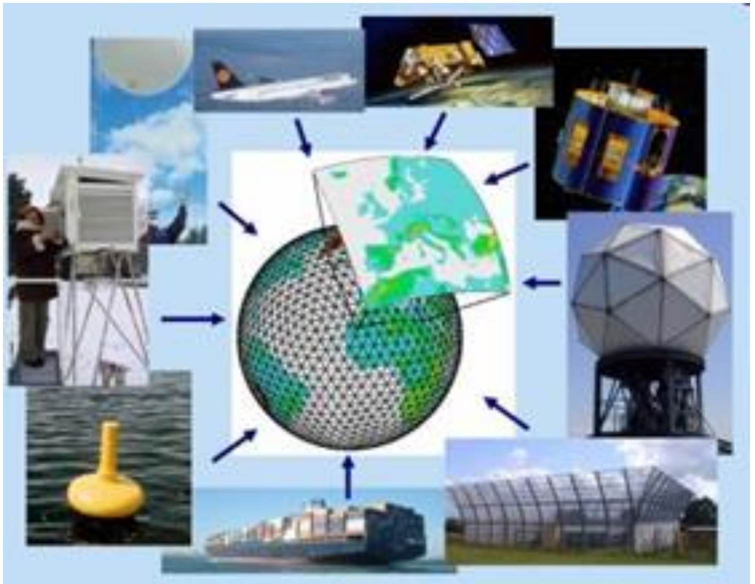
Towards Consistent representation of temporal variations of boundary forcing in reanalyses, reforecasts and climate integrations

From ECMWF:
Magdalena Balmaseda, Tim Stockdale, Retish Senan, Souhail Boussetta, Angela Benedetti, Gianpaolo Balsamo, Frederic Vitart
From Meteo France: Constantin Ardilouze, Lauriane Batte, Gyldas Dayon
From CNR-ISAC: Andrea Alessandri, Fransje van Oorschot
From BSC: Roberto Bilbao, Etienne Tourigne , Pablo Ortega

The quality warrant of climate monitoring and initialized predictions



1) most sophisticated and well-validated Earth System Models (ESM)

2) data assimilation capabilities, able to consistently and synergistically **integrate a**

3) wealth of Earth Observations (EO)

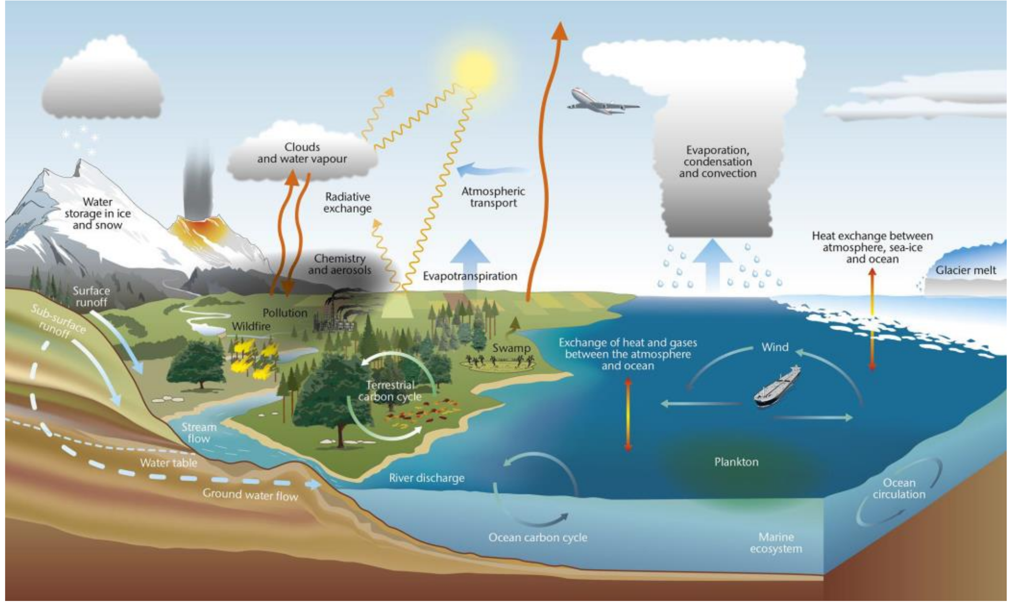
to estimate the past and present state of the climate, and to propagate this information into the future via initialised predictions

What is missing from the above 3 bullets?

Treatment of the temporal evolution of the boundary forcings, an essential ingredient to ensure temporal consistency

Earth System Complexity in a monitoring and forecasting system

- Physical basis for inclusion
- Ability to model
- Ability to initialize
- Affordability



Hierarchical representation of an earth system component

Tier 1
- Prescribed climatology
- Temporal variations not represented

Vegetation, land use aerosols

Tier 2
- Temporal variations from observations

C02 in reanalyses Solar

Tier 3
- Modelled and initialized
- Component Interaction and feedback

Atmosphere, ocean, waves, sea-ice, soil moisture, snow,

Motivation

- Radiative forcing, land cover-use and vegetation are prescribed as boundary conditions in reanalyses and subseasonal-seasonal –decadal integrations .
- Their temporal variability impacts the solution.
- There are new high-accuracy observational datasets for the recent period (last 30-20 years) that are not yet used in reanalyses and reforecasts
- There is need to create temporally consistent records with those used in operational NWP

CONFESS aims at **improving the representation of global trends and regional extremes in next generation of C3S earth system reanalyses and Seasonal forecasts,** by taking stock of observational data sets and model developments across different Copernicus Services on vegetation, land cover, atmospheric composition and biomass burning.

Ultimate aims:

avoid discontinuities between reforecasts and real-time forecasts

to improve the representation of trends and extremes

find converging best practices for reanalyses, initialized predictions and climate simulations

CONFESS Strategic Objectives

- Representation, **for the first time**, of **temporal variations of land cover and vegetation** in C3S systems by exploiting state of the art Copernicus observational datasets

- **Improved** temporal representation of **tropospheric aerosols by harmonization of CMIP6 and CAMS datasets.**

- **Increased prognostic capabilities** by inclusion of prognostic vegetation and new capabilities for response to volcanic and biomass burning emissions.

It is expected that temporal variations of LULC, LAI and aerosol will affect interannual variaibility, trends and extremes

CONFESS Topics covered in this presentation

- **Land Use/Land Cover**: how land is used (agriculture, irrigation, forests, pasture, built-up terrain, water bodies). It affects surface fluxes (heat, momentum, carbon) and soil storage capacity. It is by nature a boundary condition for geophysical models.

- **Leaf Area Index (LAI):** area of of green leaf area per unit of ground surface. It can be detected by remote sensing, and it can also be modelled with prognostic vegetation models.

- **Anthropogenic tropospheric aerosols**: sulphate, nitrates, biomass burning, black carbon. Aerosols interact with radiation (direct effect), affecting the spatial distribution of heating, atmospheric circulation, climate sensitivity. They also affect cloud properties (indirect effect, not dealt with here). Aerosols can be modelled or prescribed. If the former, emissions are needed.

CONFESS Topics not covered in this presentation:

- Volcanic aerosols
- Impact of biomass burning

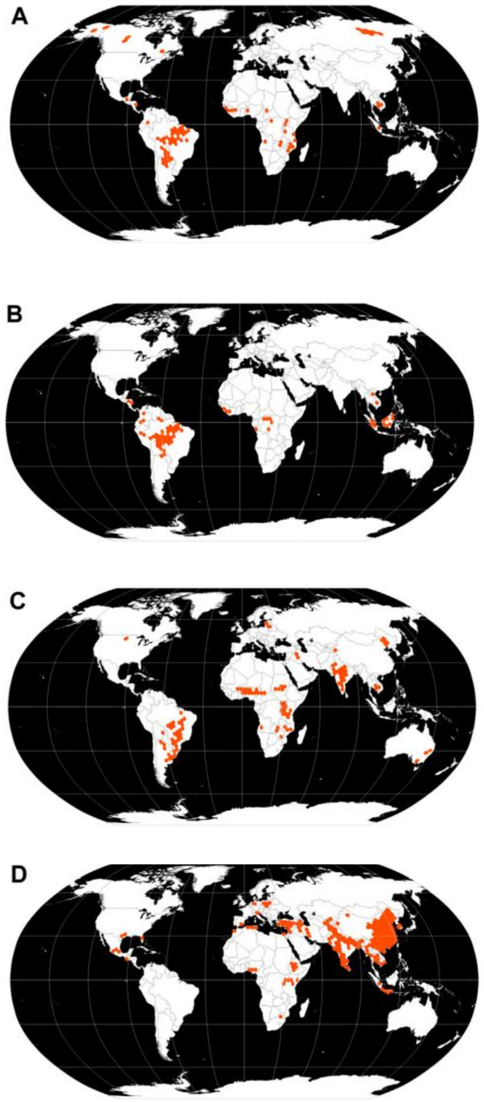
Land Use/Land Cover

Satellite based datasets

- **ESA-CCI** 1992-2019. [Distributed by C3S](#) (used in CONFESS): 300m resolution, yearly frequency.
    - Based on MERIS (2003-2012) and updated/harmonized with
    - AVHRR (1992-1999)
    - SPOT-VEGETATION (1998-2012)
    - PROBA-V and Sentinel3 OLCI from 2013 onwards

- GLAD Global Land Cover and Land Use Change, 2000-2020. Potapov et al 2022. 30m spatial resolution
    - Based on MODIS and LandSat reprocessing
    - It includes tree cover, croplands, built-up land, open water, and perennial snow and ice.
    - It includes reference maps for a year and the maps of change for the period 2000-2020, for the different thematic areas.

GLAD Global 2000-2020 LCLU change hotspots



A) Deforestation

B) Forest Above Ground Carbon

C) Cropland expansion.

D) Built-up expansion

From Potapov et al 2022

LULC has undergone substantial changes in the last 30 years

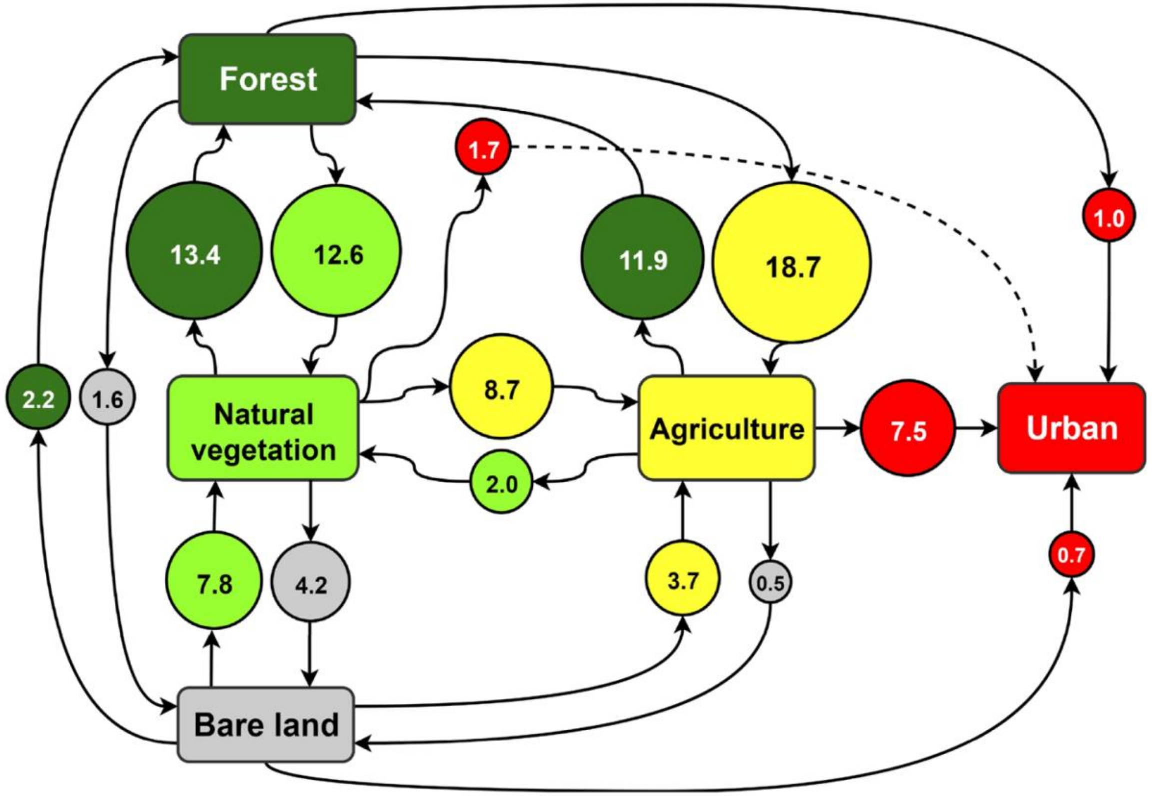


Figure 6. Schematic representation of global LC transitions between 1992 and 2018. The transitions are expressed in percentage terms relative to the total global LC area that changed over this period. Note that the sum of the percentages equals 98.2% as the minor LC transitions involving water bodies were not included. For visualisation purposes, the size of each circle is proportional to the magnitude of the LC transition it represents and exact figures are provided within the circle.

