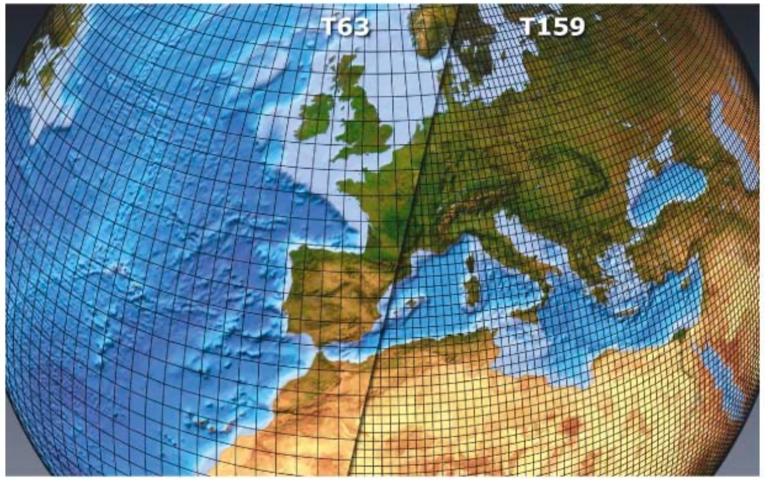
Downscaling ESMs

ESM Guest Lecture (24-05-2023)

Tim Hermans (t.h.j.hermans@uu.nl)



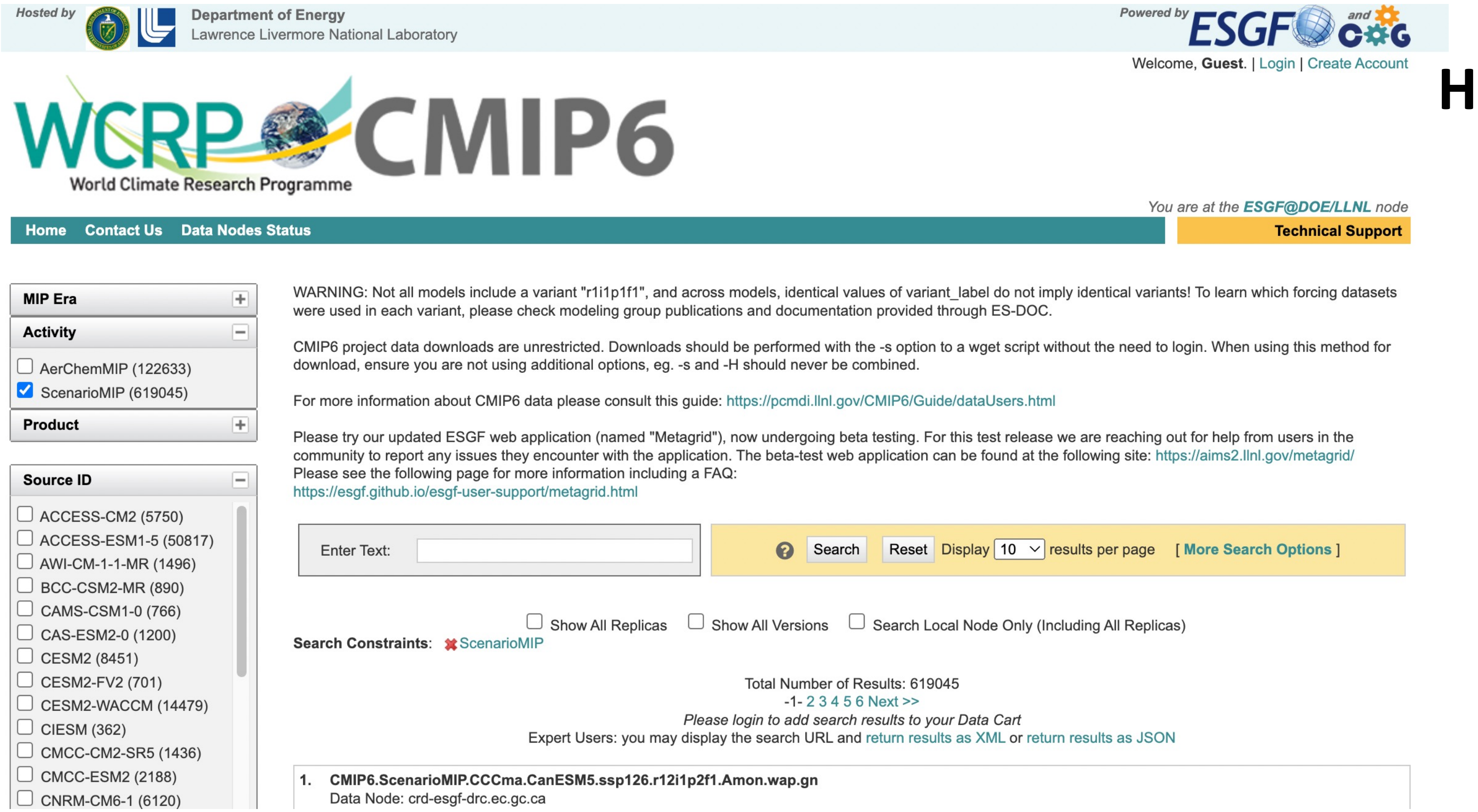
In this guest lecture:

1. Typical resolution & related limitations of ESMs

2. Methods to obtain high-resolution information from ESMs

3. Example of a dynamical downscaling set-up & applications

Current generation ESMs: CMIP6



Horizontal resolution in the order of:

- **1 degree (ocean)**
- **1-3 degrees (atmosphere)**

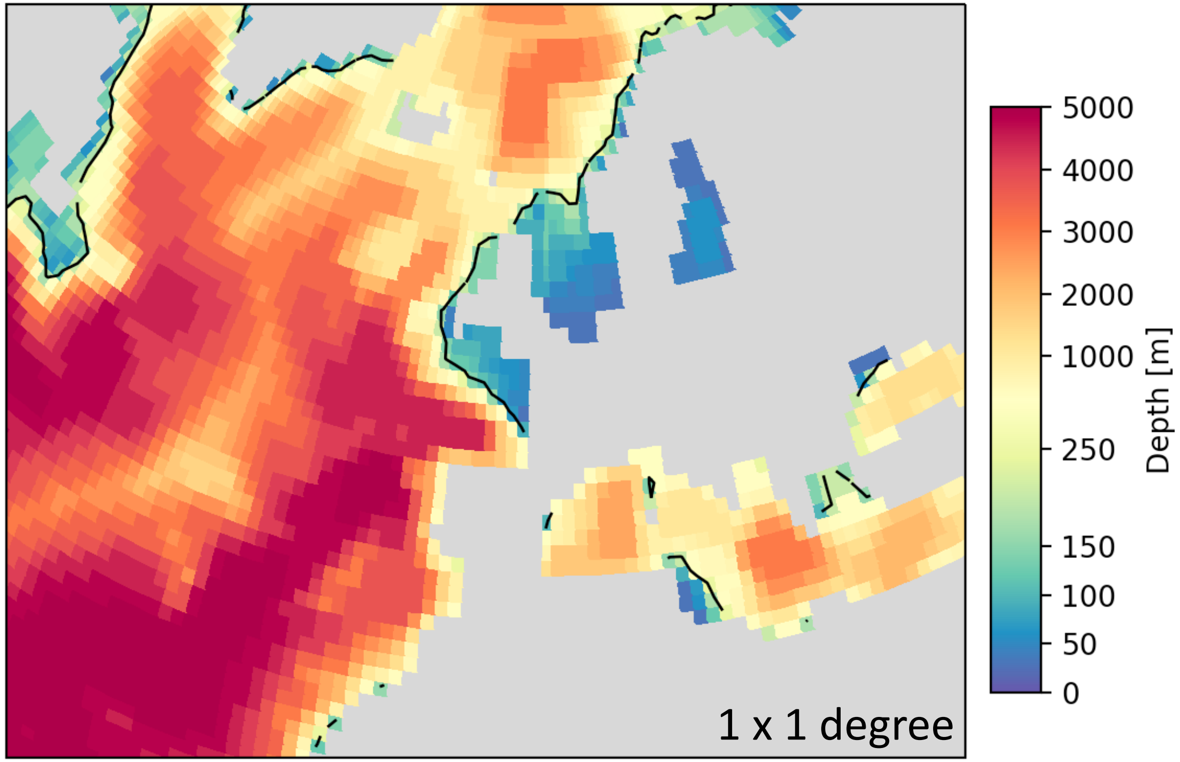
Why? Trade-off:

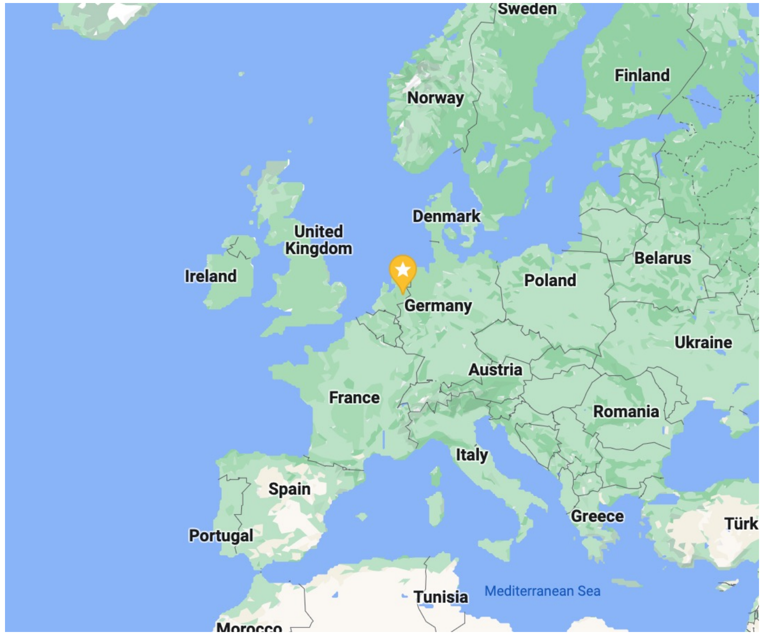
- Resolution
- Model complexity
- Number of scenarios
- Length of simulations
- Number of ensemble members

Typical ocean of a CMIP model

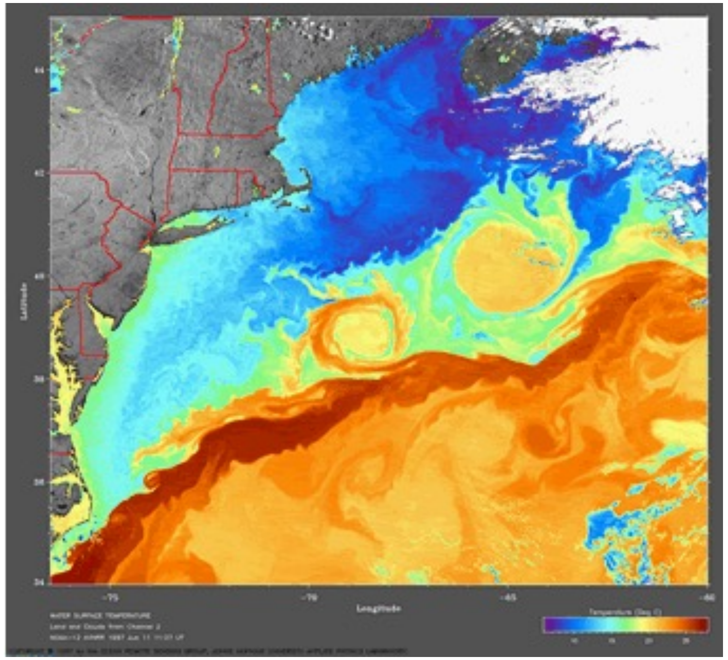
- HadGEM2-ES (CMIP5, but similar CMIP6 models)

HadGEM2-ES





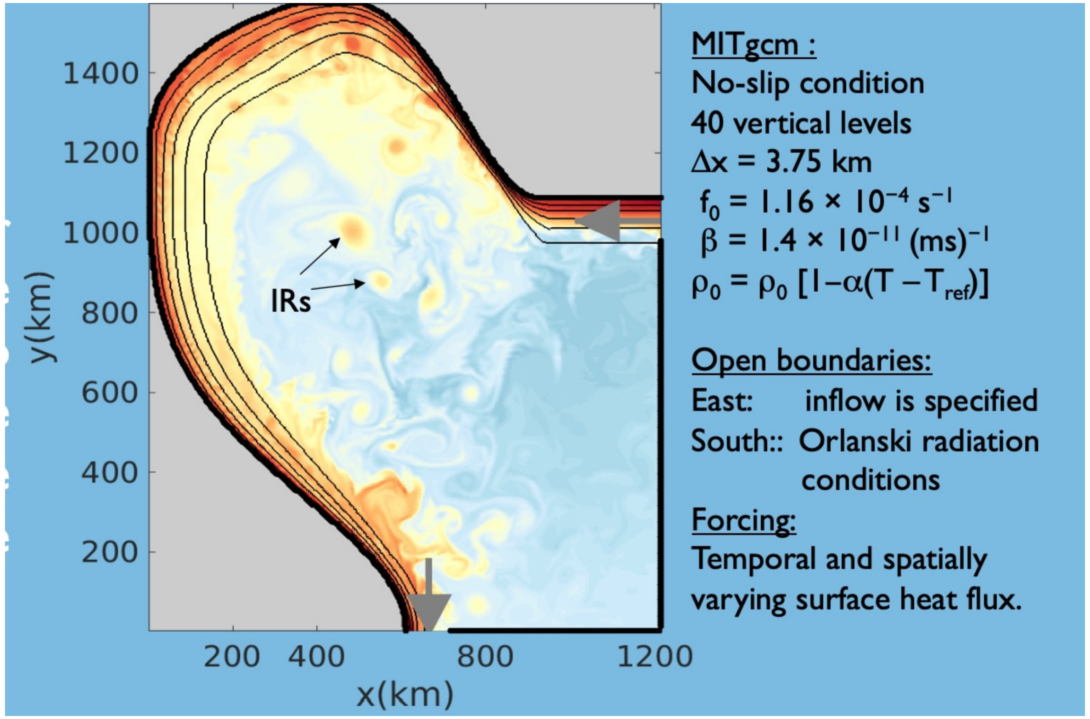
Limitations low resolution: ocean

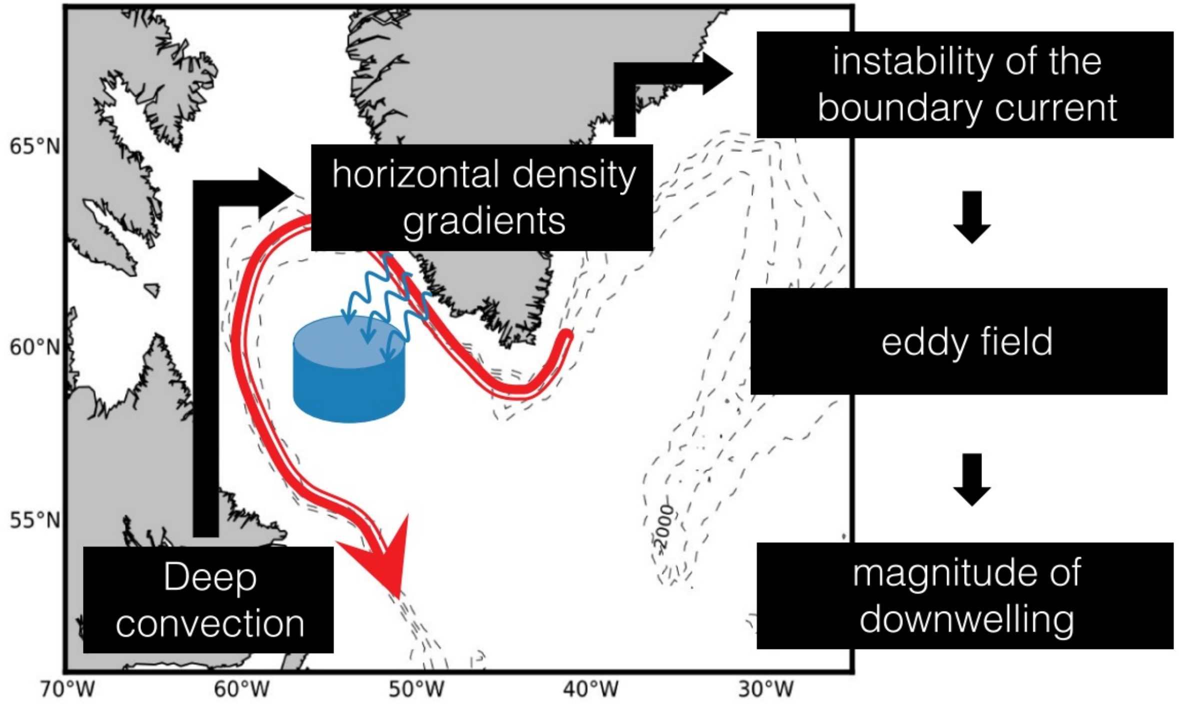


- Coastal (semi-enclosed) seas poorly resolved
  - Bathymetry, narrow straits, no tides
- Mesoscale eddies not resolved
  - 1 degree = eddy parameterising
  - 1/4th degree = eddy present/permitting
  - 1/10th degree = eddy rich
- Separation/path of western boundary currents & ocean circualtion

