CLIMATE SPHINX

Stochastic **P**hysics **HI**gh resolutio**N** e**X**periments

High-resolution present-day and future climate simulations with an improved representation of small-scale variability

***Jost von Hardenberg*[1]**, *Paolo Davini*[2,1], *Susanna Corti*[1],
Hannah Christensen[3], *Stephan Juricke*[3], *Aneesh Subramanian*[3]
Peter A.G. Watson[3], *Antje Weisheimer*[3], *Tim Palmer*[3]

(1) Institute of Atmospheric Sciences and Climate (ISAC-CNR), Italy
(2) Laboratoire de Météorologie Dynamique / IPSL, ENS, France
(3) Atmospheric, Oceanic and Planetary Physics, Oxford University, UK

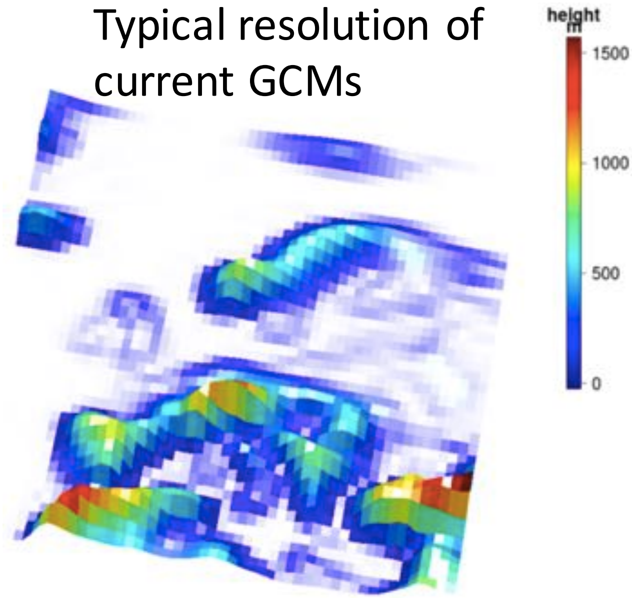
ROLE OF SPATIAL RESOLUTION FOR GLOBAL CLIMATE MODELS

- Typically current, lower-resolution, climate models:
  - Underestimate the number of observed storms
  - Simulate poorly midlatitude atmospheric blocking
  - Systematic errors which impact on weather regimes, regional variability

- High resolution climate models show improved representation of
  - the global water cycle
  - Large scale circulation (jet streams)
  - Blocking
  - Madden-Julian oscillation

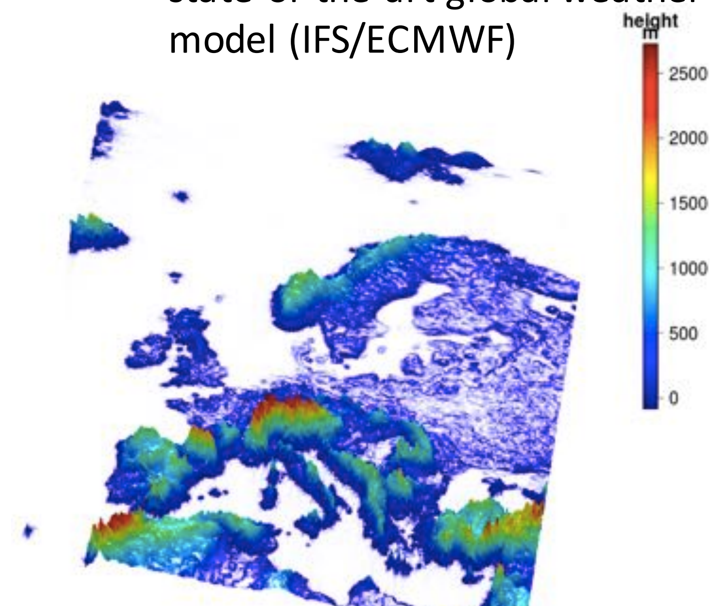
80-125 Km

Typical resolution of current GCMs



16 Km

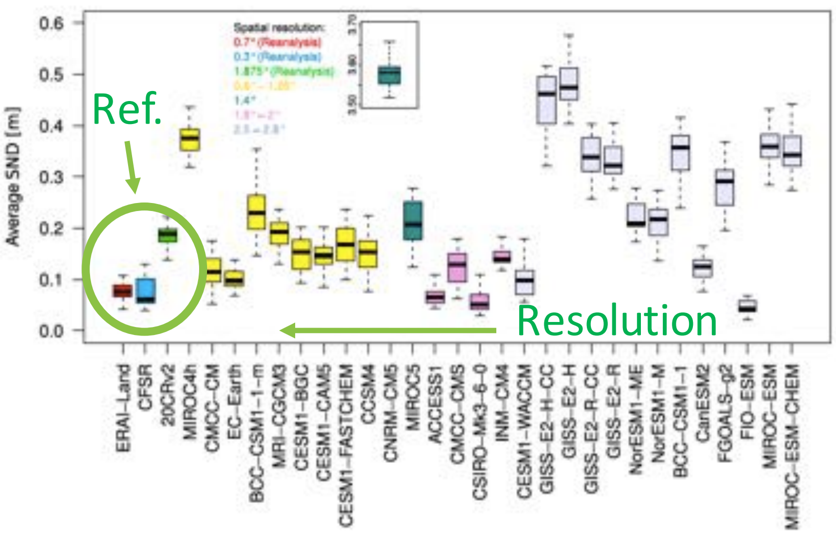
Operational resolution of a state-of-the-art global weather model (IFS/ECMWF)



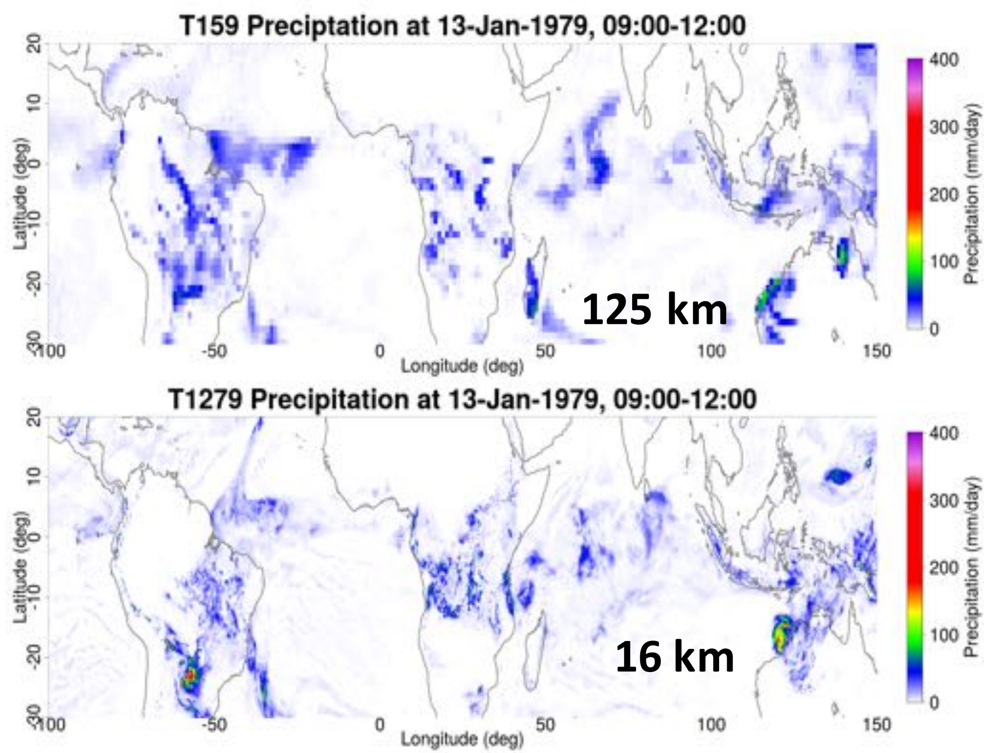
HIGH-RESOLUTION CLIMATE MODELING

- Impact of small-scale processes on large-scale atmospheric motion → Importance of representing small scale processes.
- **High-resolution global climate modeling** has the potential to improve significantly the representation of climate variability, circulation regimes, extremes and transport.
- ***BUT*** high-resolution is computationally expensive, particularly in fully coupled models and the same model parameterizations may not be suitable

Average snow depth in the Himalayan region for CMIP5 models



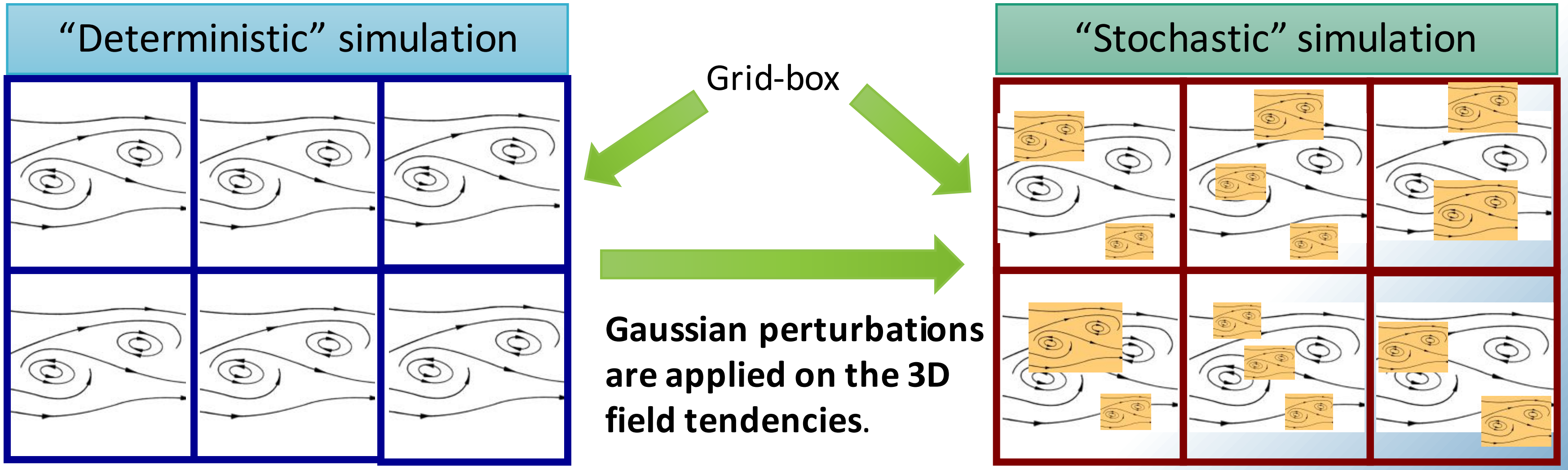
Terzago et al. 2013, JHM, 15 (6), 2293-2313



WHAT IS STOCHASTIC PHYSICS?

Instead of explicitly resolving small-scale processes by increasing the resolution of climate models, a **computationally cheaper** alternative is to **use stochastic parameterization schemes** (Palmer 2012).

