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Earth Sciences Department

Barcelona Supercomputing Center

Centro Nacional de Supercomputación

Climate Prediction and Earth System Services

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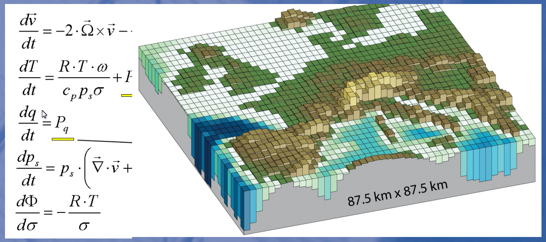
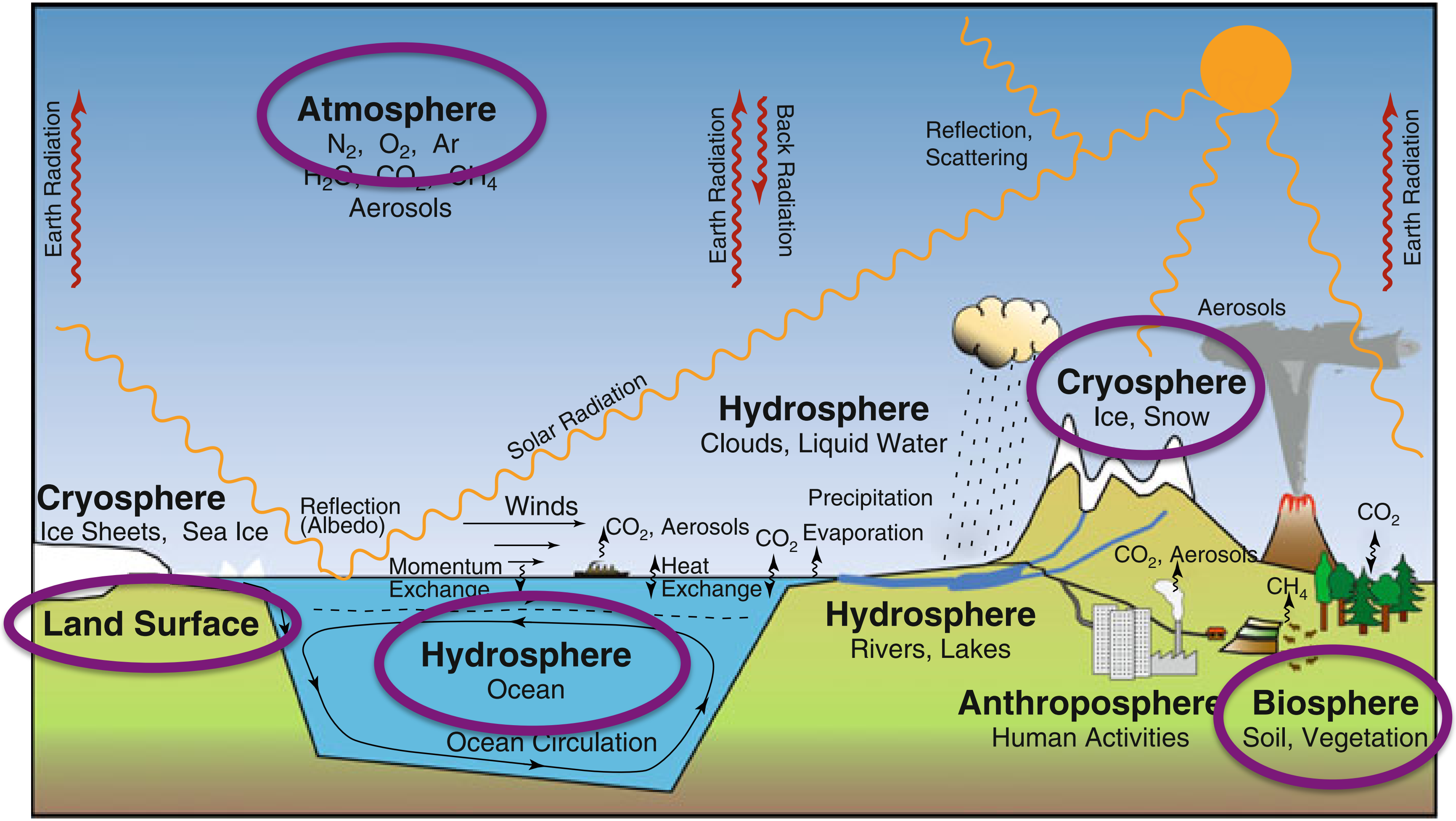
Climate Prediction Group and
Earth System Services Group



Barcelona, 4 February, 2016

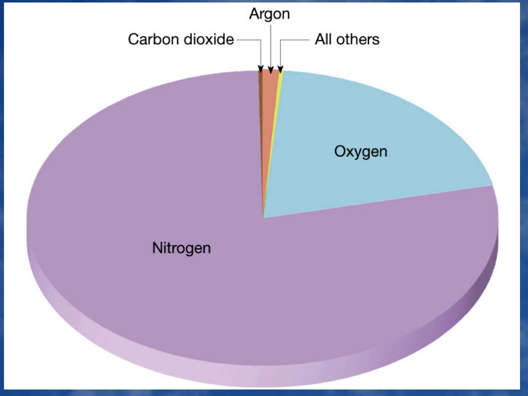
Earth climate system



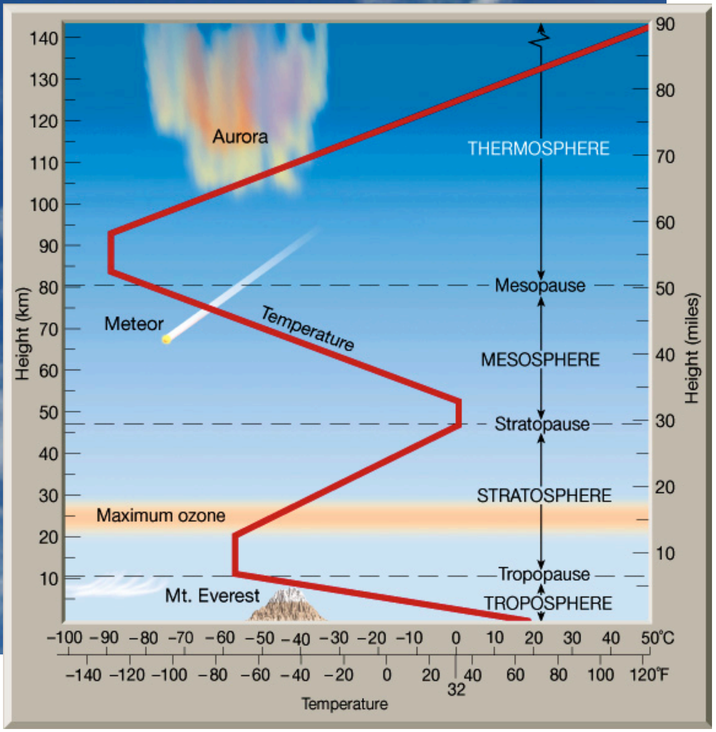
The Earth's climate is a complex nonlinear system that is constituted of **five interactive components** primarily driven by the solar energy

Atmosphere

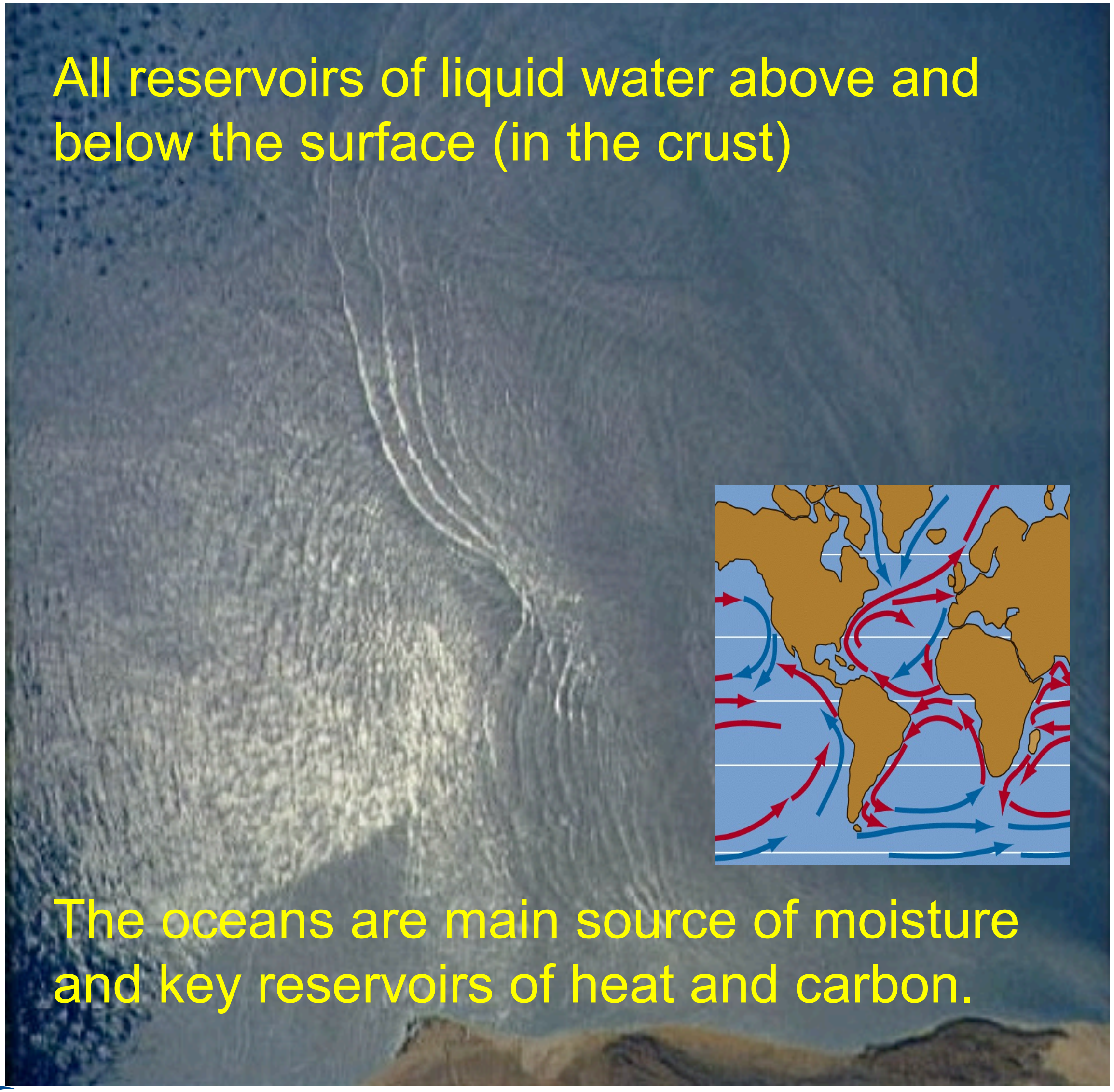
Gaseous part (N_2, O_2 and Ar) above the surface including trace amounts of other gaseous (CO_2, CH_4, …), liquid and solid substance (H_2O, …).