Deep convection in Labrador Sea

- Strongly controlled by eddies spawning from the boundary current

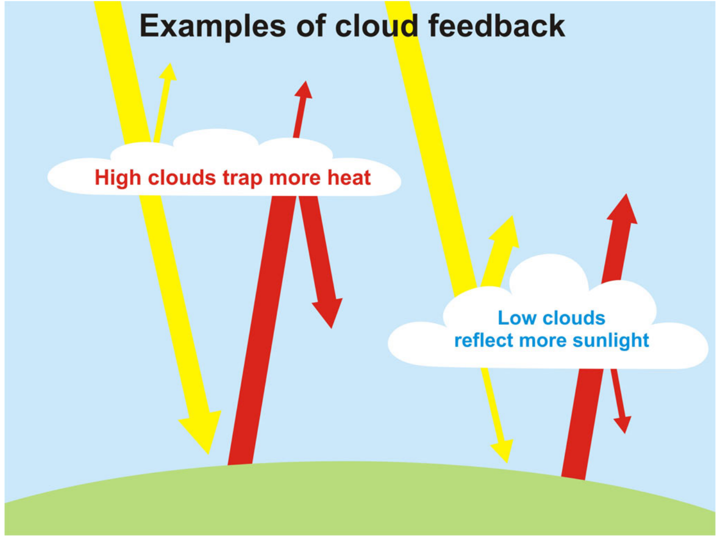


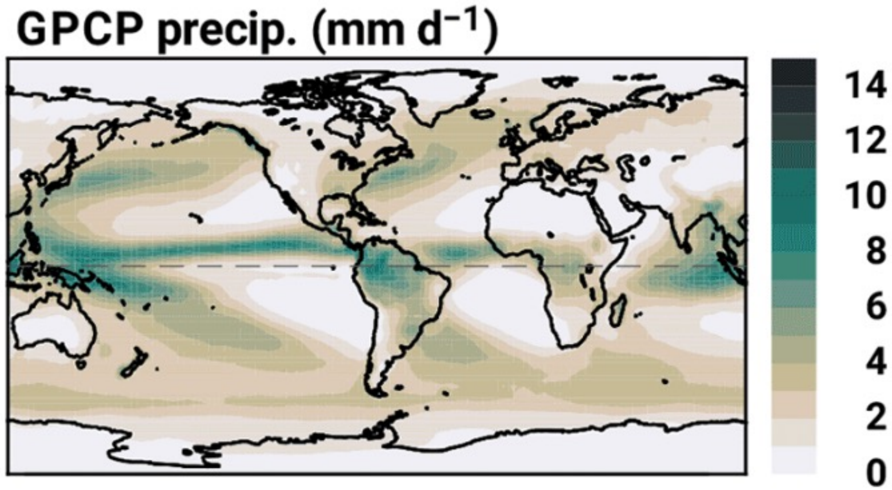


Georgiou et al. (2019)

Limitations low resolution: atmosphere

- Convection/clouds need to be parameterized, transport heat/moisture
  - Affects climate sensitivity of ESMs
- High-impact weather events (tropical cyclones, thunderstorms) not well resolved
- Complex orography/vegetation cover not well captured
- Double intertropical convergence zone (ITCZ) problem





Moreno-Chamarro et al. (2022)

How to obtain high-resolution information?

How to obtain high-resolution information?

1. Use a high-resolution global model

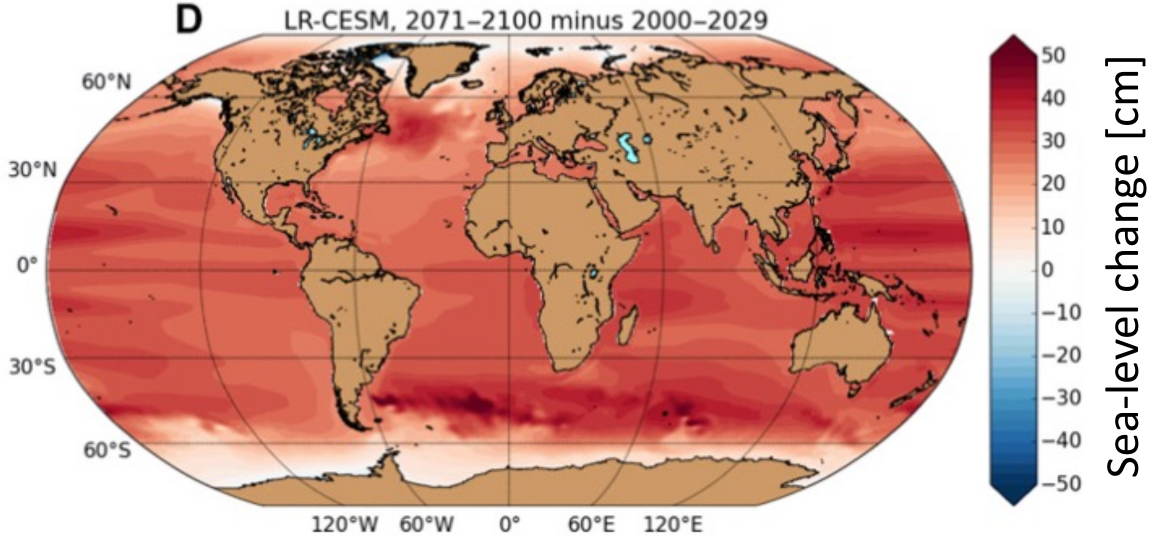
2. Use a global model with a high resolution regionally

3. Use a high-resolution regional model (= dynamical downscaling)

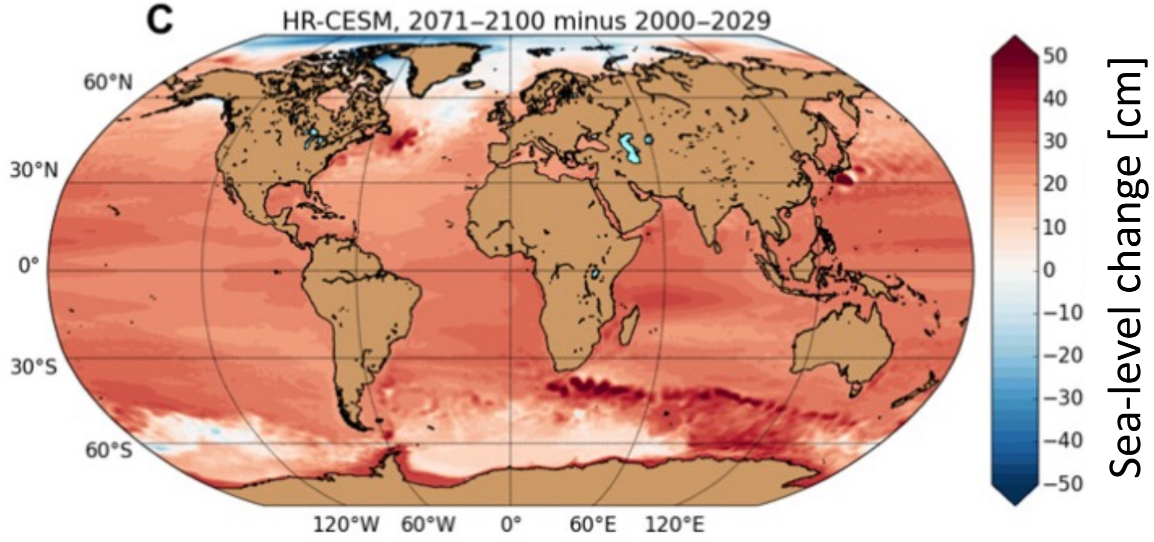
4. Use observations and statistical relationships (=statistical downscaling)

Example of a global high-resolution model

- Van Westen & Dijkstra (2021) @ IMAU:



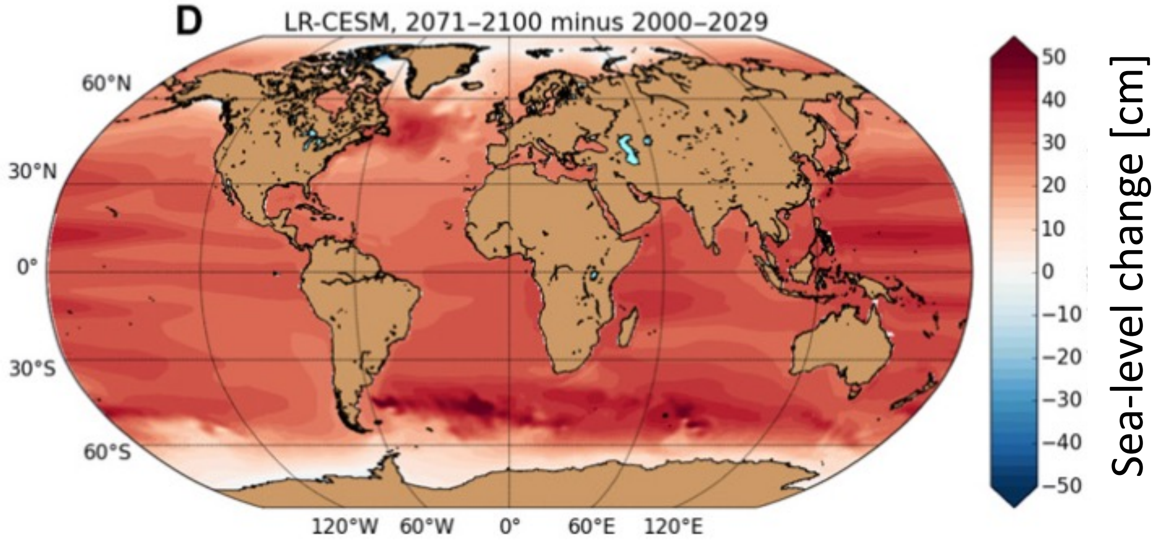
LR-CESM
Atmosphere: 1 x 1 degree
Ocean: 1 x 1 degree



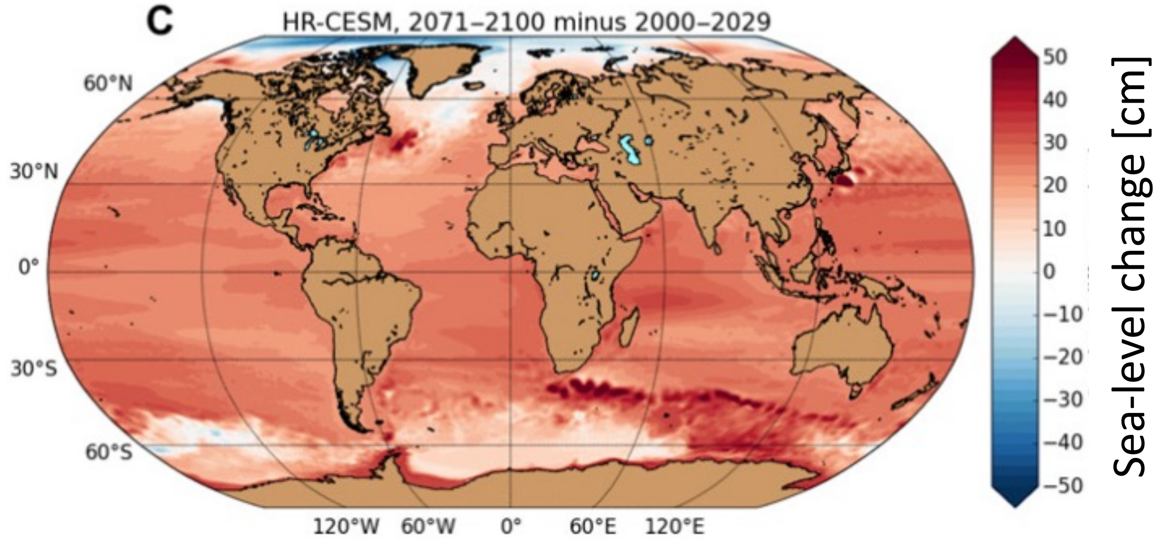
HR-CESM
Atmosphere: 0.5 x 0.5 degree
Ocean: 0.1 x 0.1 degree

- What differences do you see?

Example of a global high-resolution model



LR-CESM

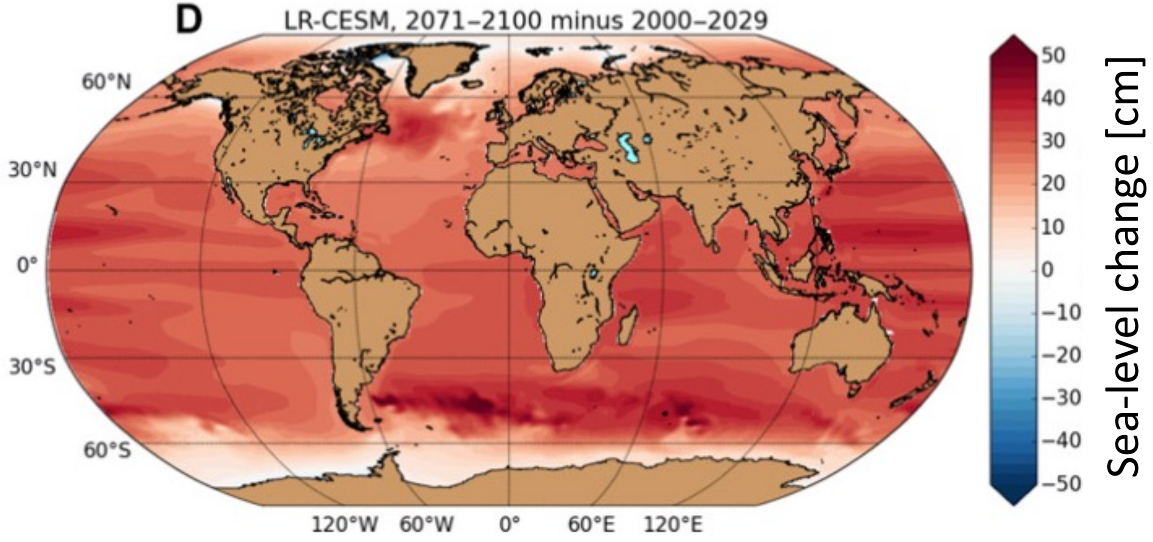


HR-CESM

- Southern Ocean circulation bettter resolved
- Sea-level change differs
  - Less high subsurface ocean temperature increases
  - Less basal melt of the Antarctic Ice Sheet, less sea-level change

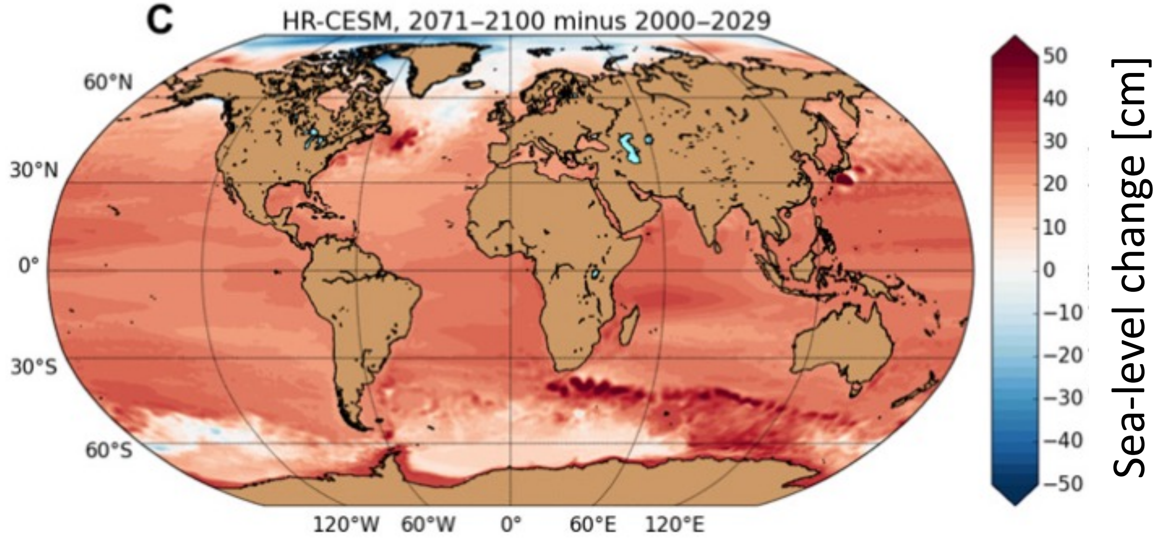
But at what cost?