From Radwan et al 2021

LULC: Advancing the stat of the art

Currently in NWP/Reanalyses/Reforecasts

LCLU is kept constant (GLCC, Loveland et al., 2000)
Usually high resolution : Km scale or finer (300m)

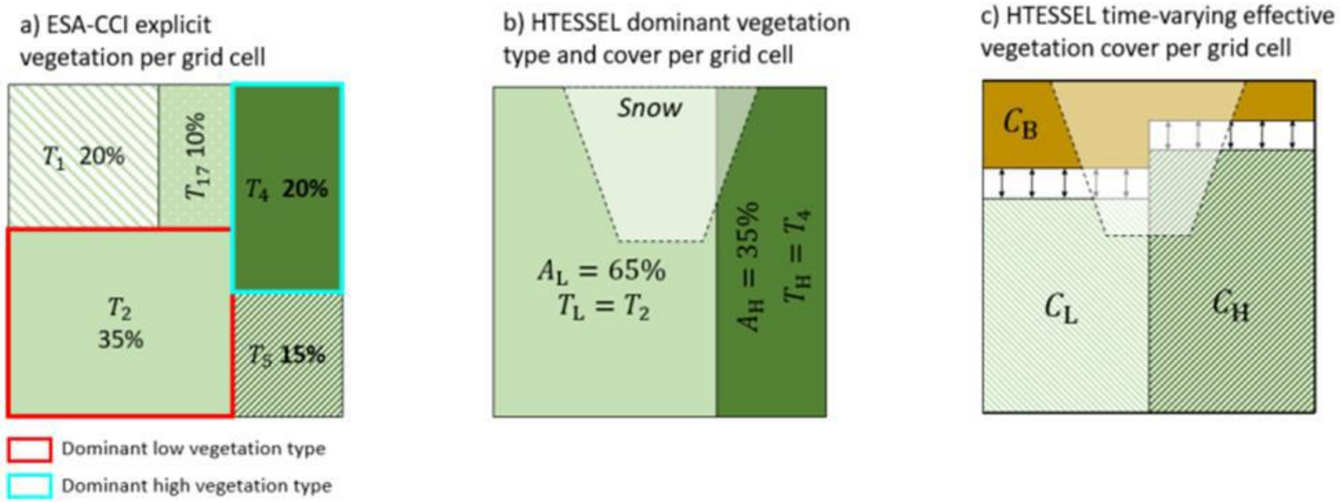
CONFESS

Include temporal variations exploiting recent data-sets
ESA-CCI: **1992-2020**. Distributed by C3S

Need to harmonize /translate Land Use/LC an into vegetation types used in models. Conversions are done via Cross-Walking Tables

See Boussetta and Balsamo, CONFESS Deliverable D1.1

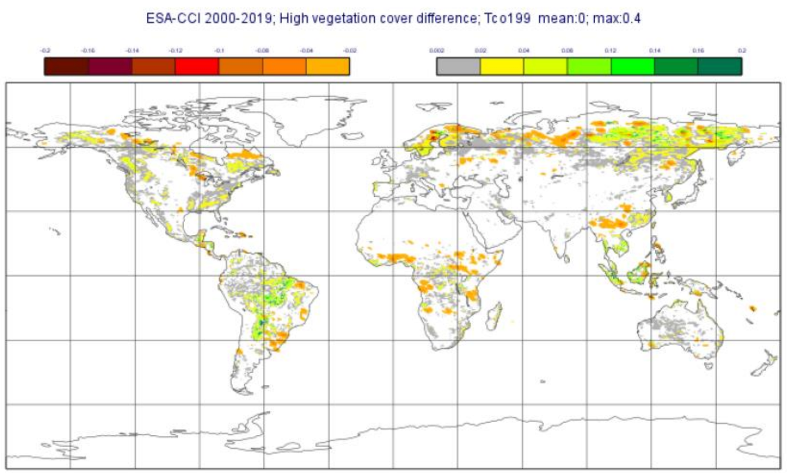
Possible implementation in ERA6



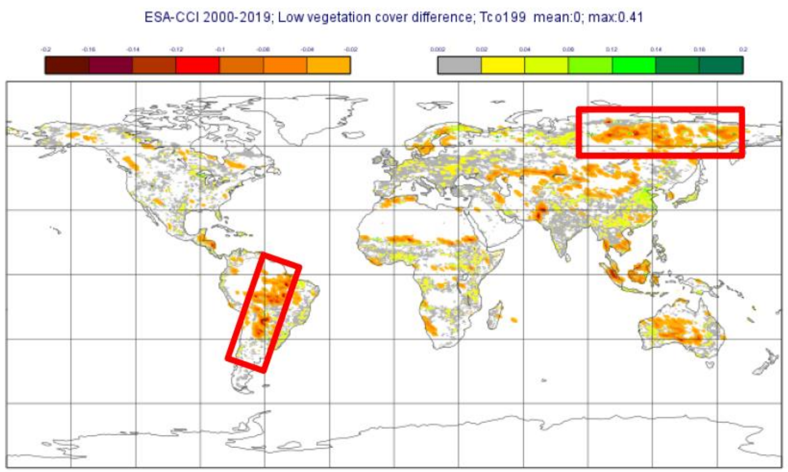
Main driver: impact of LC/LU in atmospheric variables and surface exchanges

Changes in vegetation distribution (C3S LULC)

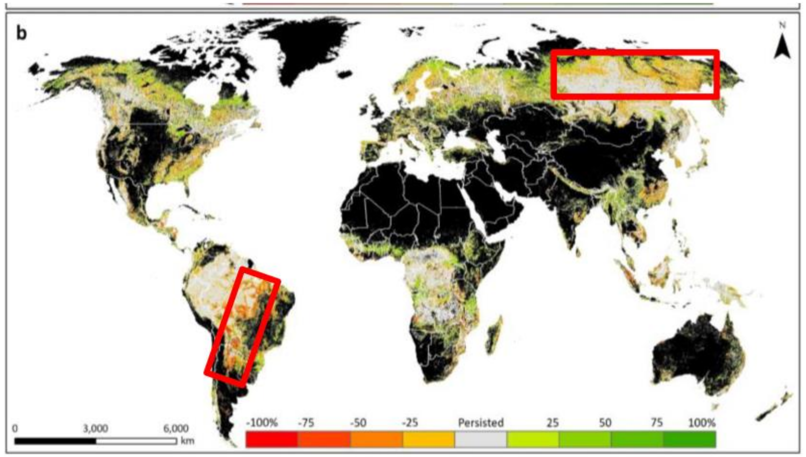
Low vegetation



High vegetation



Vegetation cover differences between 2000-2019
(red indicates a cover reduction)



Spatial distribution of LC changes between 1992 and 2018. for forest cover (Radwan et al,. Nature 2021).

In the last 20 years there has been a decrease of high vegetation over tropical rainforest (Brazil, Borneo) and Siberia boreal forest, and an increase in low vegetation

Smith et al 2023 report reduction in tropical precipitation associated to forest lost

Leaf Area Index, Land Cover and Surface fluxes

Most models do not have interactive vegetation. Prescribing temporal variations of LAI is challenging:

- Need harmonized datasets consistent with LU/LC
- Need to translate LAI into effective vegetation cover for their impact on surface fluxes

LAI

- prescribed
- Modelled

Effective Vegetation Cover

$$C_{v,L} = 1 - \exp(-k \cdot LAI_L)$$

$$C_{v,H} = 1 - \exp^{(-k \cdot LAI_H)}$$

or from look up tables

Flux exchange, A coeff

$$C_H = C_{v,H} \cdot A_H$$

$$C_L = C_{v,L} \cdot A_L$$

$$C_B = 1 - C_H - C_L$$

Water reservoir

$$W_{1m} = W_{1max} * \left(C_B + C_H * LAI(T_H) + C_L * LAI(T_L)\right)$$

Temporal variations of LAI and FCOVER

LAI (AVHRR, CGLS; 1993-2019)

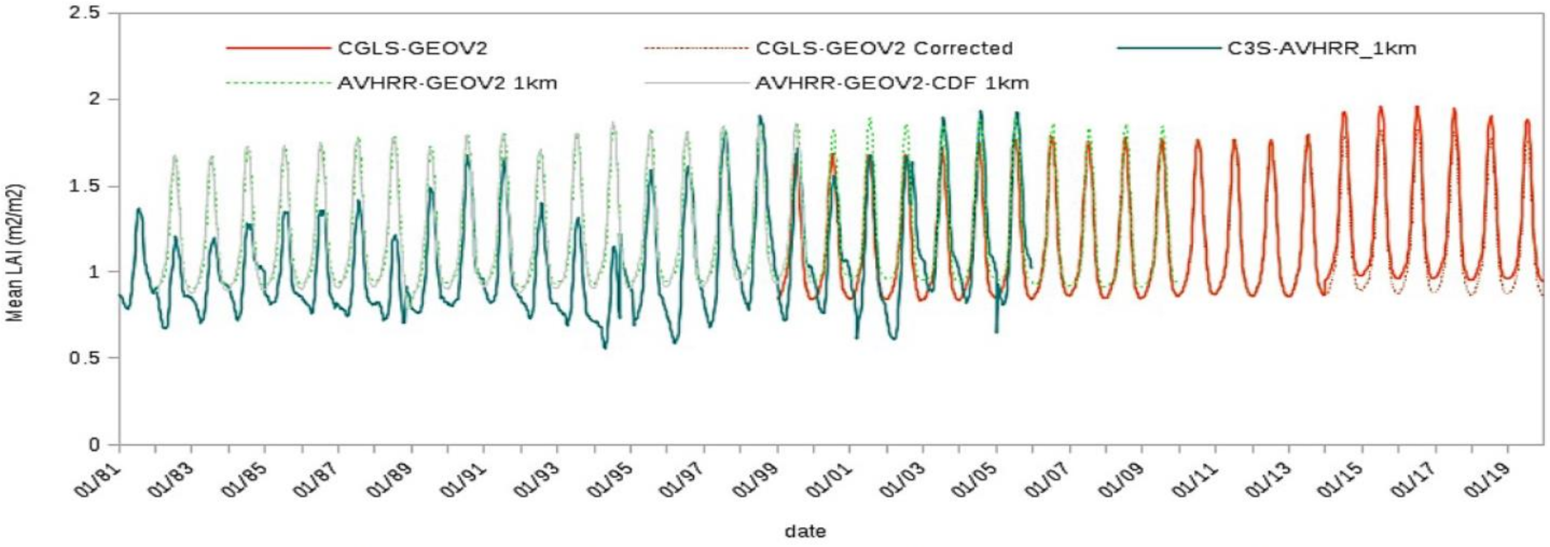
FCOVER (CGLS, 1999-2019)