Stratopause ≈
50 km << 6378 km
= radius of Earth



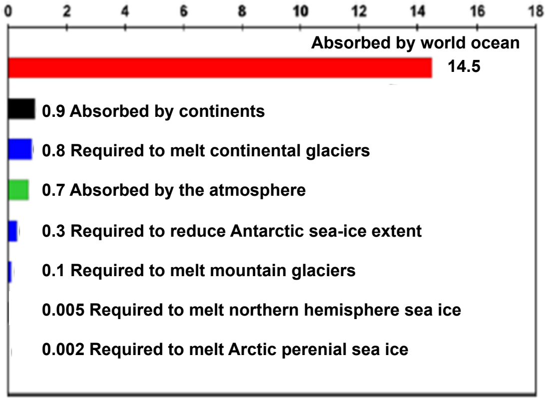
Hydrosphere (oceans + lakes + rivers + groundwater)

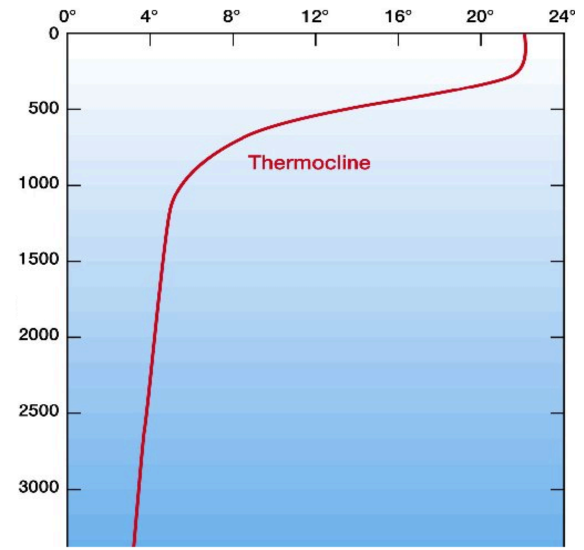


All reservoirs of liquid water above and below the surface (in the crust)

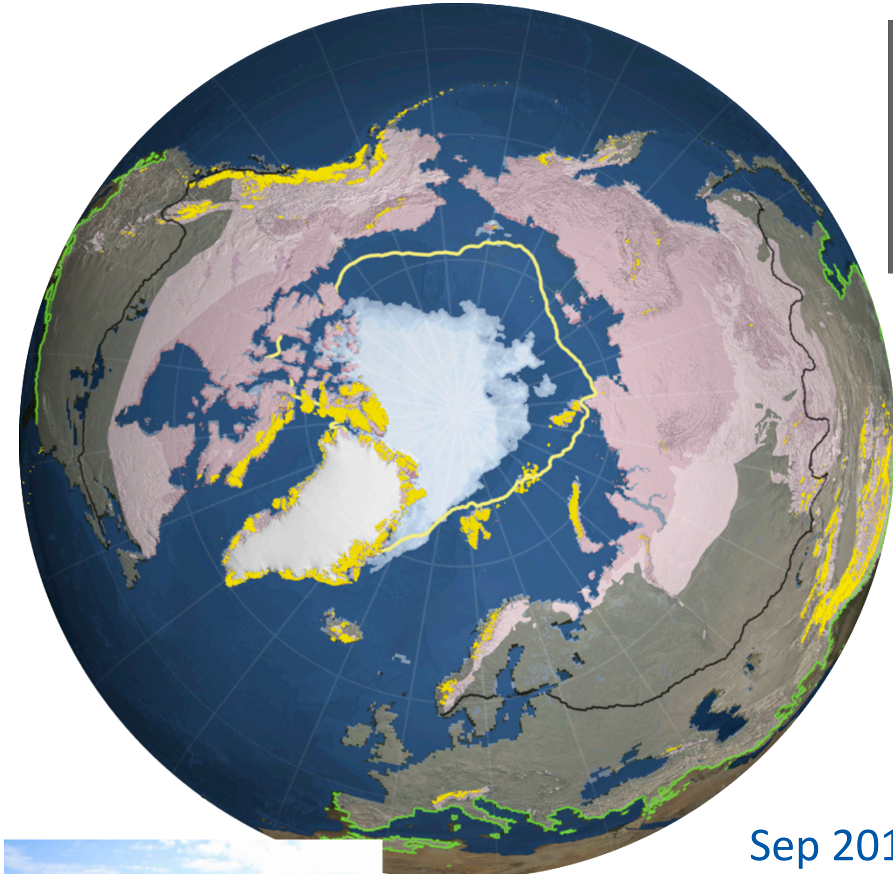
The oceans are main source of moisture and key reservoirs of heat and carbon.

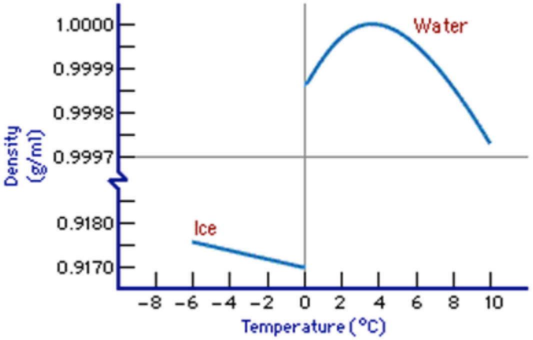
Estimates of Earth's heat balance components (10^{22} J) for 1955-1998 period (Levitus, et al., 2005).



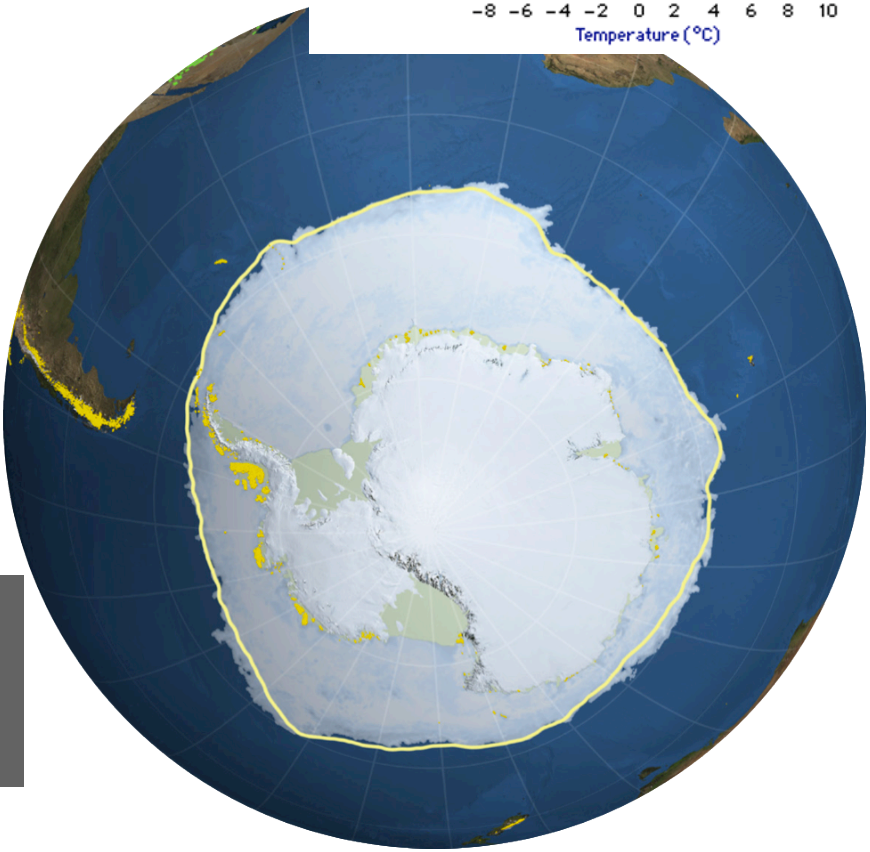


Cryosphere (sea ice, snow, glaciers, permafrost, ..)





Sep 2012



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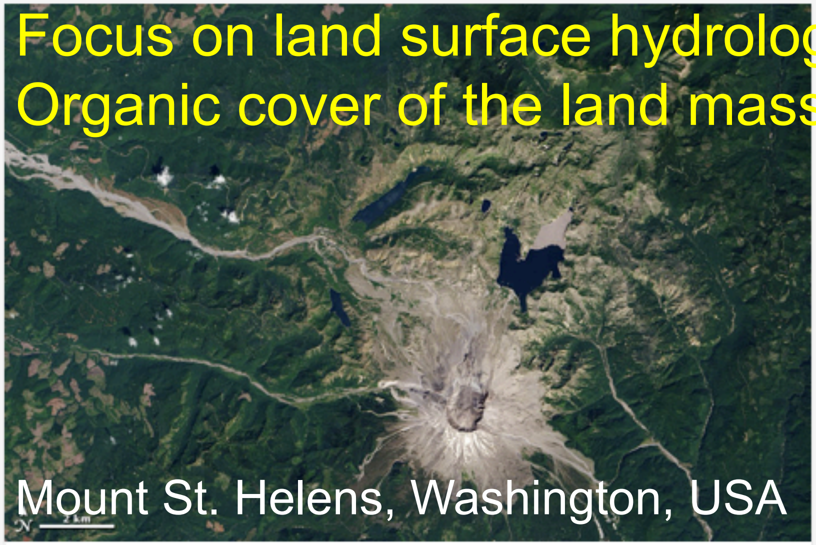
Land surface and biosphere

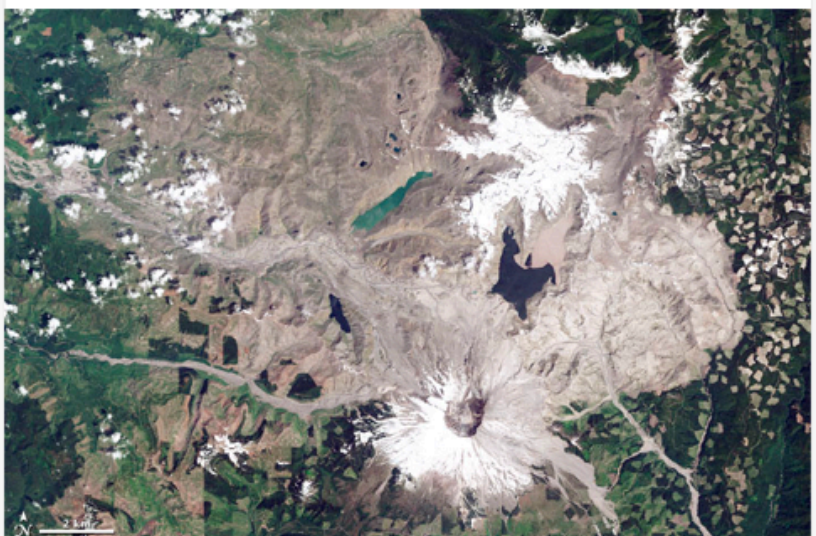
Focus on land surface hydrology

Organic cover of the land masses and marine organisms



Mount St. Helens, Washington, USA

download large image (5 MB, JPEG, 4108x4166) acquired August 20, 2013



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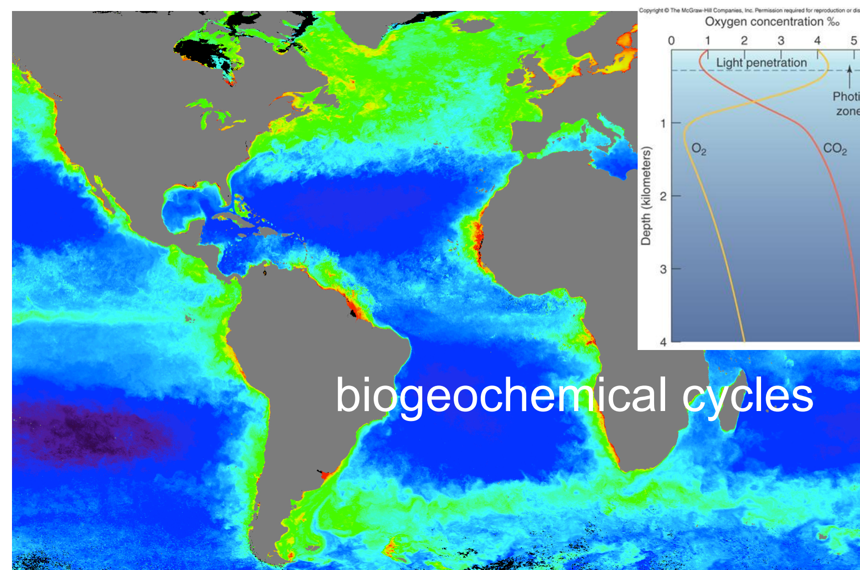
focus on evapotranspiration and