- Van Westen & Dijkstra (2021) @ IMAU:



LR-CESM
Atmosphere: 1 x 1 degree
Ocean: 1 x 1 degree

80 simulation years/day



HR-CESM
Atmosphere: 0.5 x 0.5 degree
Ocean: 0.1 x 0.1 degree

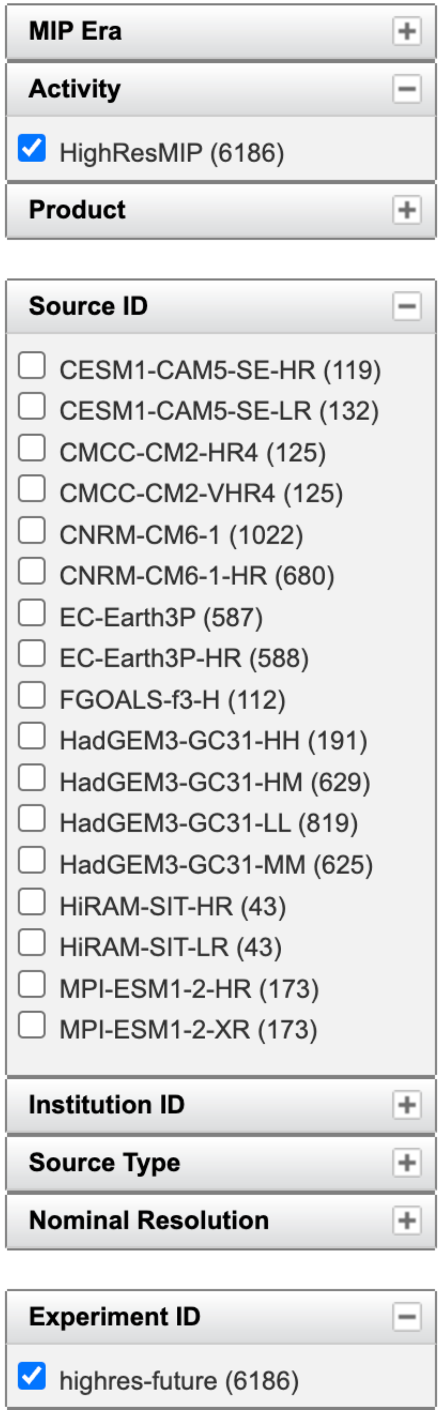
1 simulation year/day

A single scenario run until 2100 takes months…

CMIP6: HighResMIP

- Protocol for high-resolution contributions to CMIP6
  - 1950-2050, high-end emissions scenario
  - 25-50km atmosphere
  - At least 0.25 degree ocean resolution (eddy-permitting)
- ~8 modeling centers participating

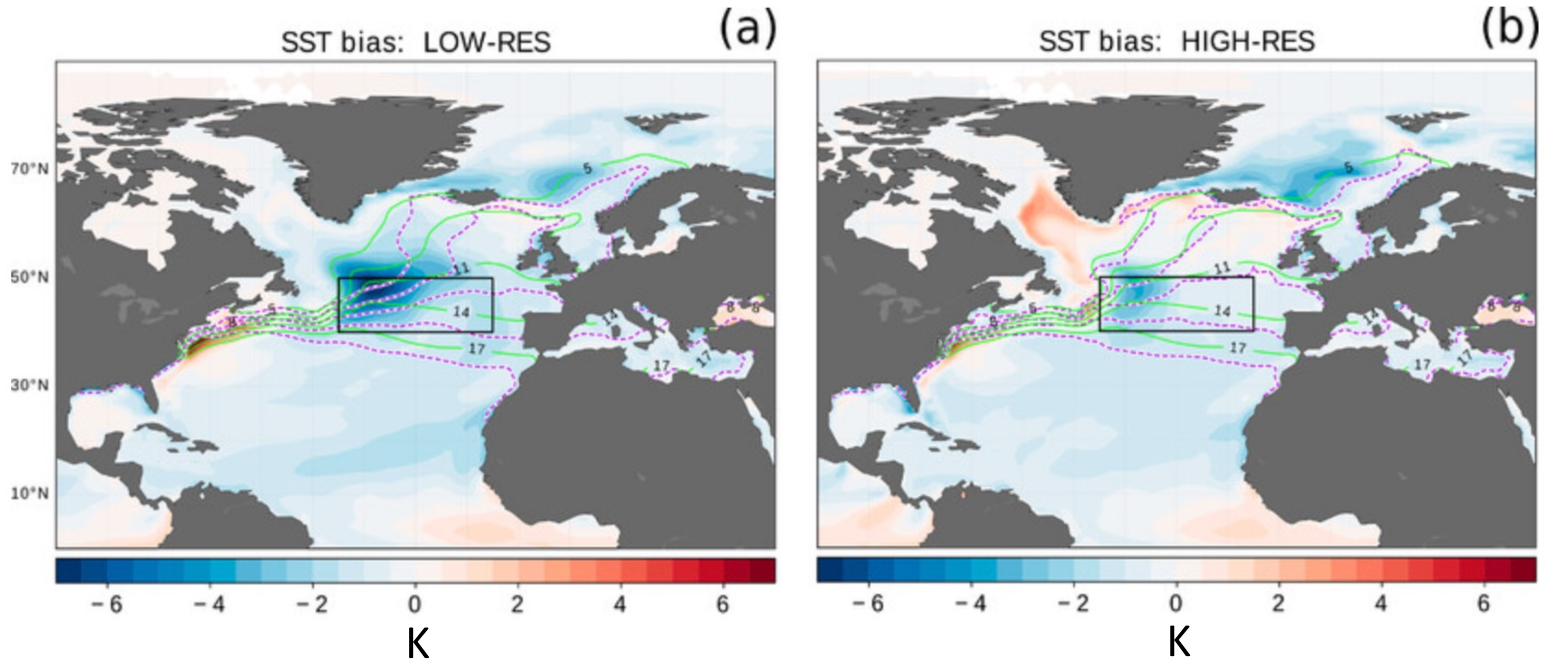
- Small ensemble sizes, limited spin-up, low signal to noise
- Assessment of impact resolution on climate simulations



HighResMIP & North Atlantic SST

- Winter sea-surface temperature (SST) bias
    - Related to separation & too zonal Gulf Stream
- Affects atmospheric circulation: cyclones, precipitation, jet stream
- Grey zone: resolution v.s. parameterizations

Ensemble means ->



How to obtain high-resolution information?

1. Use a high-resolution global model
   +Consistent high-resolution information everywhere
   -High computational demand, need to compromise other aspects, grey zone

2. Use a global model with a high resolution regionally

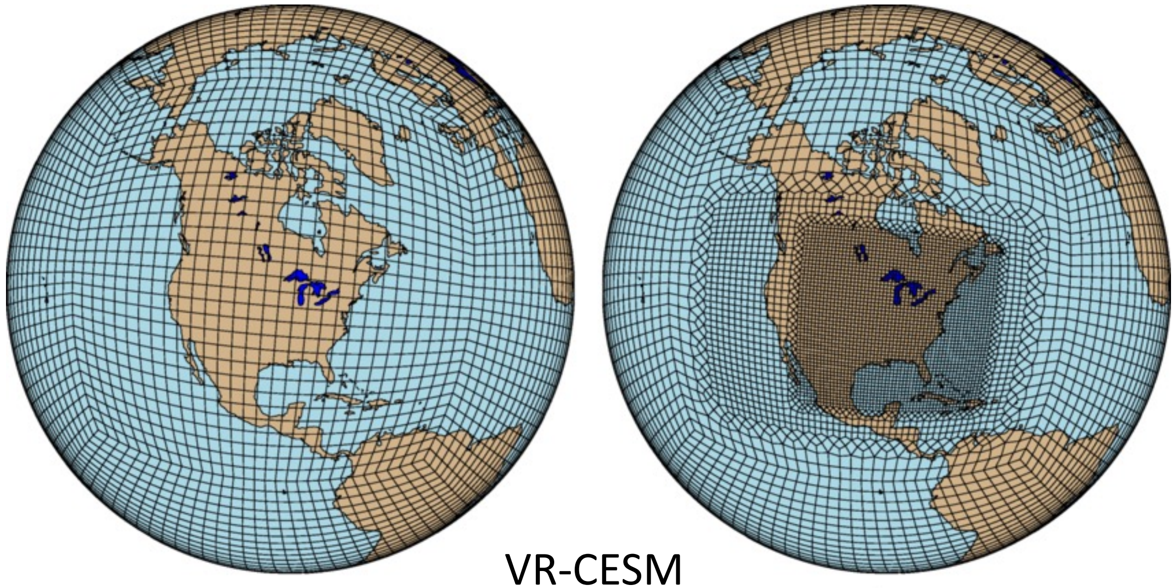
3. Use a high-resolution regional model (= dynamical downscaling)

4. Use observations and statistical relationships (=statistical downscaling)

Variable-resolution ESMs

- Enhance resolution in specific region by changing the grid
- For instance: VR-CESM, ICON (atmosphere)
- Computing fluxes across grid cells more difficult
- Parameterizations in the model need to be resolution-dependent

ICON



VR-CESM

a b

How to obtain high-resolution information?

1. Use a high-resolution global model
   +Consistent high-resolution information everywhere
   -High computational demand, need to compromise other aspects, can still not resolve everything

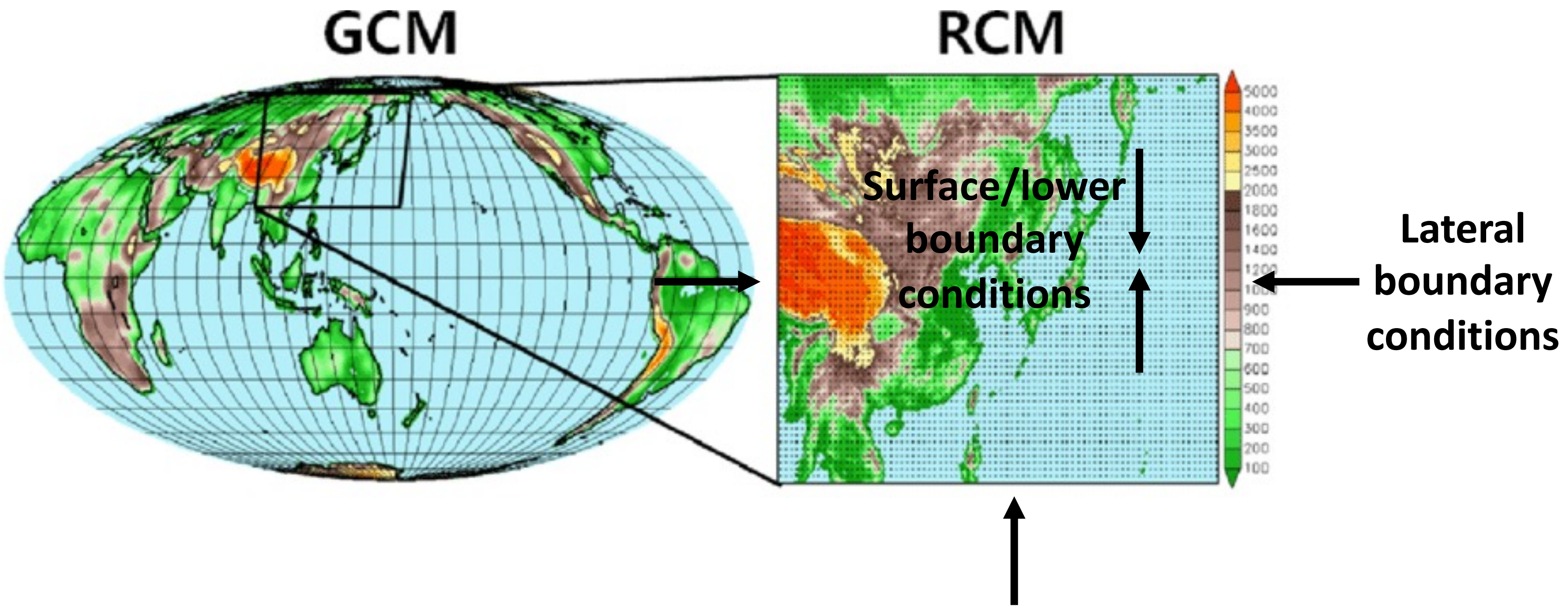
2. Use a global model with a high resolution regionally
   +Less high computational costs, high-resolution information in region of interest, consistent
   -More complicated grid & numerics, parameterizations are resolution-dependent

3. Use a high-resolution regional model (= dynamical downscaling)

4. Use observations and statistical relationships (=statistical downscaling)

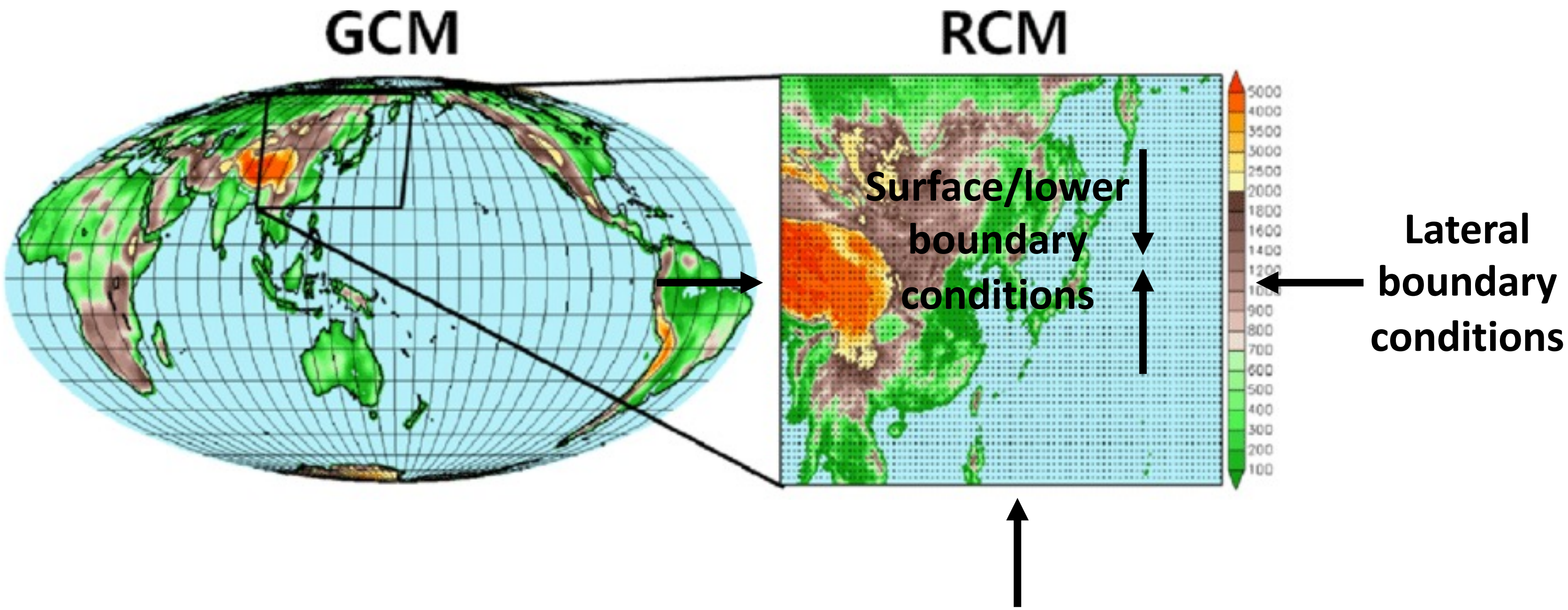
Dynamical downscaling

- Use a high-resolution regional model of the atmosphere or ocean
- Obtain *boundary conditions* from the GCM/ESM
- Run regional model to obtain a regionally high-resolution solution



Dynamical downscaling

- Computationally less expensive than ESM
- Often only one-way information, no atmosphere-ocean coupling
- Implementation boundaries is not straightforward



EURO-CORDEX

- Coordinated downscaling experiment for the atmosphere

Experiment

- evaluation (1171)
- historical (2218)
- rcp26 (290)
- rcp45 (1195)
- rcp85 (2402)