A stochastic scheme includes a **statistical representation of the small scales**, and hence is able to represent the impact of such small-scale processes on the resolved scale.



There is mounting evidence that stochastic parameterizations are beneficial for climate variability in GCM simulations (Dawson et al, 2012):

- Better representation of flow regimes
- Reduction of systematic biases

Climate SPHINX (Stochastic Physics High Resolution Experiments) is a PRACE project (2015-2016) investigating **high-resolution** climate simulations and the role of **stochastic parameterizations**

- **20 million of core hours** on **Supermuc** @ LRZ Computing Center, Garching, Germany.
- 1.5PB of raw data produced, about **150 TB** of post-processed data available
- More than 110 ensemble members at resolutions from 125 to 16km available.

Model: EC-EARTH3 **global climate model** with additional tuning.

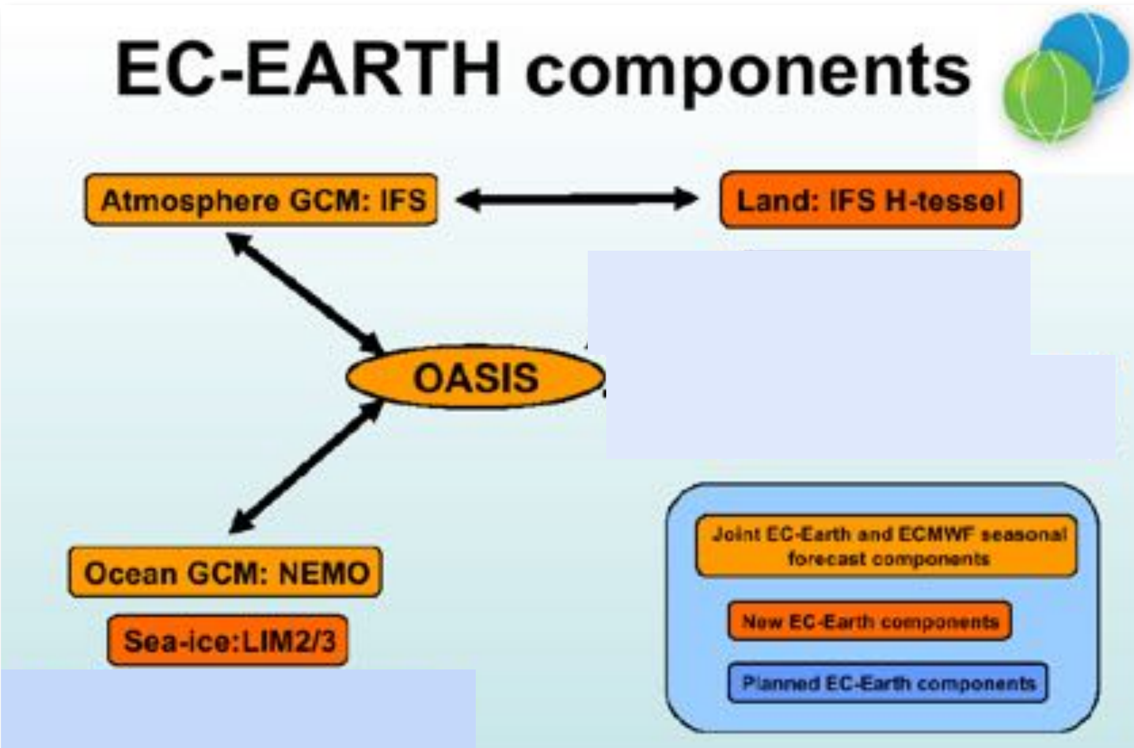
Collaboration between ISAC-CNR (Italy) and Oxford University

Connections with other science and HPC projects:

- PRIMAVERA H2020 Project (2015-2020)
- CRESCENDO H2020 Project (2015-2020)
- NextDATA National Project of Interest (2011-2015)
- ECMWF special projects (2014-2016)-(2016-2018)
- Gauss EXPRESS project (2013-2014)
- ECOPOTENTIAL H2020 Project (2015-2019)

THE EC-EARTH GLOBAL CLIMATE MODEL

ECMWF IFS atmosphere (36r4 – T255L91/N128)+ H-Tessel Land/veg module + NEMO 3.3.1 ocean (ORCA1 L46) (will be 3.6) + LIM 3 sea ice



Integrated Forecast System ECMWF

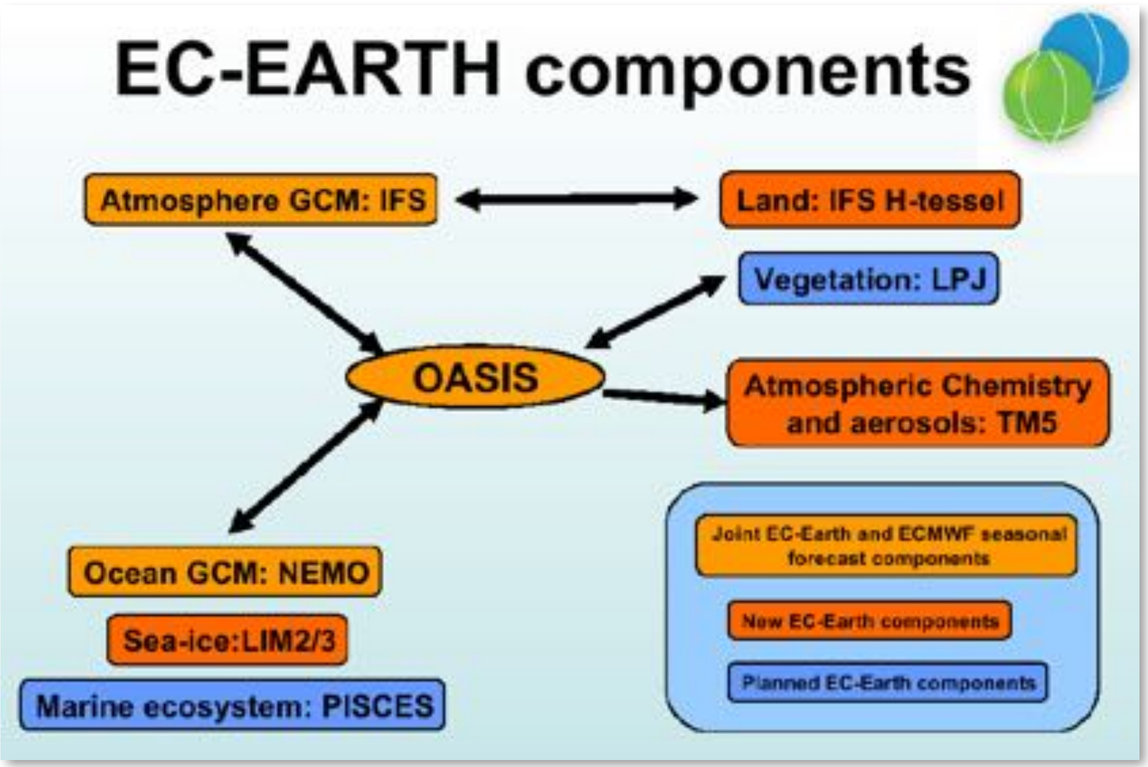
Louvain La Neuve Ice Model LIM3 (ECE v3)

H-Tessel Land-surface model

Ref.: Hazeleger, W. et al., 2009. EC-Earth: A Seamless Earth System Prediction Approach in Action. *Bull. Amer. Meteor.*

THE EC-EARTH GLOBAL EARTH-SYSTEM MODEL

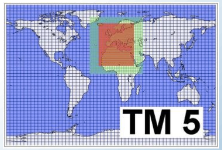
ECMWF IFS atmosphere (36r4 – T255L91/N128)+ H-Tessel Land/veg module
+ NEMO 3.3.1 ocean (ORCA1 L46) (will be 3.6) + LIM 3 sea ice
+ TM5 chemistry/aerosols (6°x4° / 3°x2°)



Integrated Forecast System ECMWF

Louvain La Neuve Ice Model LIM3 (ECE v3)

H-Tessel Land-surface model



TM5 atmospheric chemistry and transport model

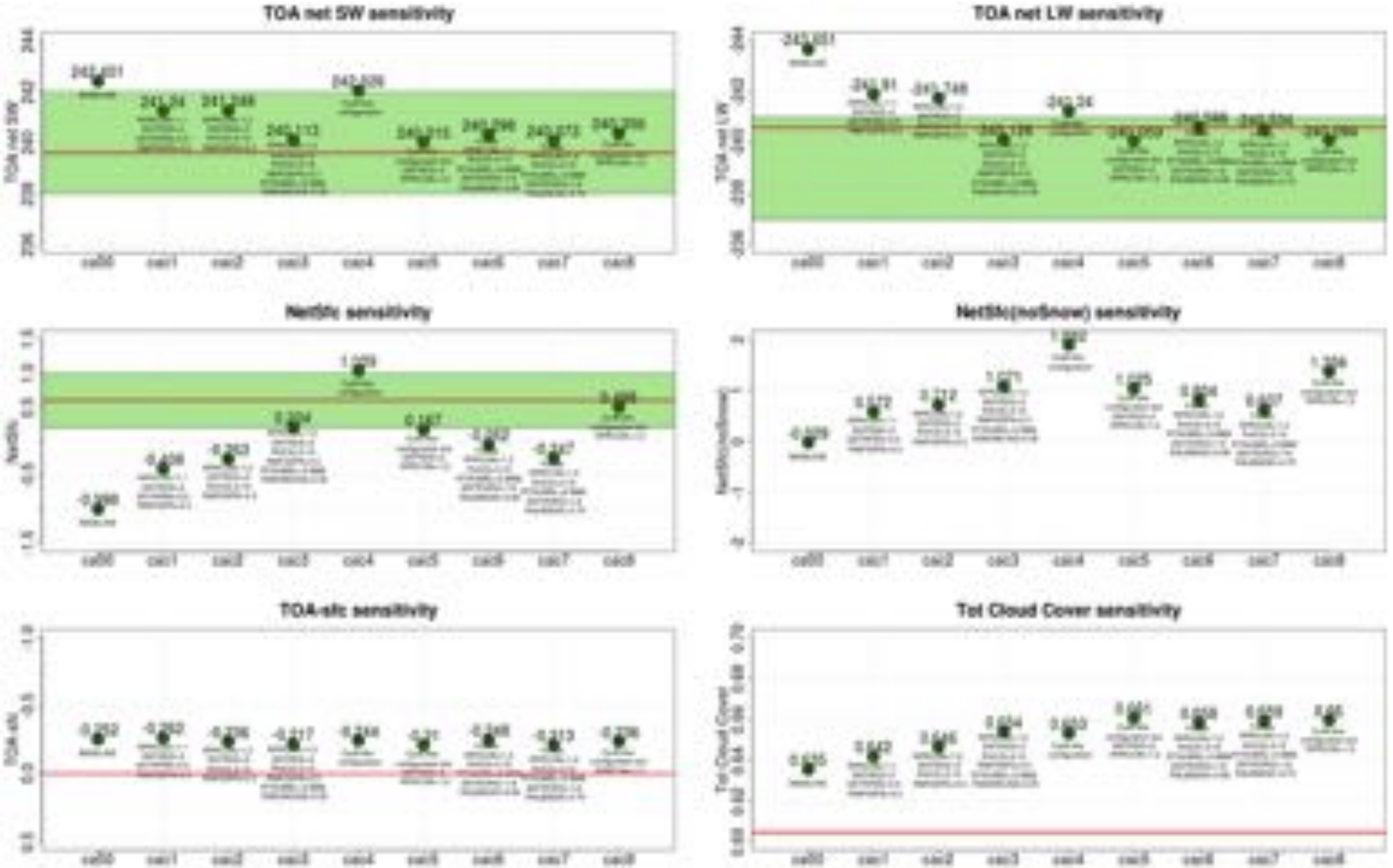
LPJ-Guess dynamic vegetation

Ref.: Hazeleger, W. et al., 2009. EC-Earth: A Seamless Earth System Prediction Approach in Action. *Bull. Amer. Meteor. Soc.*