biogeochemical cycles

Governing conservation equations → dynamical models

$$\frac{\partial w}{\partial t} + \cdots = \cdots$$

$$\frac{\partial P}{\partial z} = -\rho g$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

$$\rho = \rho(T, S, P)$$

$$\vec{u} = (u, v, w)$$

$$\frac{\partial u}{\partial t} + (\vec{u} \cdot \vec{\nabla})u - f\,v = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + D_u + F_u$$

$$\frac{\partial v}{\partial t} + (\vec{u} \cdot \vec{\nabla})v + f\,u = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + D_v + F_v$$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T = D_T + F_T$$

$$\frac{\partial S}{\partial t} + \vec{u} \cdot \vec{\nabla} S = D_S + F_S$$

- Incompressible
- Boussinesq
- Shallow water
- Hydrostatic

Surface boundary conditions

Kinematics

$$\frac{\partial \eta}{\partial t} + \vec{u} \cdot \vec{\nabla}\eta = w\Big]_{surf} + P + R - E$$

No explicit Steric Effect

Flux

$$K_v \frac{\partial T}{\partial z}\Big]_{surf} = -\rho C_p Q_{NSOL} \qquad K_v \frac{\partial S}{\partial z}\Big]_{surf} = 0 \qquad A_v \frac{\partial u}{\partial z}\Big]_{z=0} = \frac{1}{\rho_0}\tau_x \qquad A_v \frac{\partial v}{\partial z}\Big]_{z=0} = \frac{1}{\rho_0}\tau_y$$

An example: hydrostatic primitive equations of the ocean

Numerical (approximative) models

$$\frac{D_r u}{Dt} - \frac{uv\tan\phi}{r} - 2\Omega\sin\phi v + \frac{c_{pd}\theta_v}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} = \boxed{-\left(\frac{uw}{r} + 2\Omega\cos\phi w\right)} + S^u$$

$$\frac{D_r v}{Dt} + \frac{u^2\tan\phi}{r} + 2\Omega\sin\phi u + \frac{c_{pd}\theta_v}{r}\frac{\partial\Pi}{\partial\phi} = \boxed{-\left(\frac{vw}{r}\right)} + S^v$$

$$\boxed{\frac{D_r w}{Dt}} + c_{pd}\theta_v\frac{\partial\Pi}{\partial r} + \frac{\partial\Phi}{\partial r} = \boxed{\left(\frac{u^2+v^2}{r}\right) + 2\Omega\cos\phi u + S^w}$$

Atmospheric momentum equations in spherical coordinates → impossible to solve analytically under realistic conditions

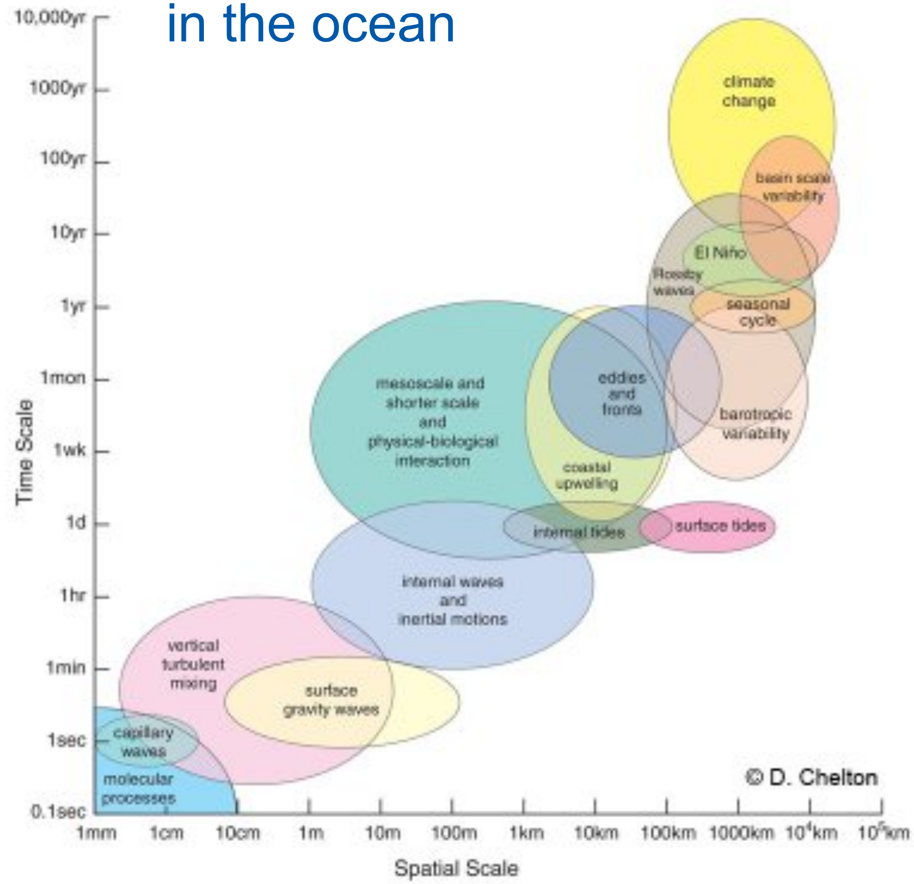
- **Discretization and numerical methods are needed to solve the governing equations of the climate system, i.e., to make weather and climate predictions**

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = 0 \quad \Longrightarrow \quad C_{m,n+1} = C_{m,n} - \frac{u\Delta t}{2\Delta x}\left(C_{m+1,n} - C_{m-1,n}\right).$$

Some characteristic time and spatial scales

Component of the Climate System	Process	Characteristic time scale	Characteristic spatial scale
Atmosphere	Collision of droplets during cloud formation	10^{-6}–10^{-3} s	10^{-6} m
	Formation of convection cells	10^{4}–10^{5} s	10^{2}–10^{4} m
	Development of large-scale weather systems	10^{4}–10^{5} s	10^{6}–10^{7} m
	Persistence of pressure distributions	10^{6} s	10^{6}–10^{7} m
	Southern Oscillation	10^{7} s	10^{7} m
	Troposhere–stratosphere exchange	10^{7}–10^{8} s	global
Hydrosphere	Gas exchange atmosphere–ocean	10^{-3}–10^{6} s	10^{-6}–10^{3} m
	Deep water formation	10^{4}–10^{6} s	10^{4}–10^{5} m
	Meso-scale oceanic gyres	10^{6}–10^{7} s	10^{4}–10^{5} m
	Propagation of Rossby waves	10^{7} s	10^{7} m
	El Niño	10^{7}–10^{8} s	10^{7} m
	Turnover of deep water	10^{9}–10^{10} s	global
Cryosphere	Formation of permafrost	10^{7}–10^{9} s	1–10^{6} m
	Formation of sea ice	10^{7}–10^{8} s	1–10^{6} m
	Formation of land ice masses	10^{8}–10^{11} s	10^{2}–10^{7} m
Land surface	Changes in reflectivity	10^{7}–10^{8} s	10^{2} m – global
	Isostatic equilibration of the crust by covering ice masses	10^{8}–10^{11} s	10^{6} m – global
Biosphere	Exchange of carbon with the atmosphere	10^{4}–10^{8} s	10^{-3} m – global
	Transformation of vegetation zones	10^{9}–10^{10} s	10^{2}–10^{7} m

Spatial and temporal scales in the ocean

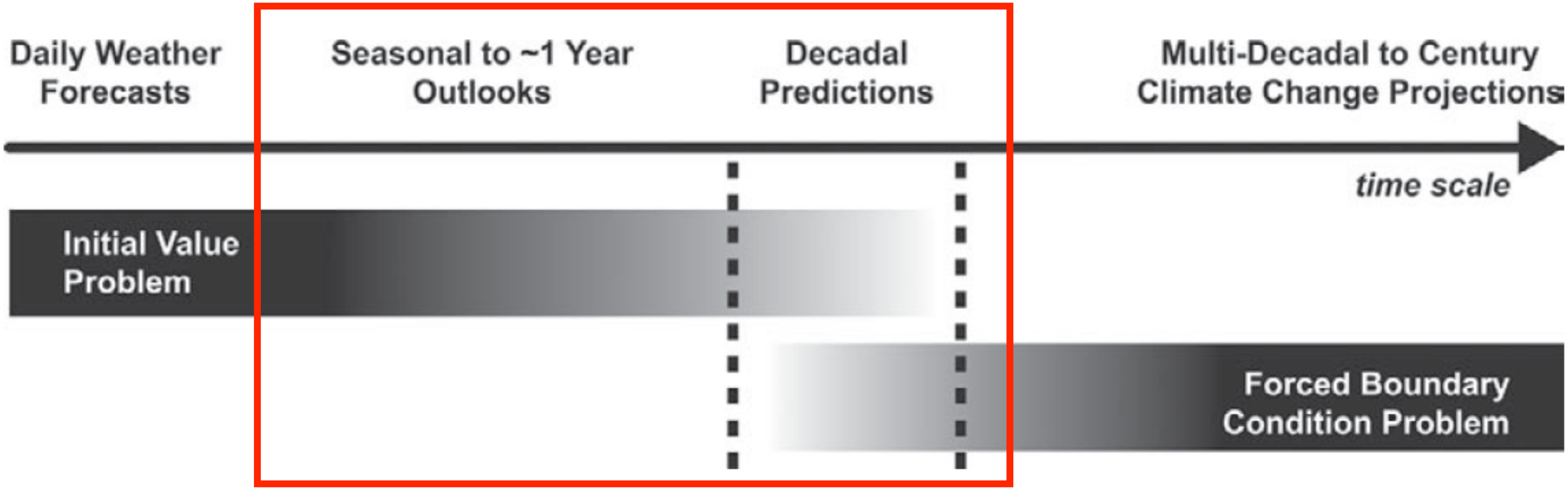


Filtering of fast processes is key for stable integration of climate models

Climate time scales → climate prediction

Medium-range weather forecast – hourly to daily forecasts up to 2 weeks ahead

Climate predictions group focuses on weekly to annual forecasts on sub-seasonal (<3 months), seasonal (3-6 months), inter-annual (multi-year) and multi-decadal times scales up to 30 years ahead



Range where memory of the initial state and boundary forcing are both critical.