LULC (ESA-CCI/C3S; 1993-2019)

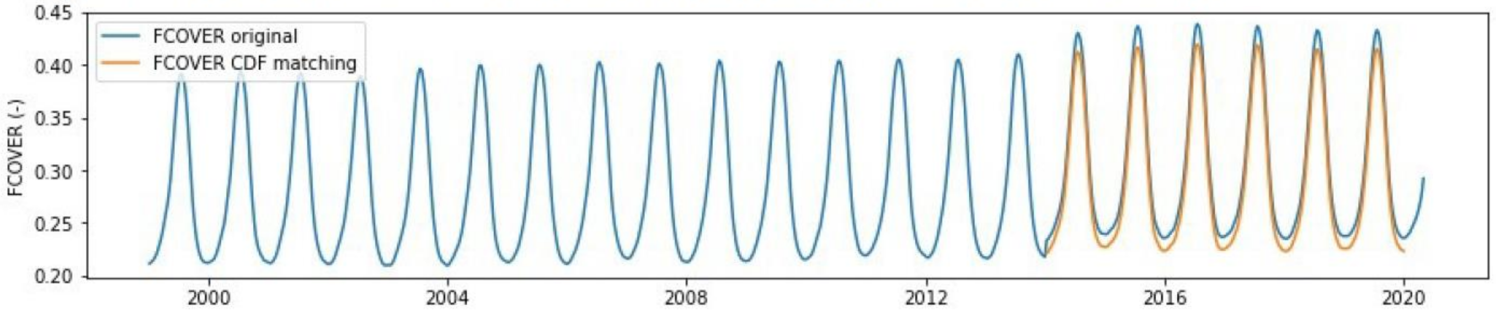
For LAI and FCOVER a CDF matching procedure was needed so as to guarantee conservation of the mean and the variance of the data.

Note: the C3S LAI exhibit unrealistic behaviour prior to 1999, and it was decided not to use it. Instead, CONFESS uses the AVHRR-CGLS. Producers were notified

- Harmonized LAI (consistent to ESA-CCI LULC)



- Harmonized FCOVER (consistent with LAI and LULC)



See also CONFESS deliverable D1.1 Report on vegetation dataset of LC and LAI

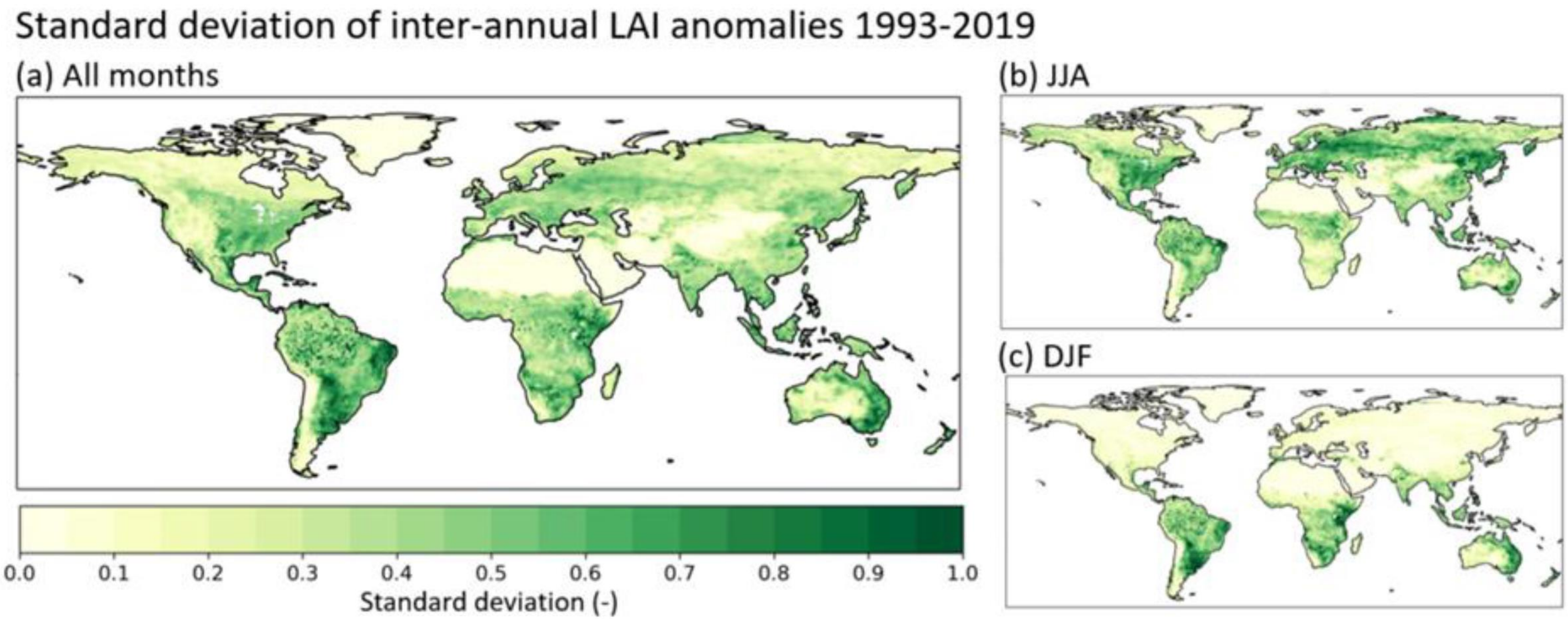


Figure 25 Standard deviation of inter-annual LAI anomaly introduced in the model in 1993-2019 for (a) all months, (b) JJA and (c) DJF.

From Alessandri et al 2022. [CONFESS deliverable D1.2]

Harmonized timeseries of LAI show a discontinuity in the tropics in 1999

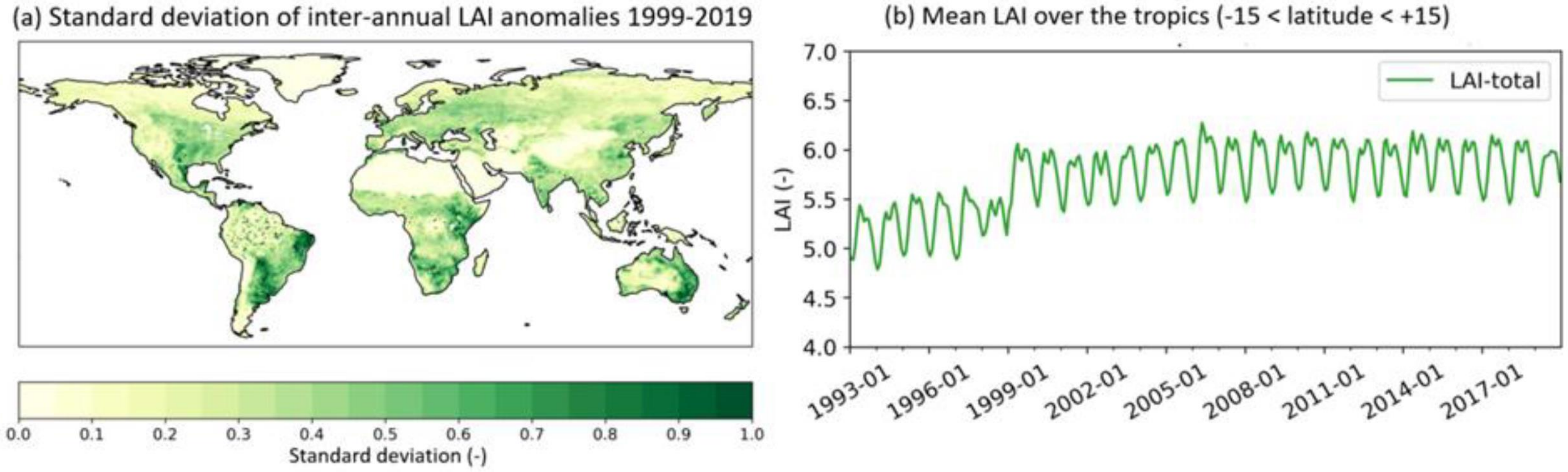


Figure 26 (a) Standard deviation of inter-annual LAI anomaly introduced in the model in 1999-2019 for all months and (b) timeseries of mean LAI over the tropics (-15 < latitude <+15).

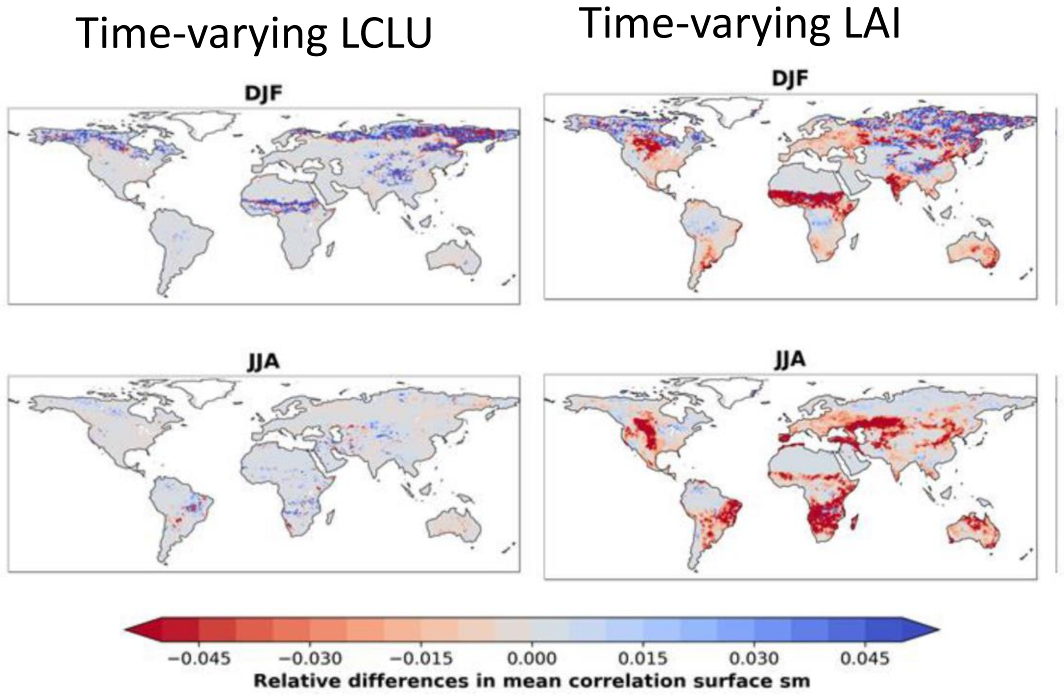
From Alessandri et al 2022. CONFESS deliverable D1.2

Land Time varying properties: evaluation methodology

1) Multi-year multi-model land simulations forced by ERA5: validation of surface fluxes and soil moisture
- IFS, EC-EARTH, Meteo-France/CNRM. The latter also provides integrations with prognostic vegetation.
- Experiments:
  - Control: LULC and LAI are kept constant (2019 value)
  - Time-varying LULC, LAI is kept constant
  - Time-varying LULC and LAI

2) Multi-model seasonal reforecasts and multi-year integrations (in progress). Impact on T2m and atmospheric circulation

