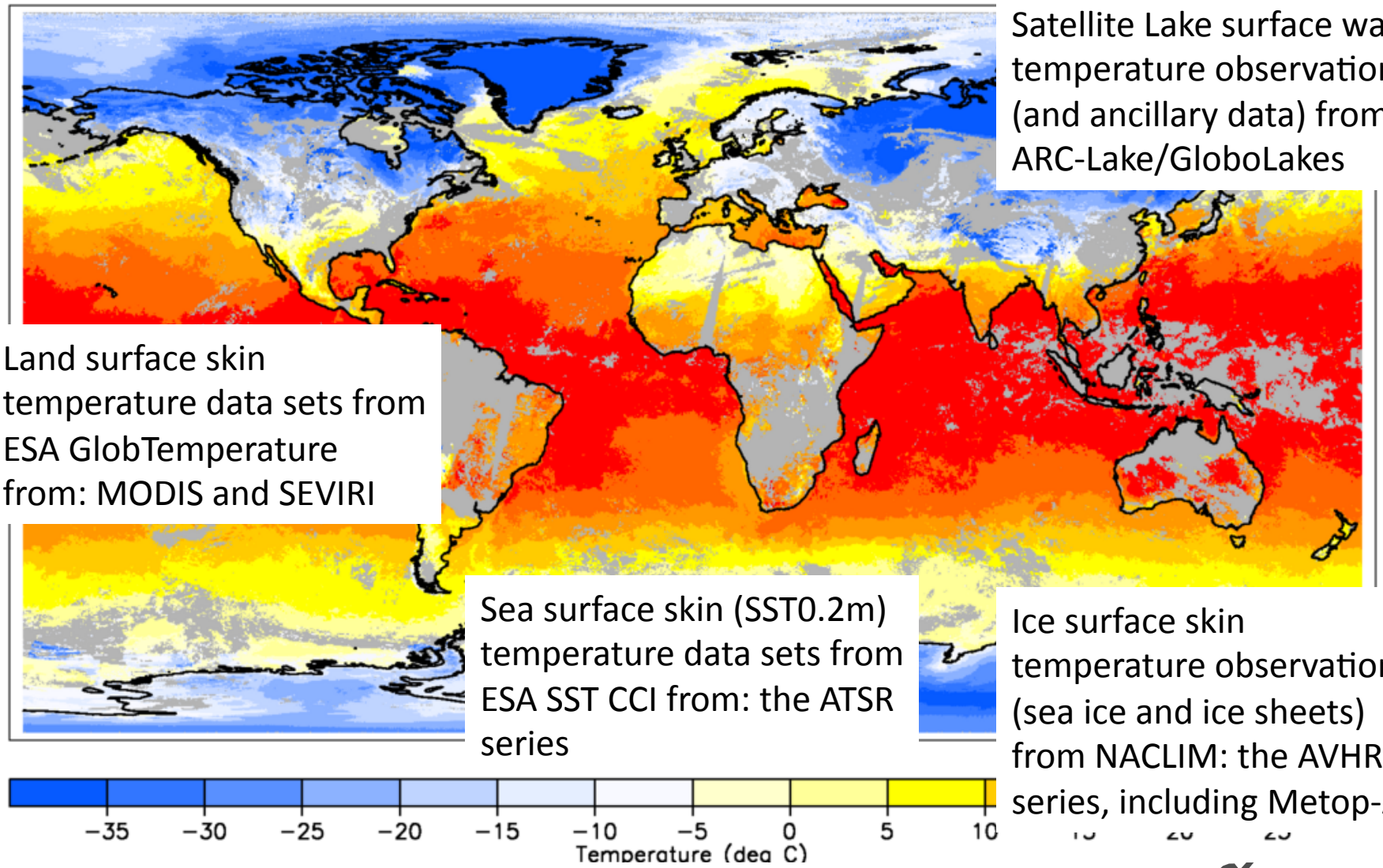
DMI

# DATA SOURCES

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# SATELLITE OBSERVATIONS (TSKIN)




Satellite Lake surface water temperature observations (and ancillary data) from ARC-Lake/GloboLakes

Land surface skin temperature data sets from ESA GlobTemperature from: MODIS and SEVIRI

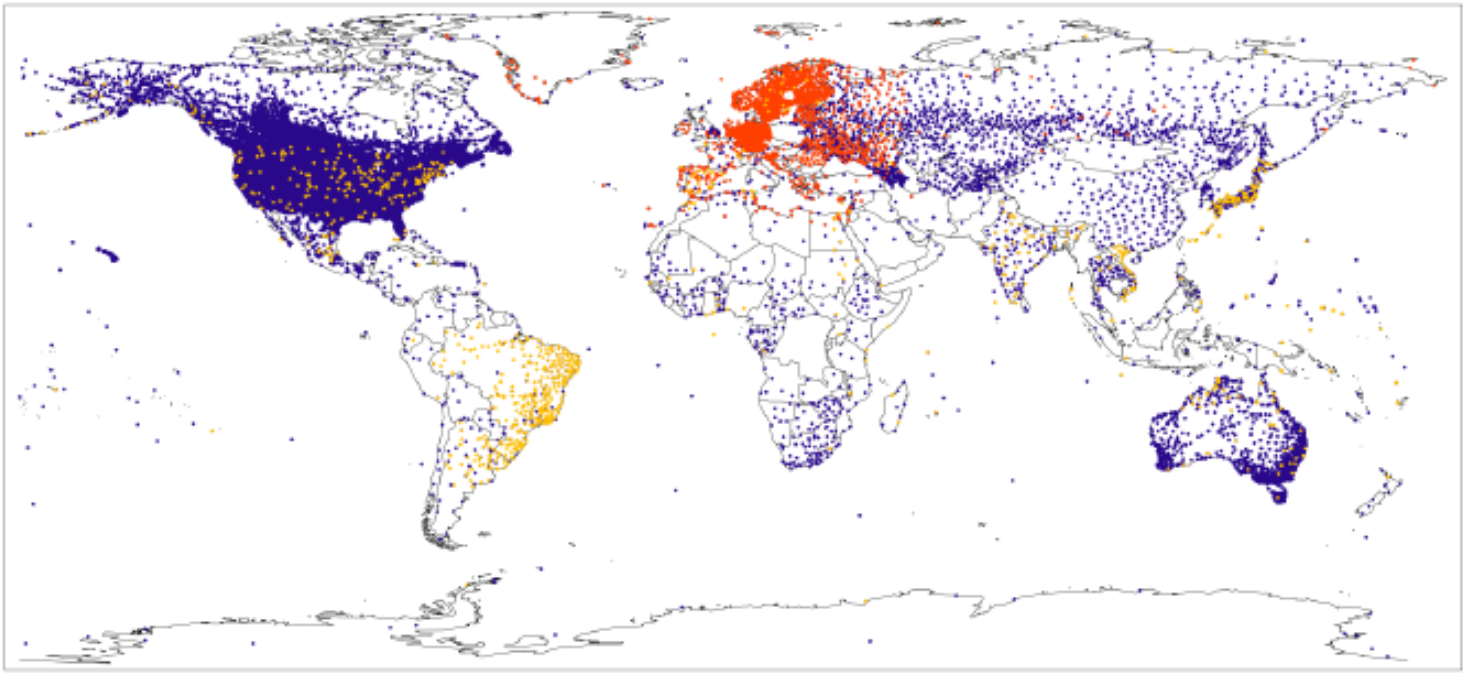
Sea surface skin (SST0.2m) temperature data sets from ESA SST CCI from: the ATSR series

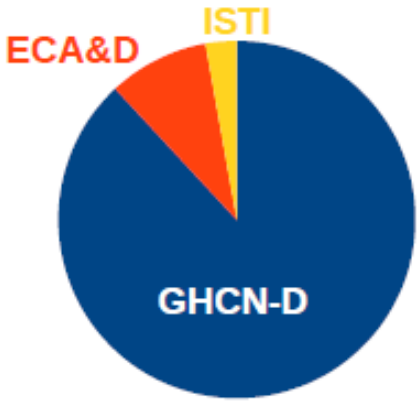
Ice surface skin temperature observations (sea ice and ice sheets) from NACLIM: the AVHRR series, including Metop-A

EUSTACE

# Data Sources

TEST DATASET





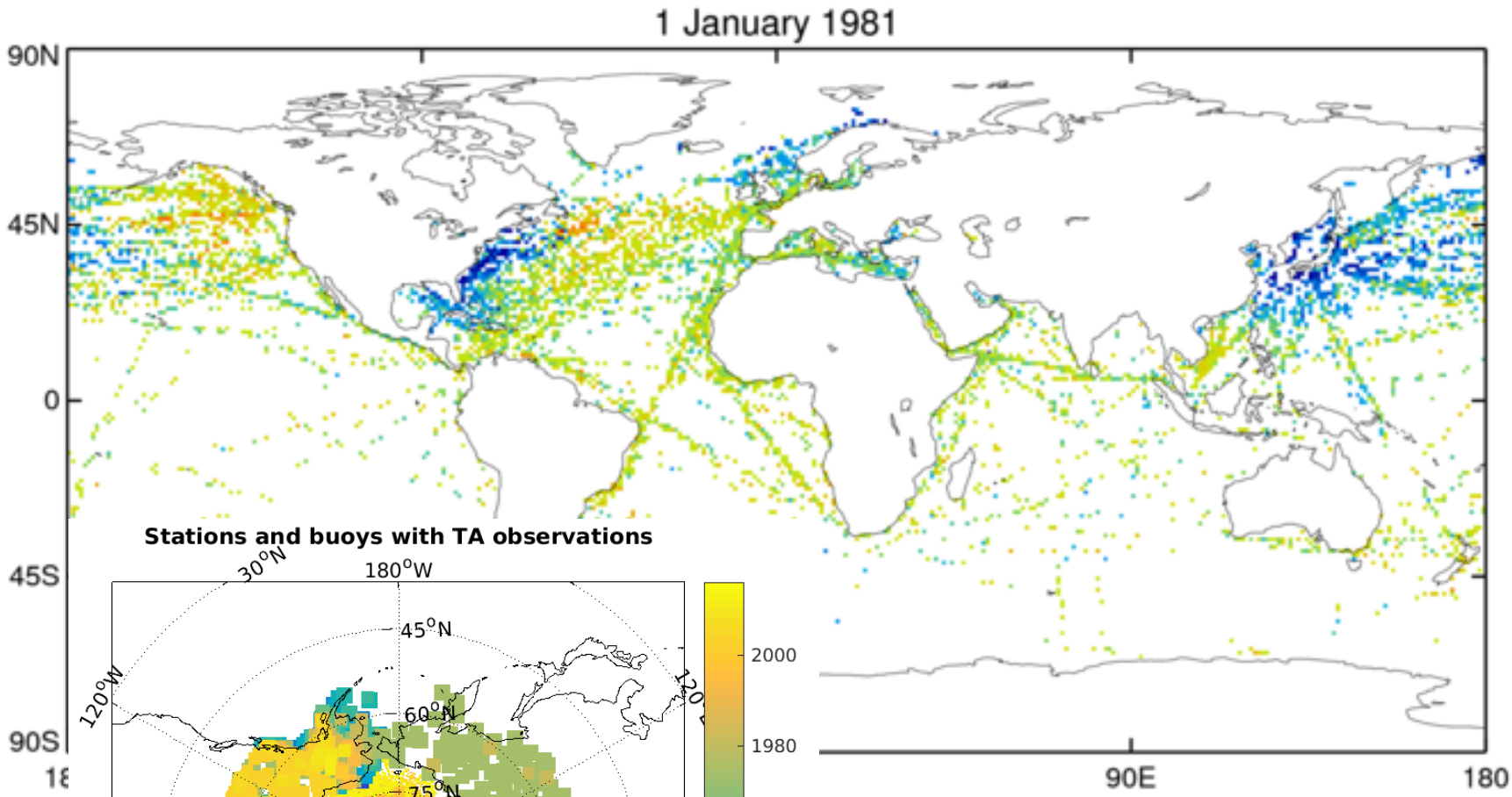

**33'511** stations
(32'041 Tmax + 32'265 Tmin)

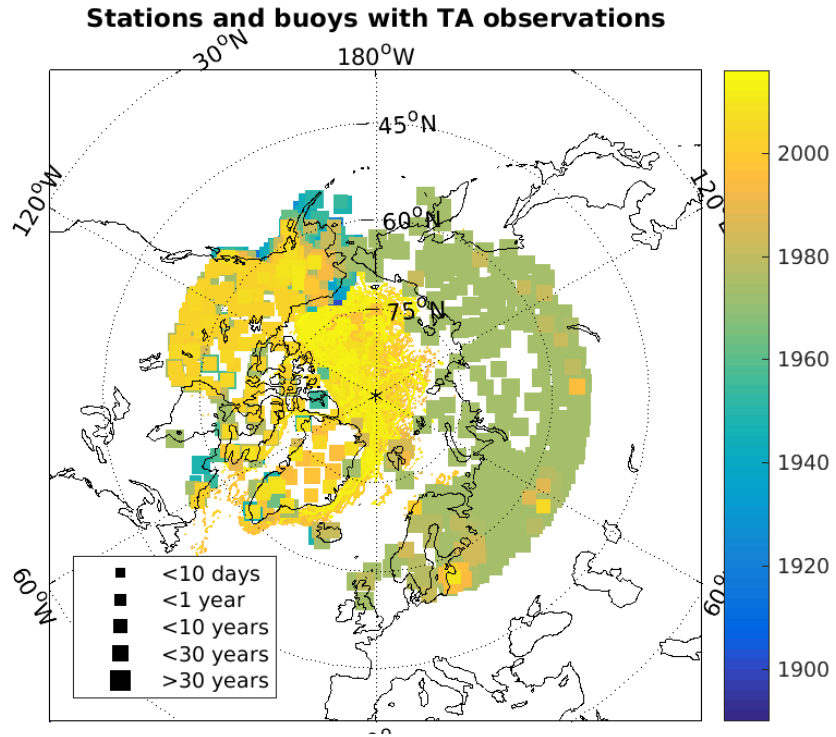
(Data are stored on EUSTACE workspace
in a common ASCII and NetCDF format)