Climate system predictability

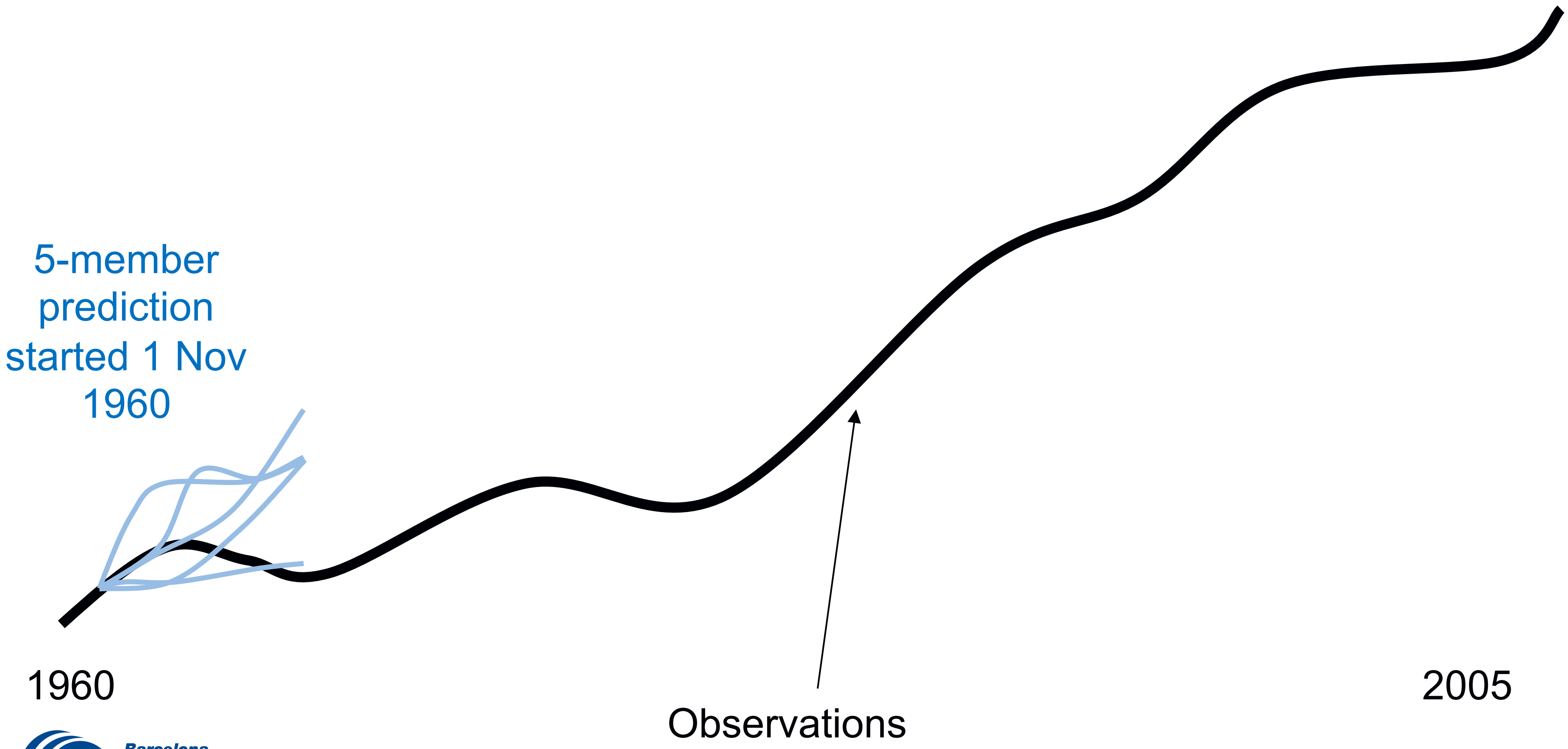
- Key climate memory (initial conditions=**IC**) on seasonal to inter-annual timescales is in the **sea ice** and **land surface (snow cover and soil moisture)**

- Key climate memory (**IC**) on inter-annual to centennial timescales is in the **ocean (SST, mixed layer heat content, ..)**

- **External radiative forcing and atmospheric composition** (solar activity, greenhouse gases, aerosols) → dynamic boundary conditions (BC) are crucial along with static BC (topography + bathymetry)

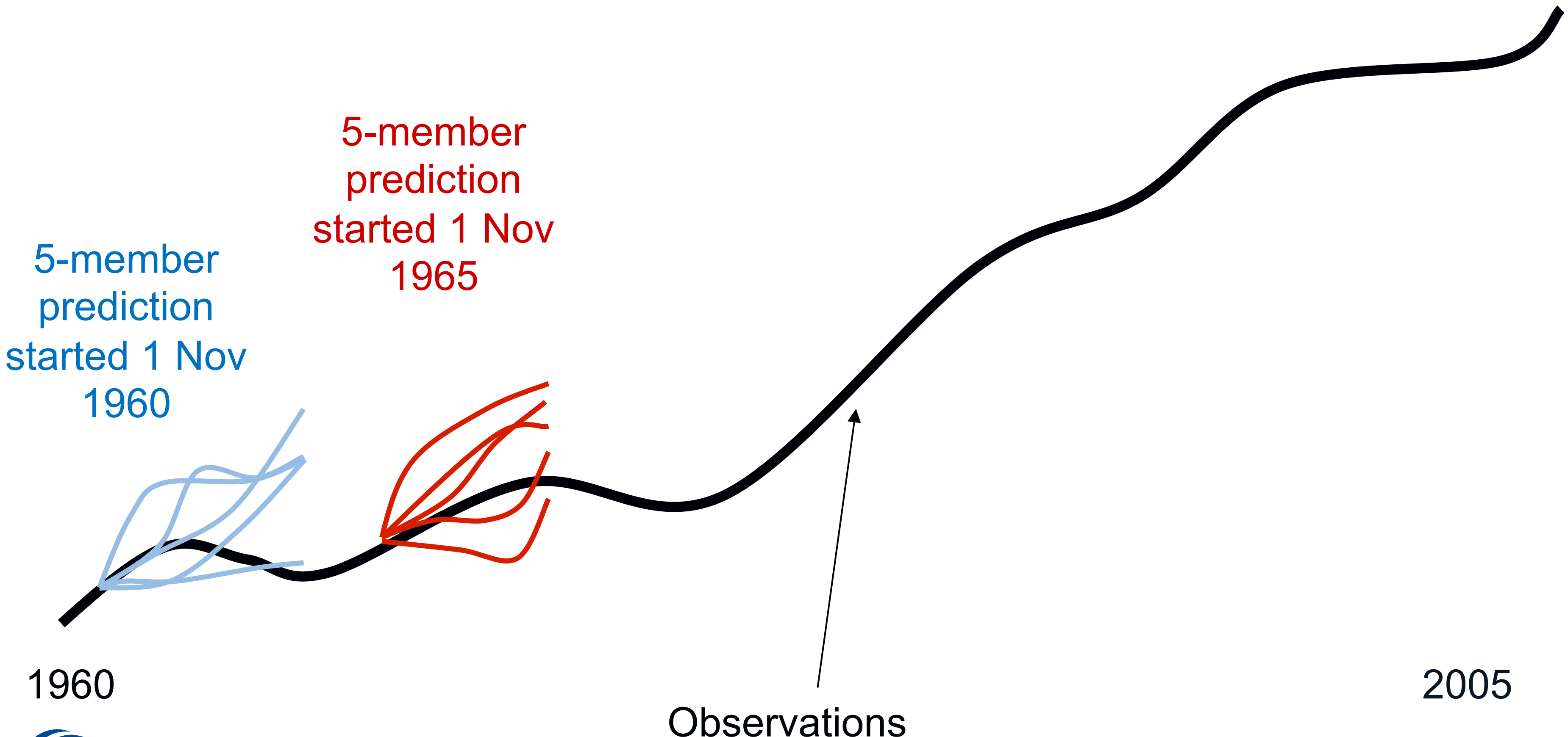
Methodology of using HPC model for climate prediction