Ec-land Impact on temporal correlation with soil moisture



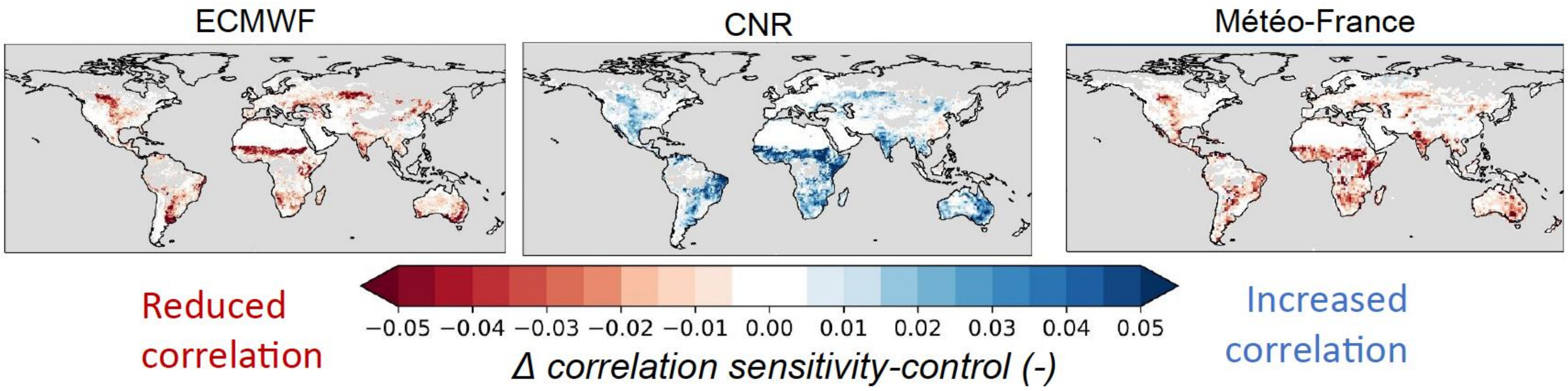
Left) slight improvement in soil-moisture with time-varying LC/LU
Right) time-varying LAI results in decreased correlation with soil moisture. Problems in tropics are visible.

From CONFESS Deliverable D1.2

Impact of time-varying Leaf Area Index (LAI) on multimodel land simulations.

Land simulations forced by ERA5 hourly forcing for 1993-2019
With time-varying and fixed climatologies of LC/LU/LAI
3 different land surface models

Anomaly Correlation of surface soil moisture with ESA SM- 5cm

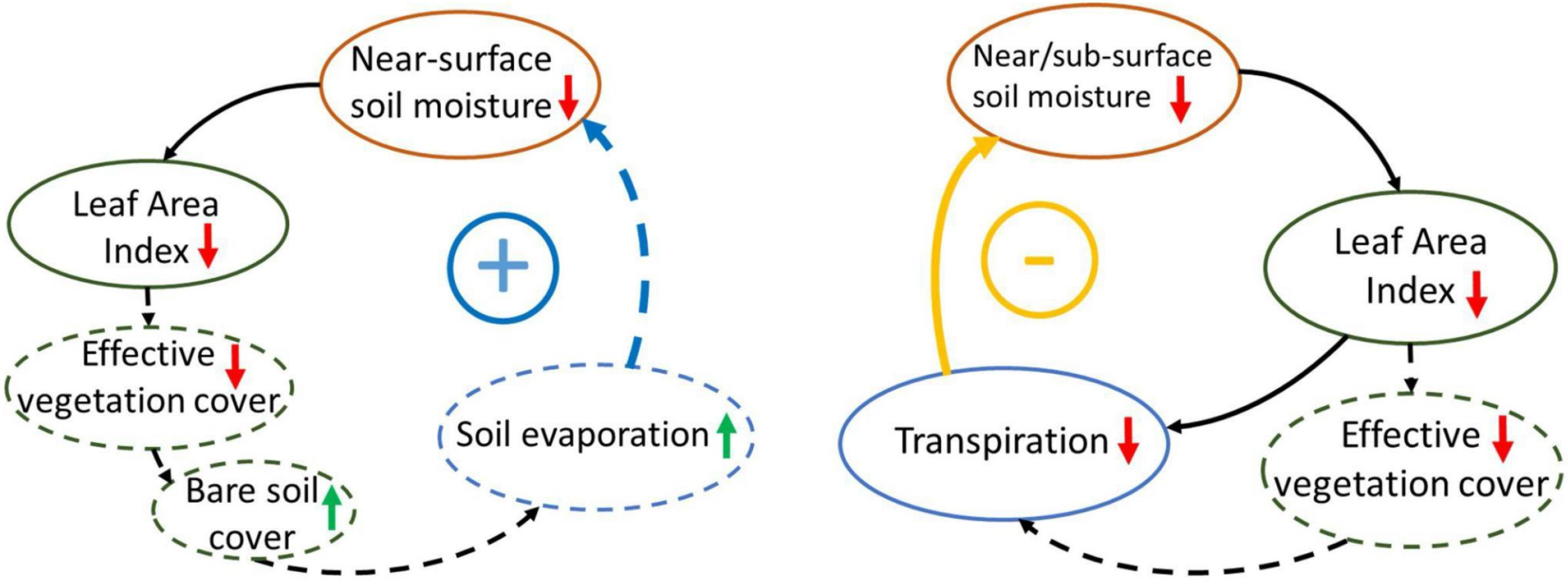


Verification Period 1993-2019

Courtesy of C. Ardilouze.

See also Ardilouze et al 2023: CONFESS deliverable D1.3 Report on suitable vegetation modelling configurations

Different Vegetation-Soil-moisture and evapotranspiration feedbacks in models? Can we quantify?



+ve feedback:
decreased vegetation leads to decreased soil moisture with increased bare soil

-ve feedback:
decreased vegetation reduces evapotranspiration and moisture remains in soil

Courtesy of Andrea Alessandri

See also CONFESS deliverable D1.3 Report on suitable vegetation modelling configurations

What about the impact on Seasonal reforecasts?

Seasonal Froecasts Experiments up to 4 months lead time.
May and November initial conditions. 100 members
Initialized from equivalent offline land simulations

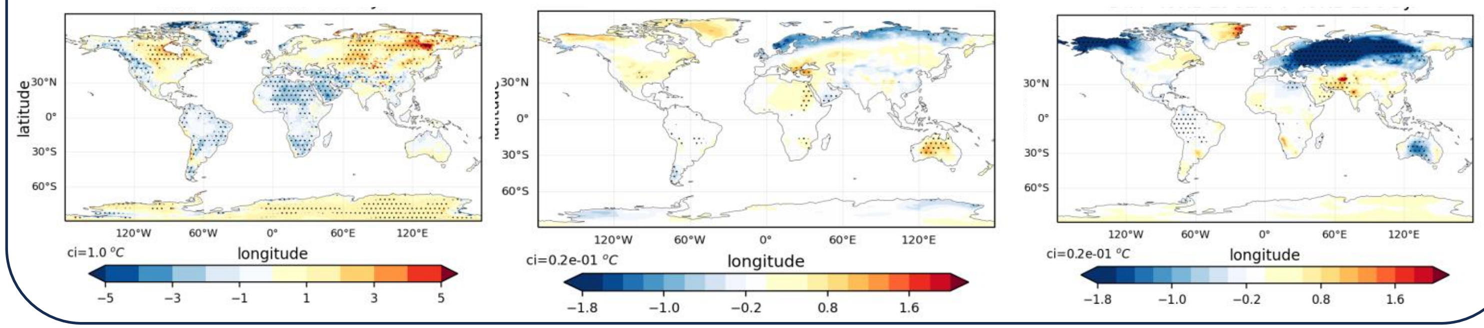
- CONTROL: Climatological (fixed) LULC-LAI
- LU-LC : Time varying LULC but fixed LAI
- LCLU-LAI : Time varying LULC-LAI

Impact on T2m:

- **Overall LAI has larger impact than LULC**
- **Impact on scores mostly neutral, with large regional and seasonal variations**
    - **Impact on T2m mean state**
        - LULC < 5%
        - LAI ~10%
    - **Impact on T2m trend errors**:
        - LULC ~10 %
        - LAI ~10%
- **Drivers for impact: local processes or circulation changes?**
- **What about specific extremes?**

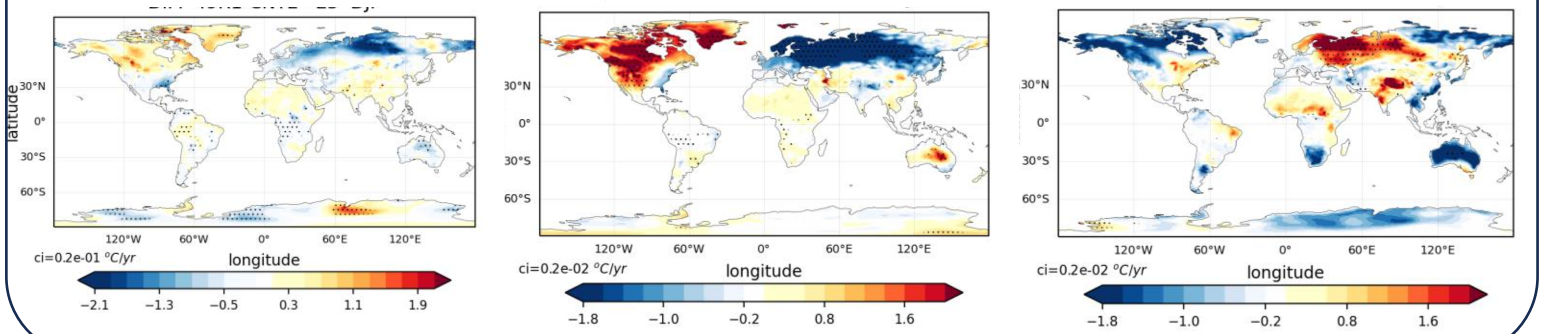
Impact on T2m bias DJF

Bias in CNTL | Impact of LULC variations | Impact of LAI variations

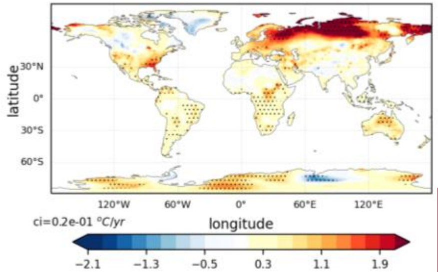


Impact on T2m trend errors DJF (2000-2019)

Trend errors in CNTL | Impact of LULC variations | Impact of LAI variations



Era5 T2m trends (2000-2019)

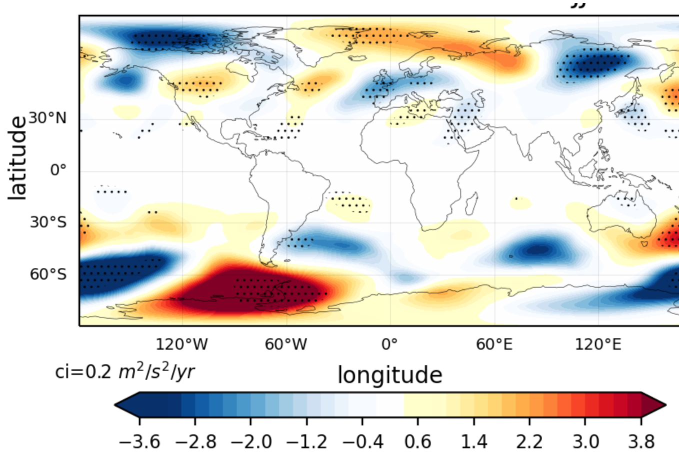


Note: relative impact in reanalyses with DA likely to be very different.
To be tested in CERISE

Impact of LULC and LAI: Local processes or circulation impact?