EC-Earth consortium

28 Research institutions from 12 different European countries.
Strong collaboration with ECMWF.

TUNING THE MODEL: SENSITIVITY TO CLOUD AND CONVECTIVE PARAMETERS



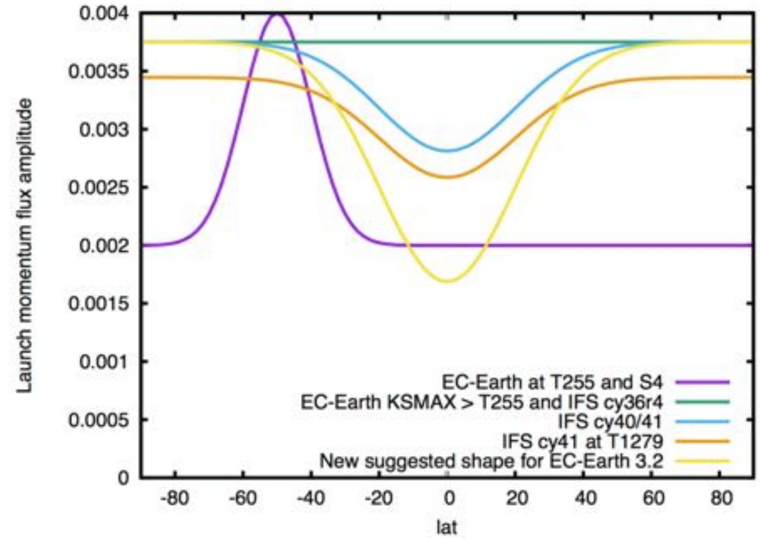
IMPROVED NON-OROGRAPHIC GRAVITY WAVE DRAG PARAMETERIZATION

- The Quasi-biennial oscillation is an oscillation of equatorial zonal average winds with a period of about 28 months.

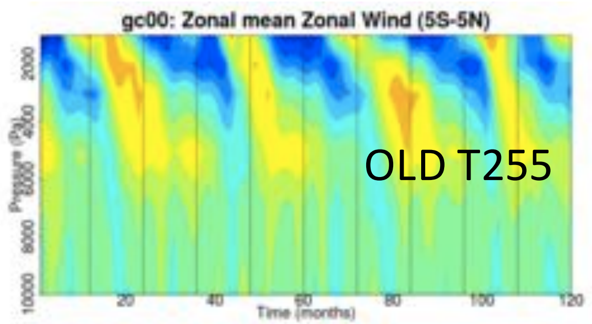
Original model
→ No Quasi-Biennial Oscillation (QBO) at higher res

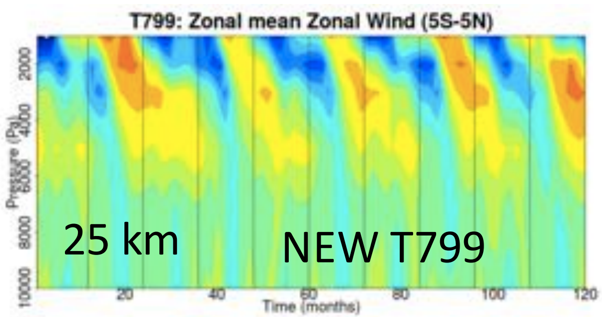
- We adopt a different recent IFS shape
- Resolution-dependent parameterization of non-orographic gravity waves

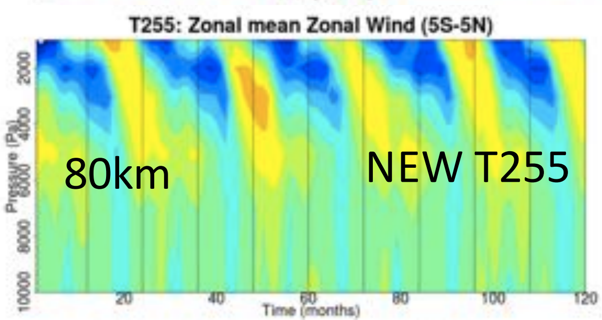
→ Improved representation of QBO also at hi-res

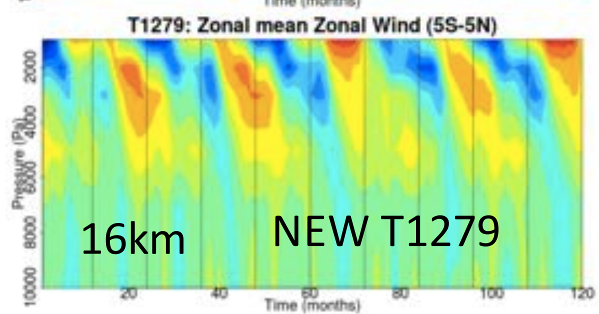


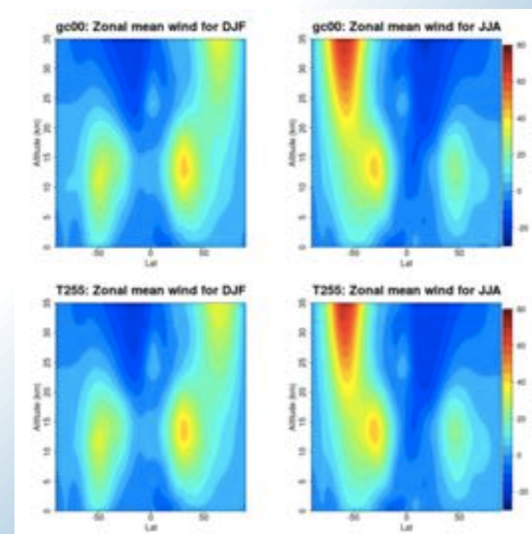
GFLUXLAUN = momentum flux launched in mid-troposphere to simulate the effects of gravity waves.







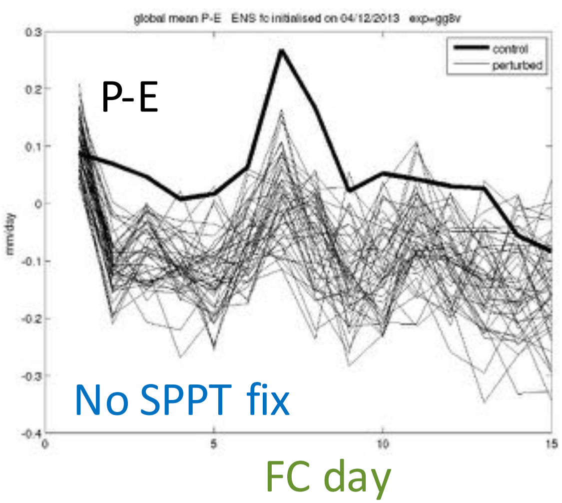


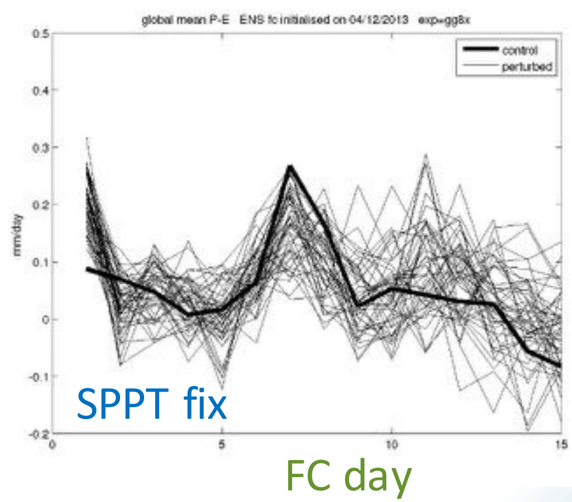


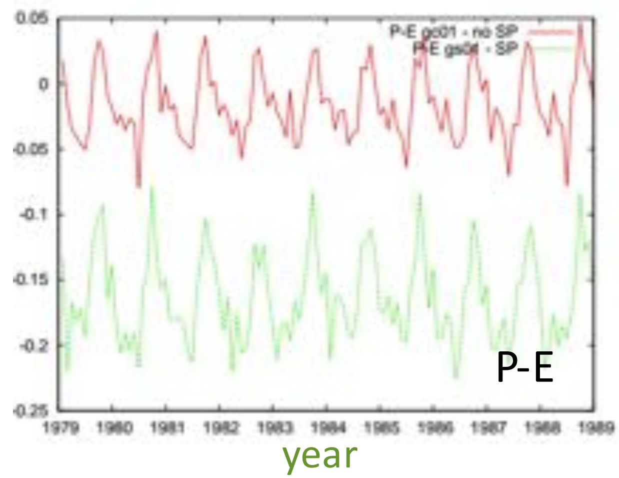
In consultation with ECMWF

TENDENCY CONSERVATION IN THE STOCHASTIC PHYSICS (SPPT) SCHEME

- The **SPPT scheme** was found not to be conservative in water vapour and energy → Leading to strongly negative Precip.-Evap. (P-E) imbalance (-0.16 mm/day) and Top of Atmosphere - Surface net radiative fluxes = 1.5 W/m2
- Implementation of a scheme enforcing (proportional) conservation of T, Q, U and V tendencies before and after SPPT
- → leads to P-E=0.016 mm/day and TOA-SRF=-0.58 W/m2







In collaboration with Antje Weisheimer (Oxford Univ.), Simon Lang (ECMWF), Linus Magnusson (ECMWF), Massimo Bonavita (ECMWF)