UNIVERSITÄT BERN

EUSTACE

# Ship observations




Met Office Hadley Centre

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

DMI

# IDENTIFYING NON-CLIMATIC BREAKS IN DAILY LAND STATION SERIES

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# DETECTING DISCONTINUITIES IN DAILY LAND STATION DATA

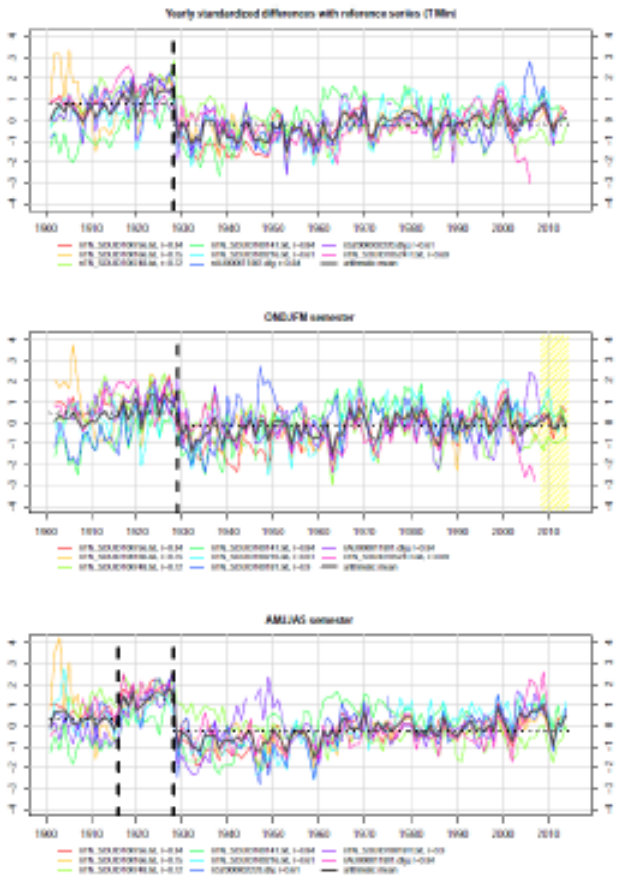
- s
- r

Para
Steve

Diffe
obse
varia
in c

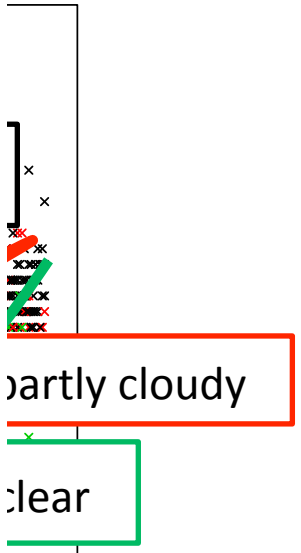
3 DETECTION METHODS
**Caussinus-Mestre**
**RHtests**
**GAHMDI**
combined:
a discontinuity is
significant if confirmed
by at least
**3 reference stations**
**using at least**
**2 of the methods**

Delivered breakpoints Basel:
**1916** and **1928**



day of year

:he mean




UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

DMI

# DEVELOPING CONSISTENT SATELLITE UNCERTAINTY ESTIMATES

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# ESTIMATING CONSISTENT UNCERTAINTIES IN SATELLITE RETRIEVALS

- Uncertainties categorised by effects whose errors have distinct correlation properties:
  - random
  - ~~locally systematic~~ aka "structured random"
  - (large-scale) systematic
- This three-component model applies to all processing levels and LST products
- Propagation of uncertainties:
  - L1 → L2 → L3 → L4 (Merged Product)

UNIVERSITY OF LEICESTER

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

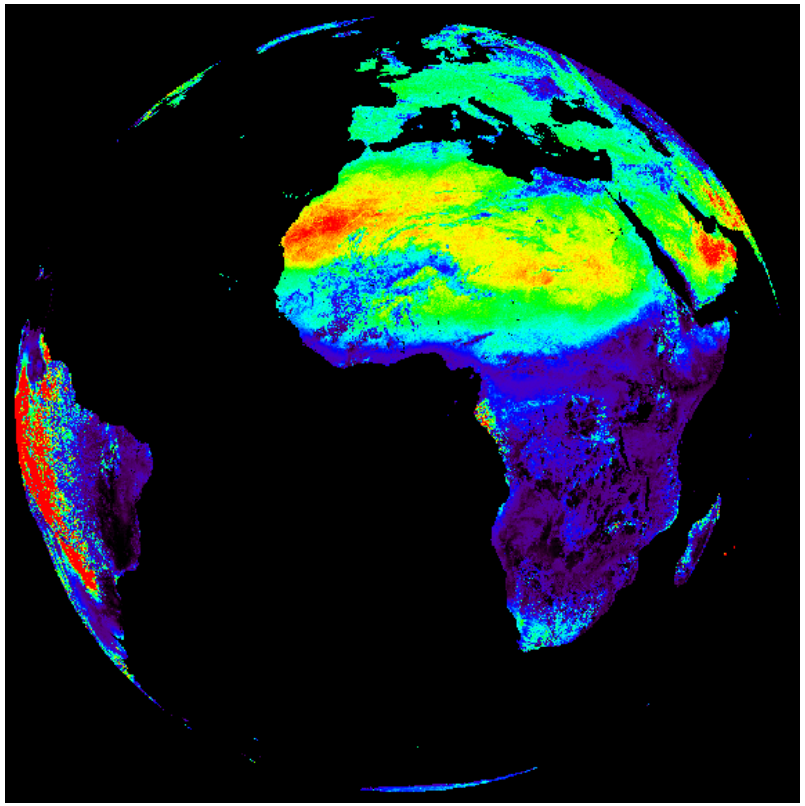
EUSTACE

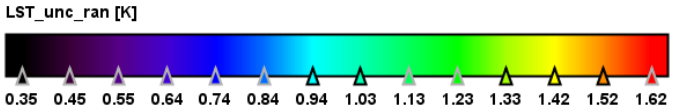
# LST Uncertainty Components

| VARIABLE | METHOD | COMMENTS |
|---|---|---|
| LST_UNC_RAN | **L2 Random 1 / Radiance noise Propagation** | $u\downarrow ran,y(x)=\sqrt{\sum_{c=1}^{n}(\partial R/\partial y\downarrow c\ u\downarrow ran(y\downarrow c))^2}$ Random component of L1 channel uncertainties propagated through the retrieval |
| | **L2 Random 2 / Emissivity noise Propagation** | $u\downarrow ran,\varepsilon(x)=\sqrt{\sum_{c=1}^{n}(\partial R/\partial \varepsilon\downarrow c\ u\downarrow ran(\varepsilon\downarrow c))^2}$ Estimate of the magnitude of pixel-to-pixel scale emissivity variability within areas based on land cover class |
| LST_UNC_LOC | **L2 Local 2 / Uncertainty from atmosphere/fit for regression-based retrieval** | $u\downarrow loc,fit(x)=\sqrt{Var(x-x\downarrow in)}$ Atmospheric fields correlated on timescales >1 day and length scales >100 km. For coefficient based retrieval methods the retrieval ambiguity is a contributor of residuals in the fit |
| | **L2 Local 2 / Uncertainty from Emissivity** | $u\downarrow loc,\varepsilon(x)=\sqrt{\sum_{c=1}^{n}(\partial R/\partial \varepsilon\downarrow c\ u\downarrow loc(\varepsilon\downarrow c))^2}$ Across a particular land class area, there may be a mean difference between the assumed and true mean emissivity |
| ST_UNC_SYS | **L2 Systemati… / Reasoned estimate** | …ctions have been applied by data pr… …nty in the bias of the satellite surf… …erature (ie from validation) |