Experimental setup : 1 grid-point



Methodology of using HPC model for climate prediction

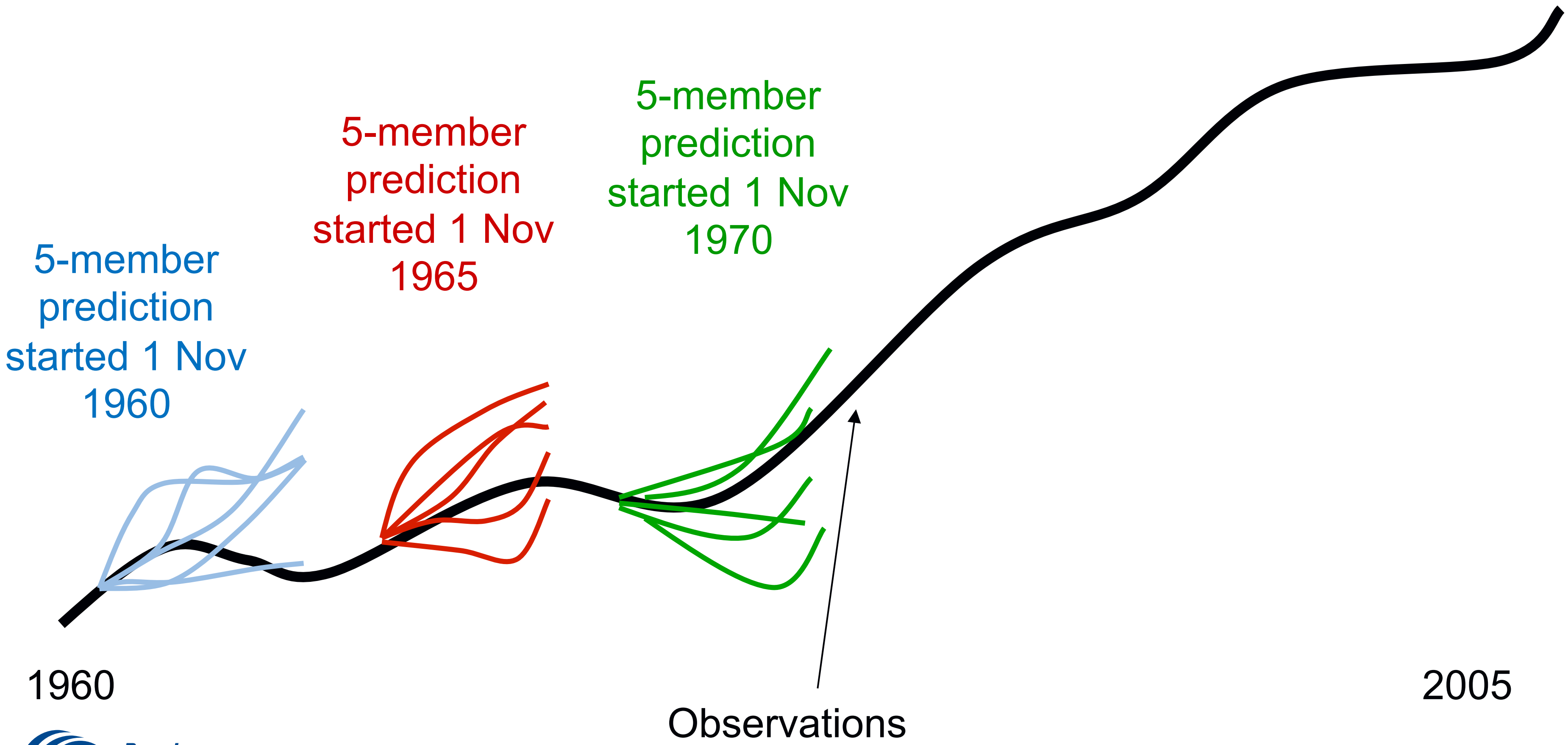
Experimental setup : 1 grid-point



Methodology of using HPC model for climate prediction

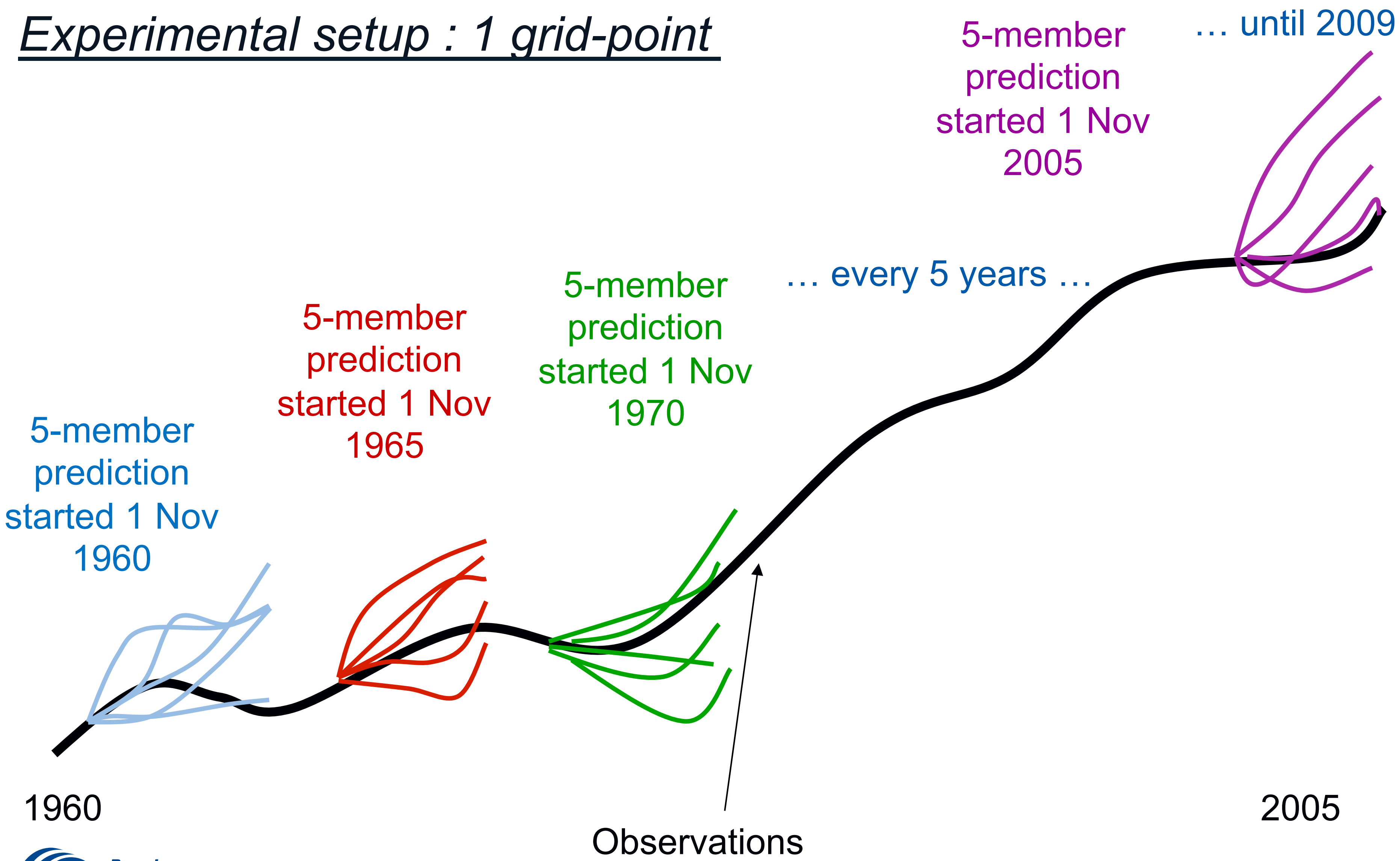
<ins>*Experimental setup : 1 grid-point*</ins>

… until 2009



Methodology of using HPC model for climate prediction

Experimental setup : 1 grid-point



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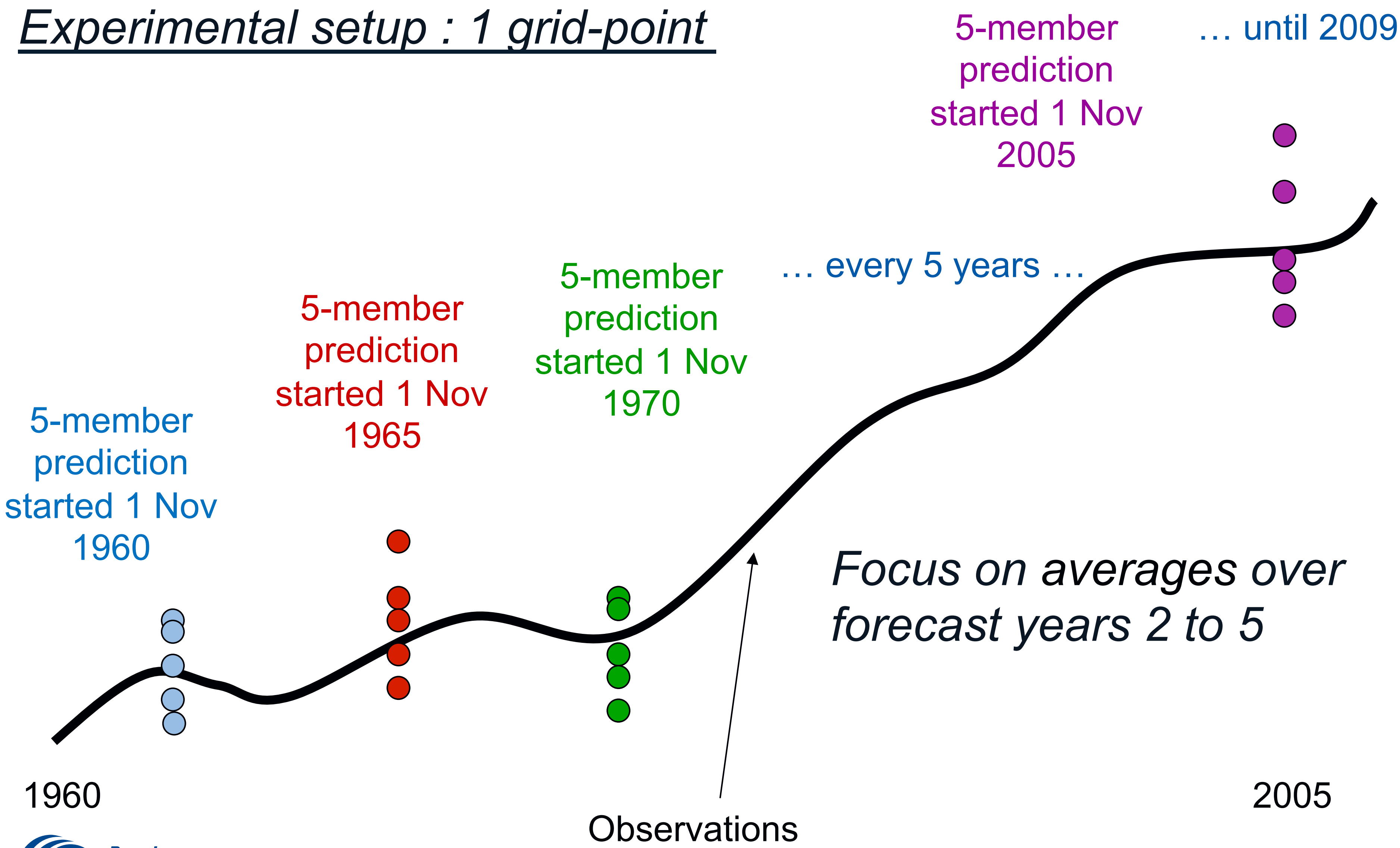

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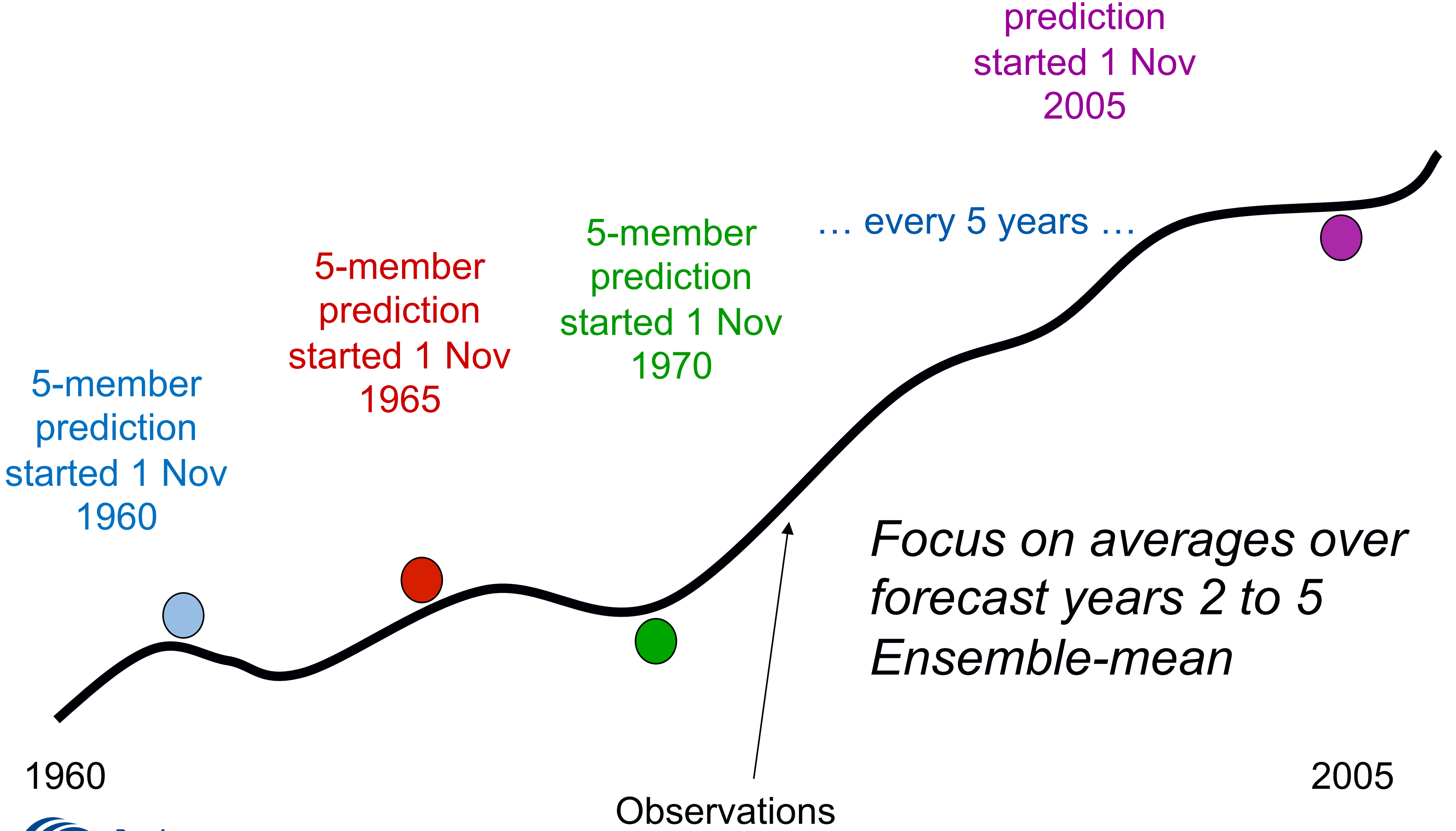
Experimental setup : 1 grid-point