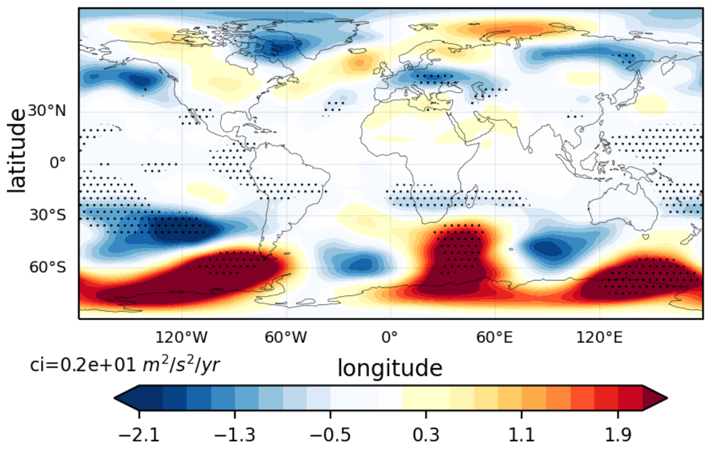
Impact on JJA trends

Impact of LULC variations

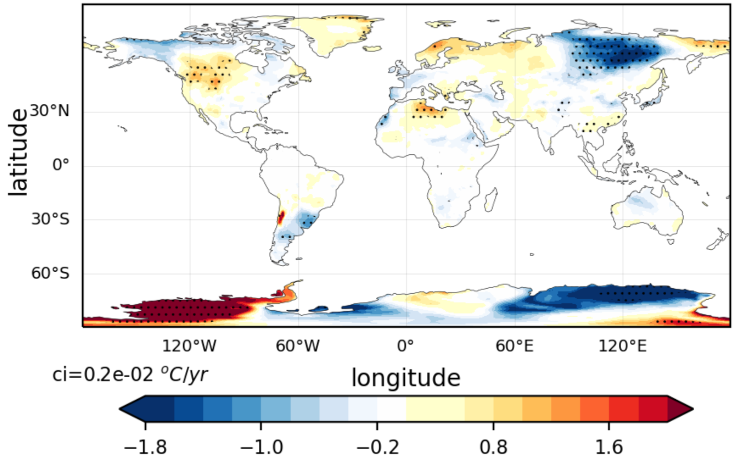


Z500

Impact of LAI variations

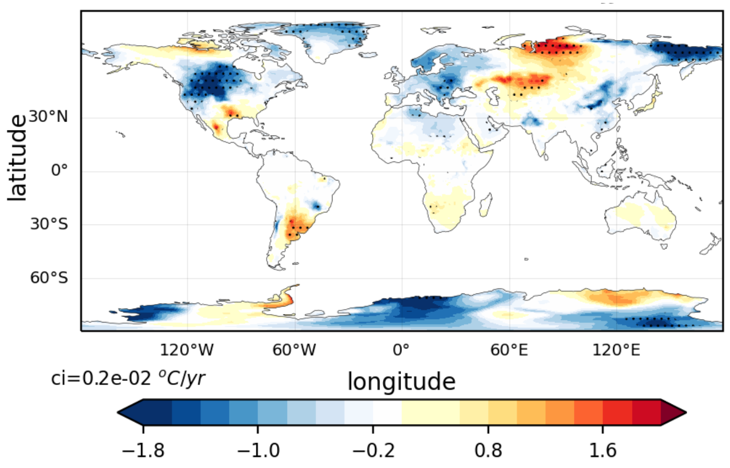


Impact of LULC variations



T2m

Impact of LAI variations

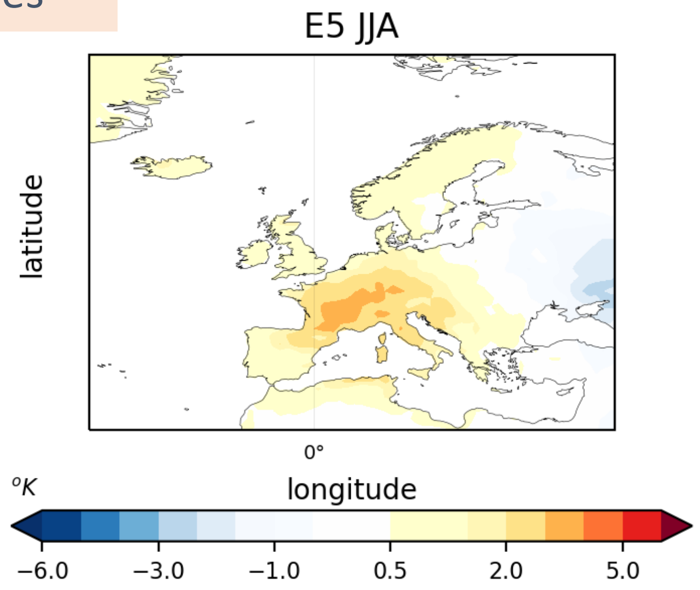


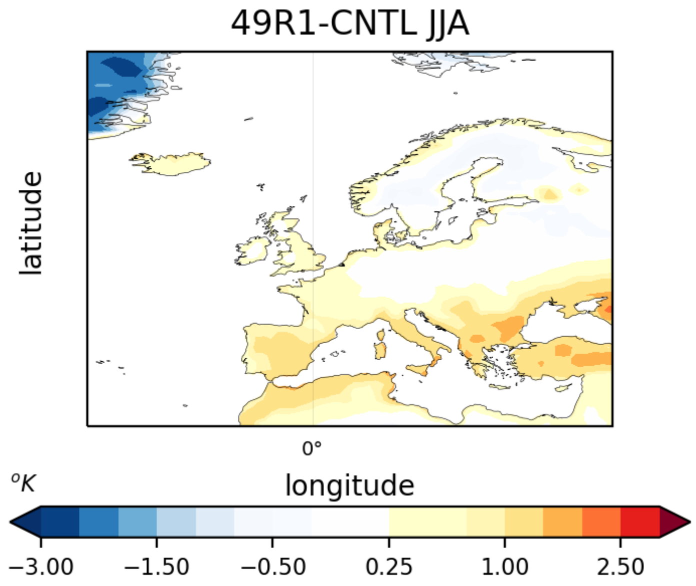
Both LULC and LAI significantly affect the circulation.

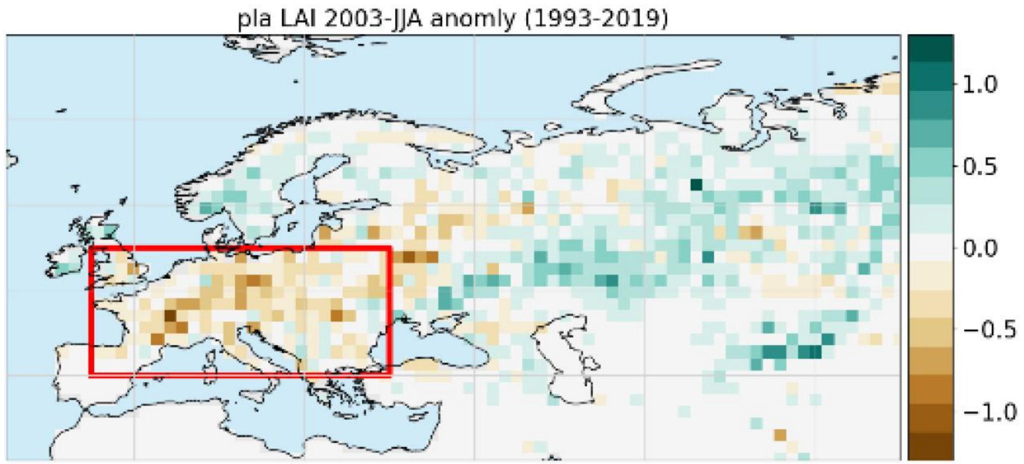
In some areas, changes in circulation patterns are consistent with T2m

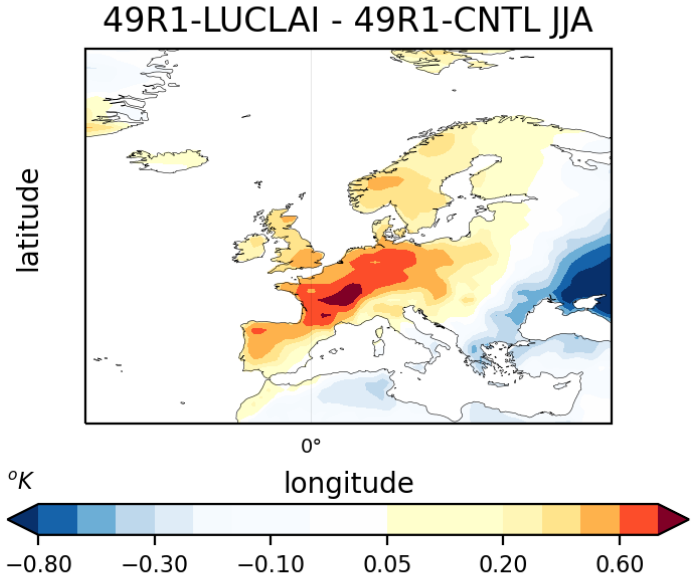
Time-varying vegetation improves the seasonal forecasts of T2m extremes

ECMWF Seasonal forecasts of T2m anomalies for JJA 2003. Forecast initialized May 2003