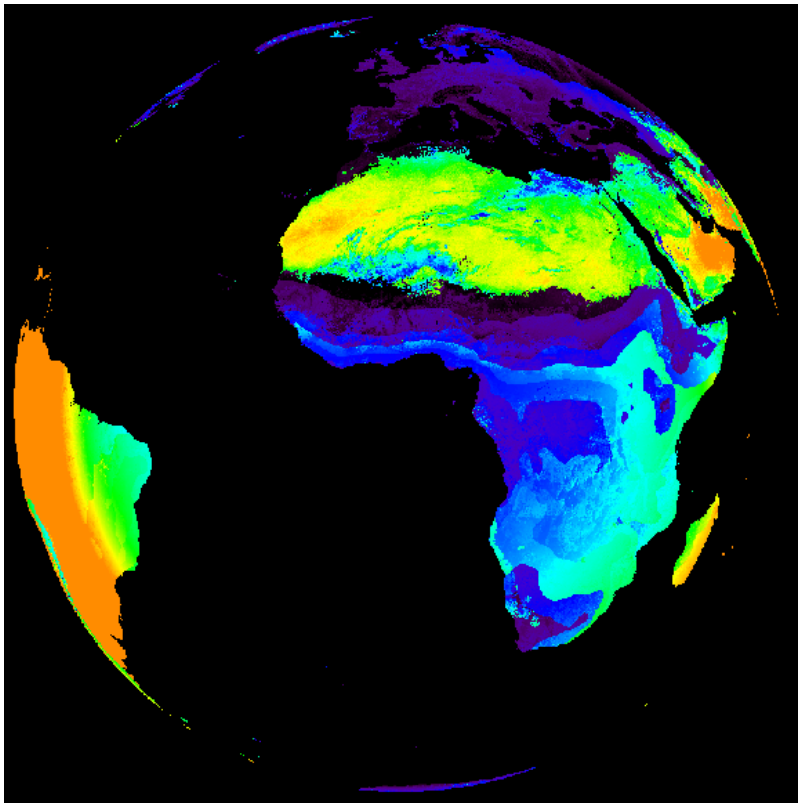
# SEVIRI Uncertainties

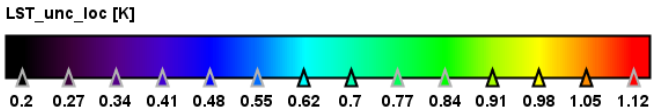
## Random






## Locally correlated/structured random



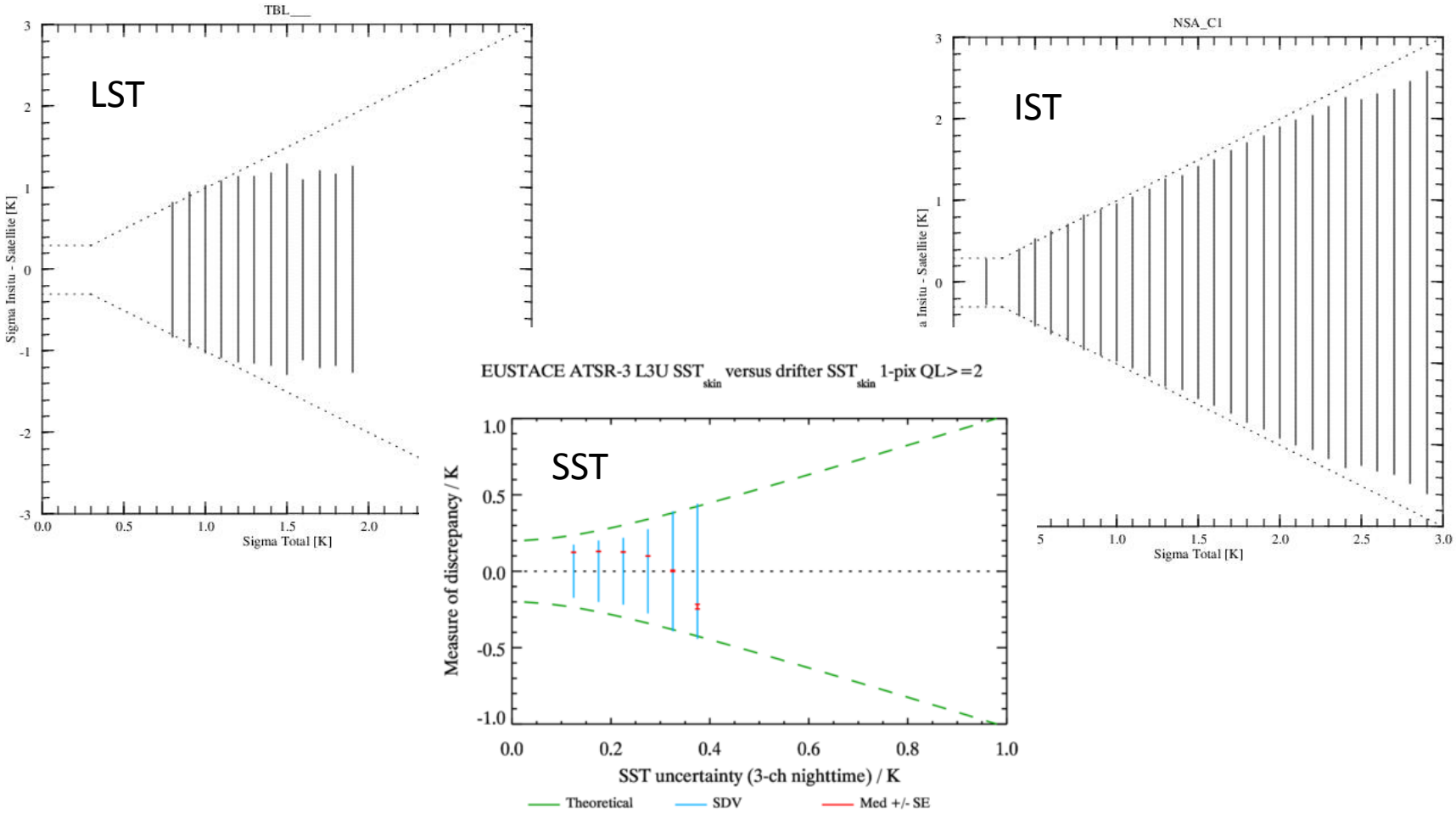



UNIVERSITY OF LEICESTER

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

EUSTACE

# VALIDATION OF LST, IST AND SST TOTAL UNCERTAINTIES AT REFERENCE STATIONS




UNIVERSITY OF LEICESTER

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

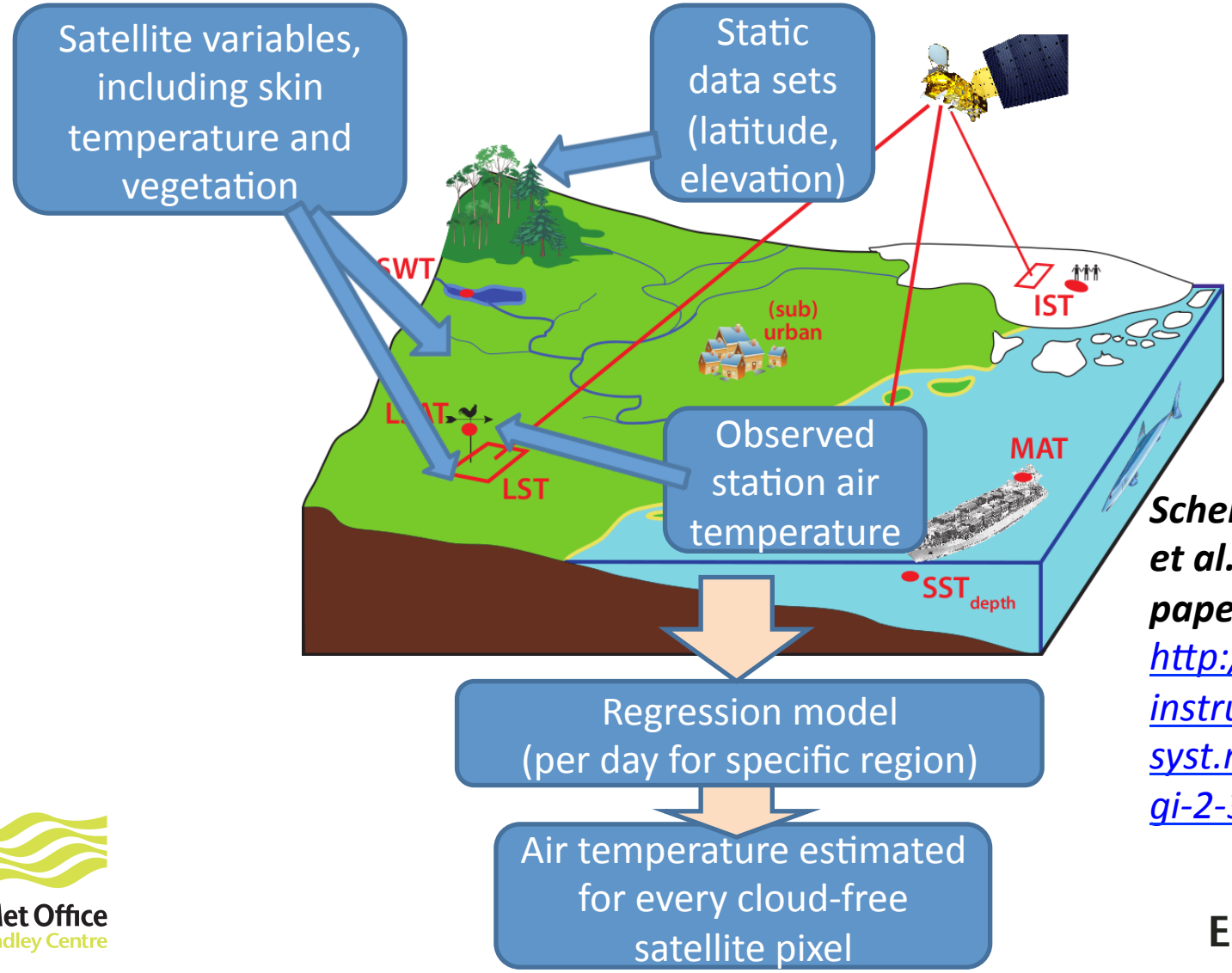
DMI

# ESTIMATING AIR TEMPERATURE FROM SATELLITE DATA: (1) LAND

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# ESTIMATING AIR TEMPERATURE FROM SKIN TEMPERATURE



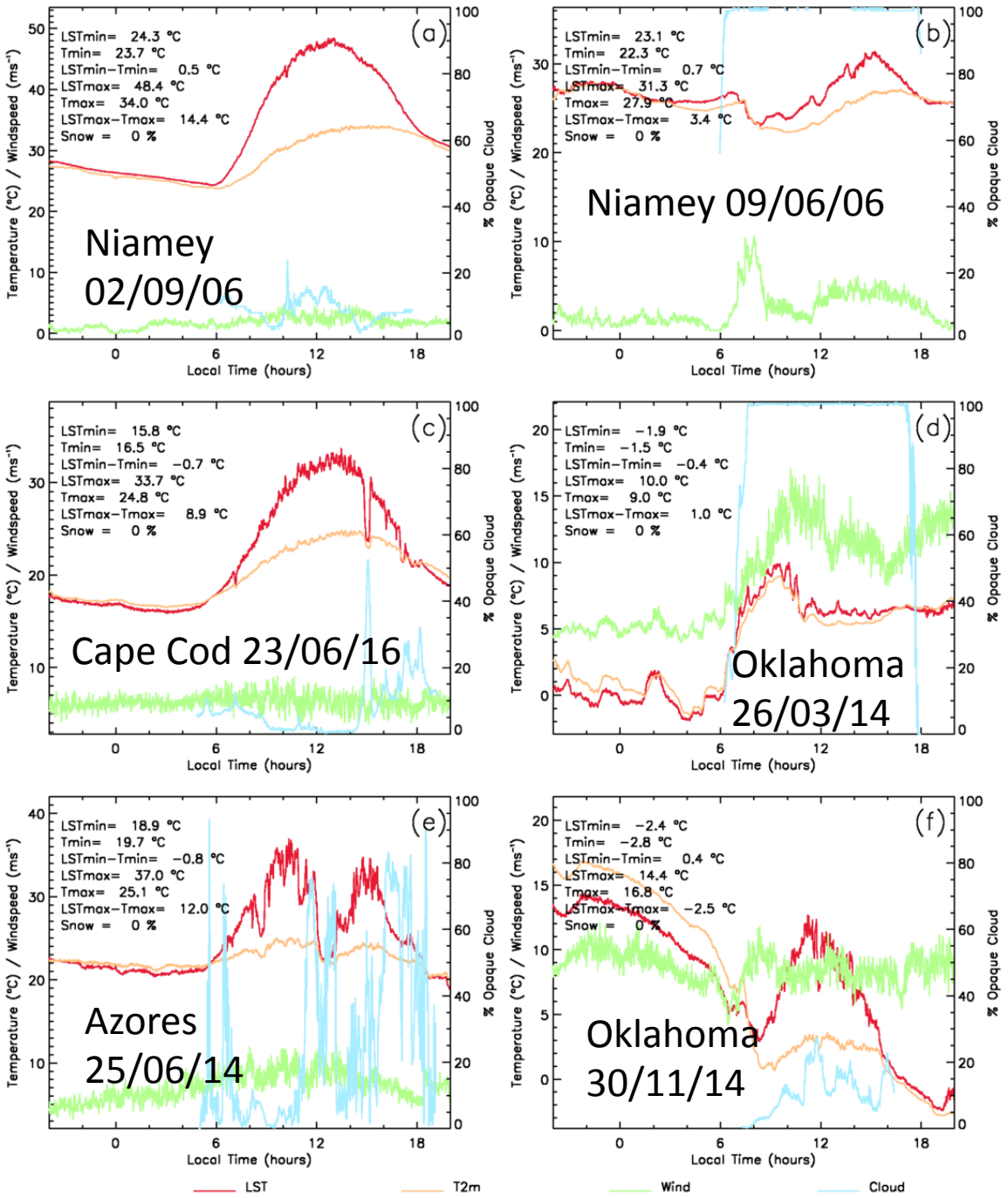

***Schematic from Merchant et al., 2013 community paper and roadmap***: *http://www.geosci-instrum-method-data-syst.net/2/305/2013/gi-2-305-2013.html*

Met Office Hadley Centre

EUSTACE

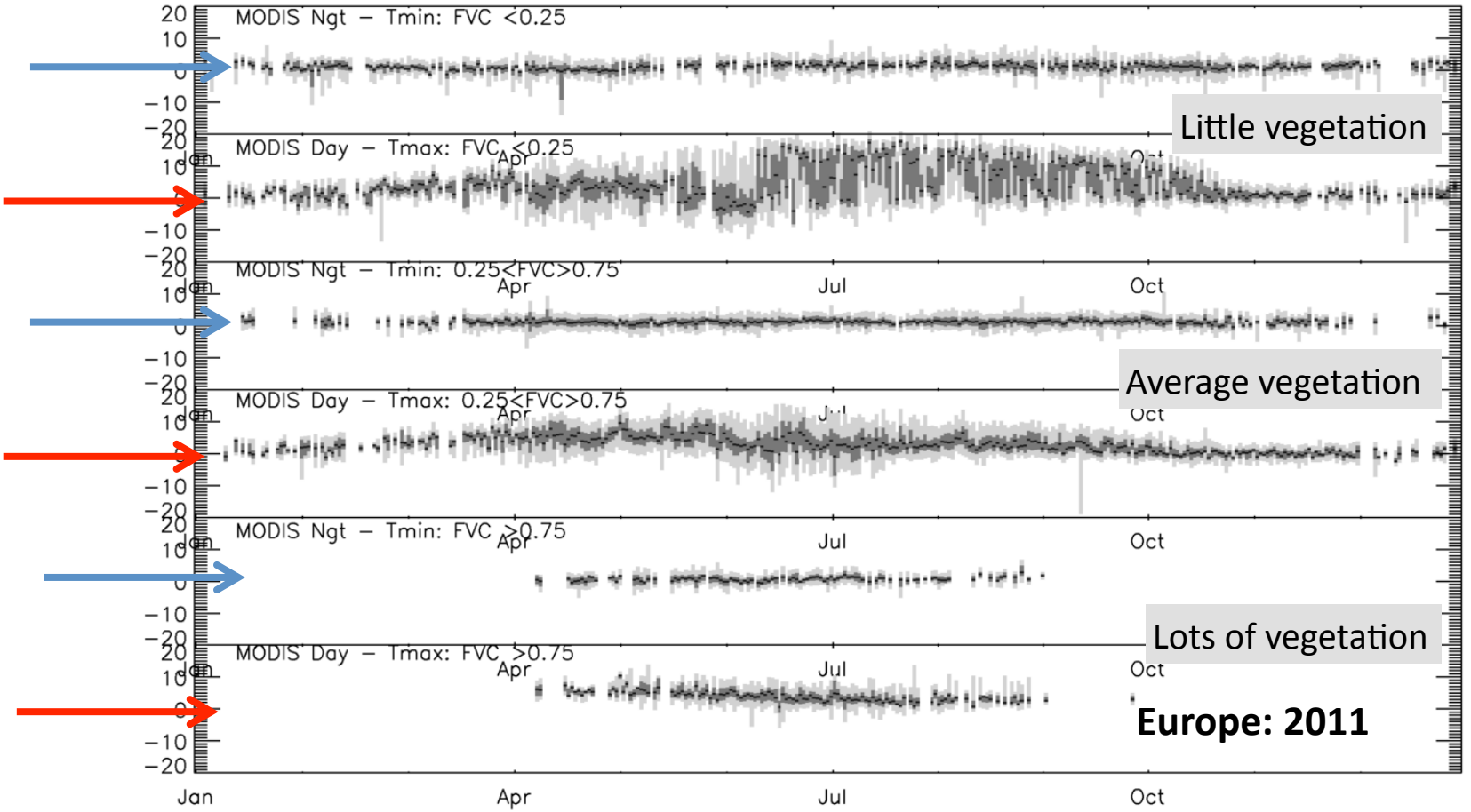
# VARIABILITY ANALYSIS

- Paper in press in JGR-Atm
  - *'An in situ-based analysis of the relationship between skin and screen-level temperatures'*
- 19 ARM deployments, analysing up to 1 year of data from each.
- Wind speed and cloud are important factors governing instantaneous Tskin-Tair differences. Influence less clear on Tskin-Tair extremes.