Focus on averages over forecast years 2 to 5
Ensemble-mean

Methodology of using HPC model for climate prediction

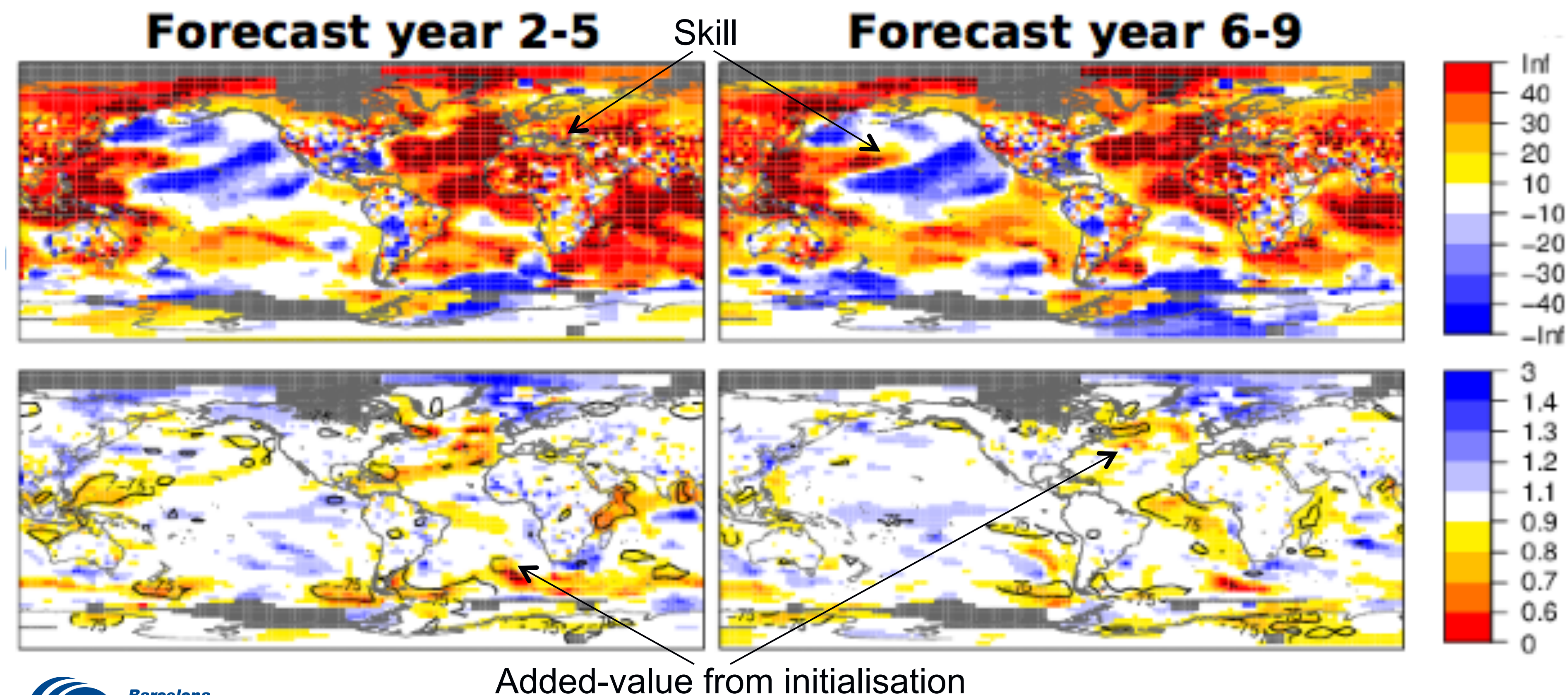
Experimental setup : 1 grid-point

As many values as hindcasts for both the model and the observations to compute skill scores. E.g. : anomaly correlations

1960 2005

Typical decadal forecast skill – IPCC AR5

(Top row) Root mean square skill score (RMSSS) of the ensemble mean of the initialised predictions and (bottom row) ratio of the root mean square error (RMSE) of the initialised and uninitialised predictions for the near-surface temperature from the multi-model CMIP5 experiment (1960-2005) for (left) 2-5 and (right) 6-9 forecast years. Five-year start date interval.



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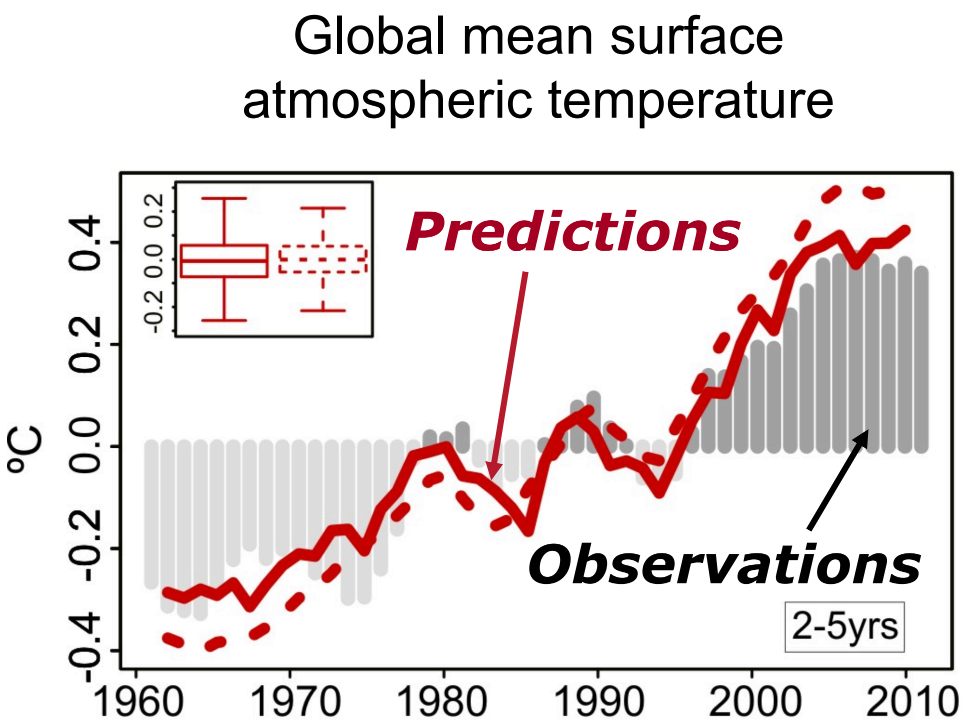
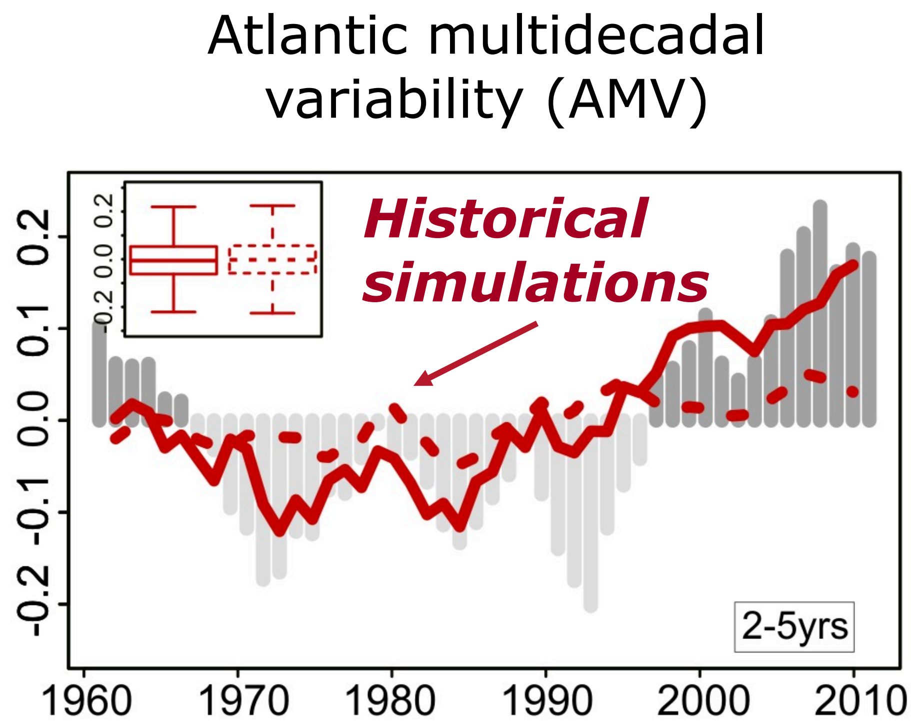
Doblas-Reyes et al. (2013) ***Nature Communications***

Impact of initialization : CMIP5 decadal predictions

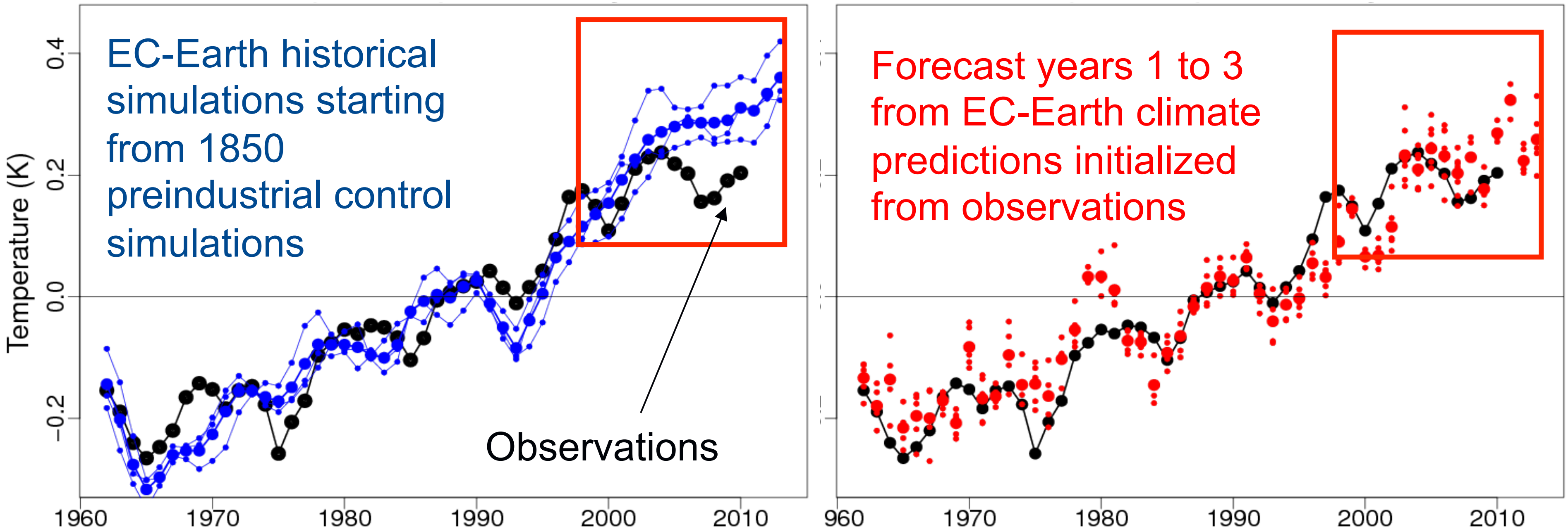
CMIP5 decadal predictions. Global-mean T2m and AMV against GHCN/ERSST3b for forecast years 2-5.