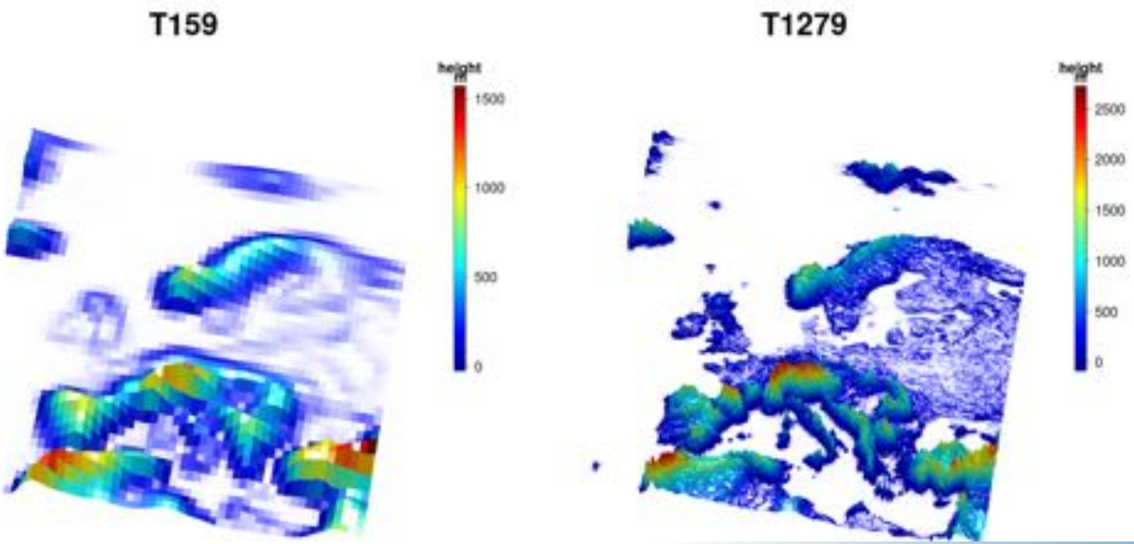
EXPERIMENTS & RESOLUTIONS

Atmospheric-only:
5 horizontal resolutions

Present day
1979-2008

Future Scenario
2039-2068 RCP85

Coupled: T255L91
1850-2100, historical + RCP8.5

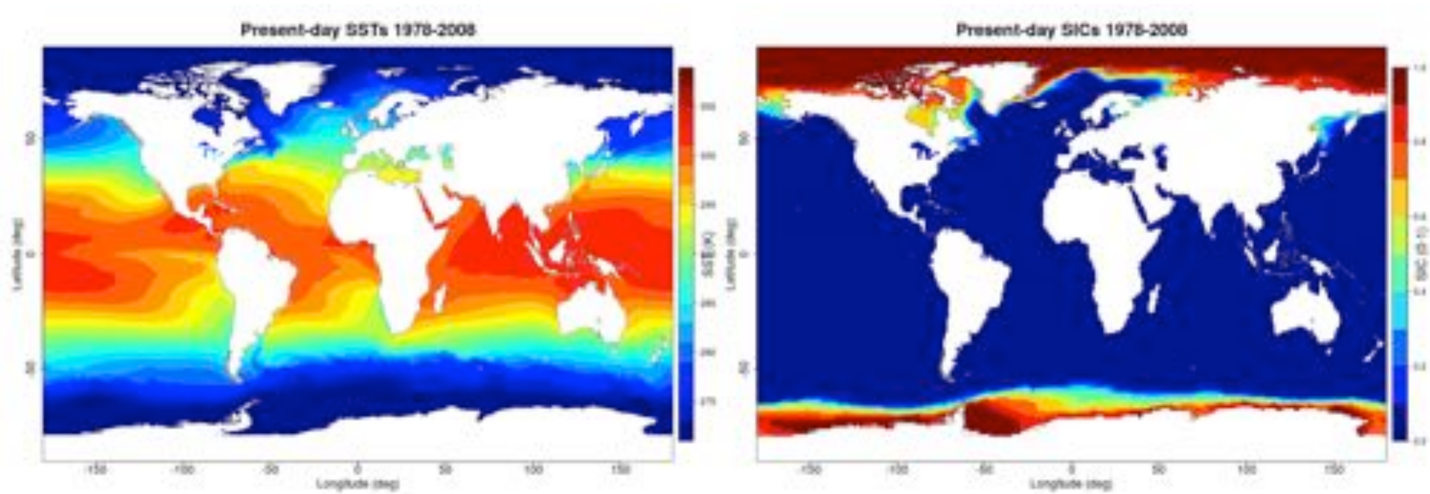


- **More than 110 simulations**
- **About 5000 model years of simulation**

T159L91 (125km): 10+10 ensemble members
T255L91 (80km): 10+10
T511L91 (40km): 5+5
T799L91 (25km): 3+3
T1279L91 (16km): 1+1

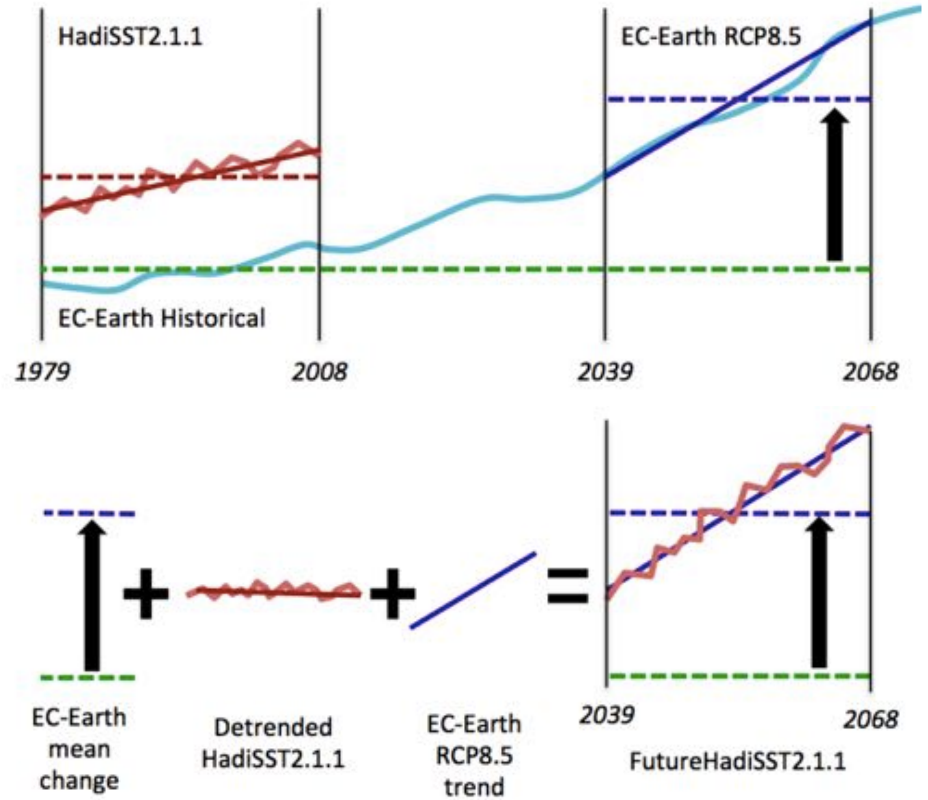
SURFACE FORCING: PRESENT DAY

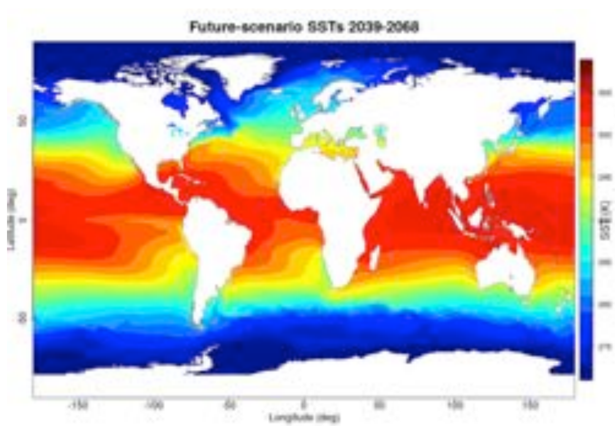
- New oceanic dataset: **HadISST 2.1.1** (Titchner et al., 2014; Kennedy et al, 2016)
- **Pentad-based daily 0.25x0.25 dataset for SST and and 1x1 for SIC.**
- Initial conditions from ERA INTERIM reanalysis 1979-01-01.
- 1979-2008: **Historical CMIP5 forcing for greenhous gases.**
- Lake (not defined inland points): **ERA INTERIM 1-month lagged seasonal cycle** (Hersbach et al., 2015), ice when below zero.
- Coastal points (land-sea mask mismatch) are extrapolated.

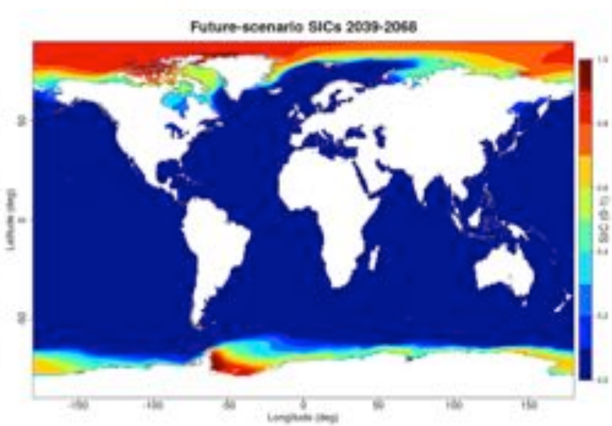


FUTURE SURFACE FORCING

- Future SSTs: **Adjusted Mizuta et al (2008) method.**
- EC-Earth 2 **CMIP5 ensemble mean for mean values and trend of SST**s.
- **Daily variability is taken from HadiSST 2.1.1**
- For SICs, we pick one ensemble member of EC-Earth CMIP5 representative of the dataset (i.e. closer to ensemble mean).