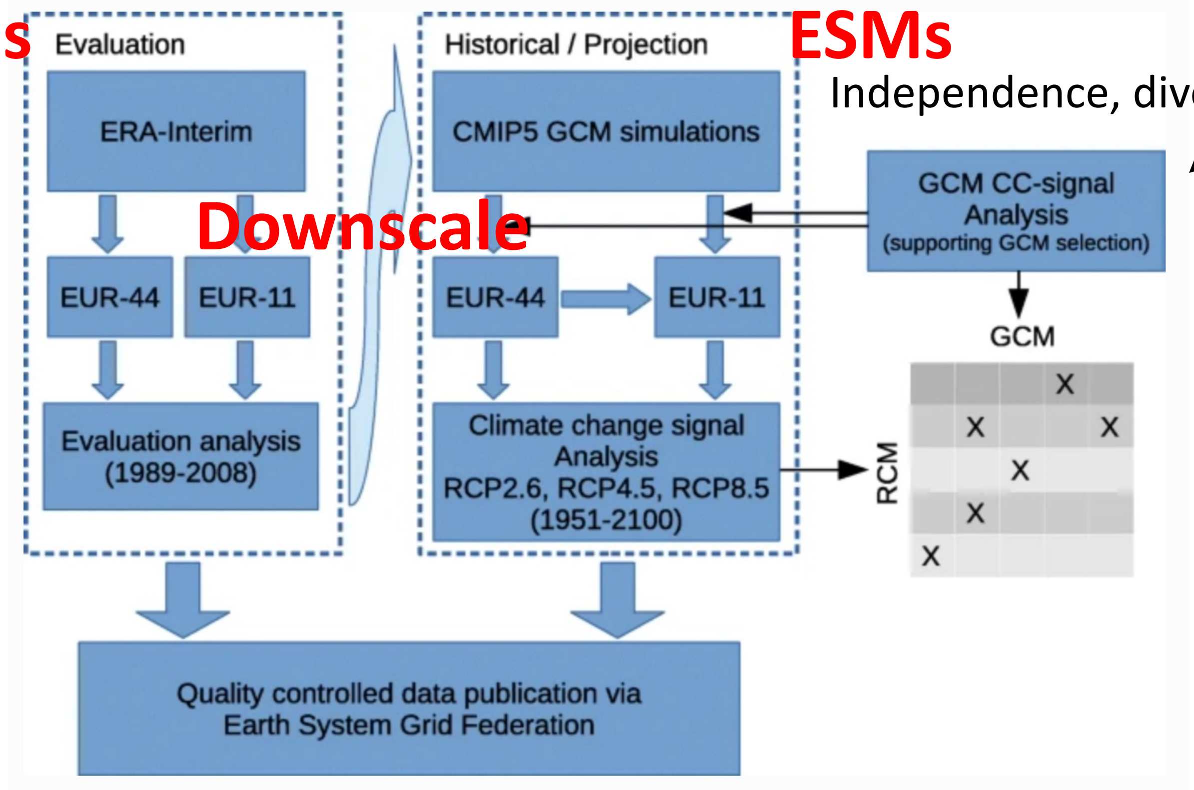
RCM Model

- ALADIN53 (422)
- ALADIN63 (2688)
- ALADIN64 (6)
- ARPEGE51 (24)
- CCAM-2008 (561)
- CCLM4-8-17 (69)
- CRCM5 (344)
- CanRCM4 (376)
- DeepESD-EE (32)
- Eta (2)
- HIRHAM5 (57)
- MAR311 (70)
- RACMO22E (81)
- RCA4 (206)
- REMO2009 (33)
- RegCM4 (199)
- RegCM4-6 (8)
- WRF (182)
- WRF331 (14)
- WRF331F (356)
- WRF331G (240)

Reanalysis

ESMs

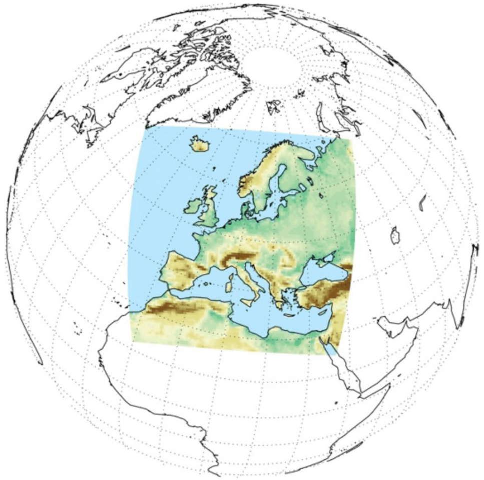
Independence, diversity, performance



Driving Model

- CCCma-CanESM2 (819)
- CNRM-CERFACS-CNRM-CM5 (1550)
- CSIRO-BOM-ACCESS1-0 (102)
- CSIRO-BOM-ACCESS1-3 (28)
- ECMWF-ERAINT (1205)
- ICHEC-EC-EARTH (269)
- IPSL-IPSL-CM5A-MR (446)
- MIROC-MIROC5 (102)
- MOHC-HadGEM2-ES (805)
- MPI-M-MPI-ESM-LR (844)
- MPI-M-MPI-ESM-MR (98)
- NCAR-CCSM4 (39)
- NCC-NorESM1-M (755)
- NOAA-GFDL-GFDL-ESM2M (214)

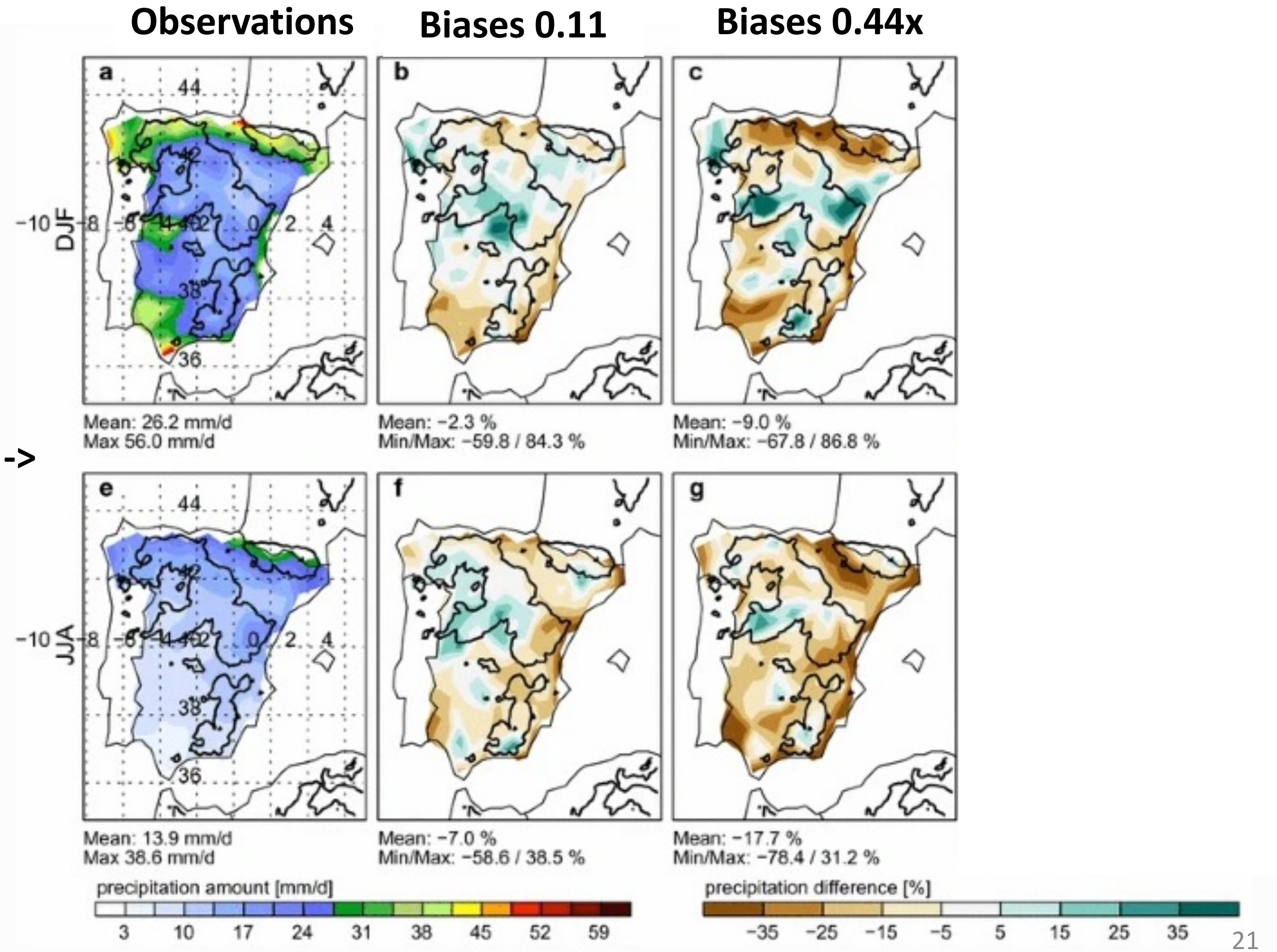
High-resolution
European domain



Extreme precipitation strength

- EURO-CORDEX
  0.44 v.s. 0.11 degree
- ERA-interim forced

Ensemble means ->



Prein et al. (2015)

How to obtain high-resolution information?

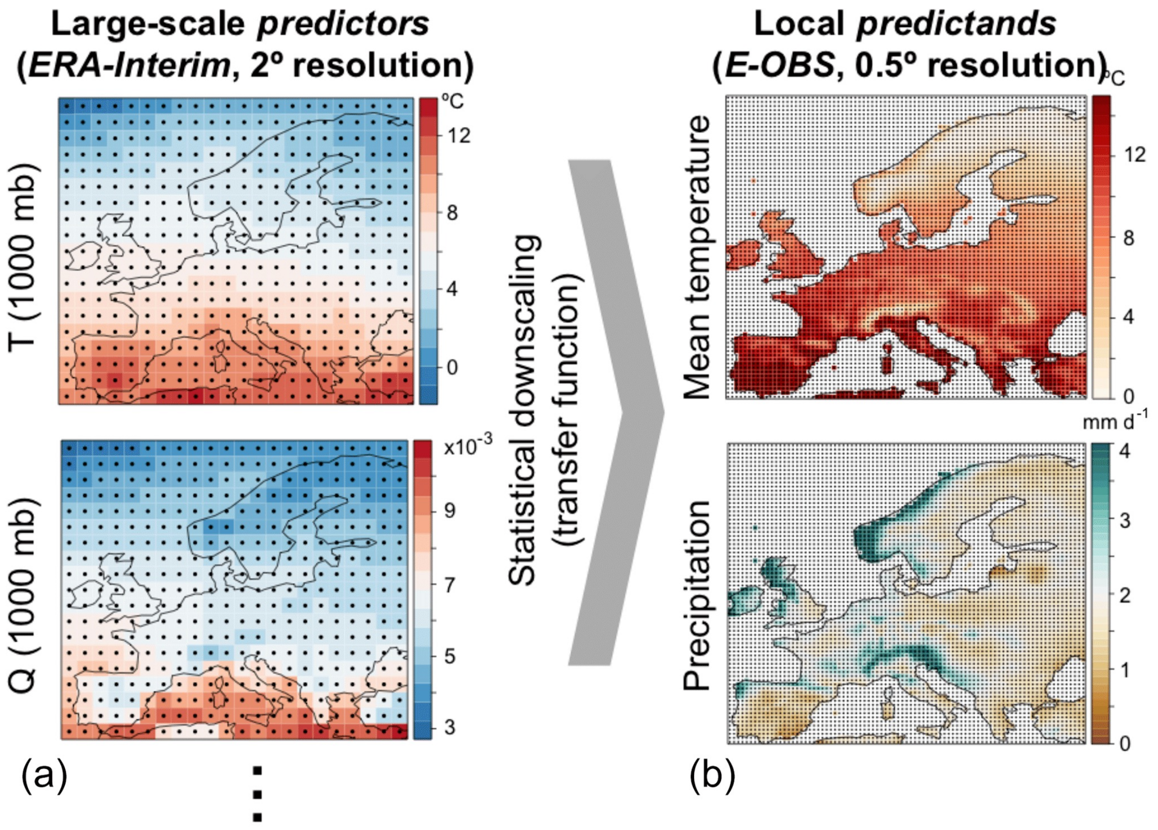
1. Use a high-resolution global model
   +Consistent high-resolution information everywhere
   -High computational demand, need to compromise other aspects, can still not resolve everything

2. Use a global model with a high resolution regionally
   +Less high computational costs, high-resolution information in region of interest, consistent
   -More complicated grid & numerics, parameterizations are resolution-dependent

3. Use a high-resolution regional model (= dynamical downscaling)
   +Lower computational costs, model can be adapted to region of interest
   -Often not coupled (‘offline’), implementation boundary conditions not straightforward

4. Use observations and statistical relationships (=statistical downscaling)

Statistical downscaling



Bano-Medina et al. (2020)

- Principle:
  - Derive relationship between small-scale variables (**predictands**) and large-scale variables (**predictors**)
    - For instance: linear regression/scaling techniques; weather classification; machine learning
  - Apply to large-scale variables in ESMs
- Cross-validation
- Not clear if observed relationships hold in the future

How to obtain high-resolution information?

1. Use a high-resolution global model
   +Consistent high-resolution information everywhere
   -High computational demand, need to compromise other aspects, can still not resolve everything

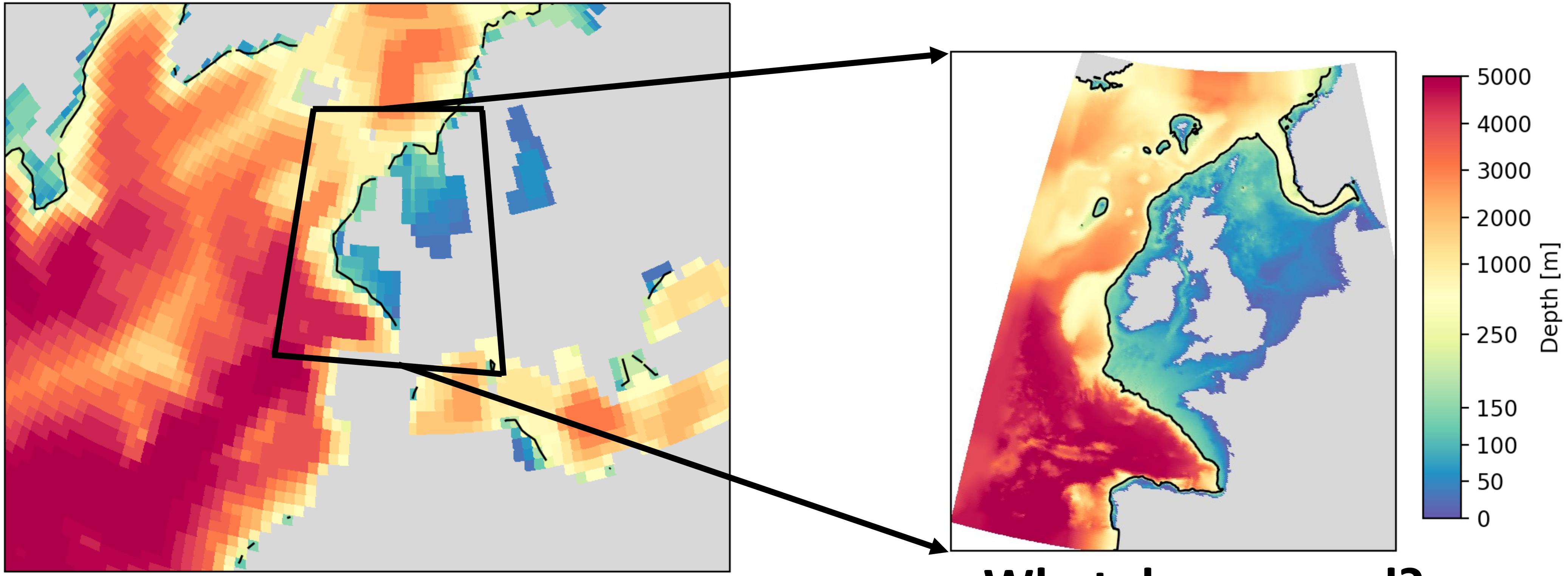
2. Use a global model with a high resolution regionally
   +Less high computational costs, high-resolution information in region of interest, consistent
   -More complicated grid & numerics, parameterizations are resolution-dependent

3. Use a high-resolution regional model (= dynamical downscaling)
   +Lower computational costs, model can be adapted to region of interest
   -Often not coupled (‘offline’), implementation boundary conditions not straightforward

4. Use observations and statistical relationships (=statistical downscaling)
   +Computationally cheap, can easily apply to different regions & compare
   -High-quality observations not available everywhere, assumes observed relationships remain the same in the future

Example of dynamical downscaling (ocean)

HadGEM2-ES (CMIP5 model)



What do we need?