Met Office
Hadley Centre

# RELATIONSHIP WITH VEGETATION



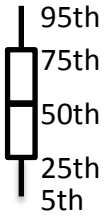

Minimum temperature difference: little impact by changing vegetation filter

Maximum temperature difference: more vegetation = less extreme differences

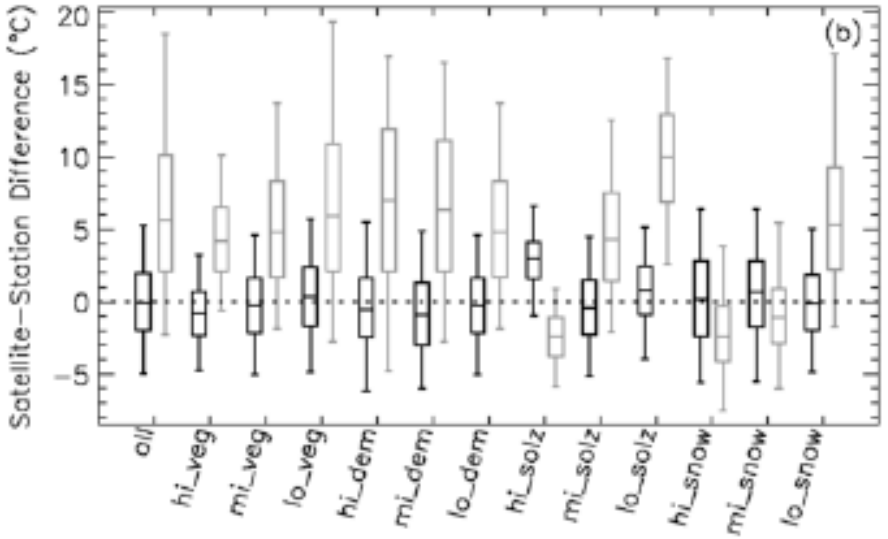
Met Office Hadley Centre

EUSTACE

# SURFACE AIR TEMPERATURE ESTIMATES

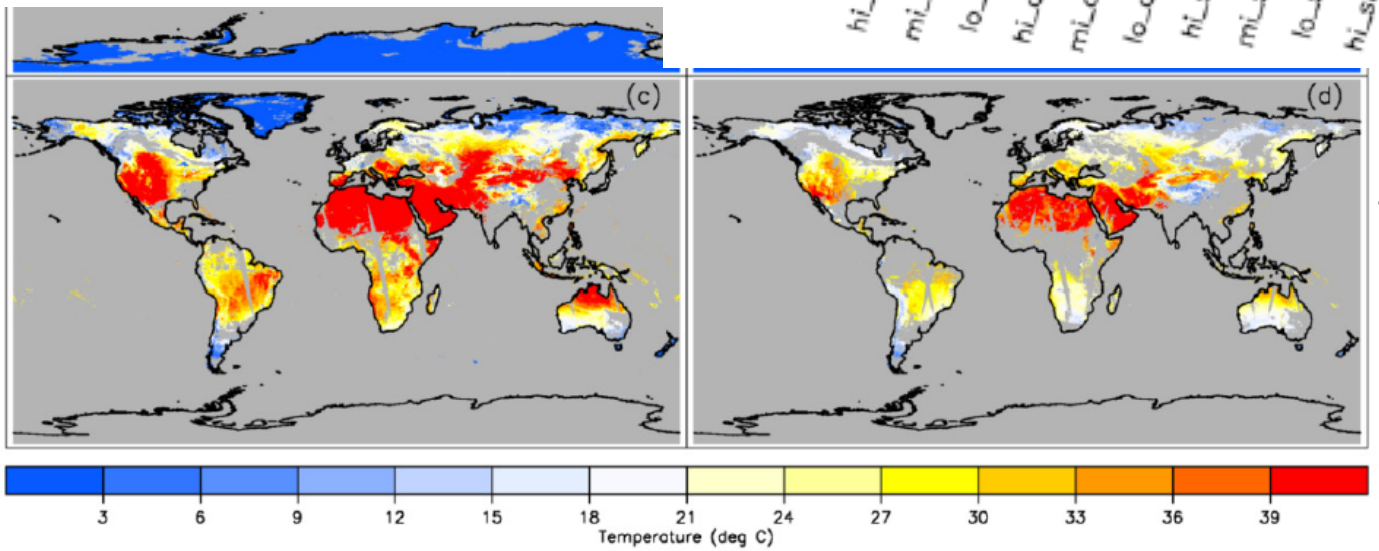



Independent evaluation 2002-2012 with 5000 GHCN-D stations not used for training




LST Nigl Grey indicates results for LST
**Black** indicates results for satellite T2m

LST Day




Tmax

Met Office Hadley Centre

Relationships are derived at 0.05 degrees and applied to 0.25 degree data. Station-satellite relationships peaks at ~0.05 deg and degrades with decreasing spatial resolution.