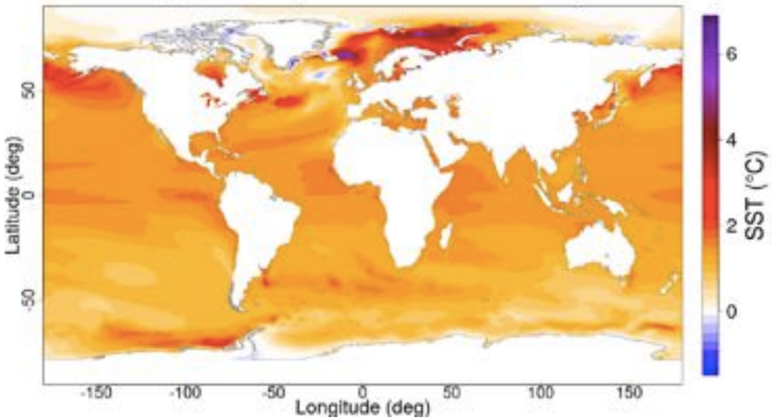




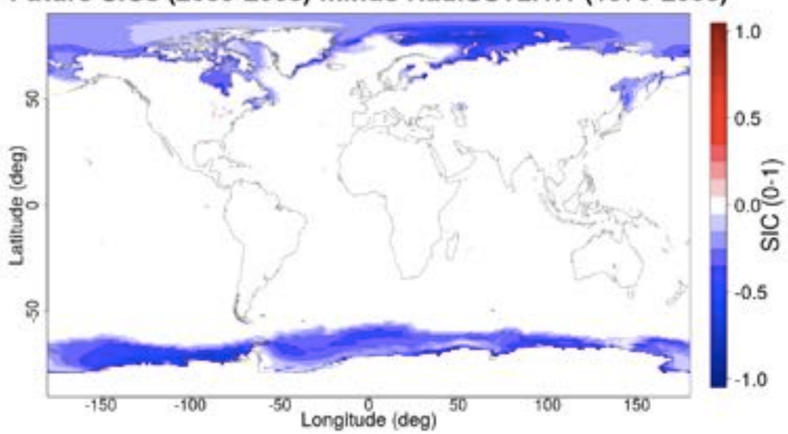


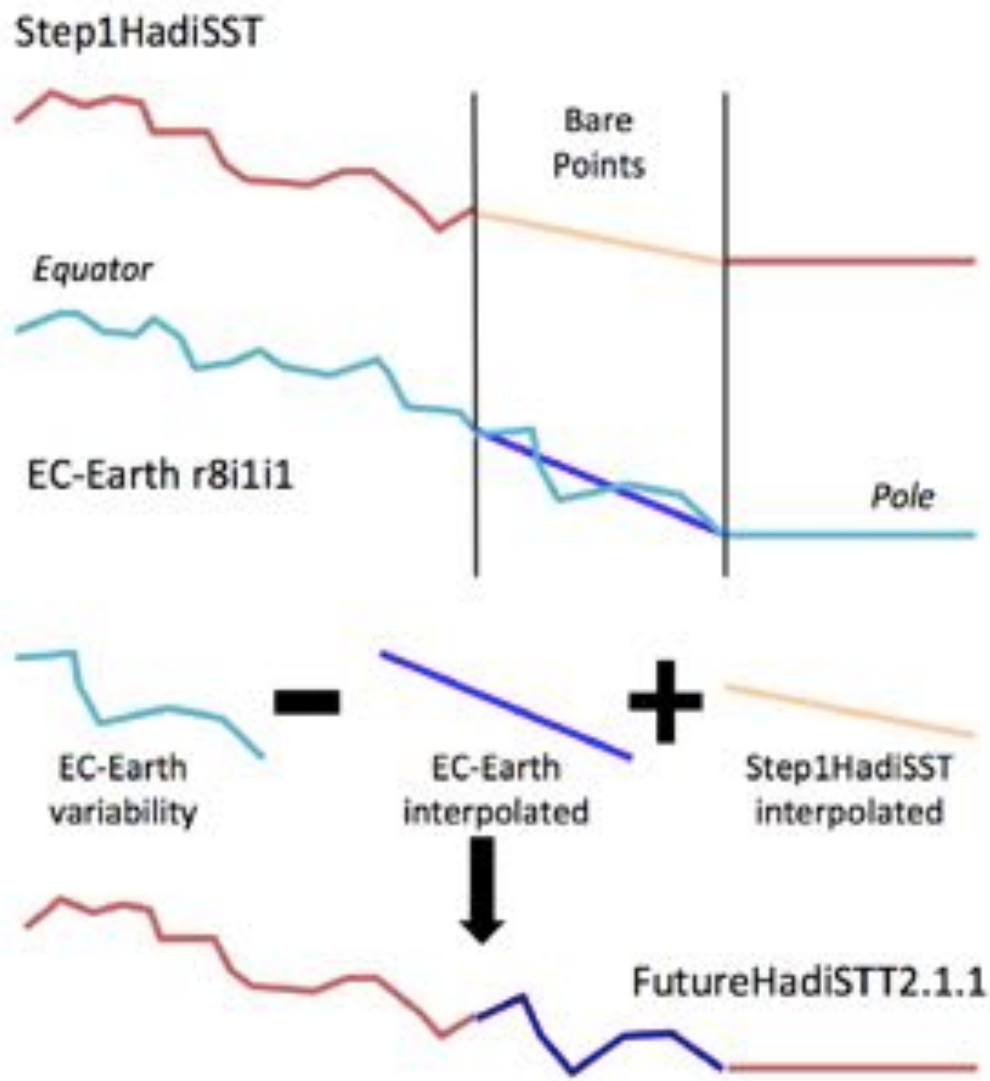
NEW ICE-FREE AREAS: FILLING THE GAPS

Future SSTs (2039-2068) minus HadiSST2.1.1 (1979-2008)



Future SICs (2039-2068) minus HadiSST2.1.1 (1979-2008)



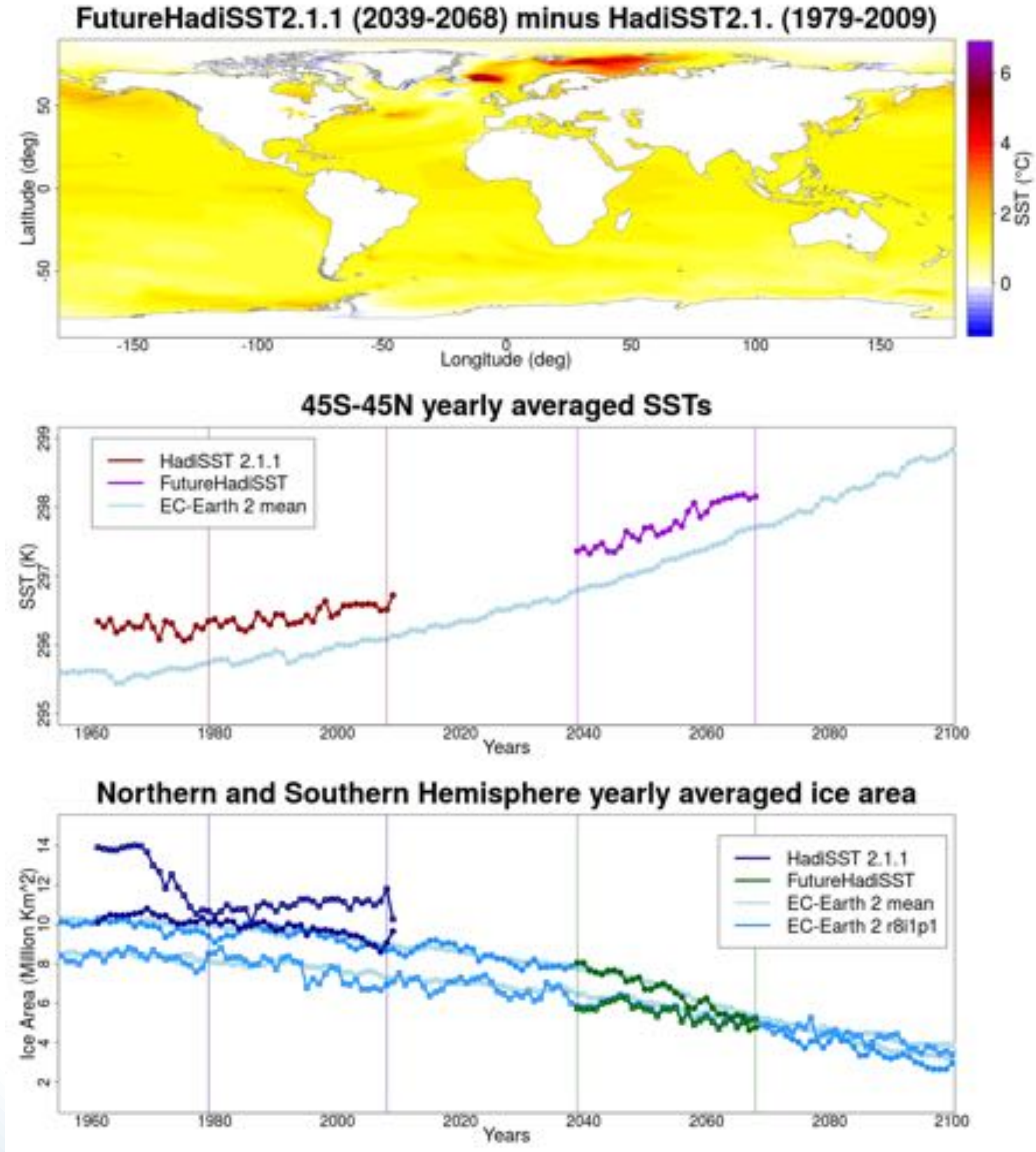


FUTURE SURFACE FORCING

- **Bare-points due to retreat of sea-ice:** specific filling combining a linear interpolation and HadISST 2.1.1 variability

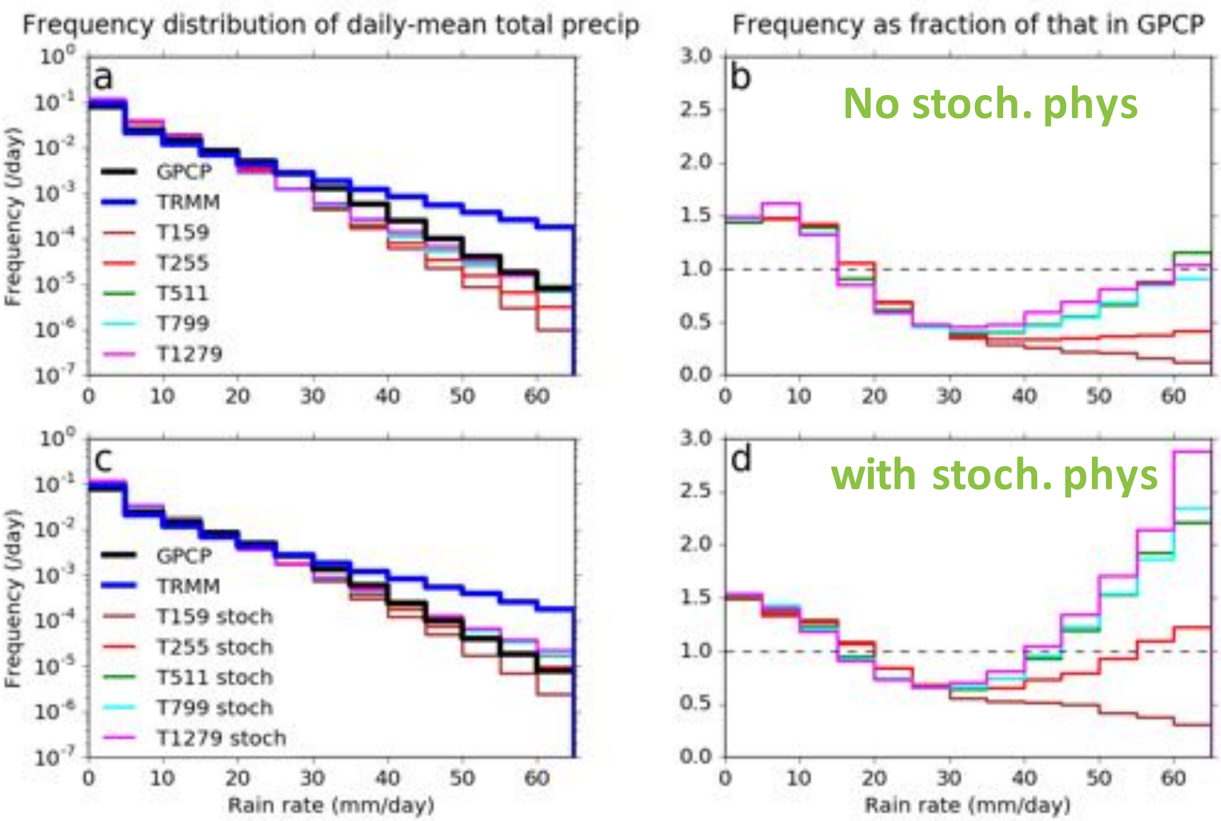
- **The new dataset has the same variability of HadISST2.1.1 and the mean field and values of EC-Earth ensemble mean**