Ocean modeling platform

- **ROMS** is a *free-surface*, *primitive equations, terrain-following* ocean model widely used by the scientific community for a diverse range of applications
  - Vertical motion at the surface
    - More accurate but requires smaller timestep
  - Simplified Navier-Stokes equations

https://www.myroms.org/

The primitive equations in Cartesian coordinates are shown here. The momentum balance in the x- and y-directions are:

$$\frac{\partial u}{\partial t} + \vec{v} \cdot \nabla u - fv = -\frac{\partial \phi}{\partial x} - \frac{\partial}{\partial z}\left(\overline{u'w'} - \nu \frac{\partial u}{\partial z}\right) + \mathcal{F}_u + \mathcal{D}_u \tag{1}$$

$$\frac{\partial v}{\partial t} + \vec{v} \cdot \nabla v + fu = -\frac{\partial \phi}{\partial y} - \frac{\partial}{\partial z}\left(\overline{v'w'} - \nu \frac{\partial v}{\partial z}\right) + \mathcal{F}_v + \mathcal{D}_v \tag{2}$$

The time evolution of a scalar concentration field, $C(x, y, z, t)$ (e.g. salinity, temperature, or nutrients), is governed by the advective-diffusive equation:

$$\frac{\partial C}{\partial t} + \vec{v} \cdot \nabla C = -\frac{\partial}{\partial z}\left(\overline{C'w'} - \nu_\theta \frac{\partial C}{\partial z}\right) + \mathcal{F}_C + \mathcal{D}_C \tag{3}$$

The equation of state is given by:

$$\rho = \rho(T, S, P) \tag{4}$$

In the Boussinesq approximation, density variations are neglected in the momentum equations except in their contribution to the buoyancy force in the vertical momentum equation. Under the hydrostatic approximation, it is further assumed that the vertical pressure gradient balances the buoyancy force:

$$\frac{\partial \phi}{\partial z} = -\frac{\rho g}{\rho_o} \tag{5}$$

The final equation expresses the continuity equation for an incompressible fluid:

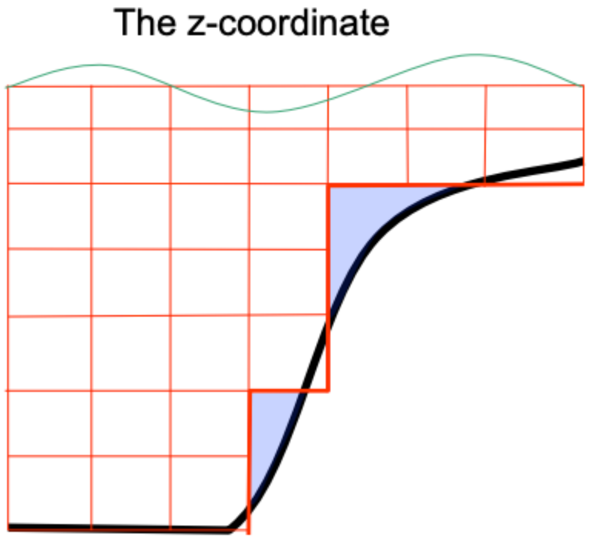
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{6}$$

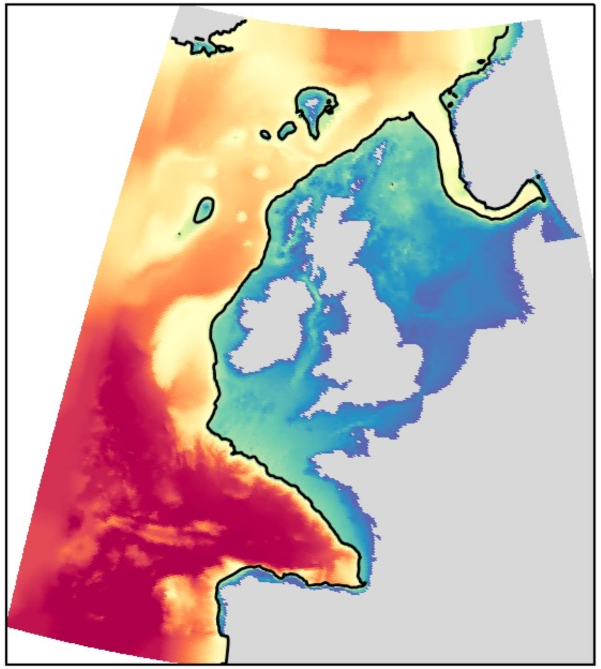
$\mathcal{D}_u, \mathcal{D}_v, \mathcal{D}_C$	horizontal diffusive terms
$\mathcal{F}_u, \mathcal{F}_v, \mathcal{F}_C$	forcing terms
$f(x, y)$	Coriolis parameter
g	acceleration of gravity
$h(x, y)$	bottom depth
ν, ν_θ	molecular viscosity and diffusivity
K_m, K_C	vertical eddy viscosity and diffusivity
P	total pressure $P \approx -\rho_o g z$
$\phi(x, y, z, t)$	dynamic pressure $\phi = (P/\rho_o)$
$\rho_o + \rho(x, y, z, t)$	total *in situ* density
$S(x, y, z, t)$	salinity
t	time
$T(x, y, z, t)$	potential temperature
u, v, w	the (x, y, z) components of vector velocity $\vec{v}$
x, y	horizontal coordinates
z	vertical coordinate
$\zeta(x, y, t)$	the surface elevation

- Turbulence expressed as function of large scale flow with some turbulunce coefficients
- **Boussinesq approximation:** Density variations small relative to density itself, ignore them for horizontal momentum
- **Hydrostatic approximation:** Vertical momentum equation = balance pressure gradient and buoyancy, no convection
- Incompressibility: continuity equation

Regional Ocean Modeling System (ROMS)

- **ROMS** is a *free-surface*, *terrain-following*, *primitive equations* ocean model widely used by the scientific community for a diverse range of applications
  - Vertical motion at the surface
    - Surface gravity waves v.s. baroclinic modes
  - Simplified equations of motion
  - Terrain-following



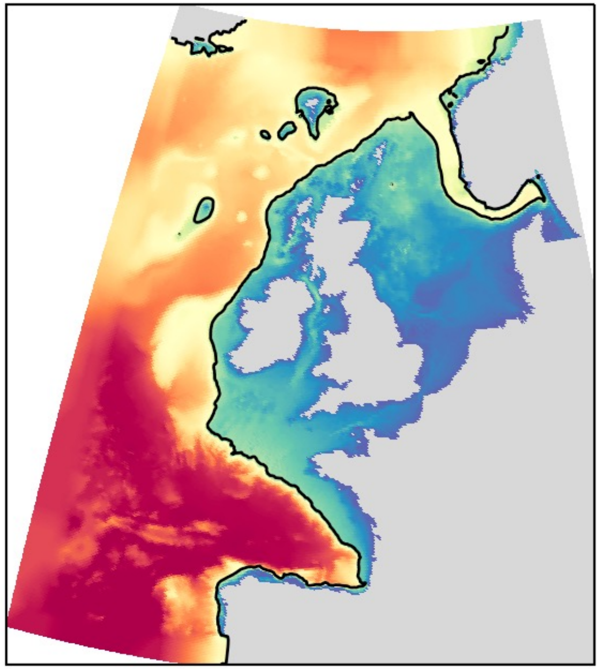


https://www.myroms.org/

Regional Ocean Modeling System (ROMS)

- **ROMS** is a *free-surface*, *terrain-following*, *primitive equations* ocean model widely used by the scientific community for a diverse range of applications
- Mostly Fortran-based
- Need a HPC

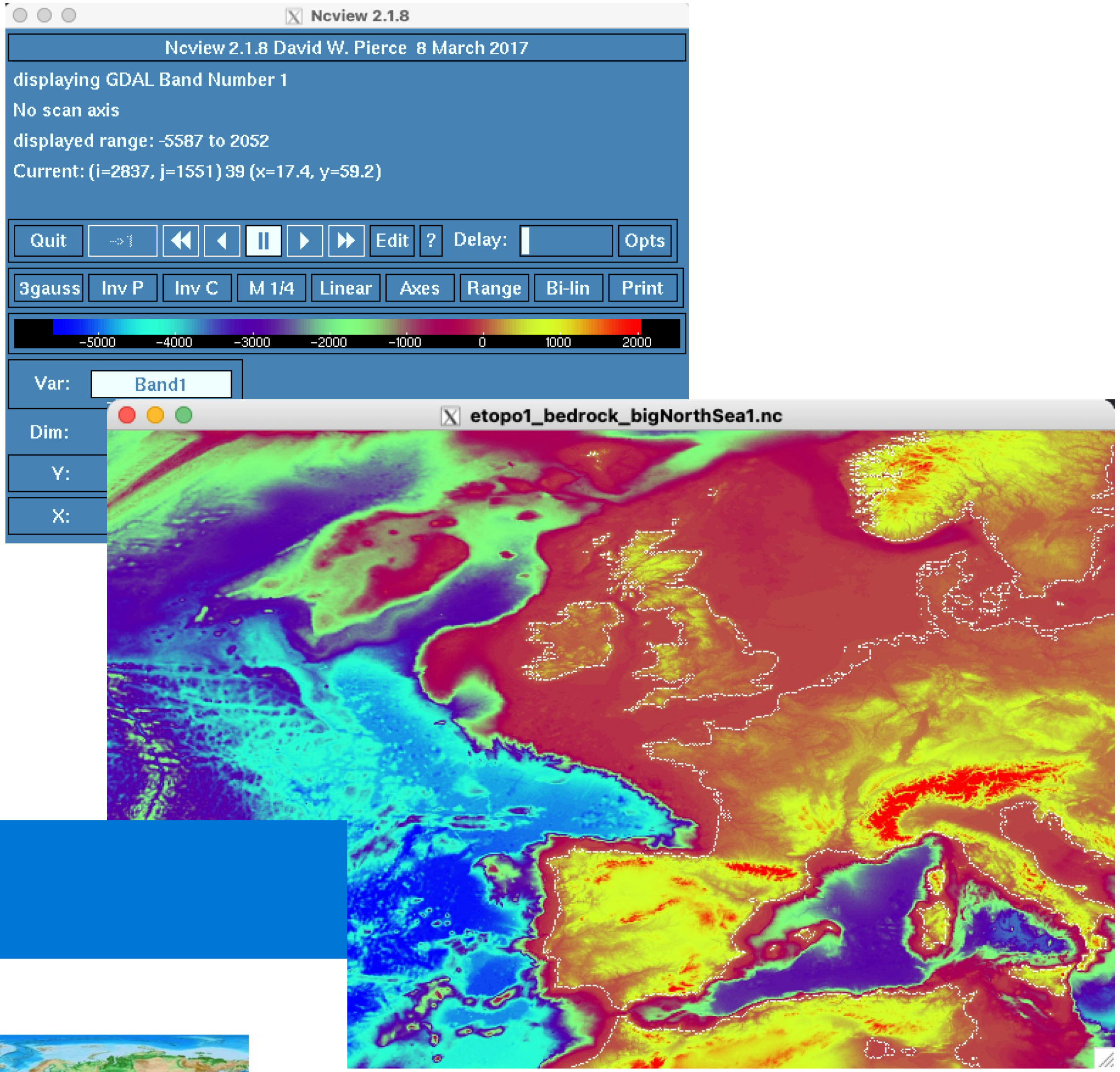
- Choose domain & resolution



https://www.myroms.org/

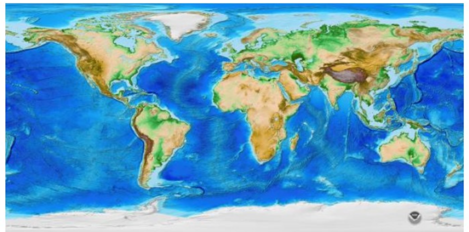
Bathymetry data

- (High-resolution) bathymetry
- Land-ocean mask

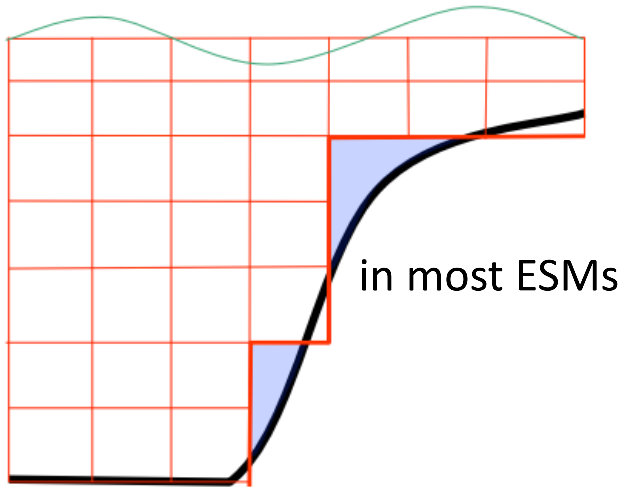


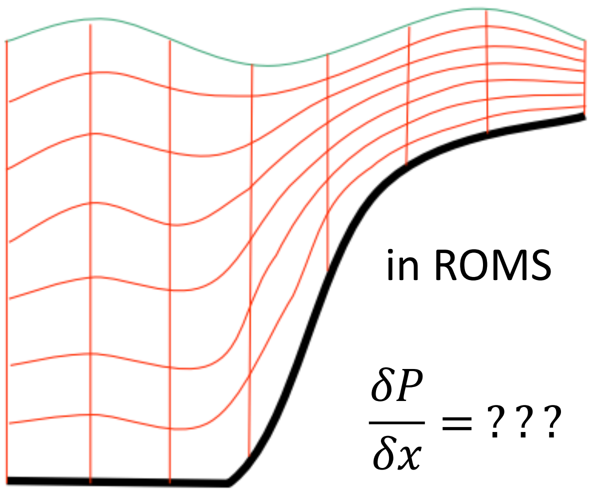
ETOPO Global Relief Model

The ETOPO Global Relief Model integrates topography, bathymetry, and shoreline data from regional and global datasets to enable comprehensive, high resolution renderings of geophysical characteristics of the earth's surface. The model is designed to support tsunami forecasting, modeling, and warning, as well as ocean circulation modeling and Earth visualization. The current version, ETOPO 2022, is available in Ice Surface and Bedrock versions that portray either the top layer of the ice sheets covering Greenland and Antarctica, or the bedrock below. For more information, email dem.info@noaa.gov .