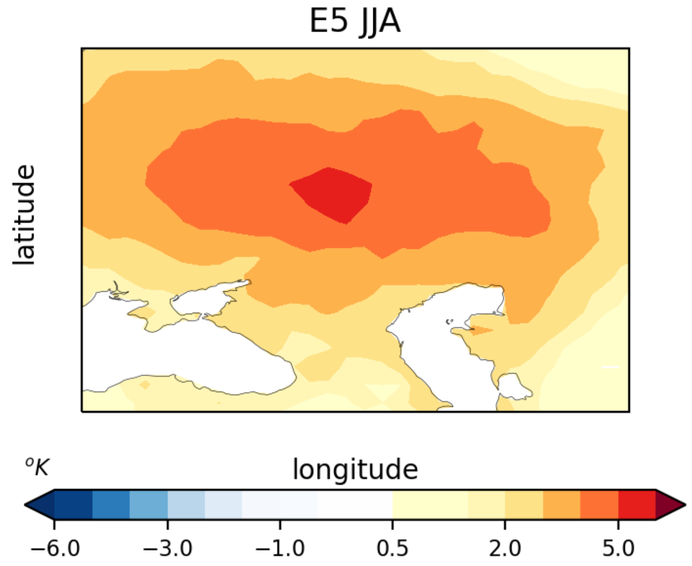


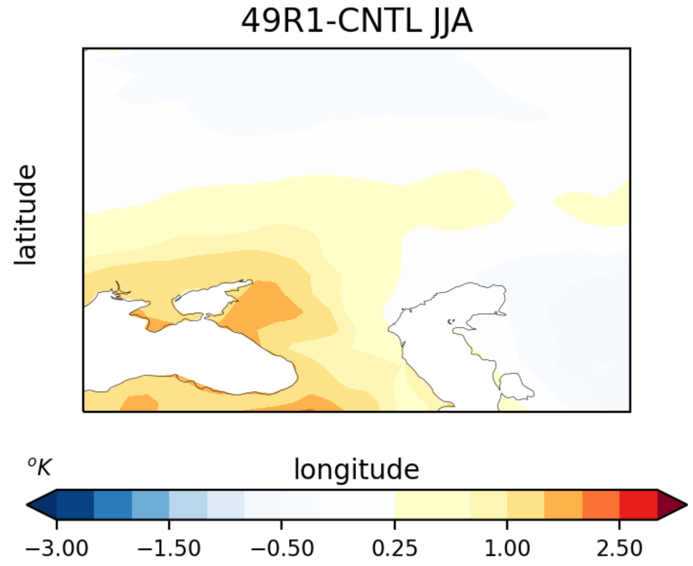


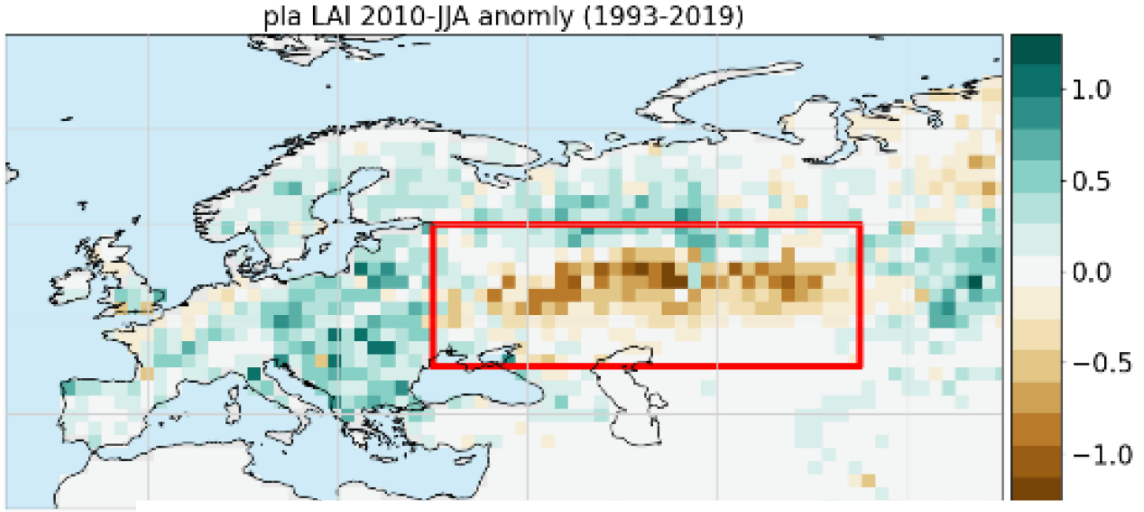
This result is consistent with the impact on surface fluxes in offline simulations (CONFESS deliverable D2.1)

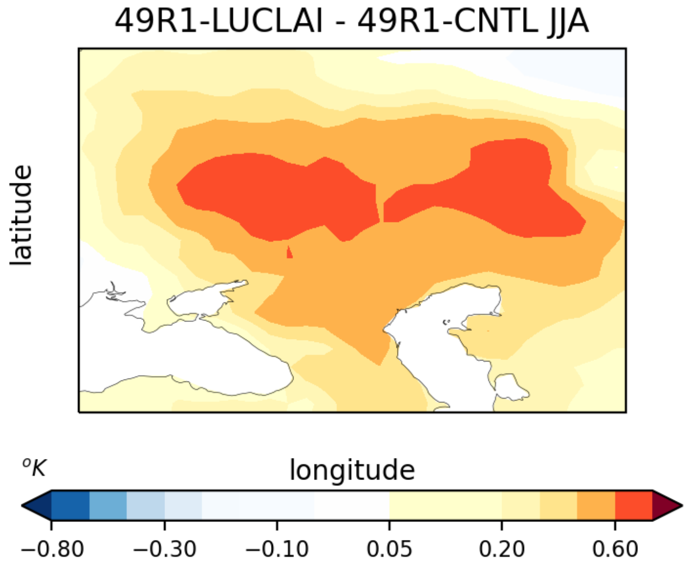
Time-varying vegetation improves the seasonal forecasts of T2m extremes

ECMWF Seasonal forecasts of T2m anomalies for JJA 2010. Forecast initialized May 2010









This result is consistent with the impact on surface fluxes in offline simulations (CONFESS deliverable D2.1)

Advancing the stat of the art

LULC Currently in NWP/Reanalyses/Reforecasts

LULC is kept constant

(GLCC, Loveland et al., 2000)

CONFESS

Include temporal variations exploiting ESA-CCI (C3S): **1992-2020**.

Possible implementation in ERA6

LULC likely to remain a boundary condition for the foreseeable future

CERISE

and beyond

Include built-up area, changes in water bodies.

Extend further back in time, making it compatible and suitable for climate modelling

Land Use/Land Cover in climate

Global historical Land Use from HYDE3.2

Climate Approach (CMIP6)

Main driver is the impact of LULC in the carbon cycle

LUH2 data set (Hurtt et al 2020)

Good temporal coverage: 850-2100.

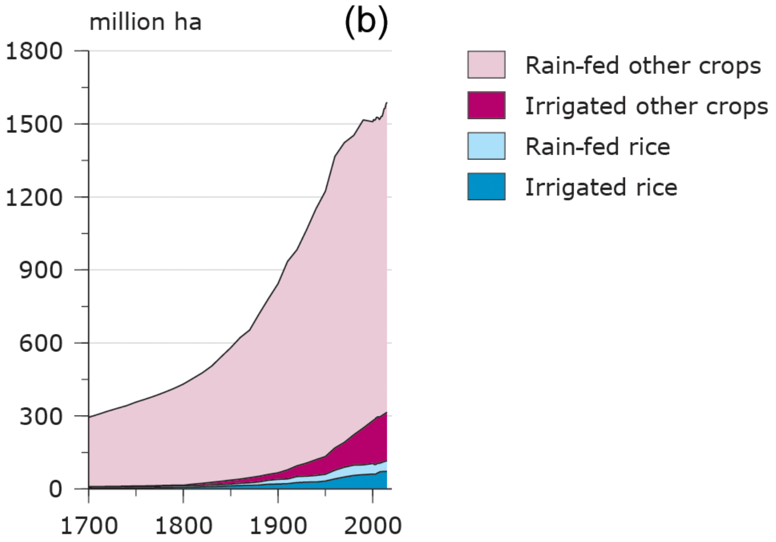
Horizontal resolution ¼ degree

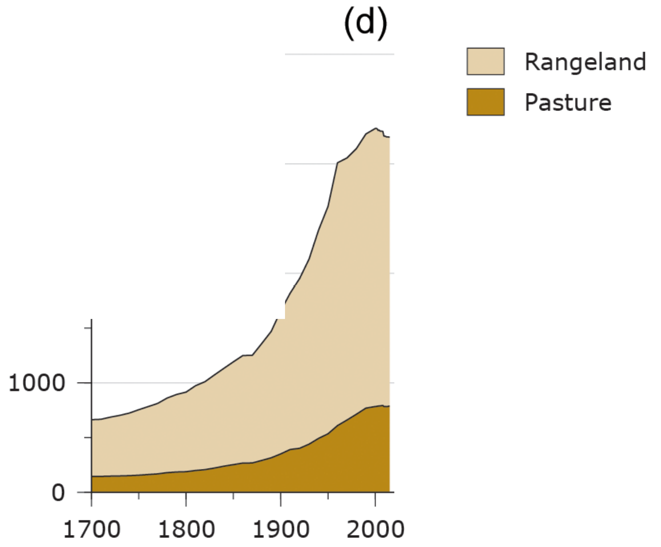
Historical records (up-to-2015) based on HYDE 3.2 (History Database of the Global Environment, Klein Goldewijk et al 2017). Source: historical records or land use from different archives (eg. UN population distribution, FAO agricultural and pasture data, **ESA MERIS 2010 reference maps**)

From 2015 onwards, for climate projections uses output of Integrated Assessment Models (IAM).

Need to translate changes in Land Use into vegetation types used in models. Conversions are done via Land Use Translators (LUTs, e.g Brown and Duh 2002, Ma et al 2020)

Current LUTs do not include urban use, and relative distribution of natural vegetation (such as forest, shrubs) are kept constant





From Klein Goldewijk et al 2017

Further harmonization of LULC can be done, using more satellite high-resolution fields for longer periods. See for instance harmonization efforts by regional community (Hoffmann et al 2022). With this approach the regional modelling needs can bridge the gap reanalysis/NWP/near-term prediction with global climate approaches. Some of this work will continue in HE project CERISE

Advancing the stat of the art

LULC Currently in NWP/Reanalyses/Reforecasts

LULC is kept constant
(GLCC, Loveland et al., 2000)

CONFESS →

Include temporal variations exploiting ESA-CCI (C3S): **1992-2020**.

Possible implementation in ERA6

LULC likely to remain a boundary condition for the foreseeable future

CERISE → and beyond

Include built-up area, changes in water bodies.

Extend further back in time, making it compatible and suitable for climate modelling

LAI Currently in NWP/Reanalyses/Reforecasts

LAI seasonal variations based on MODIS (Boussetta et al., 2013)

CONFESS →

Temporal variations tested.

Time records and modelling not mature enough for use in ERA6

future →

Near future: prescribed time variations (CERISE)

In the long term: prognostic model for LAI

TROPOSPHERIC AEROSOLS: Setting the Scene

ERA5 and SEAS5:

CMIP5 time-varying anthropogenic aerosols. They are obsolete and not easy to implement in recent IFS cycles

NWP at ECMWF

Fixed Aerosol Climatology 2003-2013. (Bozzo et al 2020)
Uses cycle 49r2. TL159L60.
Total AOD was rescaled to match CAMS reanalyses

With IFS Cy43r3 the radiation code in the IFS changed, and now requires aerosols masses

The Bozzo et al 2020 aerosols AOD climatology was translated into mass loading to give similar AOD when processed by the new radiation scheme.

The NWP aerosols climatology needs updating

CMIP6

Two flavors:

- Emissions from CEDS (Community Emissions Data System)
- Aerosol plumes from MACv2-SP

Problems:

- Some emissions from CEDS have been reported to be wrong, contaminating climate signals (e.g. Zhang et al 2021 NPJ).
- The Aerosols plumes from MACv2-SP are very simplified, treating all anthopogenic aerosols as co-varying and no longer easily adaptable to IFS.

What is going on now?

CMIP7 will revise the aerosol forcing, but will not be released in time for ERA6

The CEDS emission dataset has been updated and improved

What to do for ERA6?

CONFESS harmonized tropospheric aerosols datasets

Run CAMS model (IFS-COMPO) with updated CMIP6 emissions (CEDS, GFED/GFAS) constrained by ERA5 meteorology

- Gives an updated climatology for recent period, for use in NWP.
- Allows a time-varying climatology (anthropogenic related species) from the 1960s to present, for use in ERA6 and SEAS6.
- Consistent with CMIP6 and subsequent enhancements to emissions data.

- Natural aerosols (sea salt, dust…) are averaged to create a fixed climatology.
- Anthropogenic aerosols are represented as a 9-year running mean.
- Produced with 47r3 IFS-COMPO at TL255 L137 levels. Spatial smoothing afterwards to 21 pressure levels (2 extra compared with current NWP clim)
- Calibrated to produce similar atmospheric circulation as Bozzo et al for 2000-2010

Notes:
The updated CEDS emissions do not coincide with the emissions used by CAMS.