- **2039-2068: RCP8.5 CMIP5**



RESULTS: TROPICAL PRECIPITATION

- One aspect of the **tropical variability** of particular interest is the **occurrence of heavy precipitation events**, which can result in flooding or reduce crop yields (IPCC, 2014).
- Estimated through the **frequency distribution of daily-mean precipitation rates** averaged over 2.5°x2.5° grid boxes **between 10°S-10°N** over the period 1998-2008

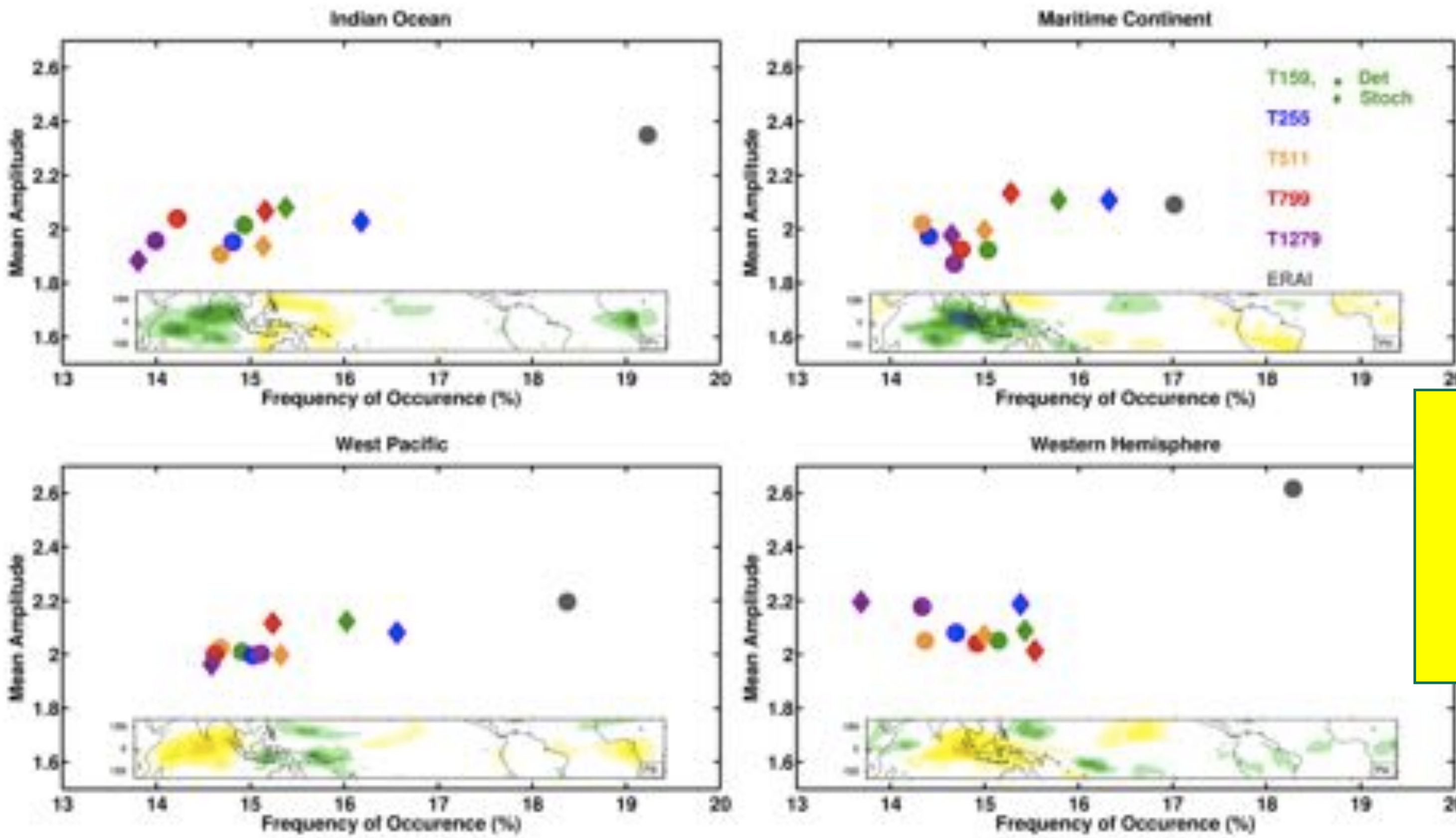


- In general, **underestimation of extreme rainfall events**
- **Increasing resolution leads to reduced bias**: however applying **stochastic parameterization improves the variability of low resolution models** (T159-T255).

RESULTS: MADDEN-JULIAN OSCILLATION

- The **Madden-Julian Oscillation** (MJO) is the dominant mode of variability in the tropical region on sub-seasonal timescales (30-90 days). Eastward travelling pattern in Indian Ocean and Pacific.
- It is a challenge for the current generation of global climate and weather models to represent the dynamics and thermodynamics of the MJO realistically

Mean Amplitude

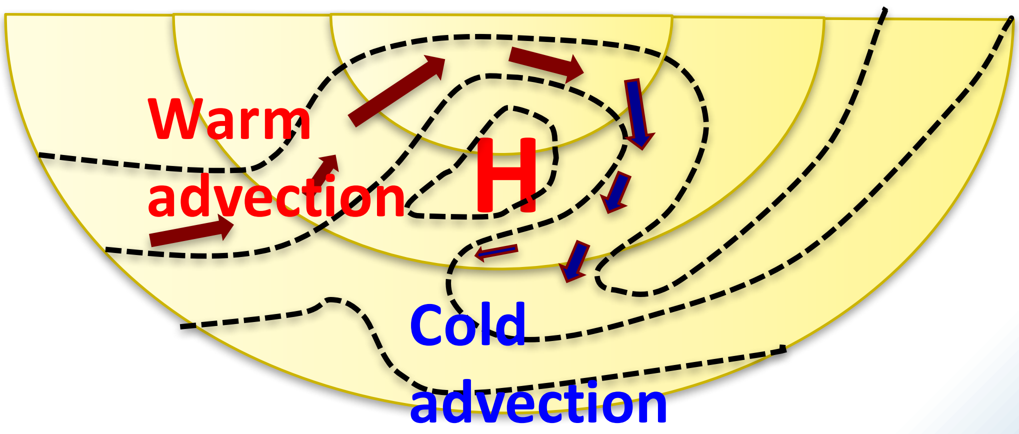


Frequency of ocurrence

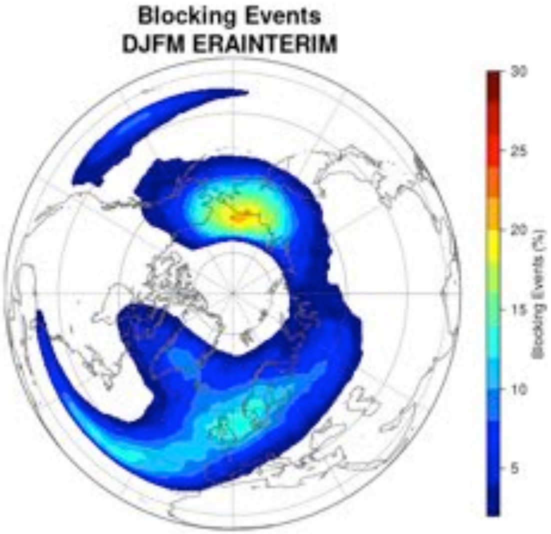
Benefit only from stochastics physics

RESULTS: BLOCKING

- Atmospheric blocking describes a mid-latitude weather pattern where a **quasi-stationary high-pressure system modifies the westerly flow**, “blocking” (or at least diverting) the eastward movement of the migratory cyclones **(Rex, 1950).**



- Blocking affects leading to **cold spells in winter (when it is more frequent) and heat waves in summer**.



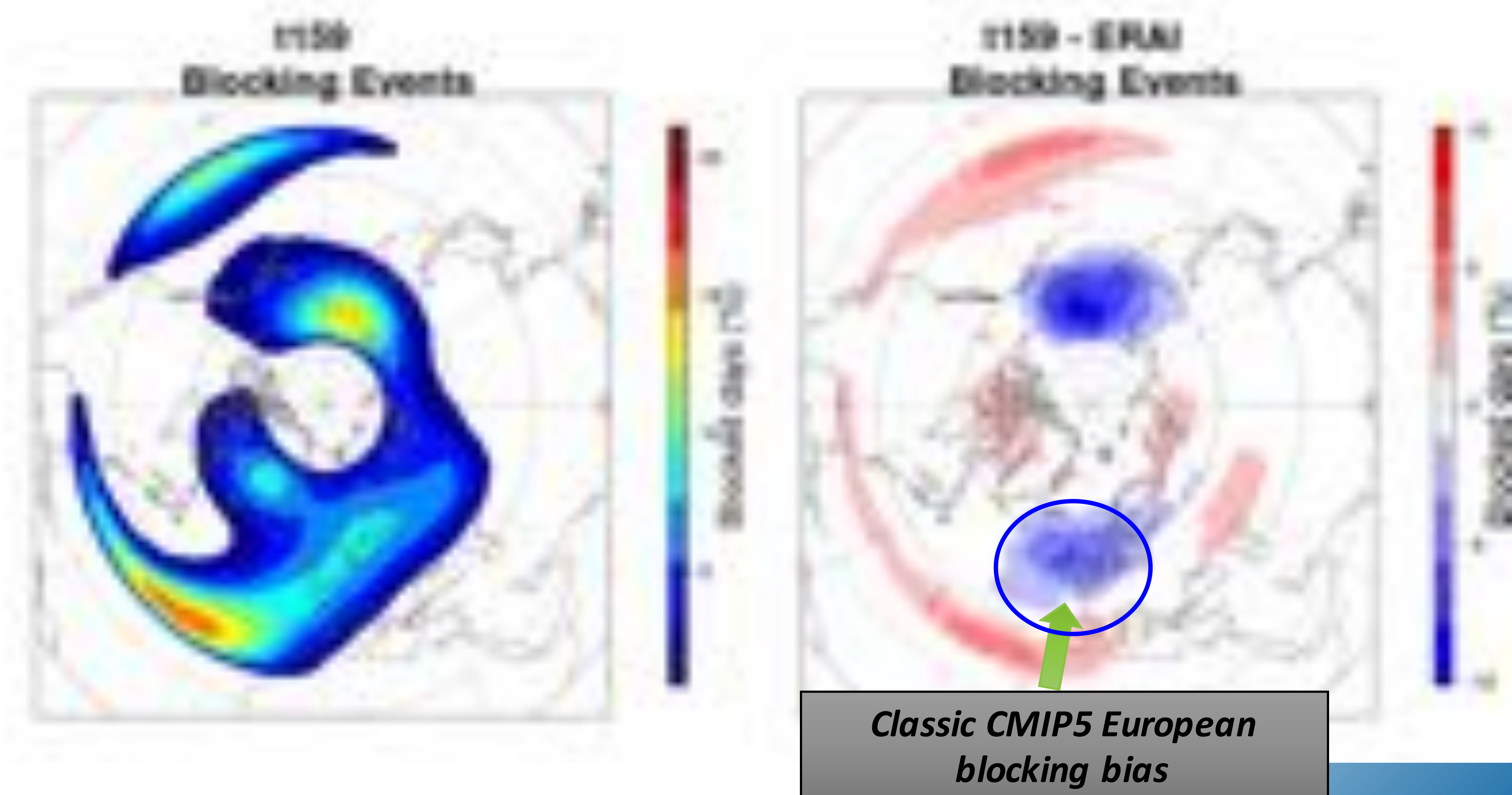
- Evaluation of winter (DJFM) **atmospheric blocking** using the 2D index extension of Tibaldi and Molteni (Davini et al 2012) in the present day (30 years).