Bathymetry smoothing

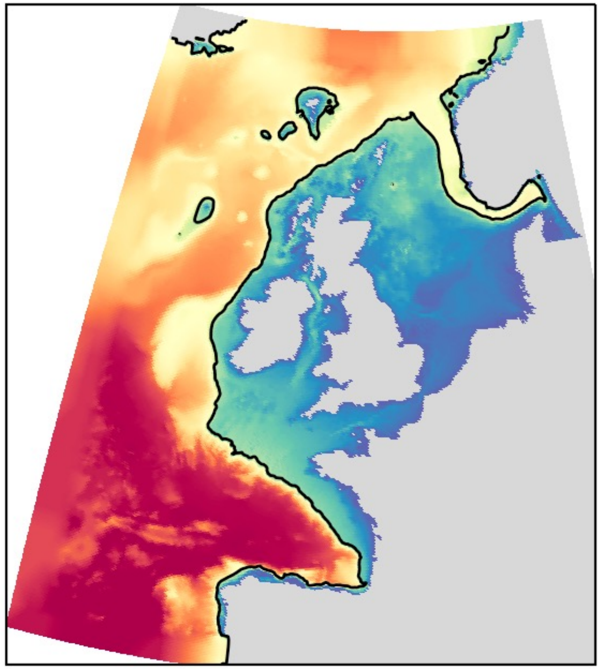




$$\frac{\delta P}{\delta x} = ???$$

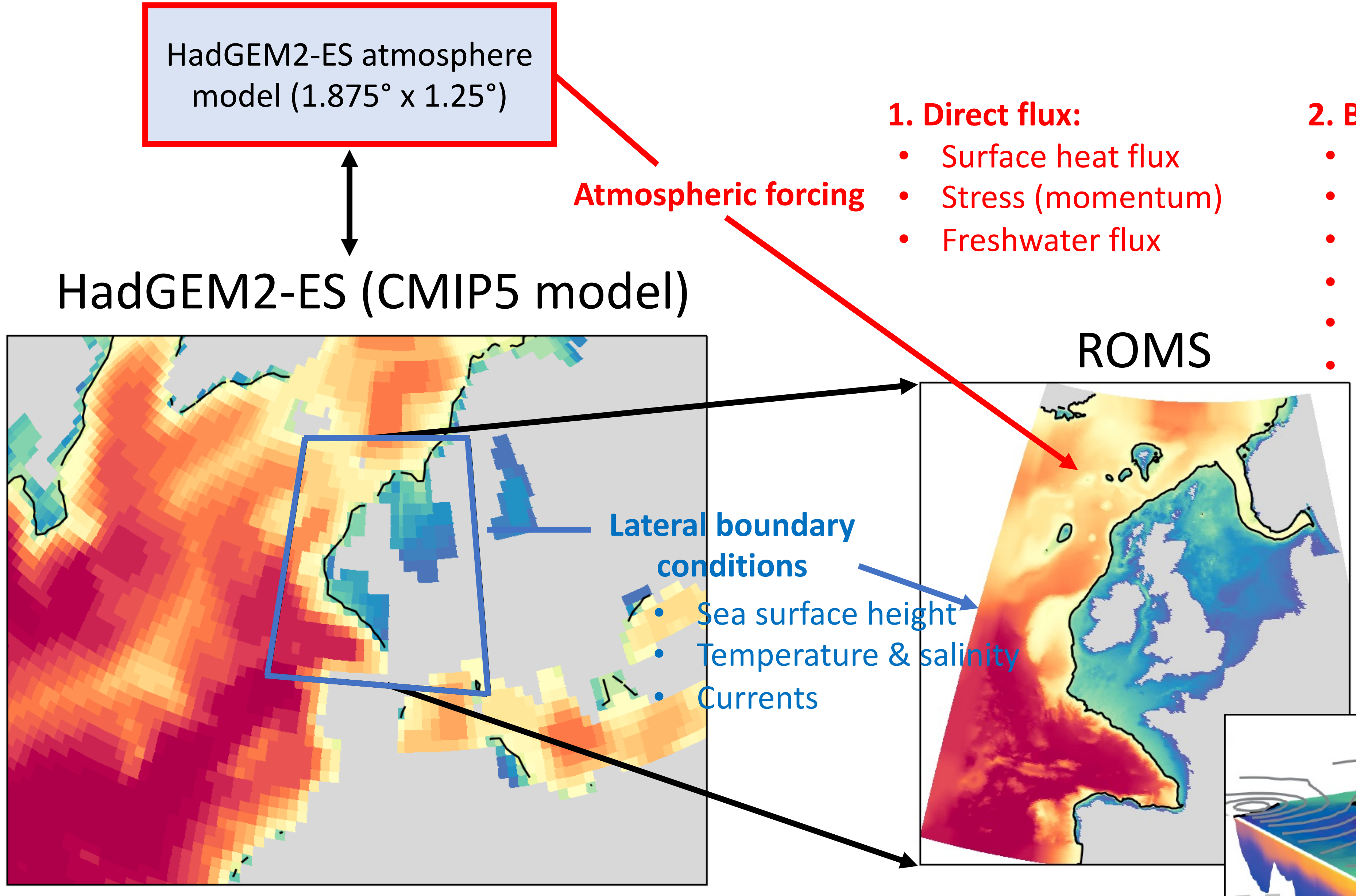
$$\sigma = \frac{z - \xi}{D}$$

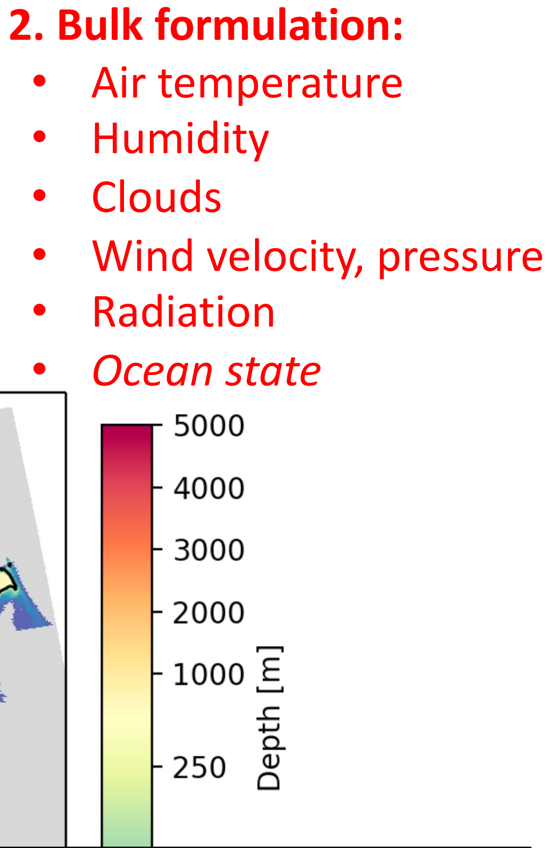
ROMS

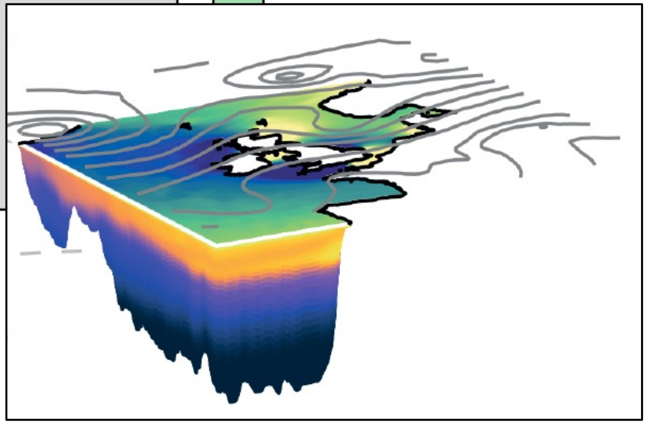


	z-coordinate	Terrain-following coordinate
Hydrostatic balance:	$\frac{\delta P}{\delta z} = -\rho g$	$\frac{\delta P}{\delta \sigma} = -\rho g D$
Pressure:	$P = \int_z^{\xi} \rho g \, dz + c$	$P = \int_\sigma^{0} \rho g D \, d\sigma + c$
Horizontal pressure gradient $\frac{\delta P}{\delta x}$:	$\frac{\delta P^*}{\delta x} = \left(\frac{\delta}{\delta x}\right) \int_z^{\xi} \rho g \delta z$	$\frac{\delta P^*}{\delta x} = \underline{\frac{\delta}{\delta x} \int_\sigma^{0} \rho g D \, d\sigma} + \underline{\frac{\delta}{\delta \sigma} \int_\sigma^{0} \rho g D \, d\sigma \left(\frac{\delta \sigma}{\delta x}\right)}$

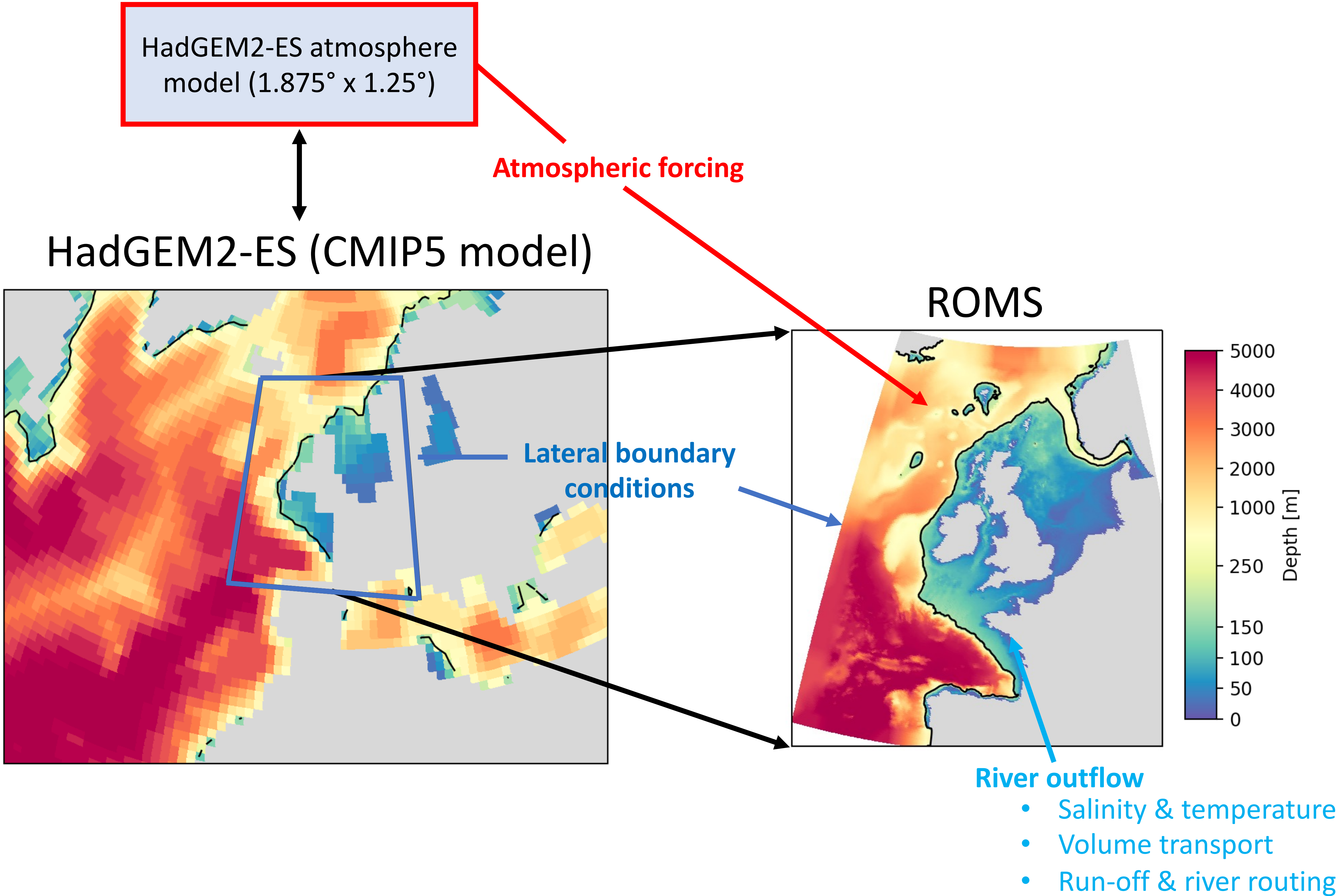
Both large & opposite signs







- To prepare the boundary conditions: 3D interpolation! (software packages available)
- Different types of lateral boundary conditions


HadGEM2-ES atmosphere model (1.875° x 1.25°)
Atmospheric forcing
HadGEM2-ES (CMIP5 model)
ROMS
Lateral boundary conditions
5000
4000
3000
2000
1000
250
150
100
50
0
Depth [m]
River outflow
• Salinity & temperature
• Volume transport
• Run-off & river routing

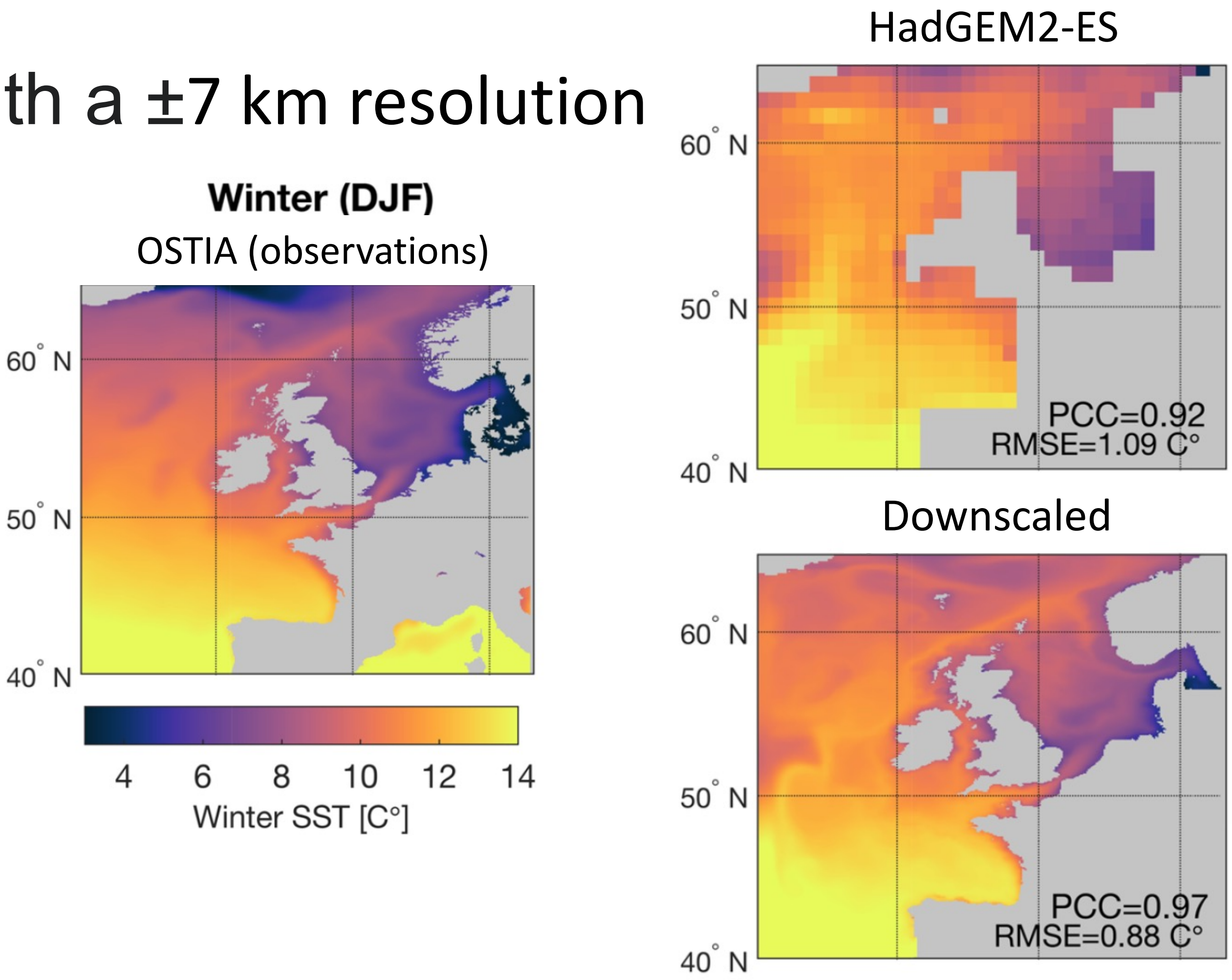
Lots of model settings

- Like:
  - Turbulance closure parameters
  - Diffusion & viscosity coefficients
  - Vertical mixing coefficients
  - Wind drag coefficient
  - Wetting/drying
  - Equation of state parameters
  - Tides on or off
  - Etc.
- Practical approach:
  - Think about what is needed for your experiment
  - Depends on resolution (e.g., eddies, mixing)
  - Follow guidance ROMS experts/forum
  - Test sensitivity & compare to observations

```
! Constants used in surface turbulent kinetic energy flux computation.

  CHARNOK_ALPHA == 1400.0d0          ! Charnok surface roughness
 ZOS_HSIG_ALPHA == 0.5d0             ! roughness from wave amplitude
       SZ_ALPHA == 0.25d0            ! roughness from wave dissipation
      CRGBAN_CW == 100.0d0           ! Craig and Banner wave breaking

! Constants used in momentum stress computation.

        RDRG == 3.0d-04                     ! m/s
       RDRG2 == 3.0d-03                     ! nondimensional
         Zob == 0.02d0                      ! m
         Zos == 0.02d0                      ! m

! Height (m) of atmospheric measurements for Bulk fluxes parameterization.

      BLK_ZQ == 2.0d0                       ! air humidity
      BLK_ZT == 2.0d0                       ! air temperature
      BLK_ZW == 10.0d0                      ! winds

! Minimum depth for wetting and drying.

       DCRIT == 0.10d0                      ! m

! Various parameters.

       WTYPE == 3
     LEVSFRC == 15
     LEVBFRC == 1
```

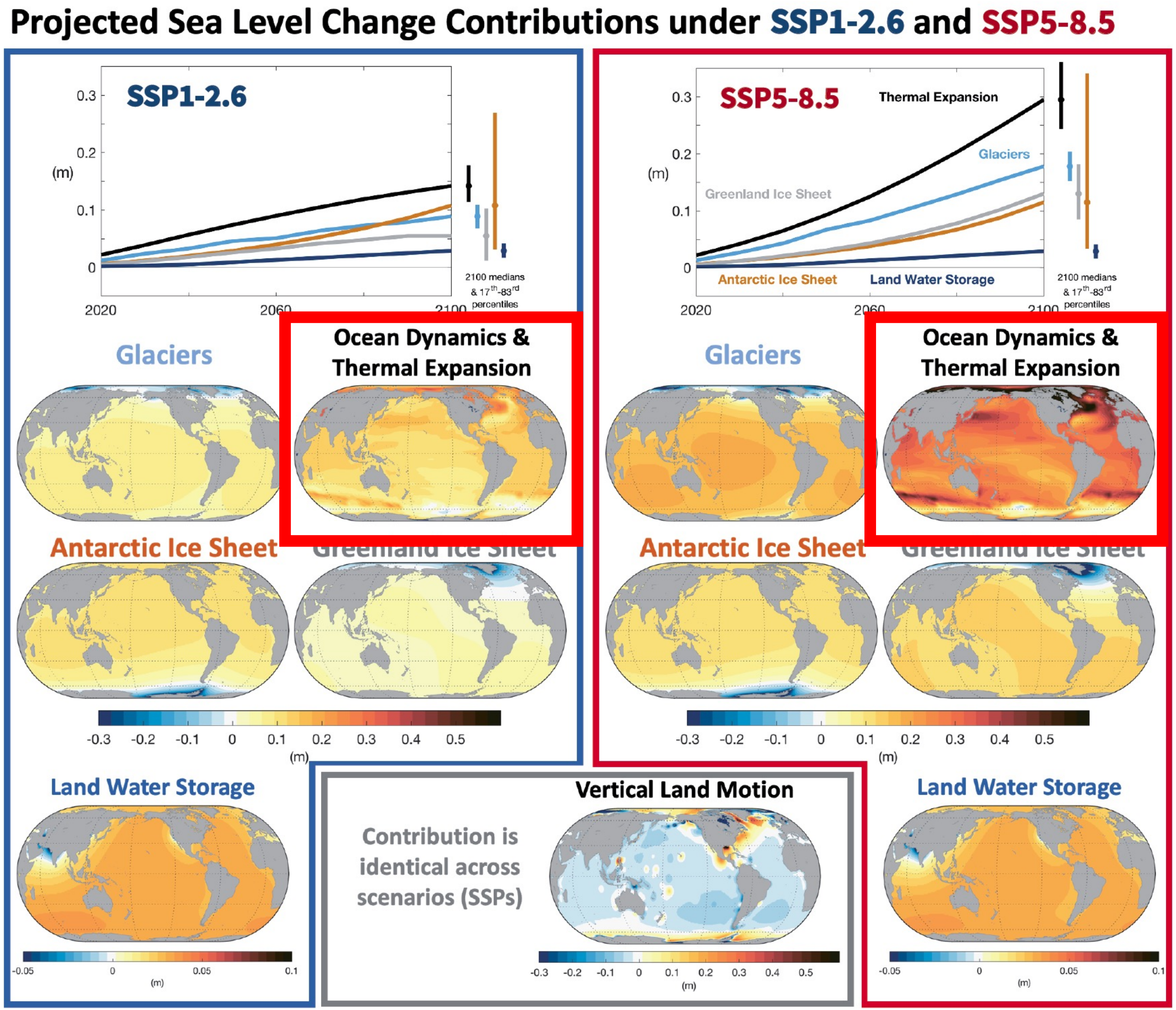
Comparison to observations & added value

- ROMS with a ±7 km resolution



Application 1

- Sea-level change in low-resolution ESMs?