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

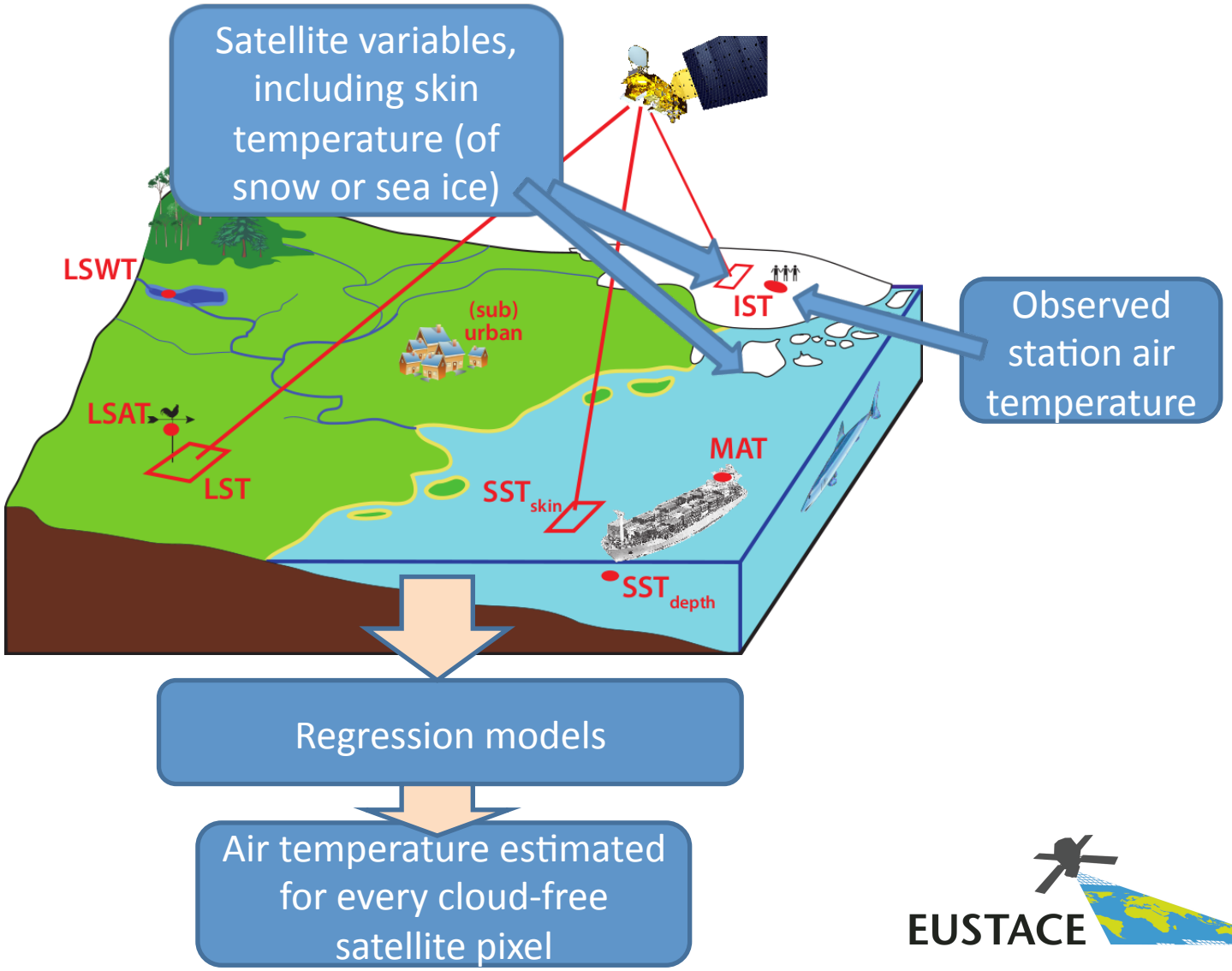
DMI

# ESTIMATING AIR TEMPERATURE FROM SATELLITE DATA: (2) ICE

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

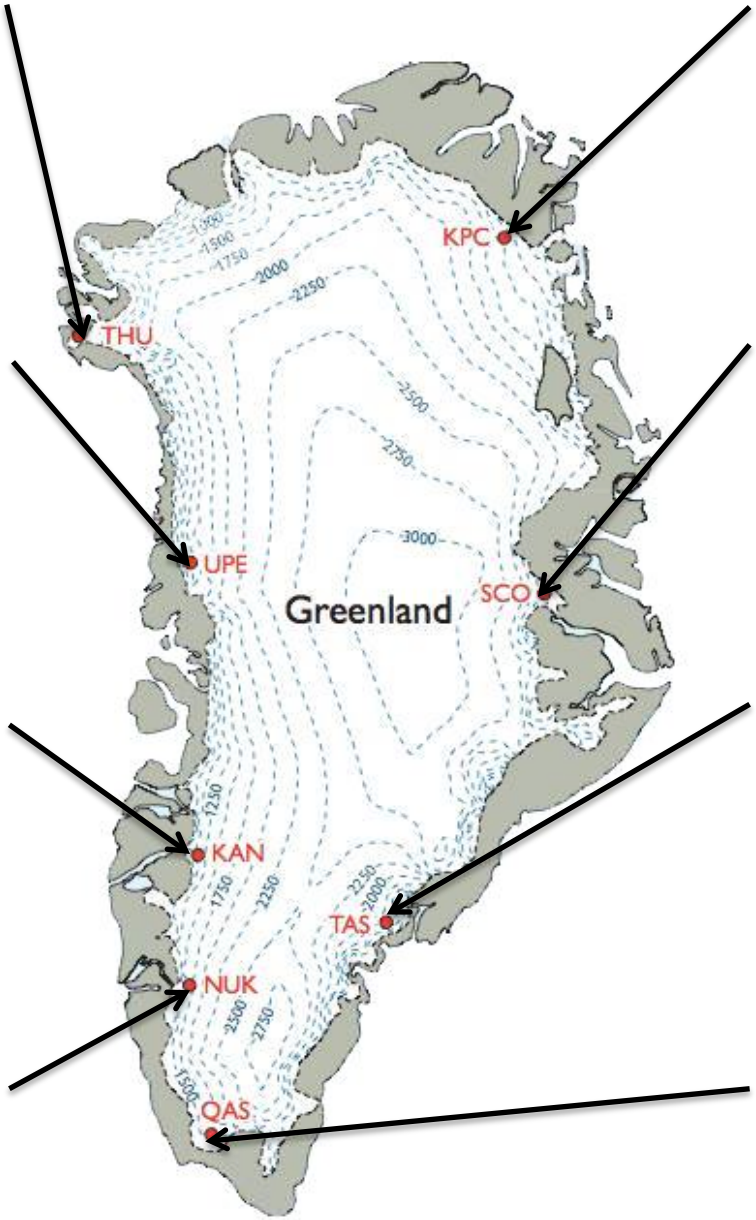
# ESTIMATING AIR TEMPERATURE FROM SKIN TEMPERATURE – OTHER SURFACES

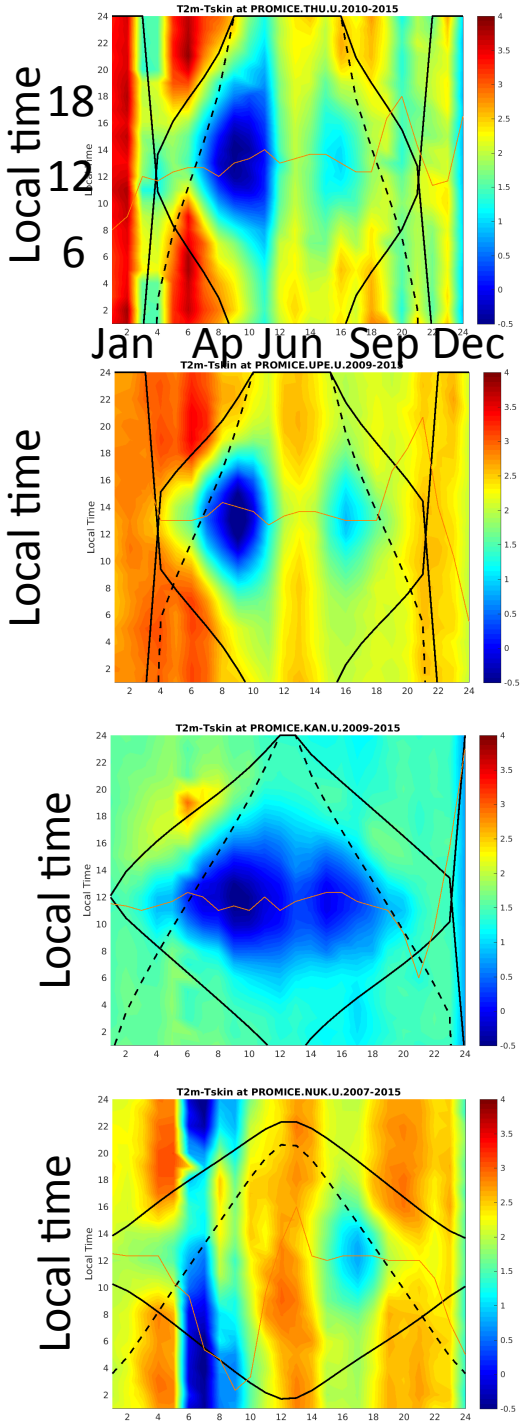


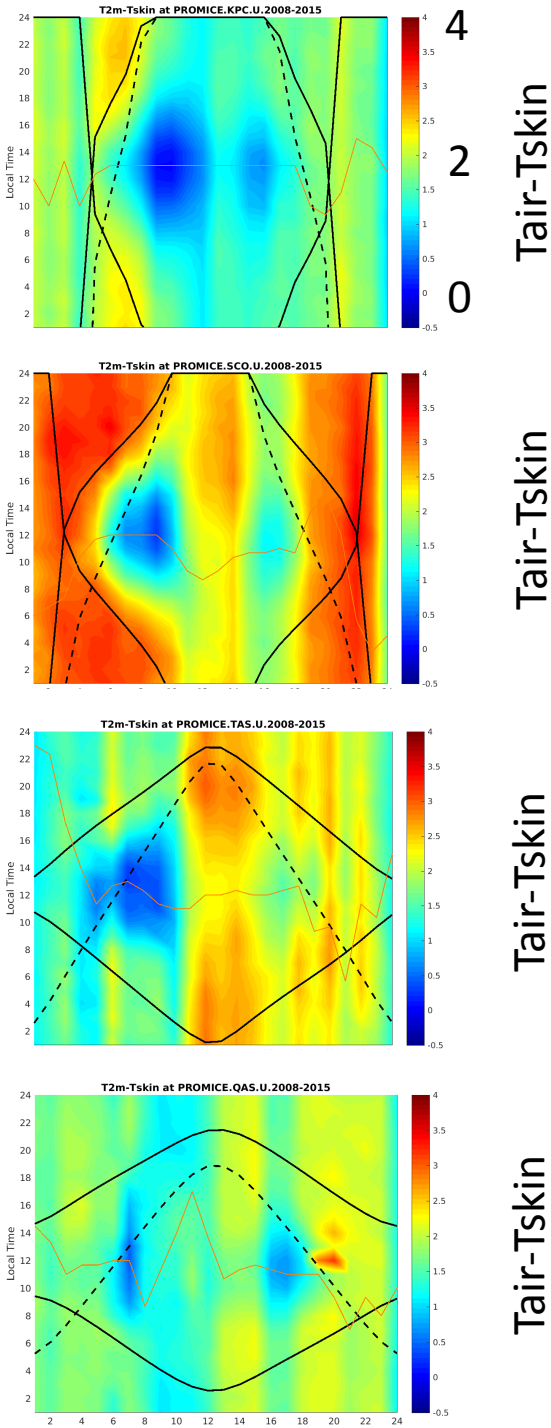

EUSTACE

# PROMICE

Programme for Monitoring of the Greenland Ice Sheet



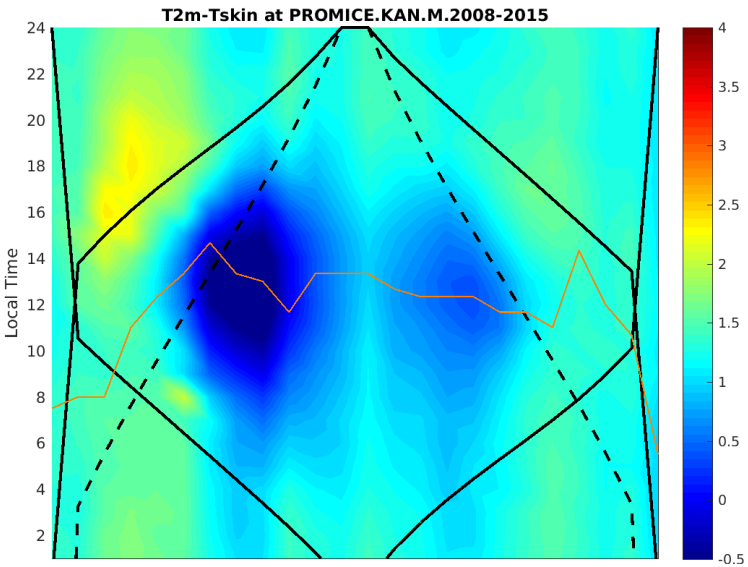



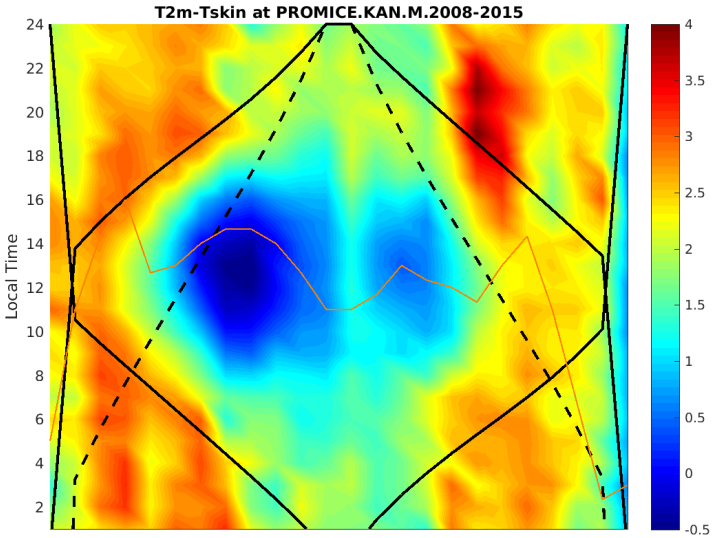
# IMPACT OF CLOUDS

## PROMICE - KAN M

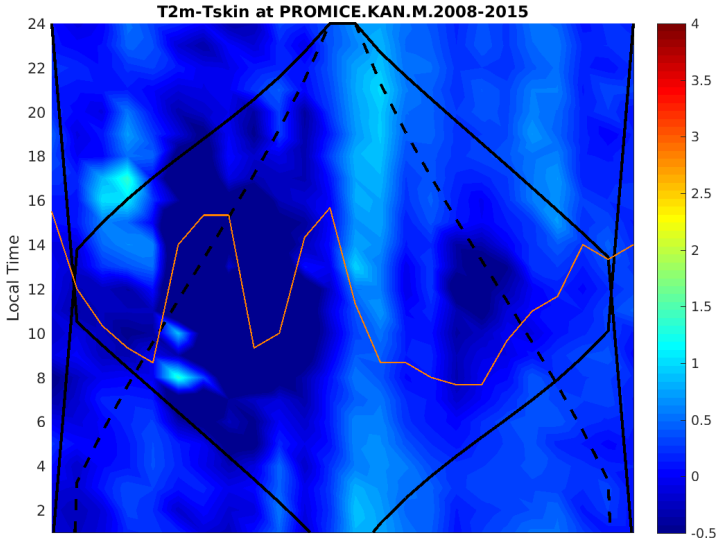
Surface and air temperature differences at KAN_M in cases of all-sky, clear-sky, and overcast conditions.

**All-sky**




**Clear sky (< 0.1)**

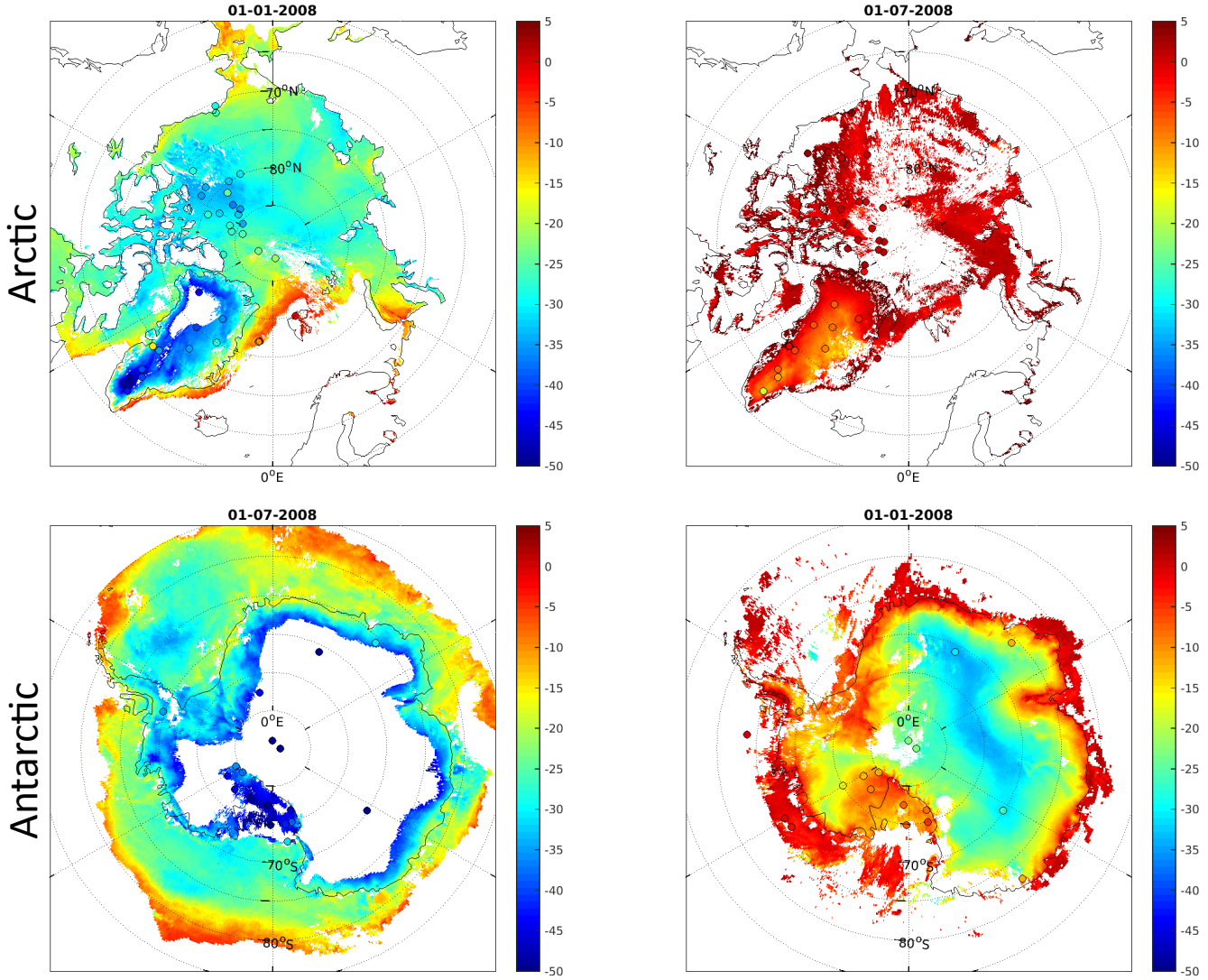



**Overcast (>0.9)**

DMI
Danish Meteorological Institute

EUSTACE

# ICE SURFACE AIR TEMPERATURES




Winter

Summer

Four examples of daily mean surface air temperature over ice (test version), estimated from satellite IST. Circles show in-situ measurements and white areas indicate missing data, often due to clouds.