- Blocking over the **Pacific** and the **Atlantic**, at the exit of the jet stream.

- **Long-standing issue in GCMs**, large negative bias over Europe even in CMIP5 models.

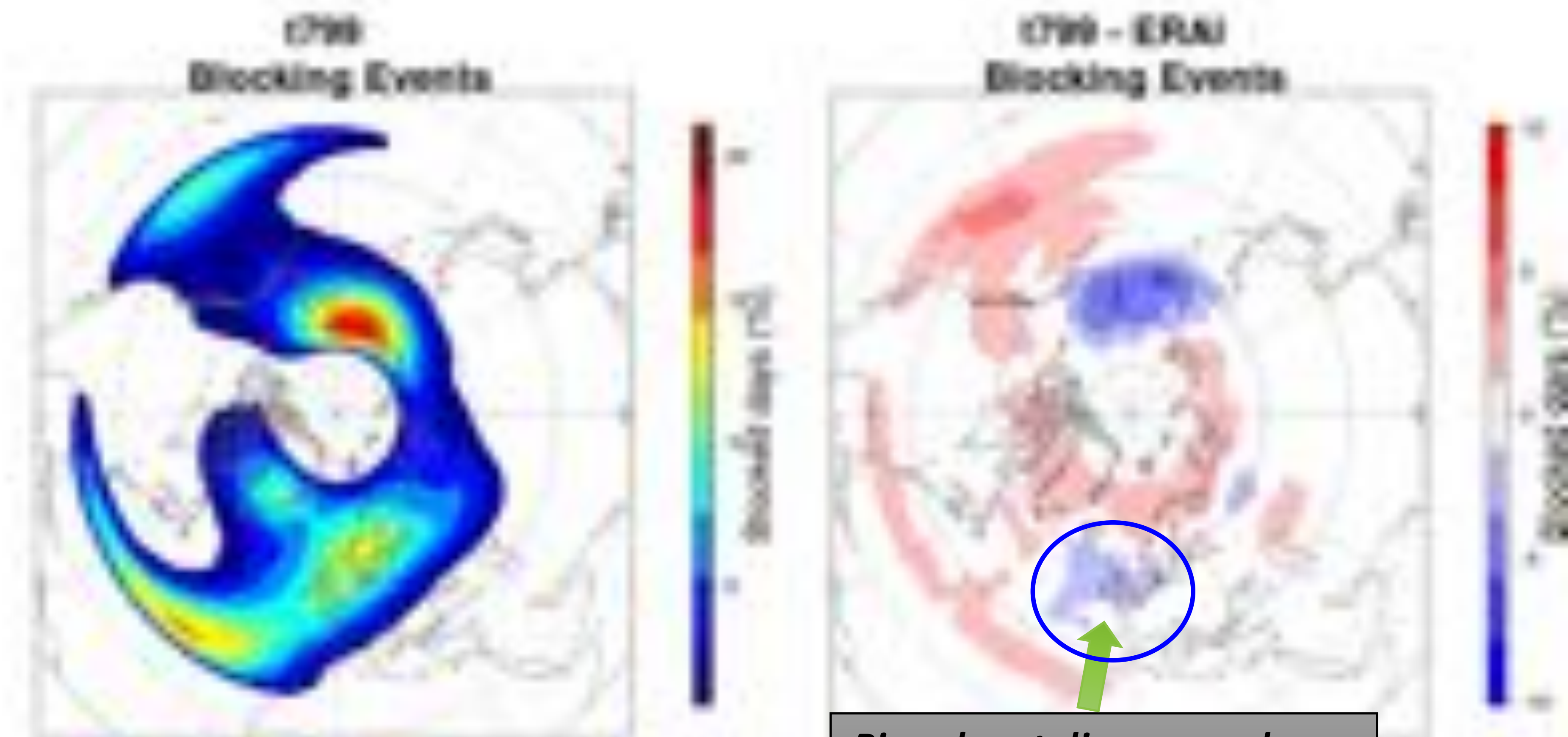
RESULTS: BLOCKING

20 ensemble members, DJFM, 125 km resolution, present day



RESULTS: BLOCKING

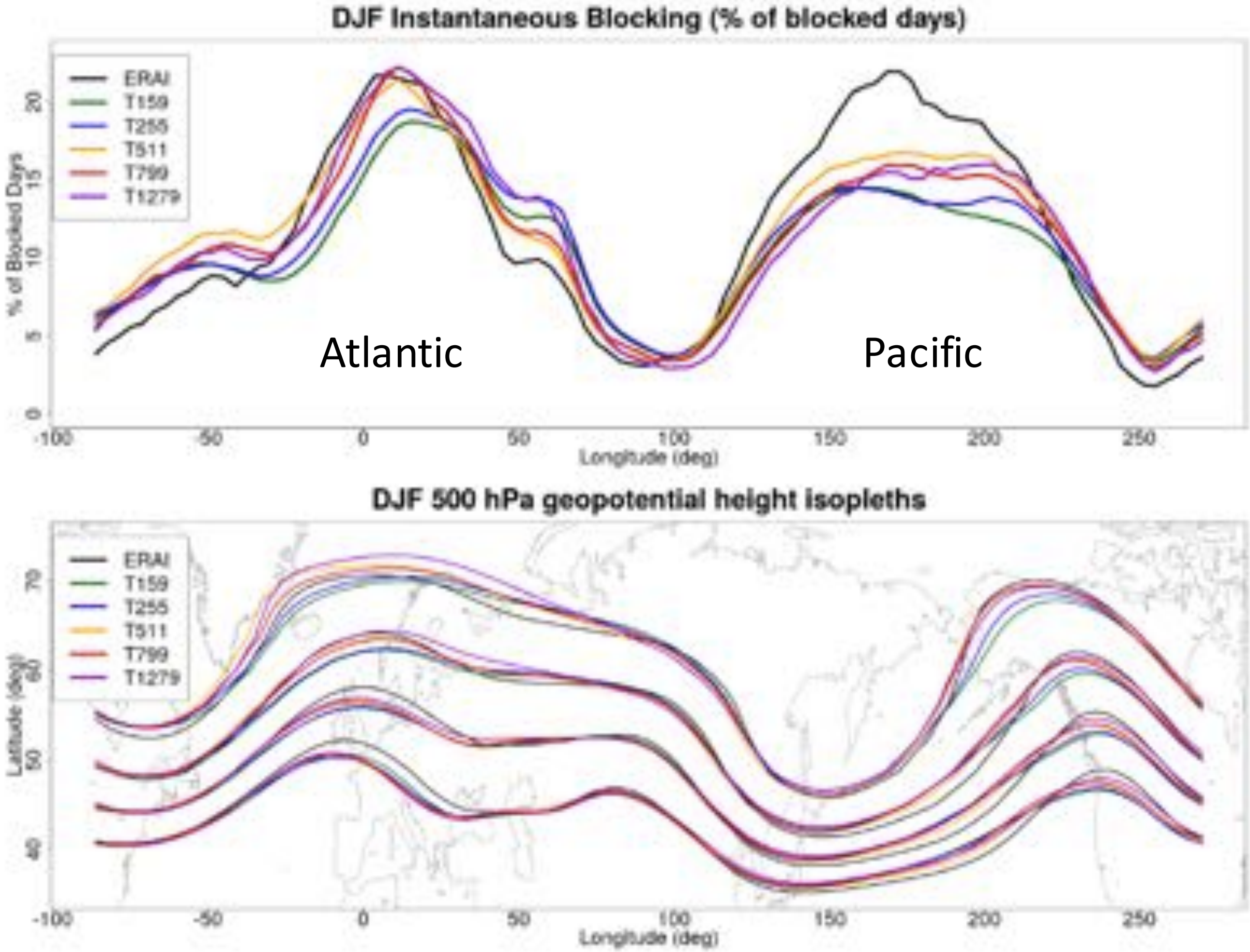
6 ensemble members, DJFM, 25 km resolution, present day



Bias almost disappeared over the Europe

RESULTS: BLOCKING

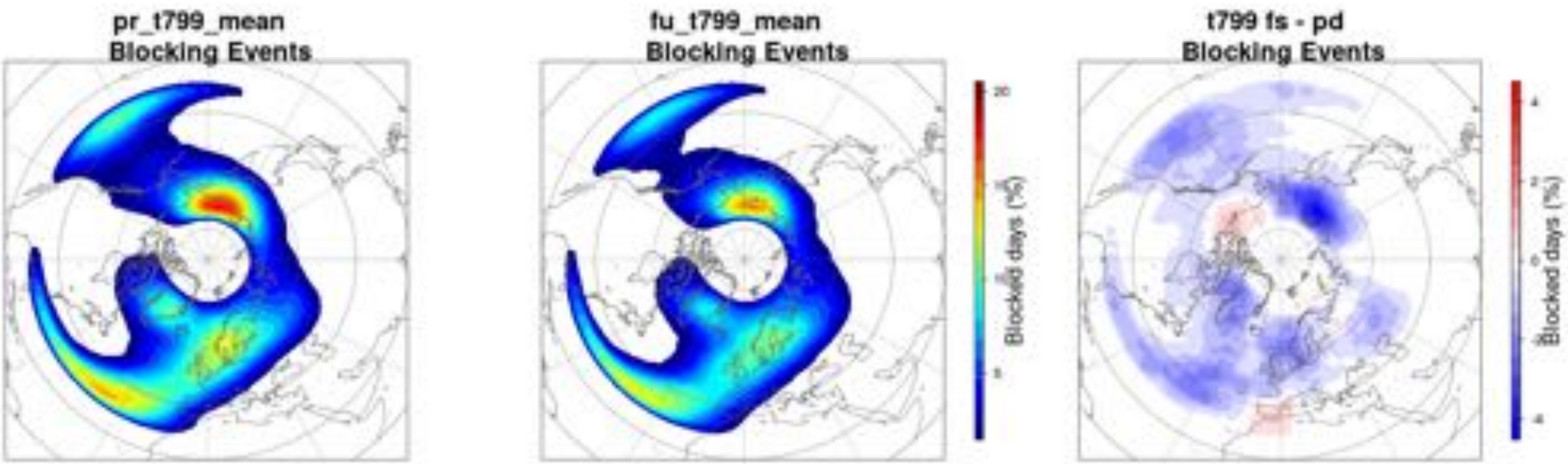
Improvements in atmospheric blocking with increasing resolution.