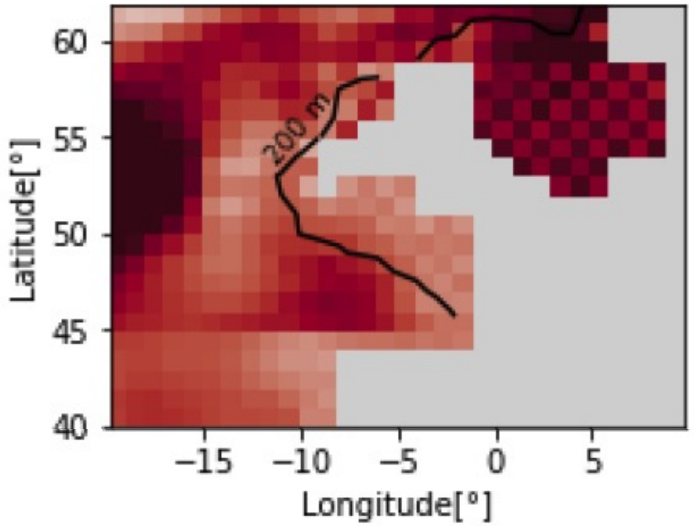


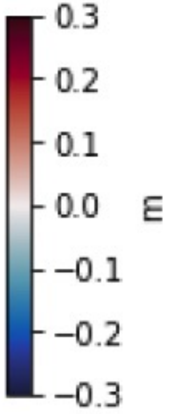
IPCC AR6 (2021)

Ocean dynamic sea-level change in 2100?

- Nearly 130 years of simulation (1972-2100) -> 1/4th degree resolution
- High emissions scenario (RCP8.5)
- Resolution can be important for sea-level projections

HadGEM2-ES

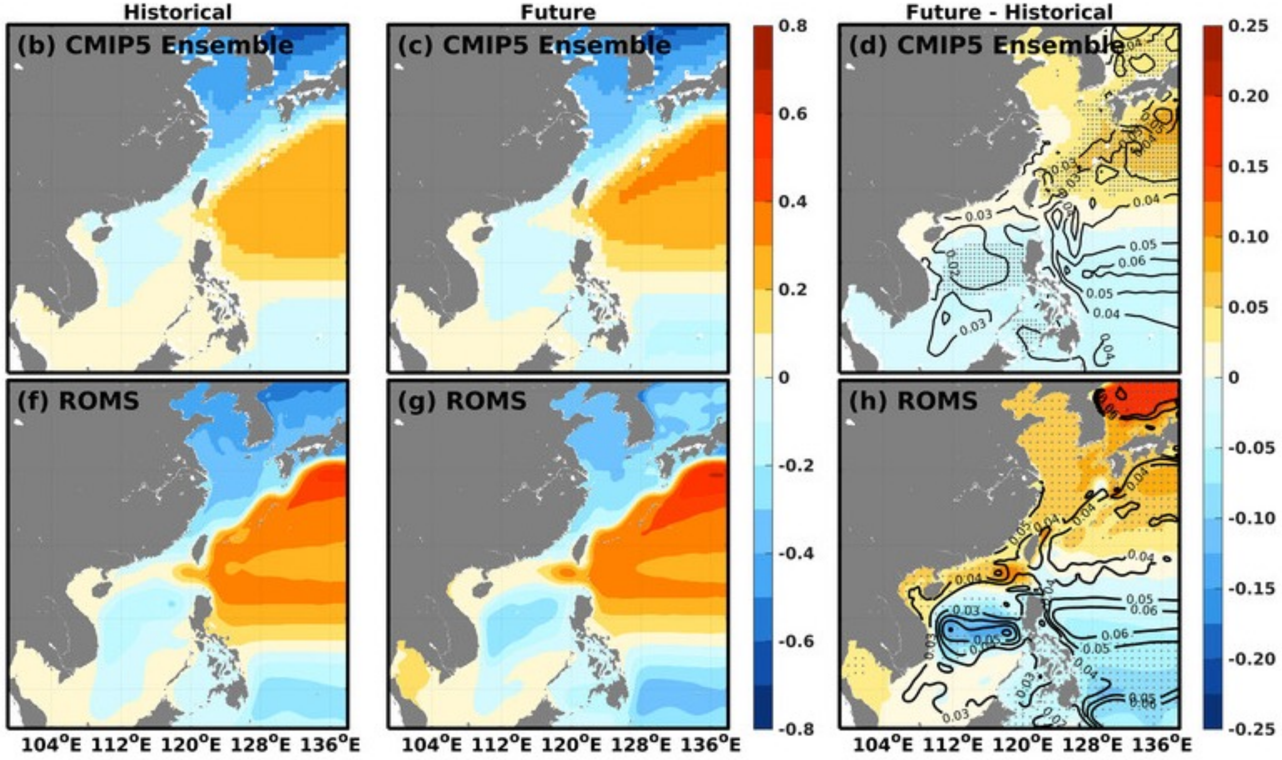


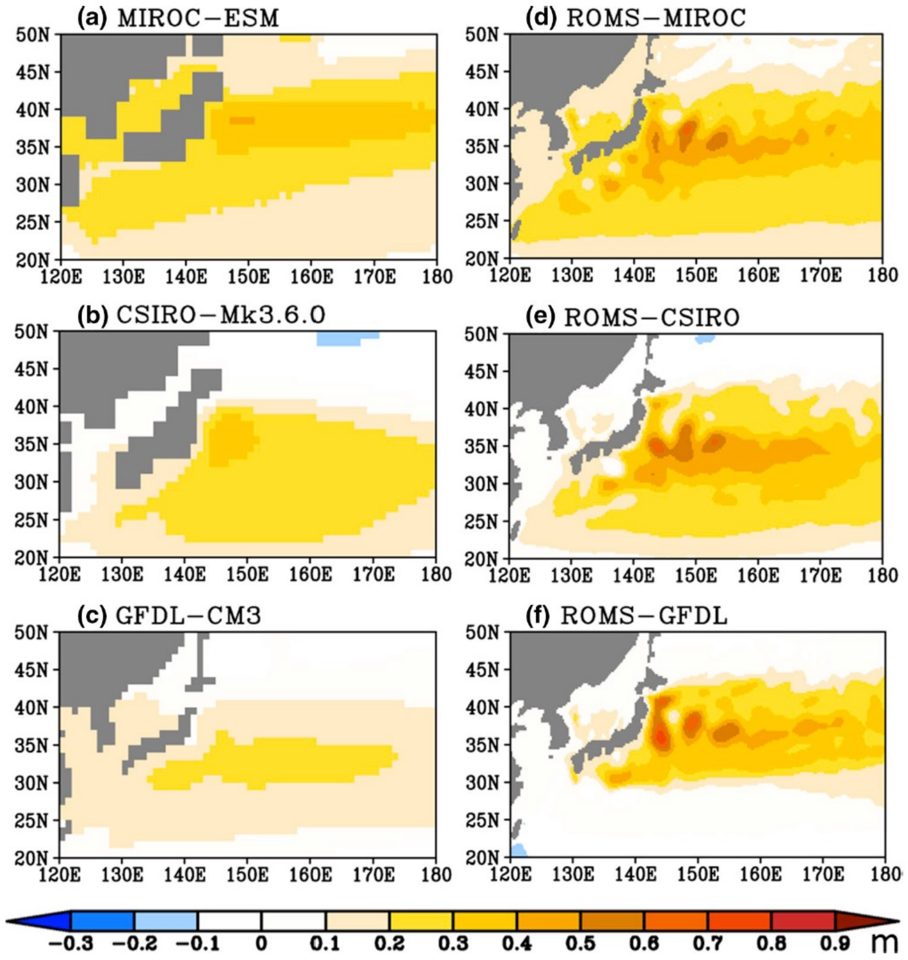


from MSc thesis Annete v/d Engel

Also in othe regions

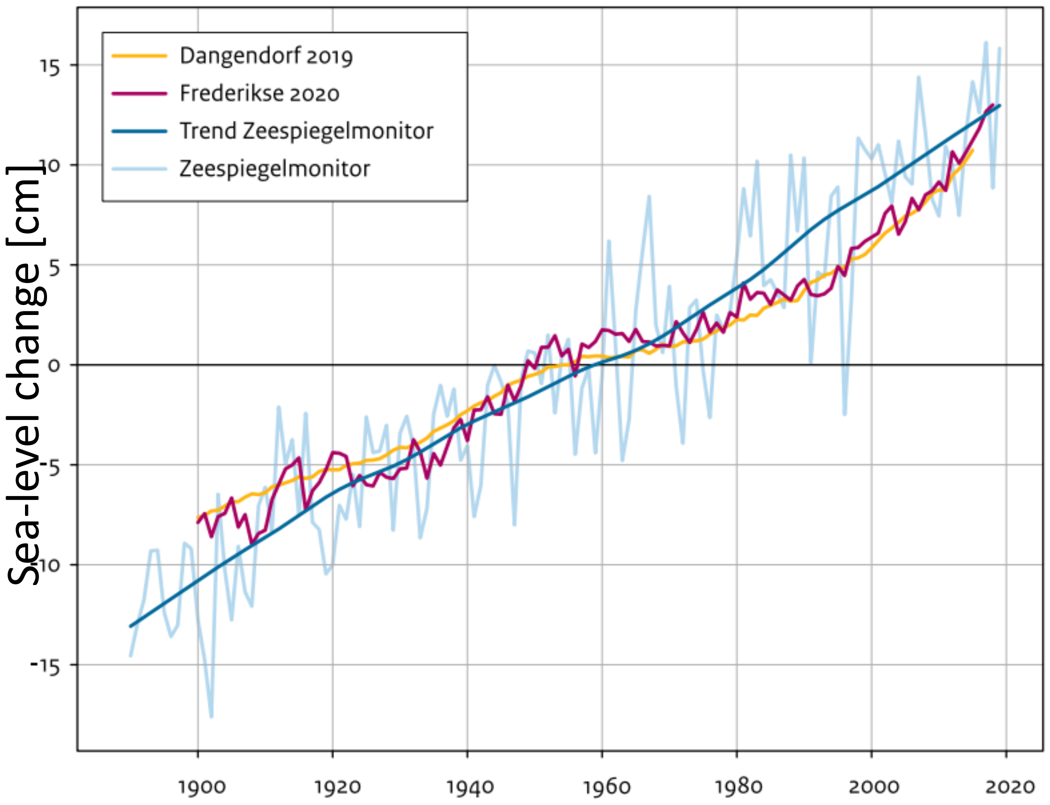
- Western North Pacific: Liu et al. (2016)
- Chinese marginal seas: Jin et al. (2021)





Application 2: Interannual sea-level variability

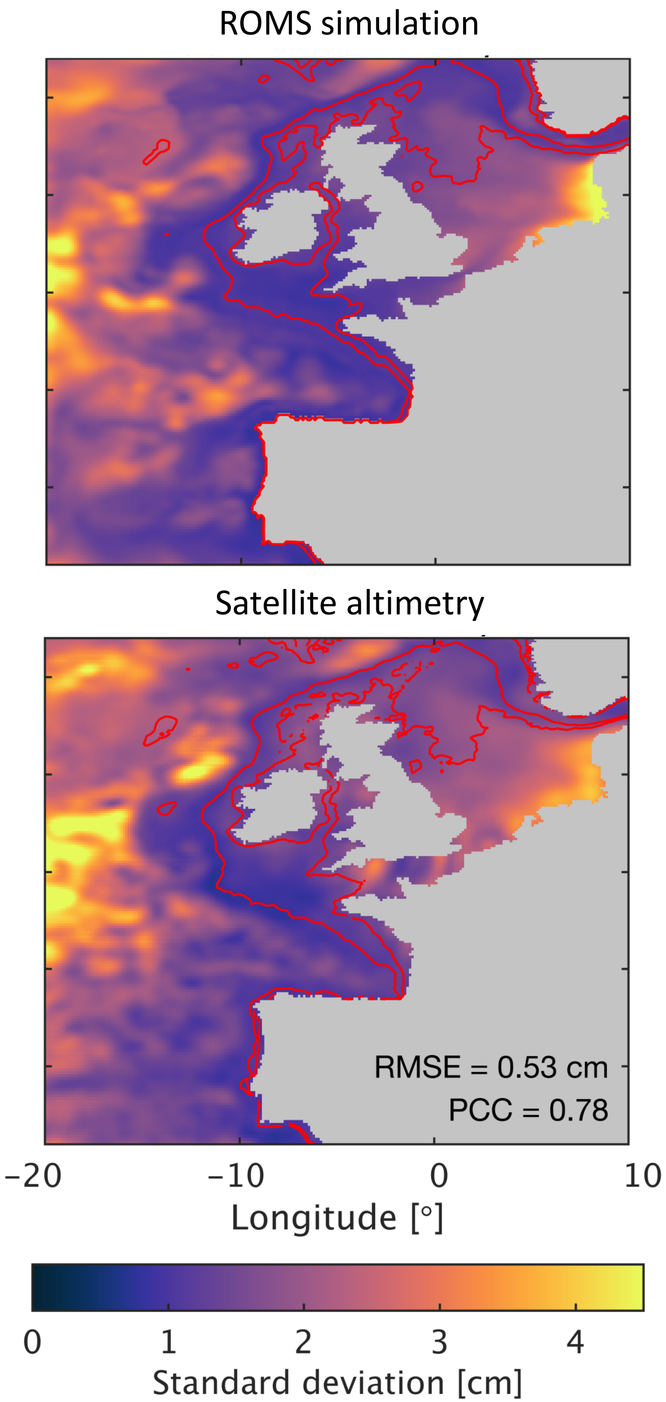
- Dutch sea-level acceleration masked by variability
- Understanding & correction?
  - Until recently only based on observations & correlations

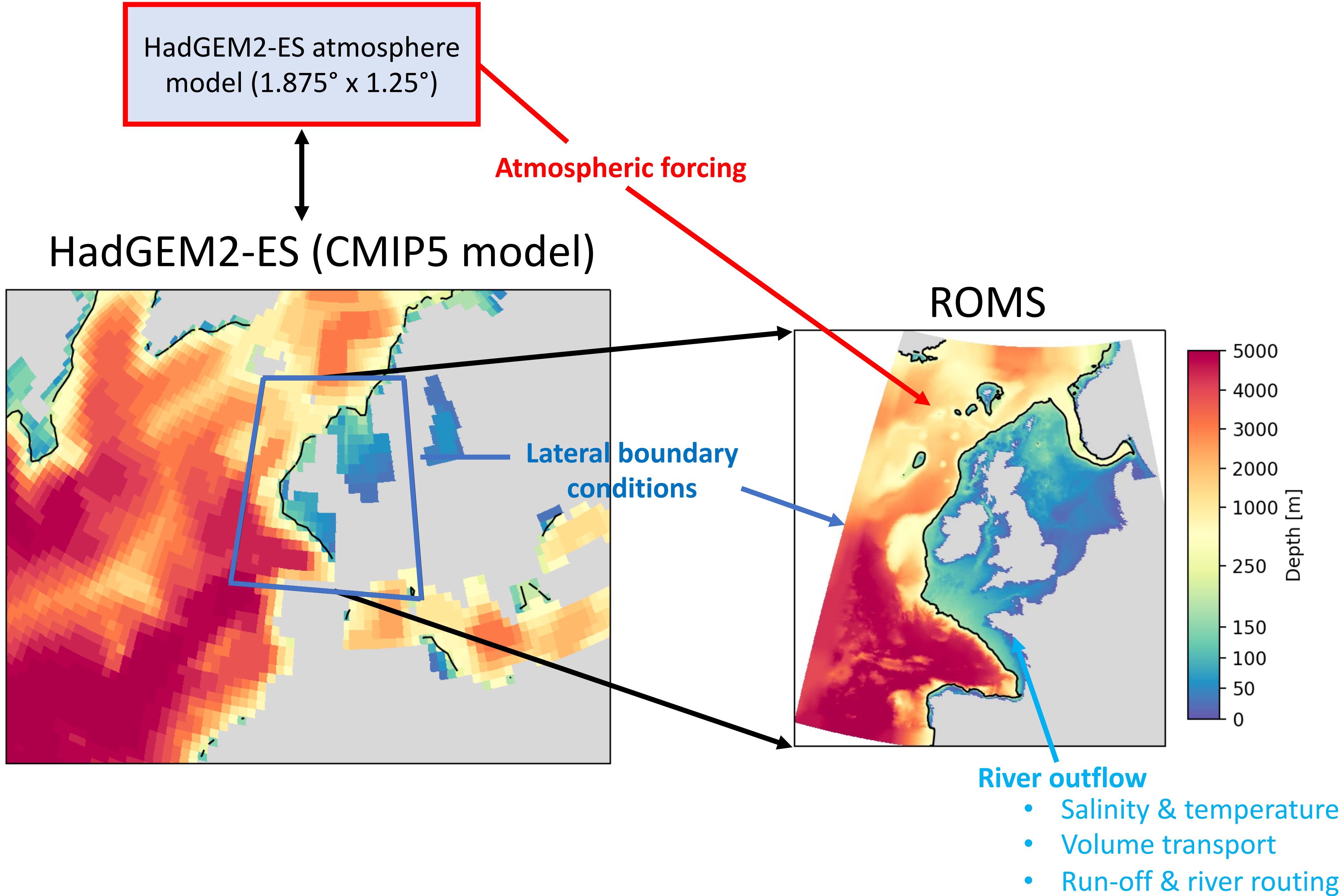


Keizer et al. (2023)

Causes of sea-level variability?