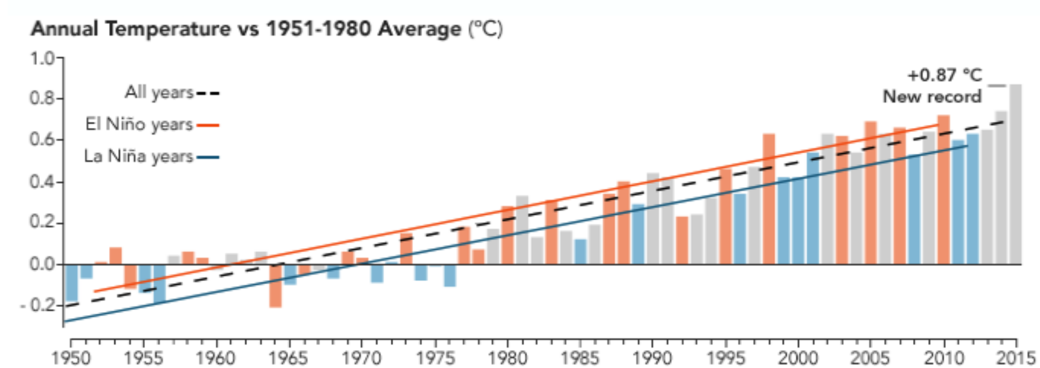


Doblas-Reyes et al. (2013) ***Nature Communications***

Crucial role of initialization from observations in capturing the plateau (temporary quasi pause in warming)

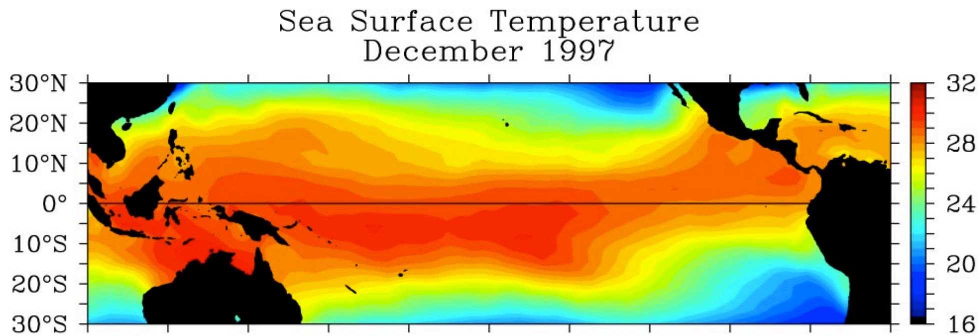


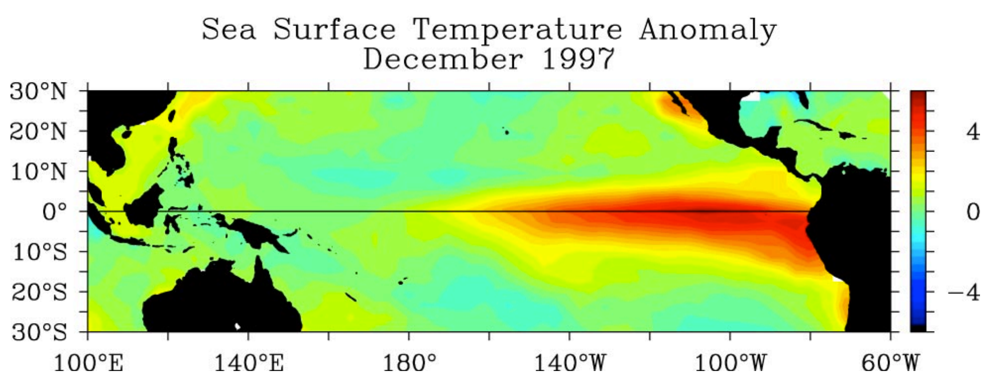
Guemas et al (2013)
Nature Climate Change

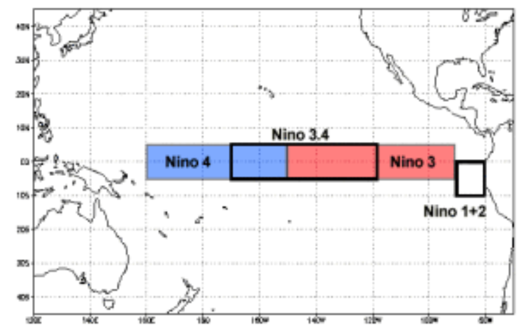


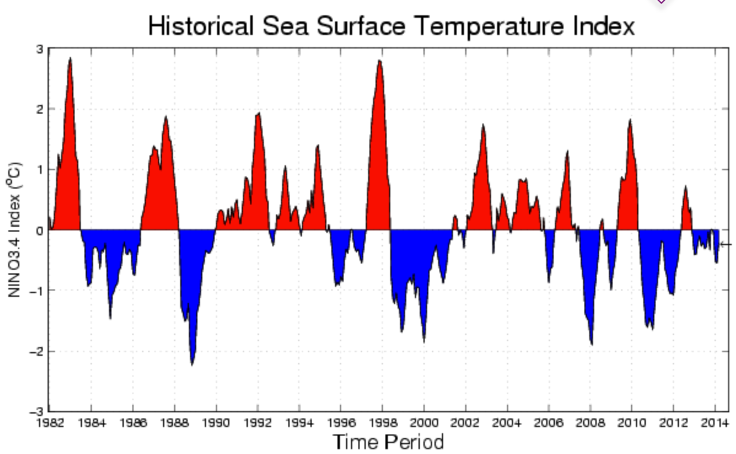
Tropical climate dynamics and predictions

- El Niño - Southern Oscillation (ENSO) phenomenon is the dominant mode of internal climate variability in the tropics
  - quasi-periodic, 2-7 years (interannual), warming/cooling of waters in the tropical Eastern Pacific strongly affects global climate









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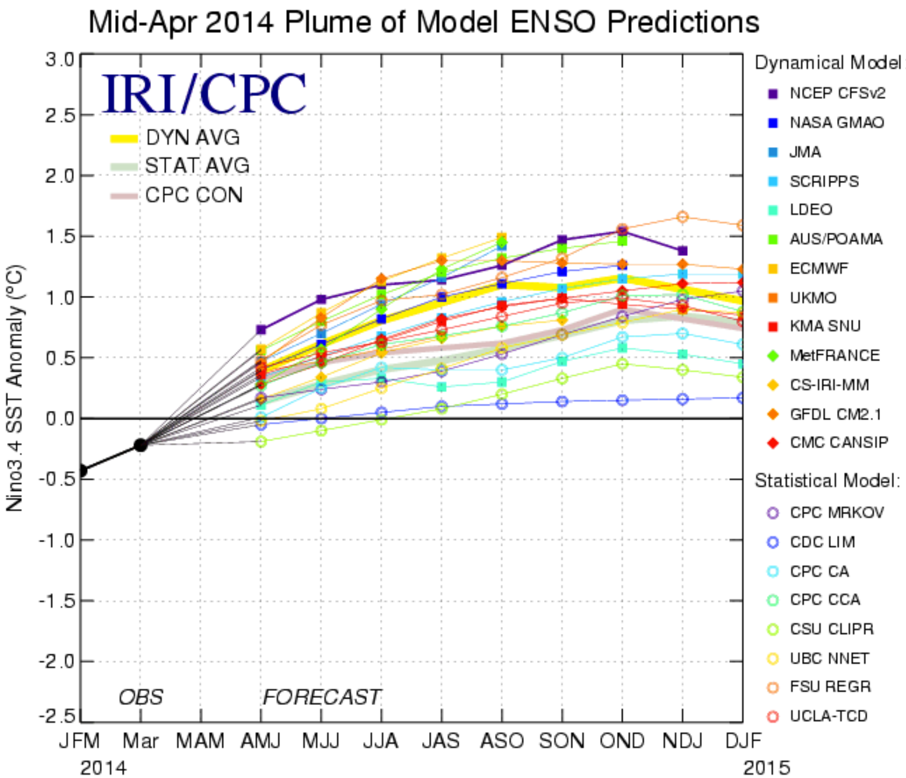
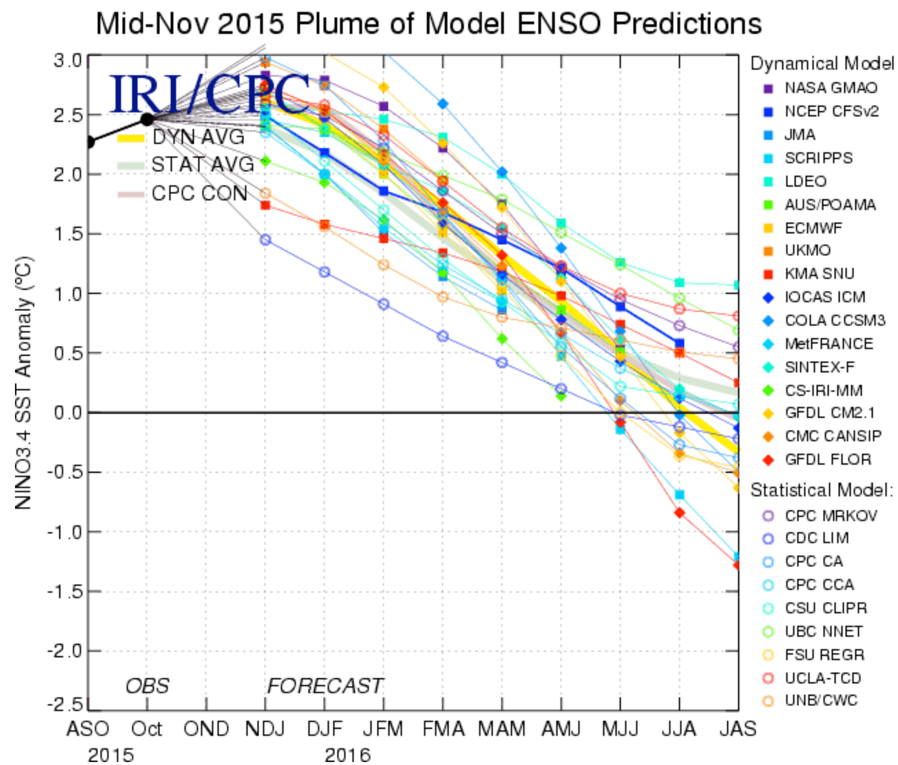
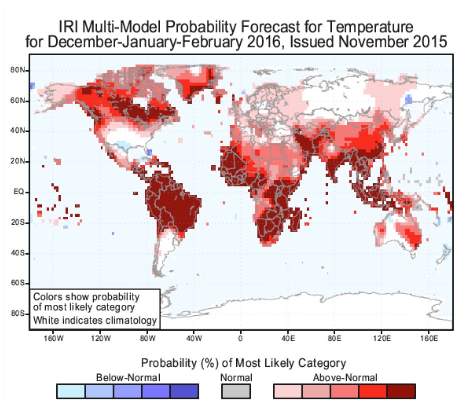
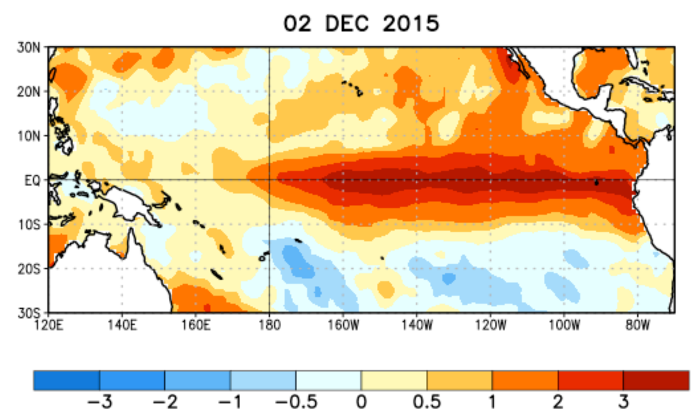
ENSO predictions – initial and boundary value problem