Blocking frequencies following D'Andrea et al. (1998

RESULTS: FUTURE BLOCKING

6 ensemble members, DJFM, 25 km resolution, future vs. present day



EC-Earth 3.1 at T799 resolution represents well present atmospheric blocking: **future climate simulations predict a large decrease of blocking activity** in every region of the globe.

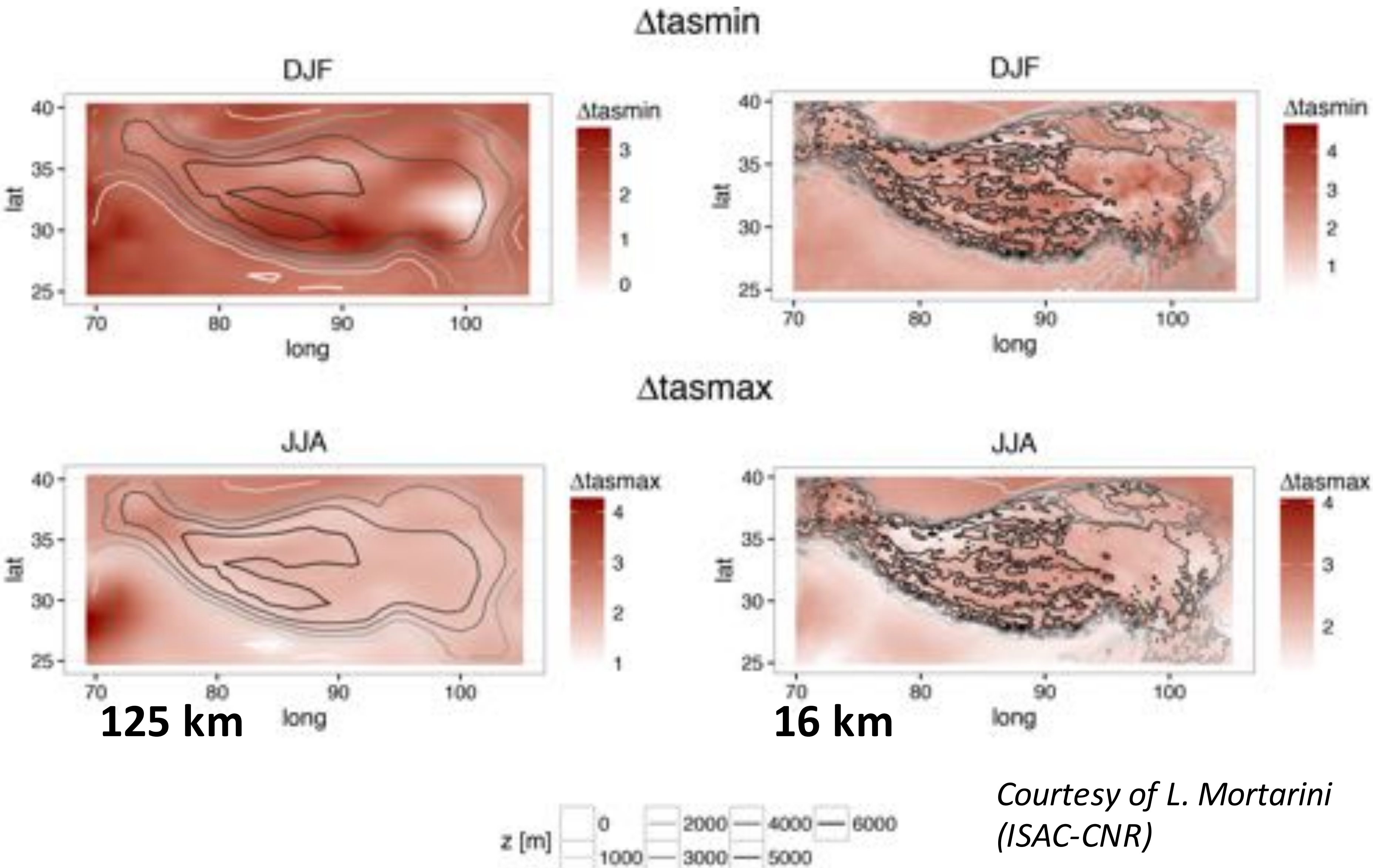
Our "contribution" to the "waviness of the jet" debate for which the Arctic Amplification should lead to more frequent blocking and colder winters (Francis and Vavrus, 2012).

COLLABORATIONS AND CURRENT RESEARCH

- ISAC-CNR:
  - Elevation dependent warming
  - Representation of snow cover
  - Continental heat waves
  - Precipitation extremes
- Oxford University:
  - MJO variability
  - Tropical precipitation variability
  - the impact of stochastic physics on ENSO in the coupled runs.
  - the impact of stochastic physics on the Indian Summer Monsoon in AMIP and coupled runs
  - low frequency variability in oceans
- IGG-CNR:
  - Climate change in the Mediterranean Area
  - Climate impacts on natural protected areas
- CMCC:
  - Medicanes/storms
- Newcastle University:
  - mix on hydrological cycle.
- COLA/George Mason University:
  - Atmospheric Rivers

INVESTIGATION OF ELEVATION-DEPENDENT-WARMING

2039-2068 minus 1979-2008 average minimum and maximum daily temperatures



Courtesy of L. Mortarini (ISAC-CNR)

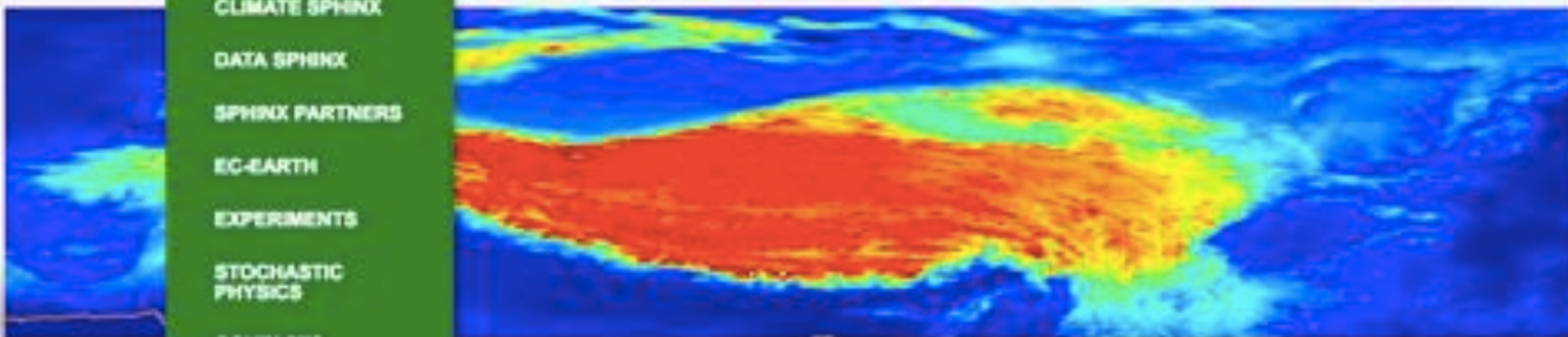
DATA STORAGE AND DISTRIBUTION

- **DATA SPHINX: an EUDAT Data pilot project** to share and distribute high-resolution climate model results.
- **Data available** @ CINECA (Italy), distributed through a THREDDS server.
- 140 TB of post-processed data available.
- Different sets of variables, CMOR-like format. Monthly mean, synoptic monthly mean, daily, 6hrs and for some selected domains (Alps, HKKH) also 3hrs.
- About 50 different physical variables stored.
- 3D fields downgraded to T255 to save disk space.
- NetCDF4 Zip (HDF5) reduces significantly the amount of space needed.

CLIMATE SPHINX

HOME | PROJECTS ▾ | DATA ▾ | DISSEMINATION ▾

- CLIMATE SPHINX
- DATA SPHINX
- SPHINX PARTNERS
- EC-EARTH
- EXPERIMENTS
- STOCHASTIC PHYSICS
- CONTACTS



What are Climate SPHINX and Data SPHINX?

Climate SPHINX (Stochastic Physics High resolutioN eXperiments) project is a multi-ensemble and multi-resolution simulation campaign aimed at evaluating the sensitivity of present and future climate to model resolution and stochastic parameteriszation. The **EC-Earth Earth-System Model** is used to explore the impact of a stochastic physics scheme in a large ensemble of 30-year **climate integrations at five different horizontal resolutions** (from 125km **up to 16km** for the atmosphere). Each integration is repeated with the implementation of the stochastic physics. The project includes more than 110 simulations in both a historical scenario (1979-2008) and a climate change projection (2039-2068), together with coupled transient runs (1850-2100). A total amount of 20.5 million core hours have been used at the SuperMUC IBM Petascale System at the Leibniz Supercomputing Center (LRZ) in Garching, Germany - thanks to a 1-year grant from PRACE (the Partnership for Advanced Computing in Europe). About 150 Tb of post-processed data are now stored at CINECA and they are freely accessible to the community thanks to an EUDAT Data Pilot project.

By comparing integrations carried out at different resolutions we will estimate the impact of the increased atmospheric horizontal resolution on the simulation of key climate processes and climate variability. By comparing experiments with and without the implementation of stochastic physics we will evaluateestimate the impact of stochastic physics on the simul... the same. By comparing experiments with the implementation ... stochastic ...

http://www.to.isac.cnr.it/sphinx

SUMMARY

- **Climate SPHINX**: a large set of global climate simulations to test horizontal resolution and parameterization of stochastic physics under both present and future forcing conditions.
- 140 TB of post-processed data from more than 110 simulations, almost 5000 model years simulated. Data access via THREDDS server @ CINECA (Italy), available.
- A first paper (Davini et al. 2016) describing the experiments and first results has been submitted.
- Further collaborative work underway with groups in Italy, UK, France, USA.
- First results: Improvements by resolution on atmospheric blocking and tropical precipitation. Stochastic physics benefits the representation of tropical variability.
- Next step: investigating **coupled** simulations and **stochastic physics parameterizations for the ocean** (new future simulations)

Please visit http://www.to.isac.cnr.it/sphinx for more information

Ref: Davini P., von Hardenberg J., Corti S., Christensen H., Juricke S., Subramanian A., Watson P., Weisheimer A., Palmer T. N., Climate SPHINX: evaluating the impact of resolution and stochastic physics parameterisations in climate simulations, submitted to GMD