DMI
Danish Meteorological Institute

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

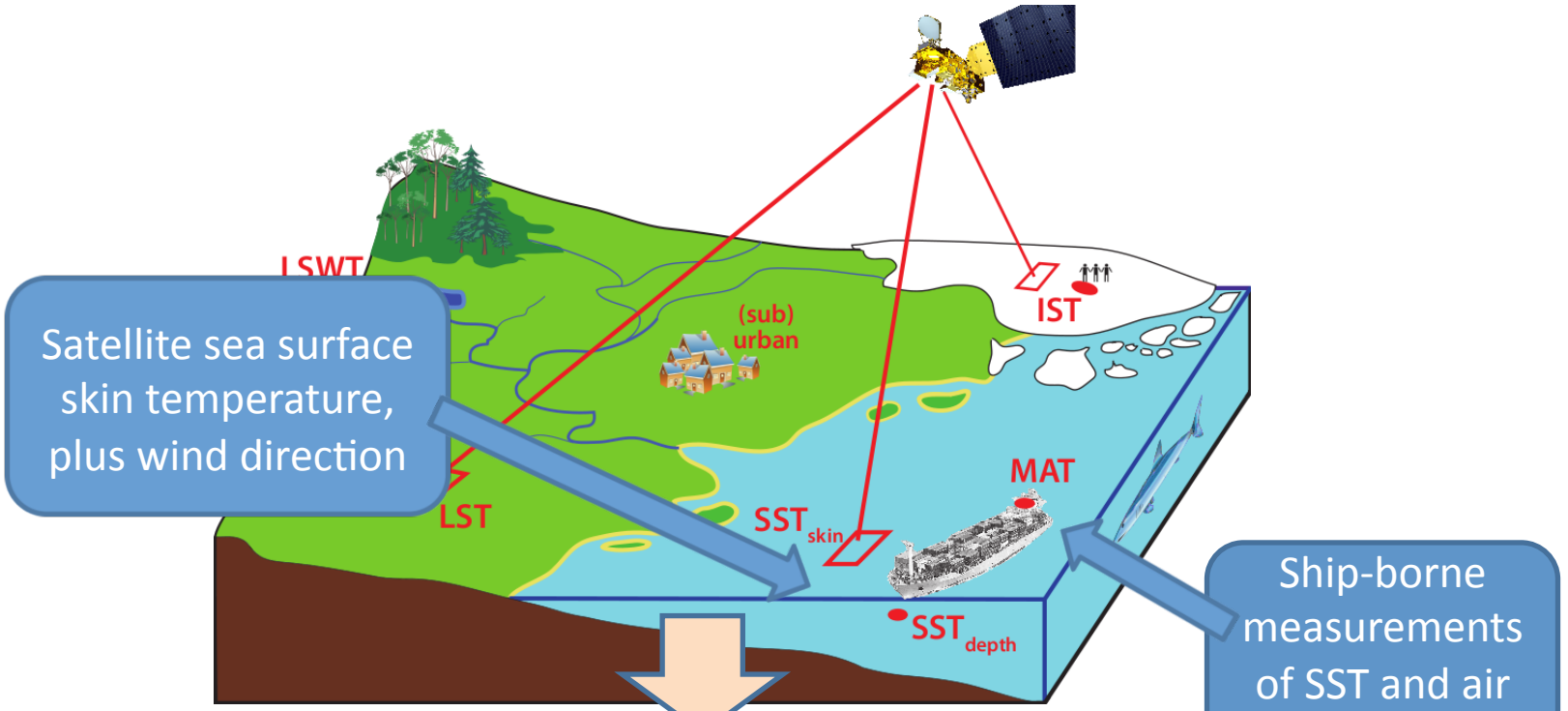
DMI

# ESTIMATING AIR TEMPERATURE FROM SATELLITE DATA: (3) OCEAN

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# ESTIMATING AIR TEMPERATURE FROM SKIN TEMPERATURE – OTHER SURFACES




EUSTACE

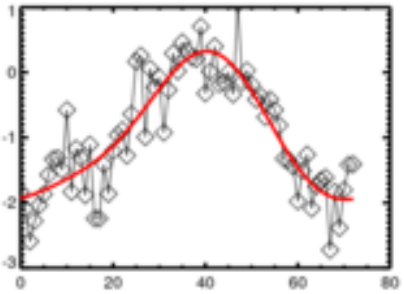
# UNDERSTANDING RELATIONSHIPS BETWEEN SST AND MAT

- Uses ICOADS 2.5 data, 1961-2000 and UIDs
- New quality control applied to SST and MAT, together with bias corrections
- Extract reports with SST and NMAT
- Night is defined as one hour after sundown to one hour after sunrise
- Estimated uncertainties in individual SST and MAT measurements is about 1°C.

Met Office
Hadley Centre

EUSTACE

# MODEL



$$MAT = SST + \Delta + \varepsilon$$

Sea-surface temperature

SST from CCI ATSR
Possibly AVHRR also

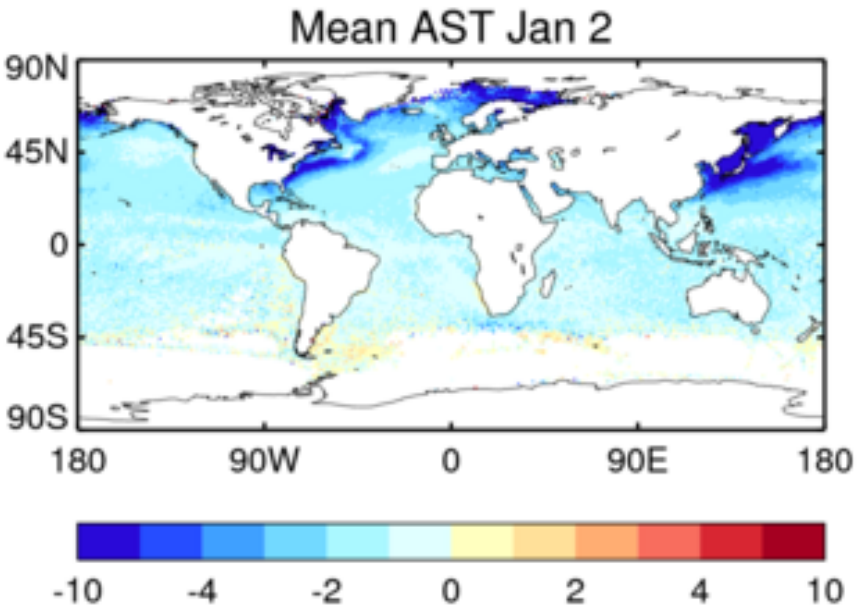
Climatological average air-sea temperature difference

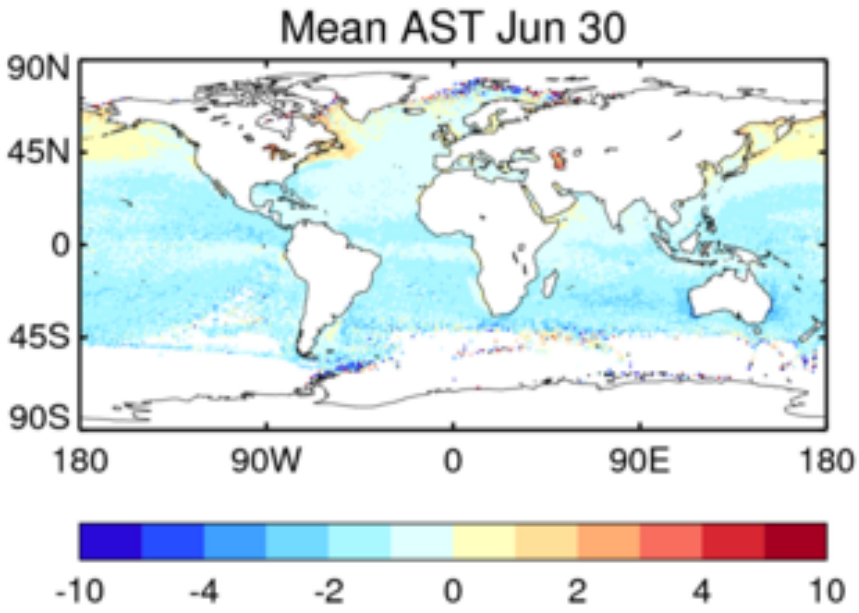
Time-varying locally-correlated "error"

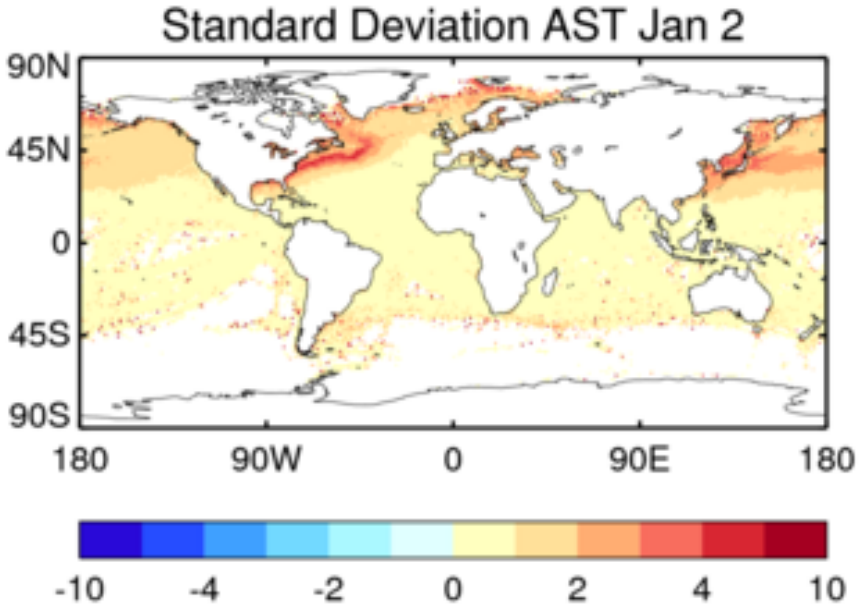
1. Simple average
2. Fixed seasonal cycle
3. Spatially varying length and time scales
4. Incorporating ship observations