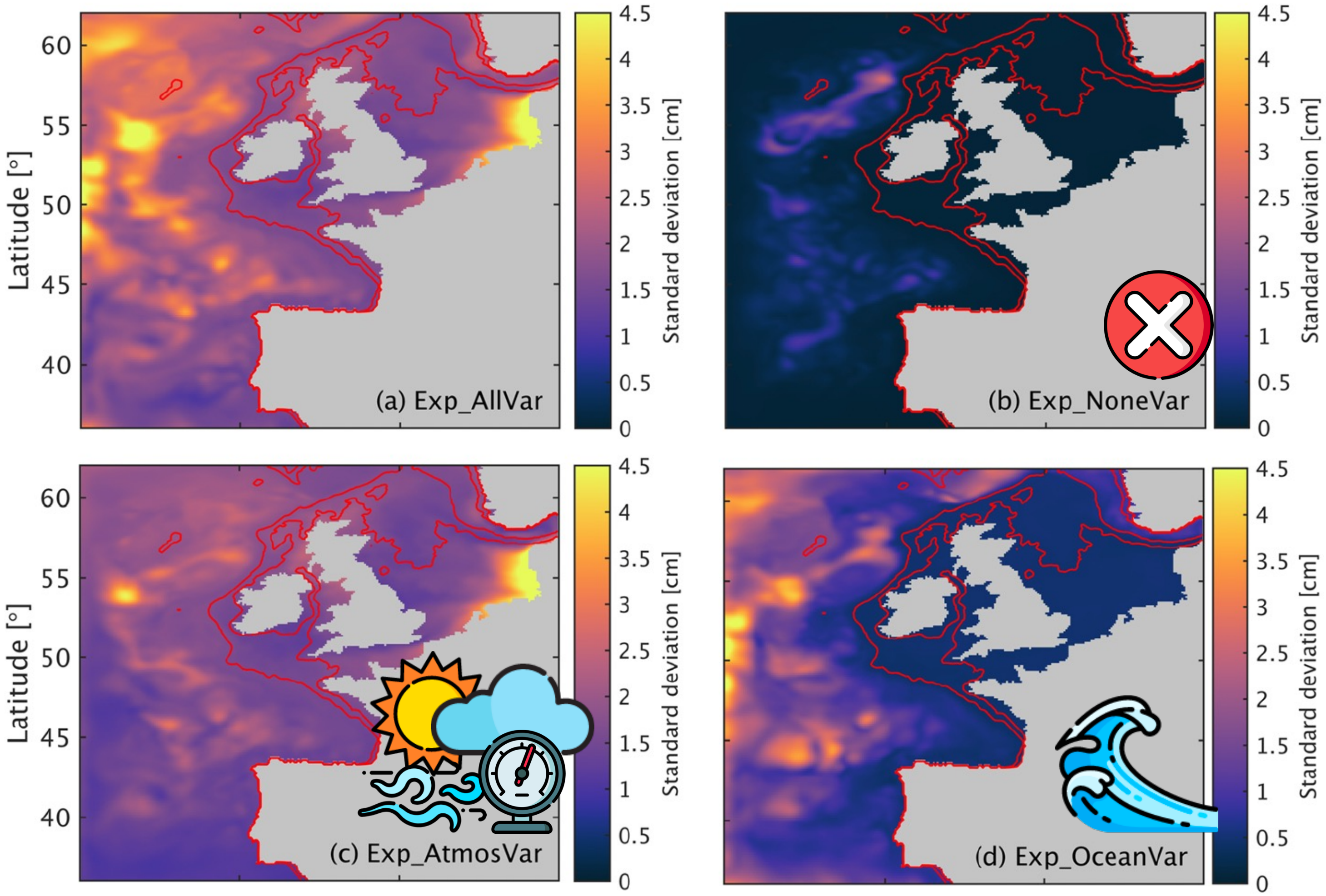
- 1/8th degree resolution, 1993-2018
- Boundary conditions from reanalysis data
  - ERA5 (atmosphere)
  - GLORYS12v1 (ocean)




HadGEM2-ES atmosphere model (1.875° x 1.25°)
Atmospheric forcing
HadGEM2-ES (CMIP5 model)
ROMS
Lateral boundary conditions
5000
4000
3000
2000
1000
250
150
100
50
0
Depth [m]
River outflow
• Salinity & temperature
• Volume transport
• Run-off & river routing

Sensitivity to boundary conditions

Varying from year to year:
- -Atmosheric forcing
- -Lateral boundary conditions



Varying from year to year:
- -nothing

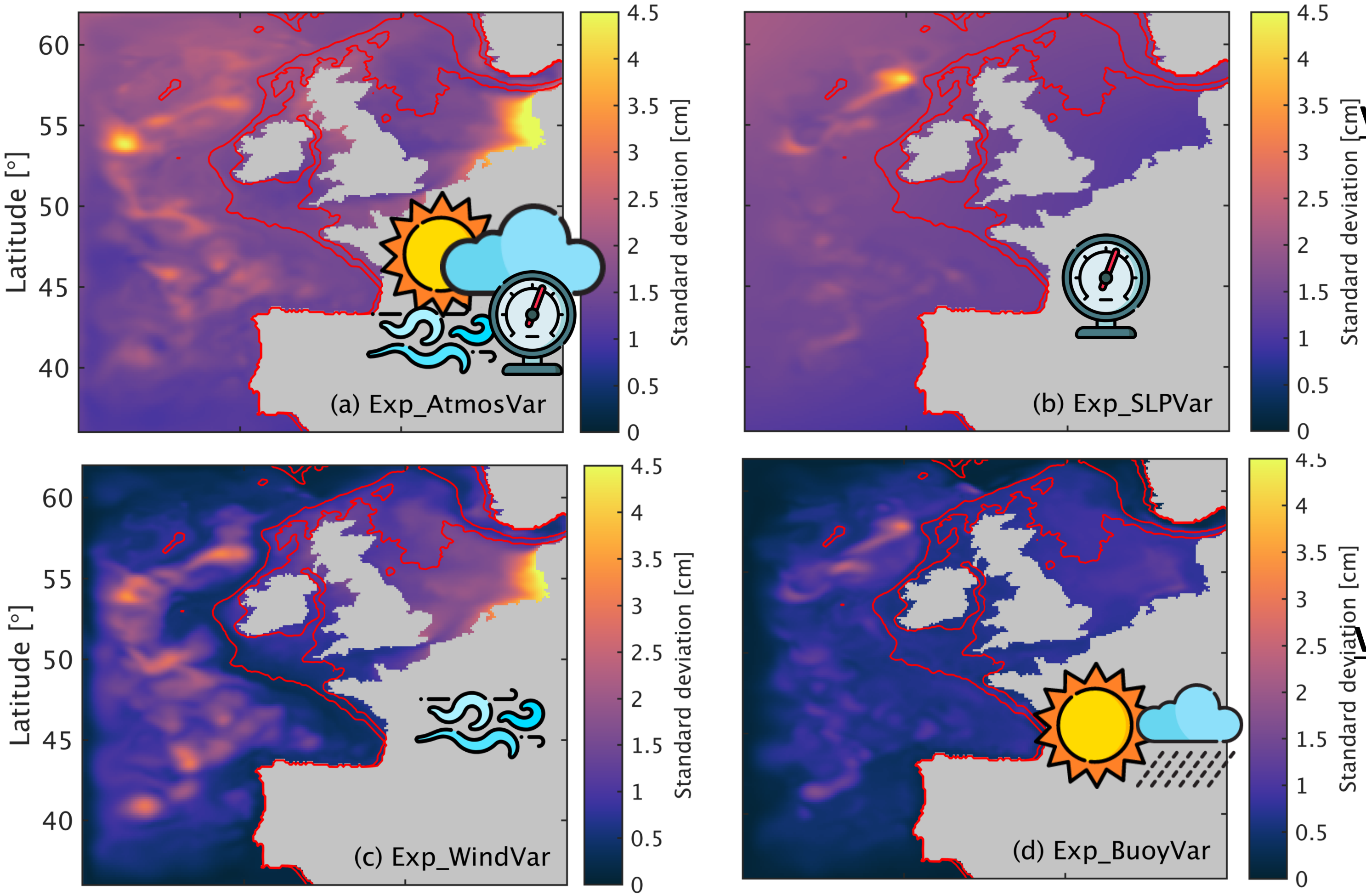
Varying from year to year:
- -Atmosheric forcing

Varying from year to year:
- -Lateral boundary conditions

Sensitivity to boundary conditions

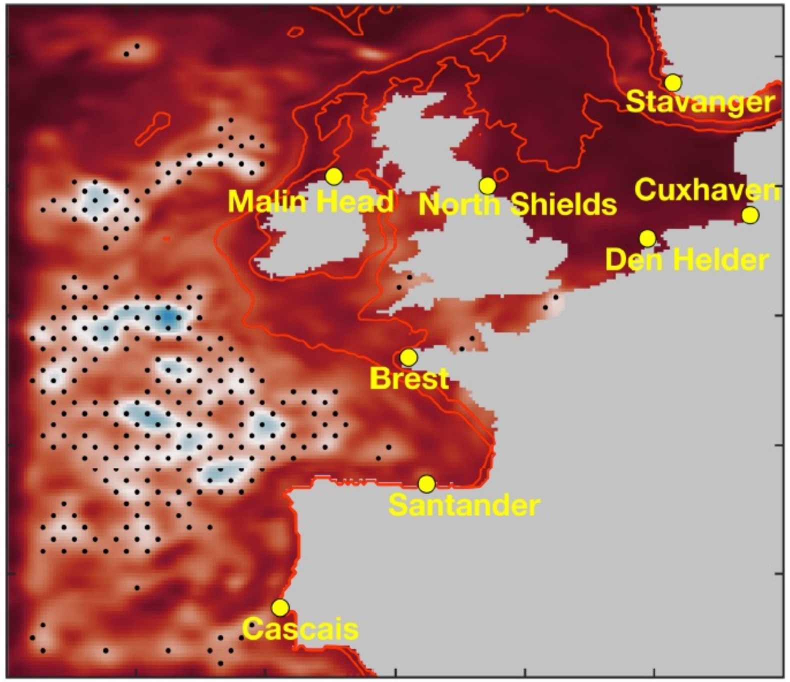
Varying from year to year:
-Atmosheric forcing

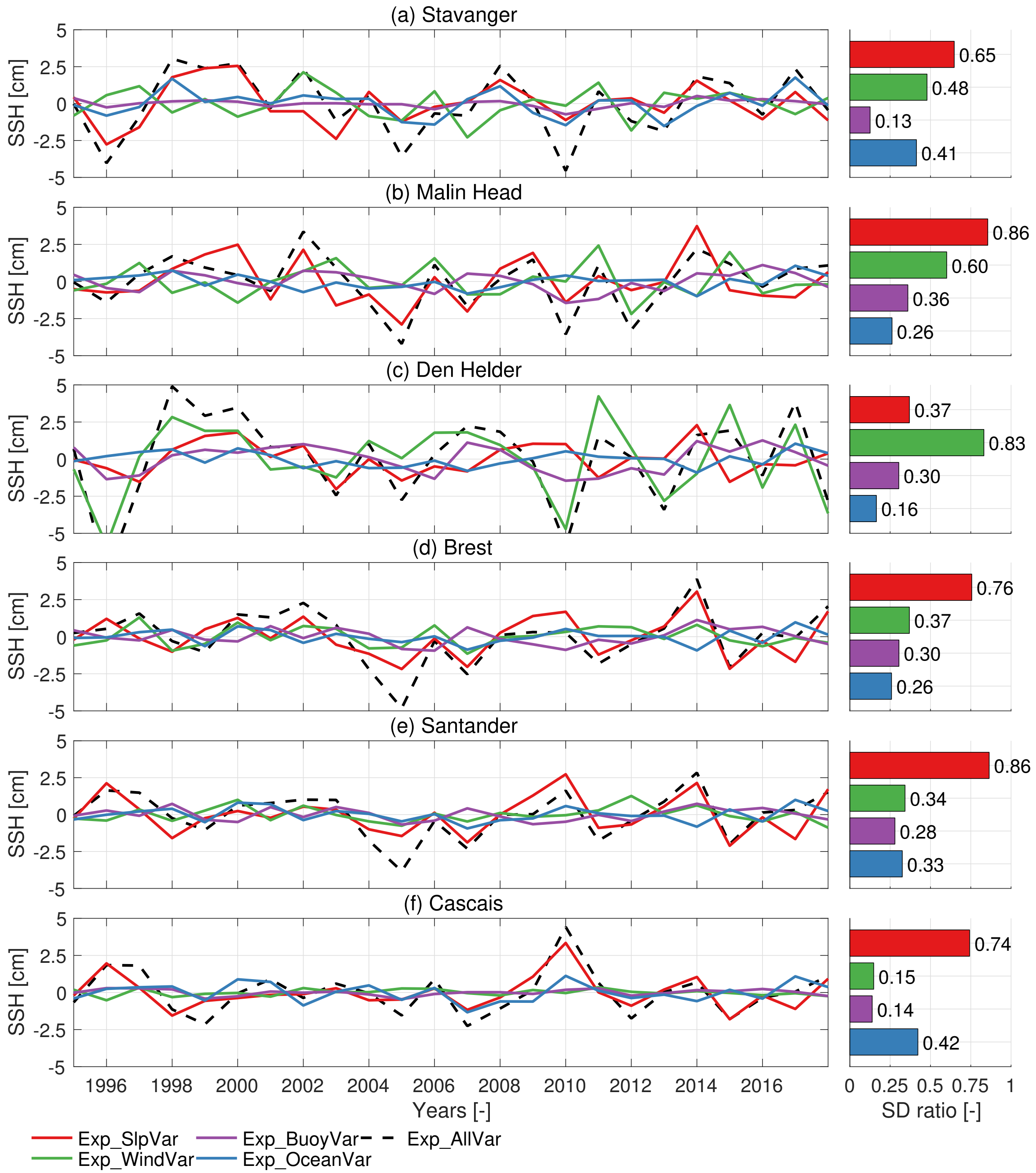
Varying from year to year:
-Sea-level pressure



Varying from year to year:
-Wind speed

Varying from year to year:
-Buoyancy fluxes





Wind

Sea-level pressure

Buoyancy fluxes

Lateral boundaries (ocean)

All

Summary

- Resolution of ESMs limited, trade-offs to be made
  - Consequences for both small-scale features and large-scale circulation/effects

- Different methods to obtain high-resolution information
  - High-resolution ESMs, variable-resolution ESMs, regional models, statistical
  - All have advantages and drawbacks

- Dynamical downscaling can be used as a tool to better understand processes