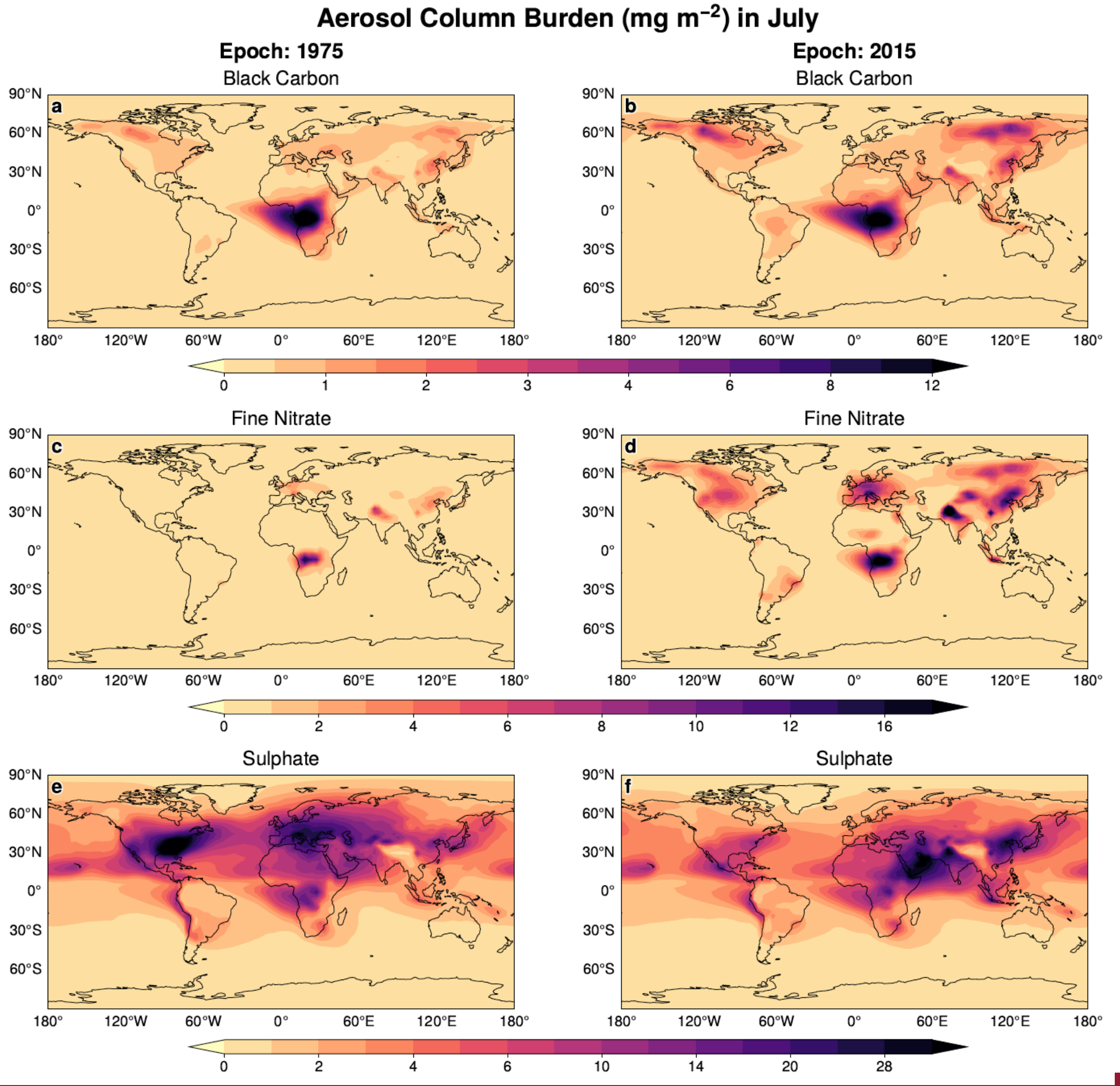
Biomass burning emissions for 2015-2019 are from Global Fire Assimilation System (GFAS), as in CAMS –based on fire radiative power- rather than using the GFED emissions used in CMIP6, which are based on burn aeras. GFED are used before 2015

Two integrations were performed using updated CMIP and CAMS emissions (the latter called CAMS-FORCED in what follows)

Courtesy of Tim Stockdale

See Stockdale et al 2020 , CONFESS deliverable D2.1 for details of model configuration, spin up, production streams, calibration and validation

Harmonized tropospheric aerosols datasets



Increase of black-carbon over NE Asia, Amazonia, Canada

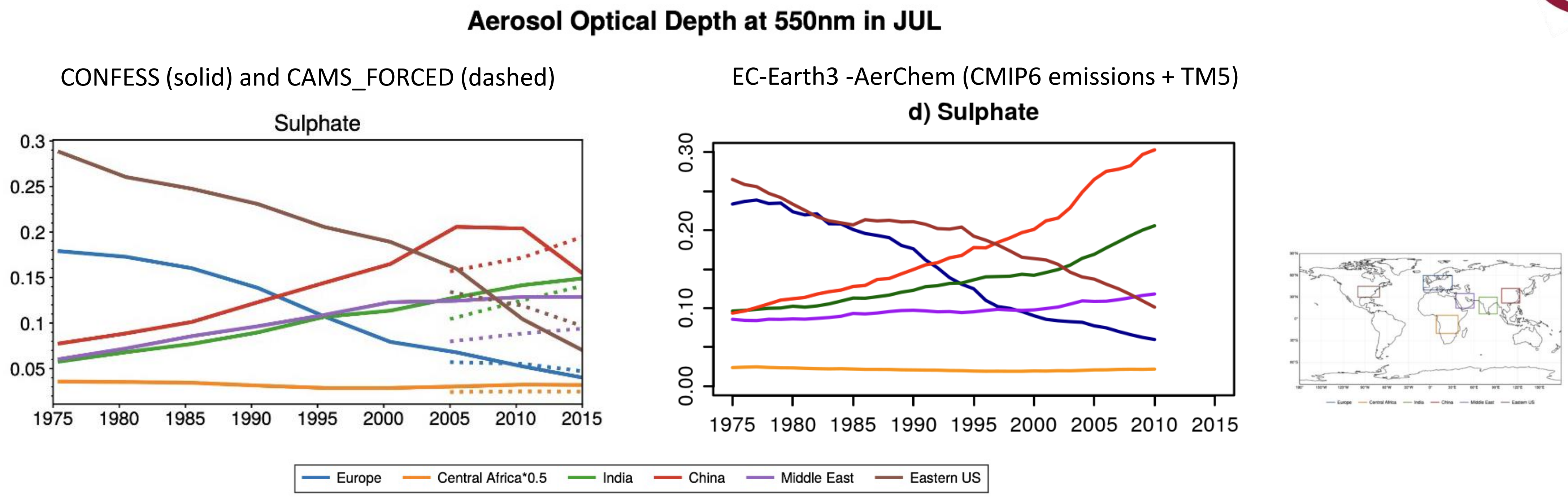
Increase of Fine Nitrate over Europe, India, China, North America and Brazil

Visible decrease of sulphate aerosols over Europe and North America.

Courtesy of Tim Stockdale

 See Stockdale et al 2020 , CONFESS deliverable D2.1 for details of model configuration, spin up, production streams, calibration and validation

Harmonized tropospheric aerosols datasets

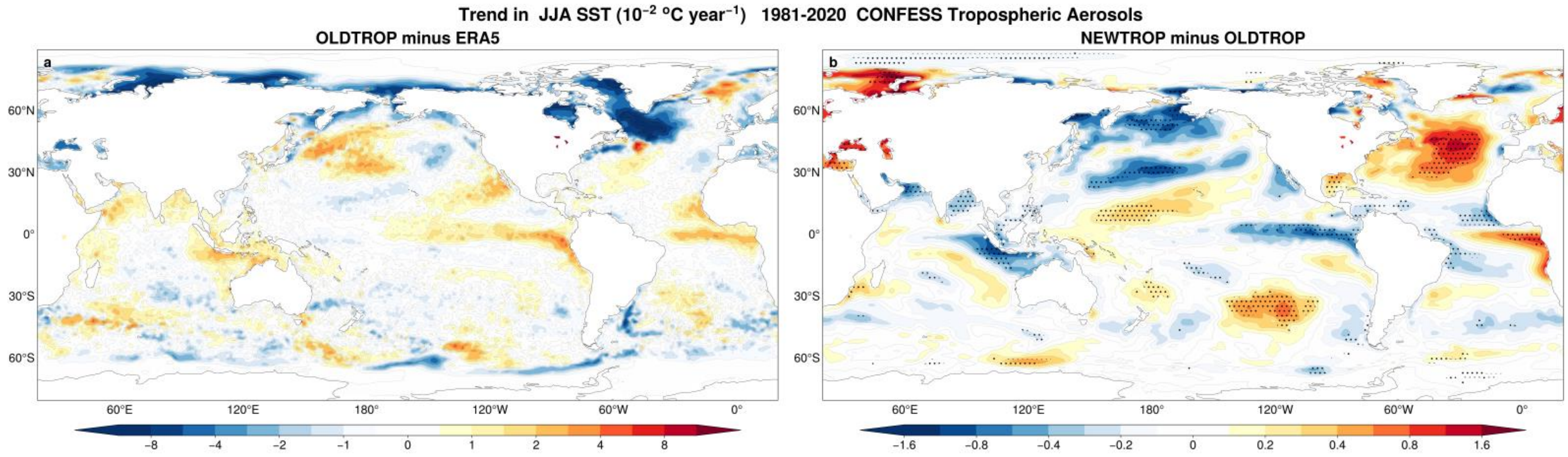


- Downward trends in sulphate aerosols over Europe and Eastern US.
- After peaking ~2006, downward trend on sulphates over China in later period, not captured by CAMS-FORCED
- Increase over India and Middle East.
- Overall consistency with time variations in EC-EARTH that uses CMIP6, but the latter has shorter records and different amplitudes

See also Stockdale et al 2022, CONFESS deliverable D2.1 Harmonized CAMS and CMIP6 tropospheric aerosols

Evaluating Impact of time varying aerosols:

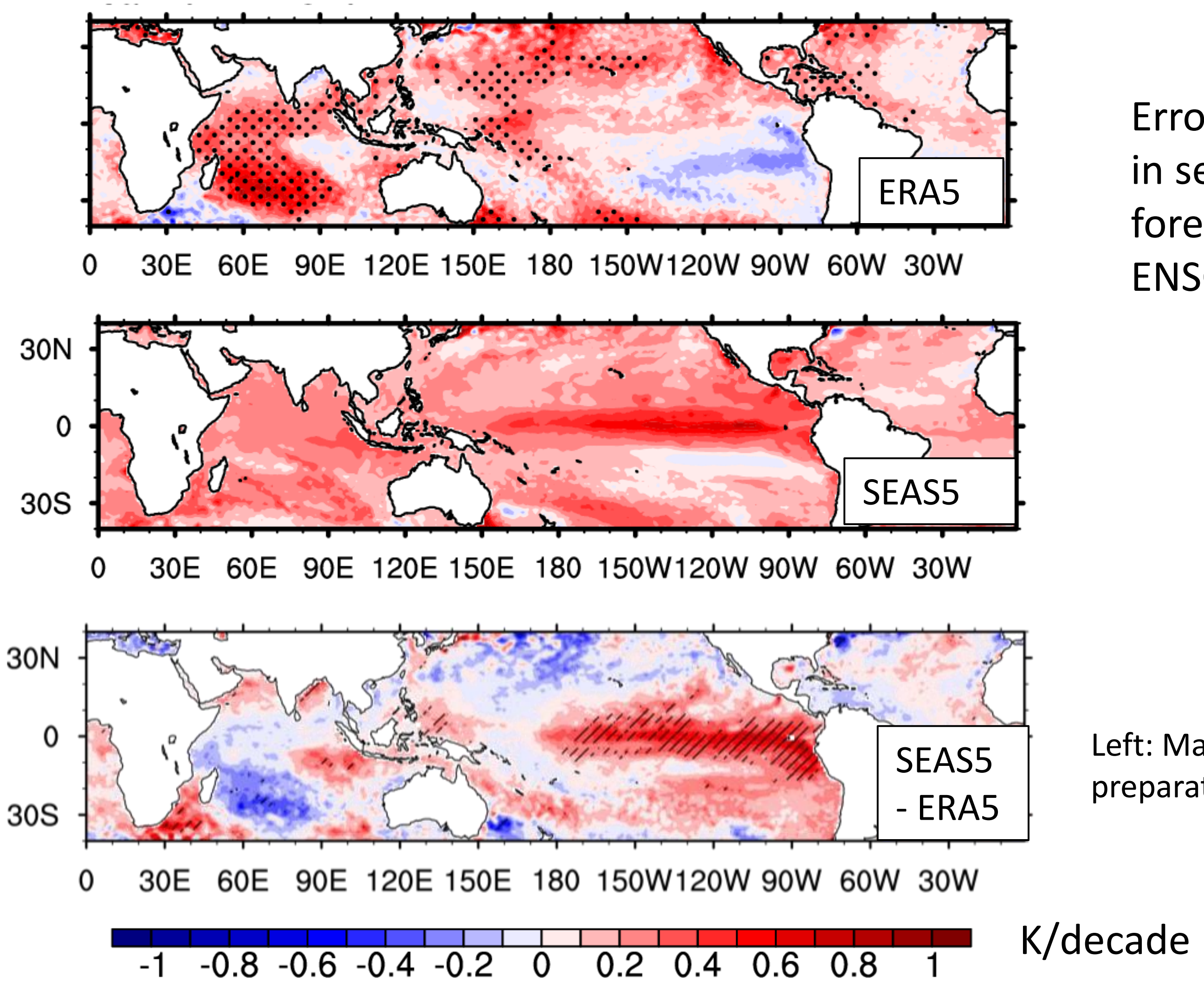
Multi-year integrations for calibration
Seasonal reforecasts: 10 ensemble members, 12 months lead-time, Nov starts 1981-2020
Multi-year integrations.
We evaluate impact on mean, trends and decadal variability



Impact of tropospheric aerosols projects into the pattern of forecast errors in trends
Forecast initialized in November, verifying in JJA

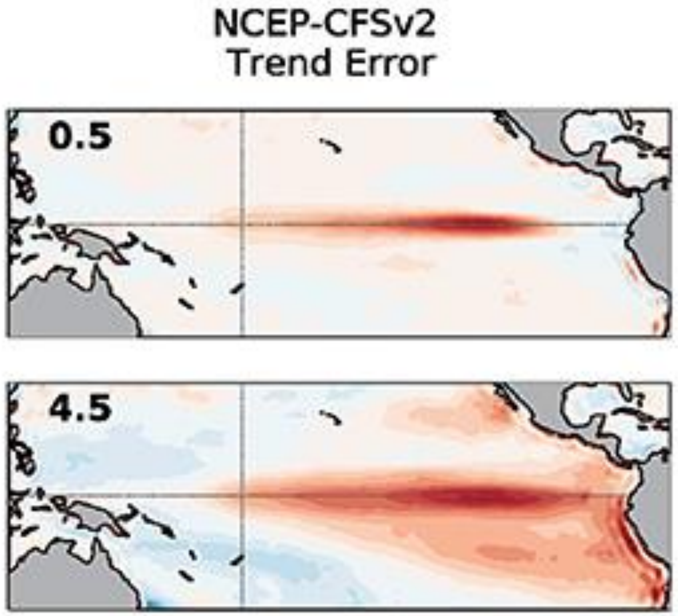
Impact on trend errors on ENSO seasonal forecasts

SST Trends



Errors in SST trends in seasonal forecast affect ENSO prediction

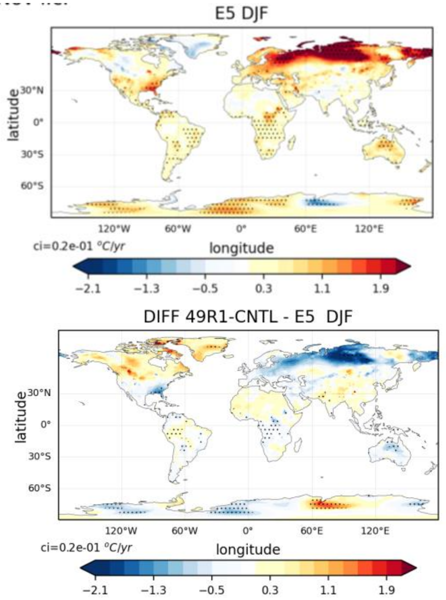
Left: Mayer et al, in preparation



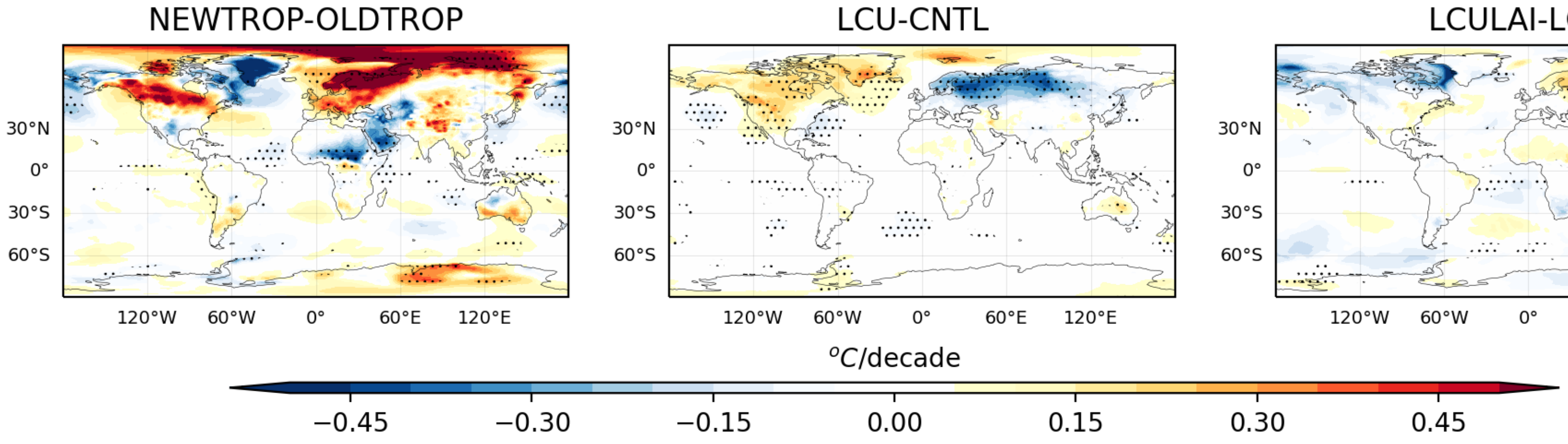
Above: L'Heureux et al. (Front. Clim. 2022):

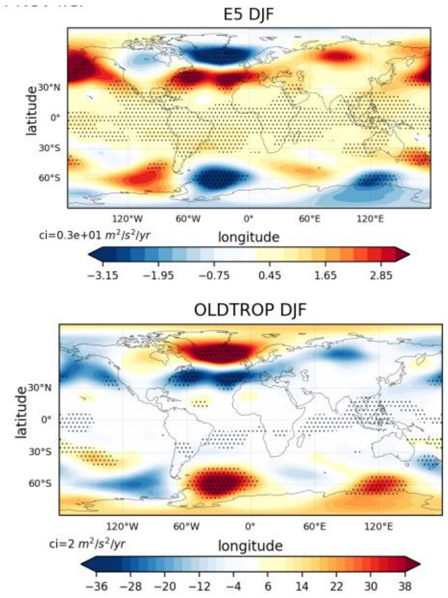
Seasonal forecasts of El-Nino in the NMME suffer from increased false alarm rate since 2000s and increasing errors

→ related to overestimation of SST trend

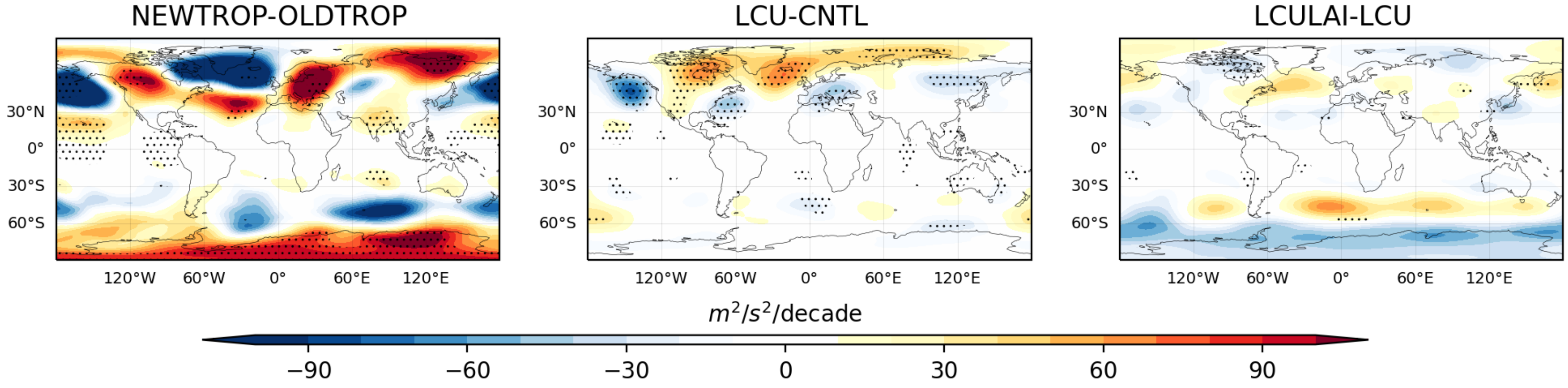


Impact on trend t2m DJF Period 2000-2019





Impact on trend z500 DJF Period 2000-2019



Impact of aerosols larger than impact of land properties

Summary

- Efforts for including consistent temporal representations of land, vegetation and tropospheric aerosols have been presented.
  - Temporal consistency is important to represent interannual variability, trends and extremes in reanalyses and reforecasts (medium range, subseasonal, seasonal and decadal)
  - In a seamless approach, it is paramount to ensure that past time-variations are consistent with the datasets used for the recent period in NWP

- Evaluation of CONFESS developments is currently underway for possible inclusion in future C3S seasonal prediction systems, and ERA6

→ Time-varying LULC influence is modest in forecast, but visible impact on trends. It could be included in ERA6

→ Time-varying LAI impact is larger, influencing mean, trends and extremes. Not mature to be included in ERA6

→ Time-evolving tropospheric aerosols have large impact and its inclusion is essential. A new dataset is being created using latest IFS-COMPO cycle (48r1).

How to improve further?

→ LULC is by nature a boundary condition. We need Further harmonization of LULC:

- Seek convergence in practices between reanalyses and climate community (compromise between spatial resolution and long periods). At least the well observed period should be common. Harmonization efforts by regional community (Hoffmann et al 2022) as example of good practice. Some of this work will continue in HE project CERISE

- Need to include water bodies and buit-up area (some of this will be done under CERISE)
- Can satellite record be extended further back (from 1992 to 1972, using LandSat and AVVHR?)

→ LAI should be represented by a prognostic vegetation model, rather than a boundary condition.

- Temporal records of LAI in need of further harmonization and uncertainty estimation. It will be good product for validation of prognostic vegetation models.

→ Aerosols: it should be easier to treat their time variations with a prognostic model rather that treated as boundary conditions.

→ Seek links with climate community for timely curation of emissions (conversations have started)