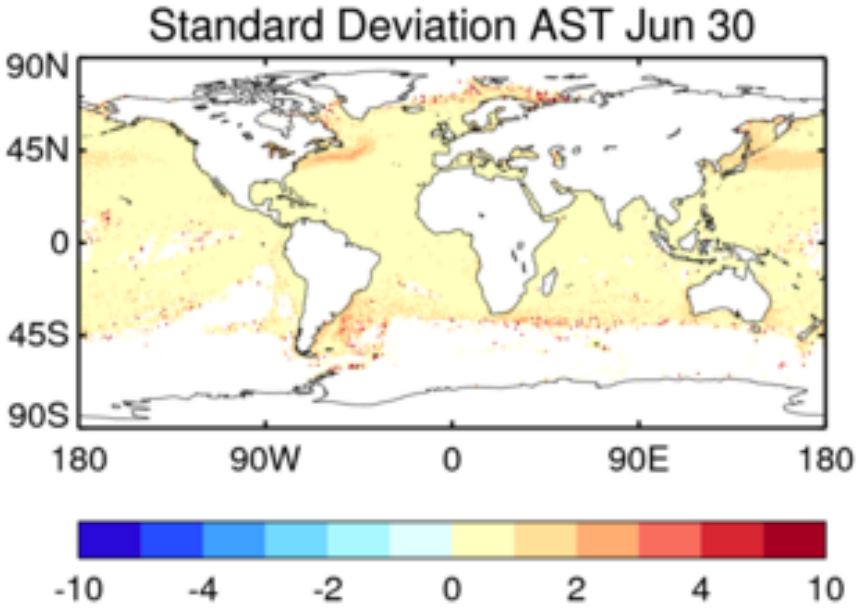
Met Office
Hadley Centre

EUSTACE



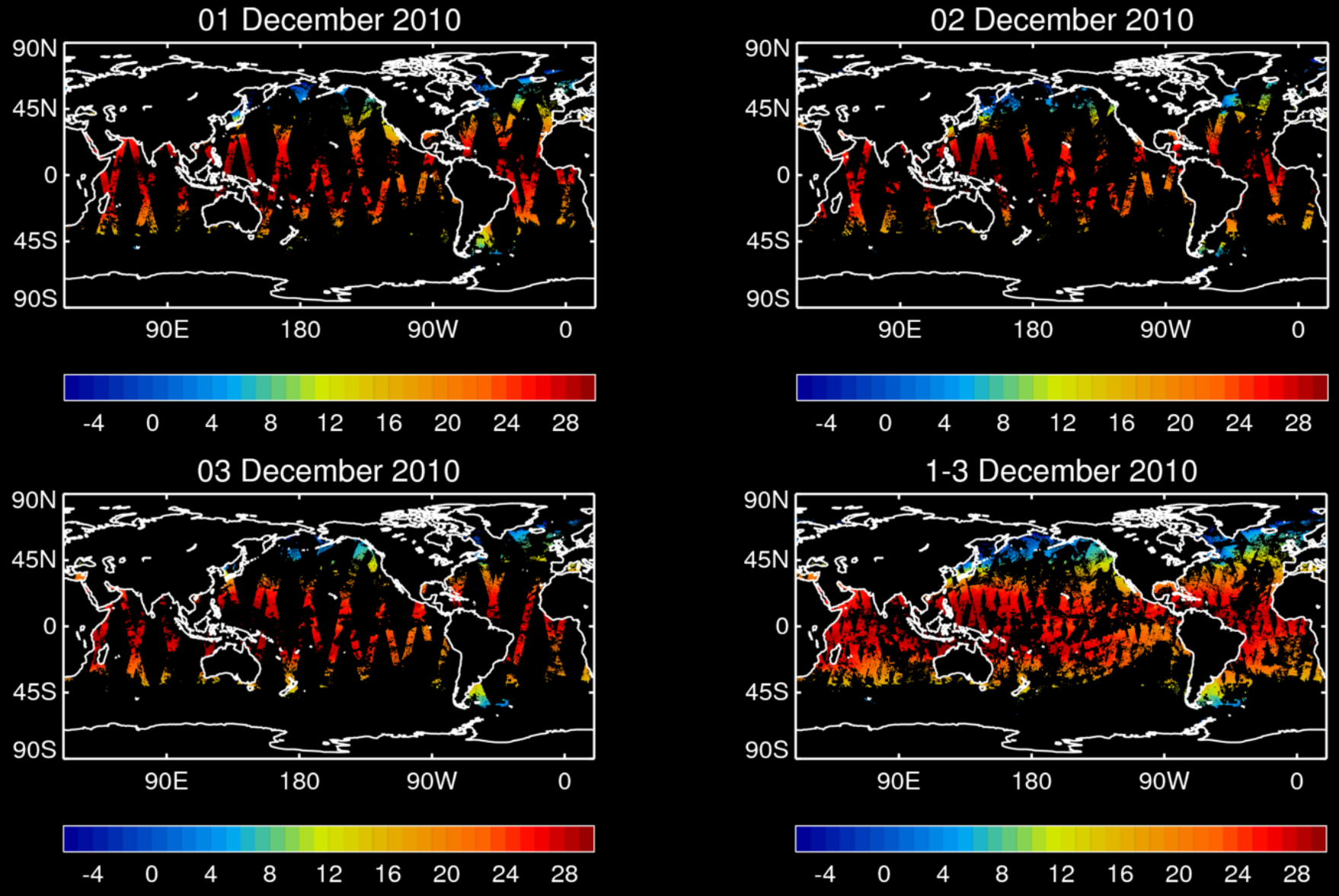




Met Office
Hadley Centre

EUSTACE

# Estimated air temperatures over oceans using ATSR series SST retrievals



# ESTIMATING UNCERTAINTY IN MAT DERIVED FROM SST

- Several components
- Uncertainty component arising from deviations from the mean air-sea temperature difference, which is represented by the standard deviation. Locally correlated with length scale of around 2000 km
- Uncertainty in the fourier components, which is correlated in time, but uncorrelated in space.
- Uncertainty in the SST, which depends on the SST source. For ATSR a combination of random, locally correlated, large scale correlated.

Met Office
Hadley Centre

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

DMI

# ESTIMATING AIR TEMPERATURE FROM SATELLITE DATA: (4) LAKES

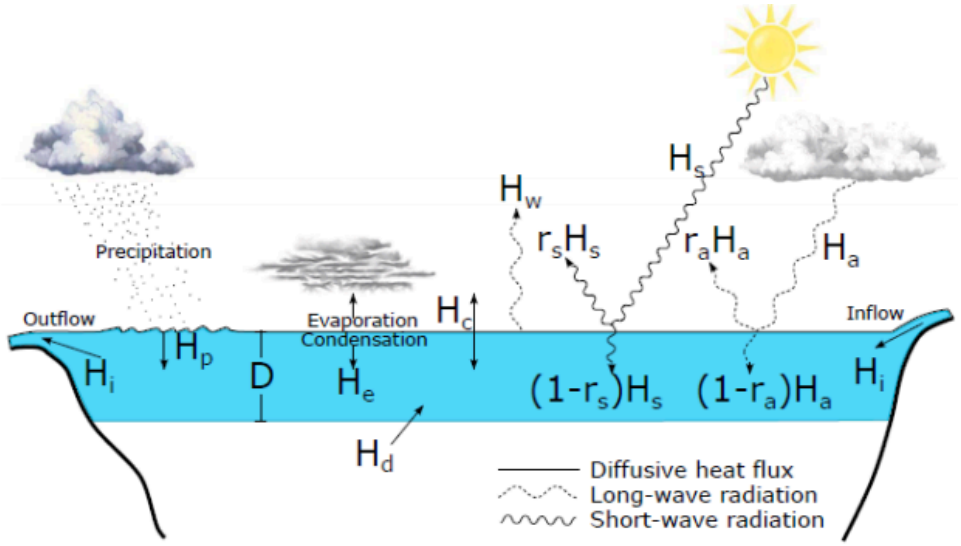
*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# RELATIONSHIP BETWEEN SAT AND LSWT

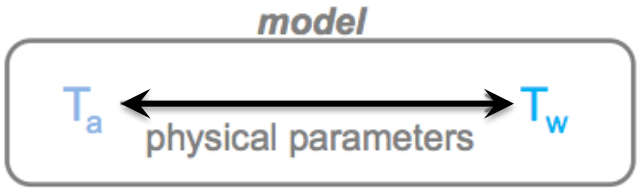
Heat budget in the well-mixed surface layer

$$\rho c_p V \frac{dT_w}{dt} = H_{net} A$$




Main forcing factor: air temperature $T_a$

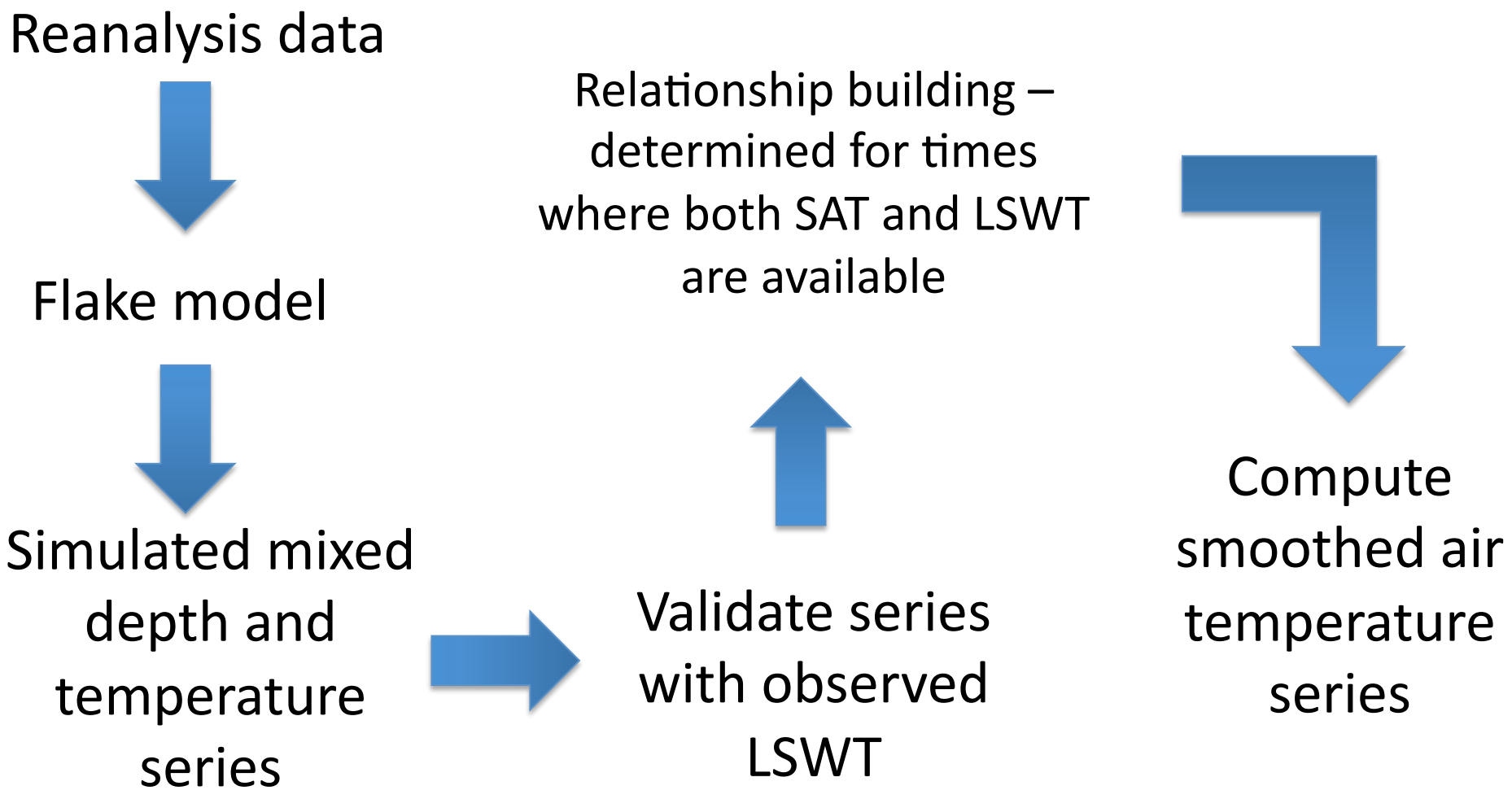
Main result: surface water temperature $T_w$




University of Reading

EUSTACE

# SUMMARY OF APPROACH




University of Reading

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

DMI

# ESTIMATE VALUES IN AREAS WHERE WE HAVE NO *IN SITU* OR SATELLITE DATA ON A PARTICULAR DAY

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# THE EUSTACE ANALYSES

- Should merge data sources, accounting for observational uncertainties to produce spatially- and temporally-complete temperature estimates, with quantified uncertainties.

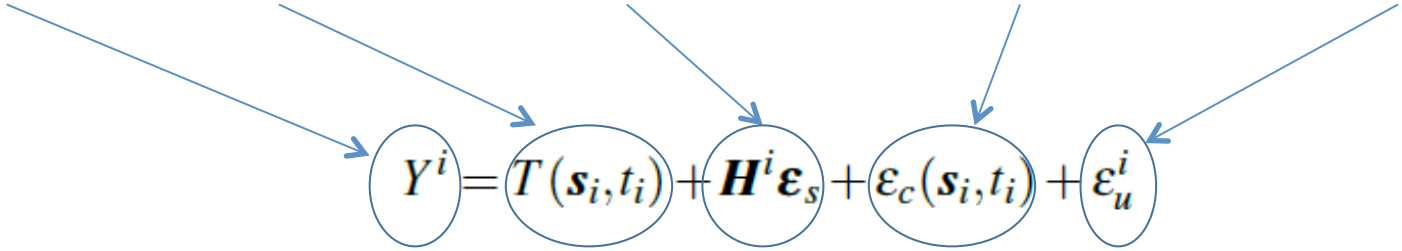
- Two methods, *Advanced Standard* and *Ambitious*, are being developed in parallel:
  - *Advanced Standard:* links to existing methods for observational climate data sets.
  - *Ambitious*: more experimental.

- Both approaches require novel techniques to work with daily data at EUSTACE resolutions.

EUSTACE

# MEASUREMENT MODEL (TMEAN)

Observation_i = Temperature + Systematic error + Locally correlated error+ Uncorrelated error




Temperature – at observation location. See next slide.

Systematic error – error terms with spatial or temporal structure described by $H^i$
(e.g. station homogenisation, covariate in calibration model).

Locally correlated – Error terms with correlation structure in space or time
(e.g. atmospheric correction errors for satellite observations).

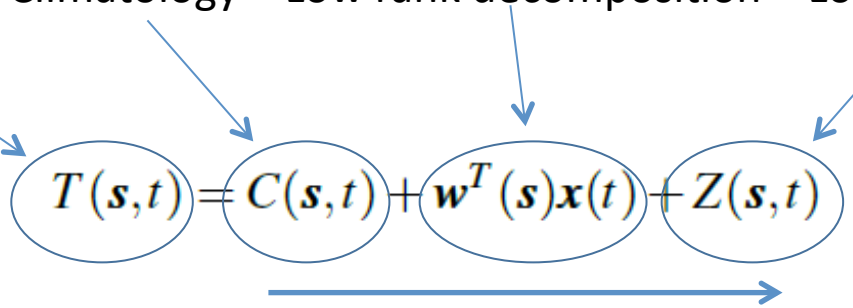
Uncorrelated error – Error associated only with observation *i.*

Met Office
Hadley Centre

EUSTACE

# THE ADVANCED STANDARD MODEL (TMEAN)

Temperature = Climatology + Low rank decomposition + Local process




*Standard approach is to estimate each component in turn, ignoring components to the right.*

Climatology – Covariates (e.g. altitude, latitude) + Seasonal component.

Low rank – Principal patterns of of variability.

Local process – “weather”

Met Office
Hadley Centre

EUSTACE

# LOW RANK COMPONENT

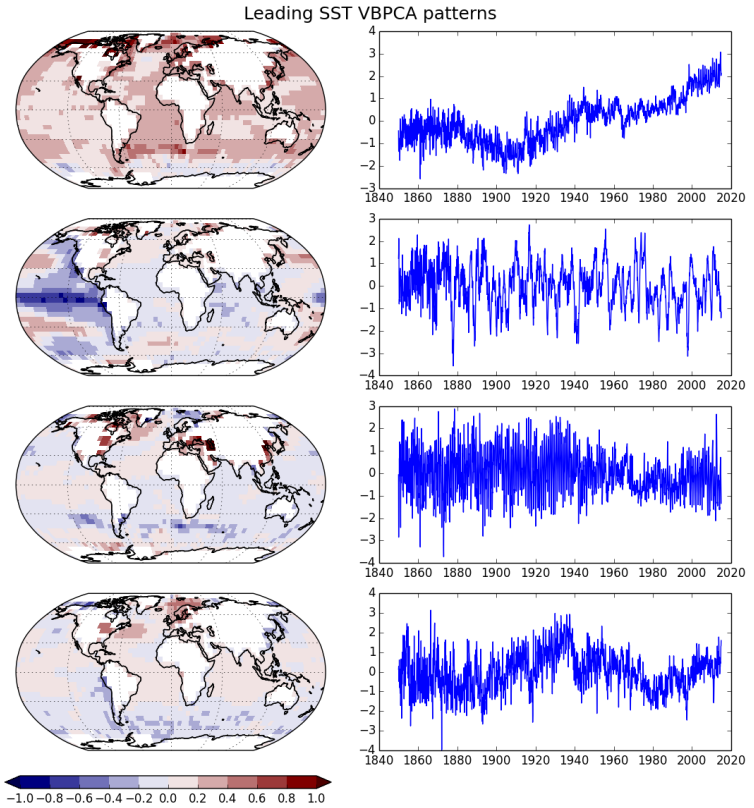
Decomposition into a small set of spatial patterns and a corresponding time series of pattern weights.

Reconstruct large scale variability as time *t* through a weighted sum of spatial patterns.

Long-term changes described by this component.

**e.g. Variational Bayesian Principal Component Analysis (VBPCA):**

- An EOF analysis method that accommodates incomplete data and (basic) measurement uncertainty.
- Other methods are also being explored




Met Office Hadley Centre

EUSTACE

# LOCAL MODEL

Temperature = Climatology + Low rank decomposition + Local process

$$T(\boldsymbol{s},t) = C(\boldsymbol{s},t) + \boldsymbol{w}^T(\boldsymbol{s})\boldsymbol{x}(t) + Z(\boldsymbol{s},t)$$

Traditional kriging likely infeasible at EUSTACE scales.

Z is Big! So let's map to a lower resolution...

$$Z(\boldsymbol{s},t) = \boldsymbol{A}_z(\boldsymbol{s},t)\boldsymbol{z}$$

Assumption is that covariates describe variation at finest scale.

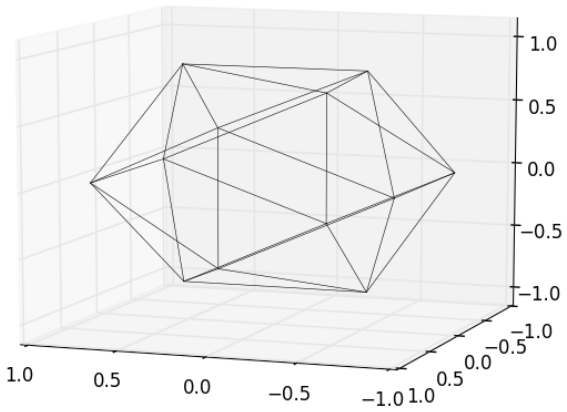
Testing:

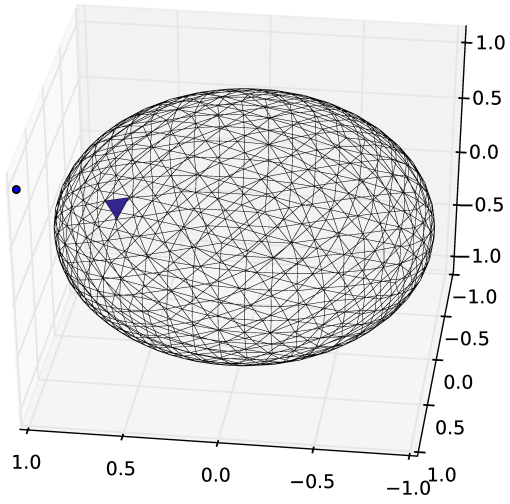
- Kriging with non-stationary covariance function (Paciorek & Shervish, 2004), on moving window;
- Compactly supported basis functions with weights from SPDE (Nychka et al., 2015);
- SPDE on triangulated sphere (Lindgren et al., 2011).

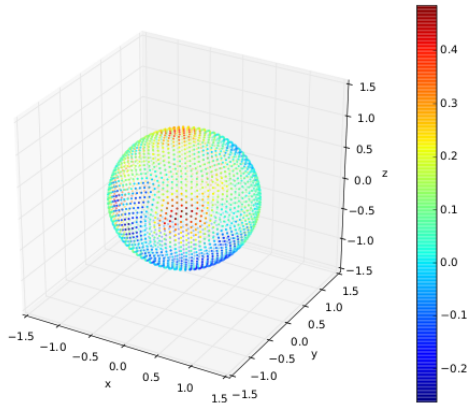
Met Office Hadley Centre

EUSTACE

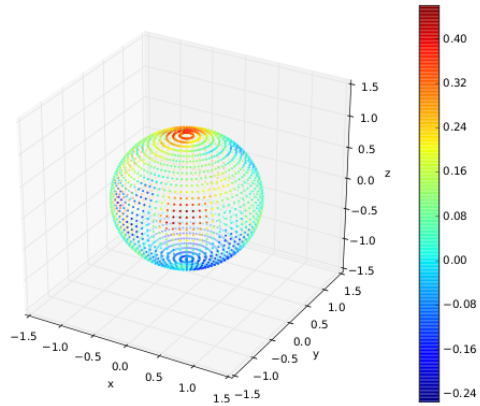
# ALL CORNERS OF EARTH



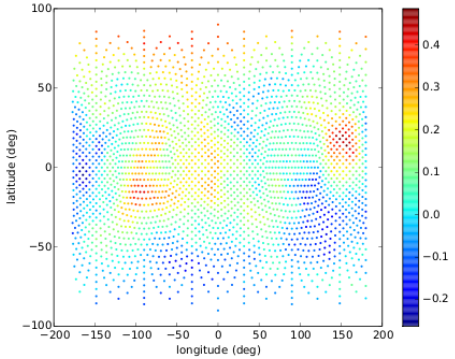



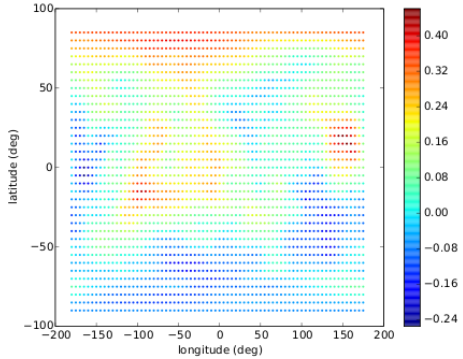

(a)




(b)




(c)

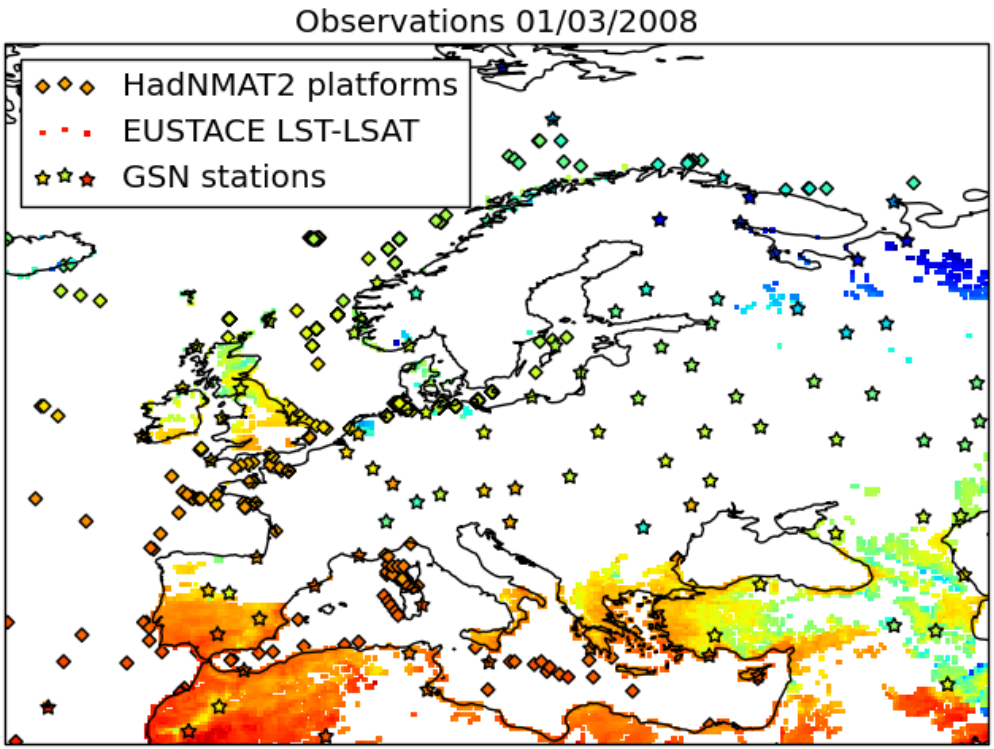


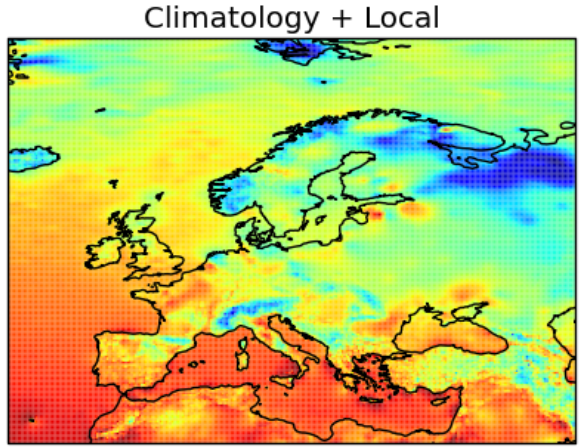

(d)

Grid does not converge at poles.

Met Office
Hadley Centre

# CREATE COMPLETE FIELDS





Met Office
Hadley Centre

Courtesy Colin Morice, Met Office

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

DMI

# VALIDATION

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# HOW WILL WE KNOW IF EUSTACE PRODUCTS ARE ANY GOOD?

We will:

- Adhere to standardised validation protocols for each surface type, with the aim to fit the profile of Quality Assurance for Essential Climate Variables Data (QA4ECV)
- Extend existing principles from SST and LST to match up collocated surface air temperature against *in situ* measurements across all surfaces:
    - Withhold sufficient fully-SI-traceable measurements for the highest quality validation, ensuring full independence from project output datasets
    - Validate the uncertainty information to increase confidence in the quality of the data products
- Inter-compare on common spatial and temporal grids the output surface temperature datasets with other surface air temperature datasets and reanalysis data


University of Leicester

EUSTACE

# USER ENGAGEMENT WITH EUSTACE

EUSTACE products will be made for wide range of users: researchers, policy makers, health, agriculture, …. etc.
User engagement needed **from the start** to assure usability/salience

Activities in which users have been engaged and/or informed:

- User workshops (Virtual user consultations, and at EGU 2015 and 2016)
- As trail blazers
- Dissemination on the progress and products through web site
- Guidance on use of products

EUSTACE will have been successful when the products are used.

If you are interested, please contact bessembi@knmi.nl


Royal Netherlands
Meteorological Institute
*Ministry of Infrastructure and the Environment*

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Universität Bern

Oeschger Centre Climate Change Research

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

DMI

# EUSTACE PRODUCTS

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE

# EUSTACE PRODUCTS

| Product | Description | Date |
|---|---|---|
| Station series and E-OBS update | Global data set of daily weather station air temperature measurements (Tmax and Tmin) with non-climatic breaks identified – Station time series and gridded for Europe | Dec 2016 |
| Satellite skin temperature retrievals | Daily satellite skin temperature estimates for all surfaces of Earth with consistent uncertainty estimates – Gridded or along satellite's track | mid 2016 |
| Skin/air temperature relationships | Understanding of the relationship between surface skin and surface air temperature over all surfaces of Earth and in different seasons – A report | Dec 2016 |
| Air temperature estimates from satellites | Daily estimates of surface air temperature from skin temperature retrievals - Gridded or along satellite's track (TBD) | Jun 2017 |
| Globally complete air temperature fields | Globally-complete daily fields of surface air temperature over all corners of Earth since 1850 – Gridded (0.25° lat/lon) perhaps an ensemble. (Tmax and Tmin over land, Tmean elsewhere.) | May 2018 |
| Derived products | For example, global means and climatologies | May 2018 |

# SUMMARY

**EUSTACE will give publicly available daily estimates of surface air temperature since 1850 across the globe for the first time by combining surface and satellite data using novel statistical techniques.** To do this, we need to:

- Identify non-climatic discontinuities in daily weather station data, *so users can trust the changes our records show*
- Understand how surface temperature measured *in situ* and by satellite relates, *to estimate air from skin temperature*
- Estimate values in areas where we have no *in situ* or satellite data, *so users can have daily information here*
- Validate our estimates using independent data

EUSTACE

Science & Technology Facilities Council

University of Leicester

Met Office Hadley Centre

University of Reading

University of Bath

Royal Netherlands Meteorological Institute
*Ministry of Infrastructure and the Environment*

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

DMI

# MANY THANKS FOR LISTENING

# TIME FOR QUESTIONS

*EUSTACE has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171*

EUSTACE