Current El Niño substantially warms surface of the globe





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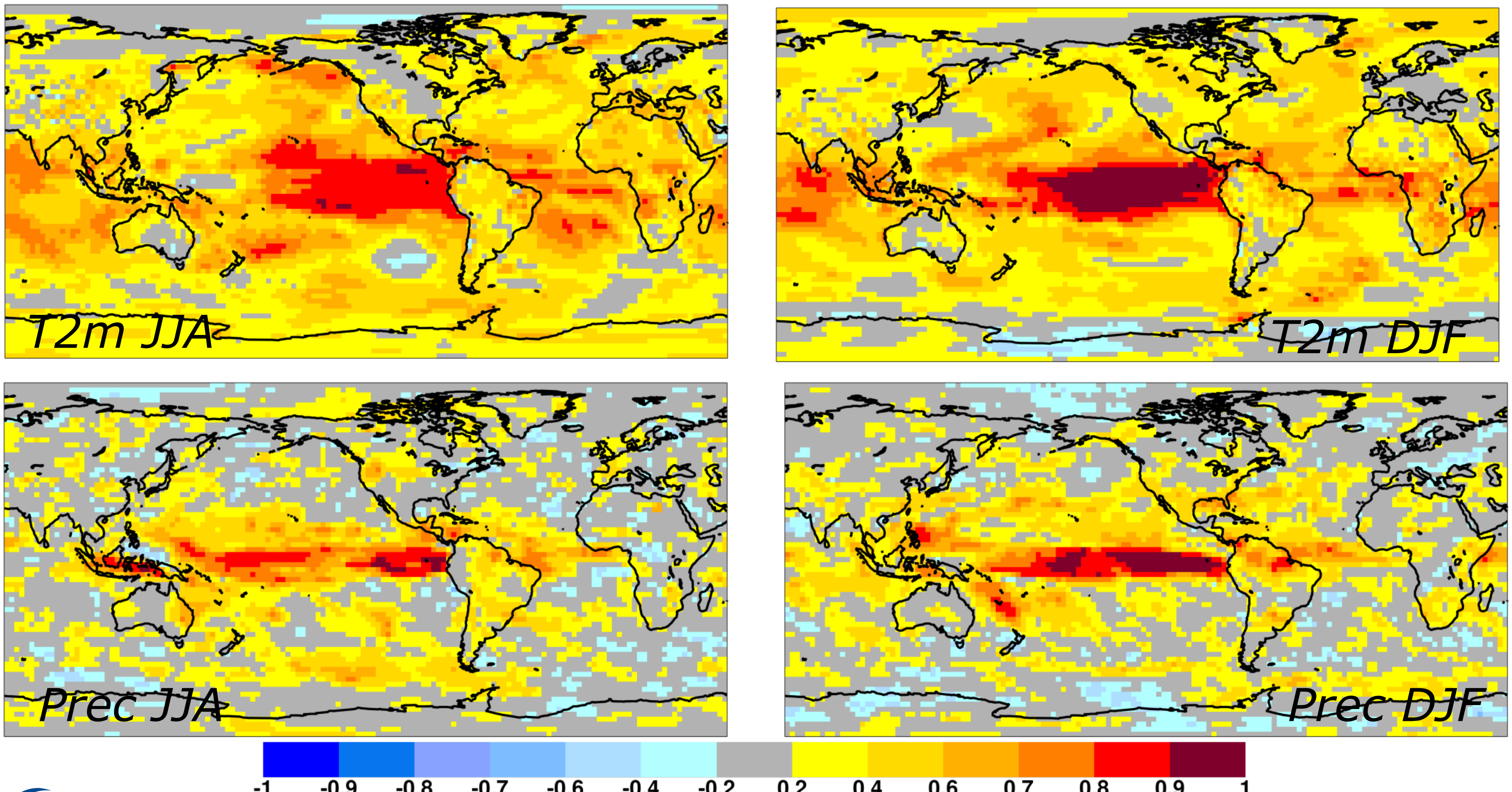
Typical seasonal forecast skill

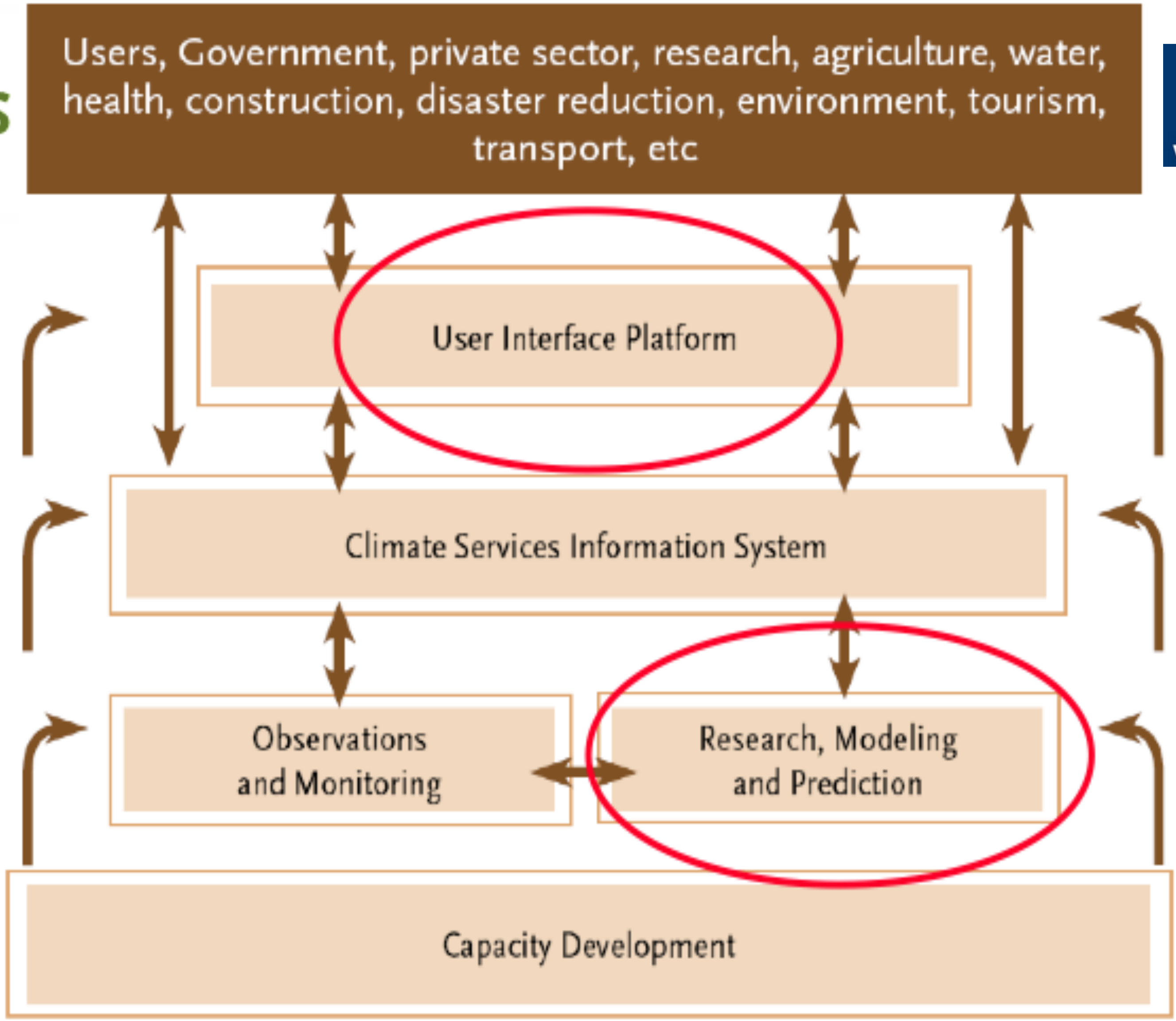
Correlation of the ensemble mean for the ENSEMBLES multi-model (45 members) wrt ERA40-ERAInt (T2m over 1960-2005) and GPCP (precip over 1980-2005) with 1-month lead



Current and planned activities

- Work on initialisation: generate a set of initial conditions (for ocean and sea ice) and compare different initialisation techniques (e.g. full field versus anomaly initialisation)
- Improving model processes: Inclusion and/or testing of model components (biogeochemistry, vegetation, aerosols, sea ice) or new parameterizations, model parameter calibration, increase in resolution
- Calibration and combination: empirical prediction (better use of current benchmarks), local knowledge.
- Forecast quality assessment: provide skill scores practical to the user, reliability as a main target, process-based verification, attribution of climate events with successful predictions, diagnostics of model weaknesses with failing predictions
- More sensitivity to the users' needs: going beyond downscaling, better documentation (e.g. use the IPCC language), demonstration of value and outreach → building versatile climate services as a part of Earth system services

Global Framework on Climate Services



Climate services provide climate information to assist decision making by individuals and organizations firstly in the priority areas

www.gfcs-climate.org

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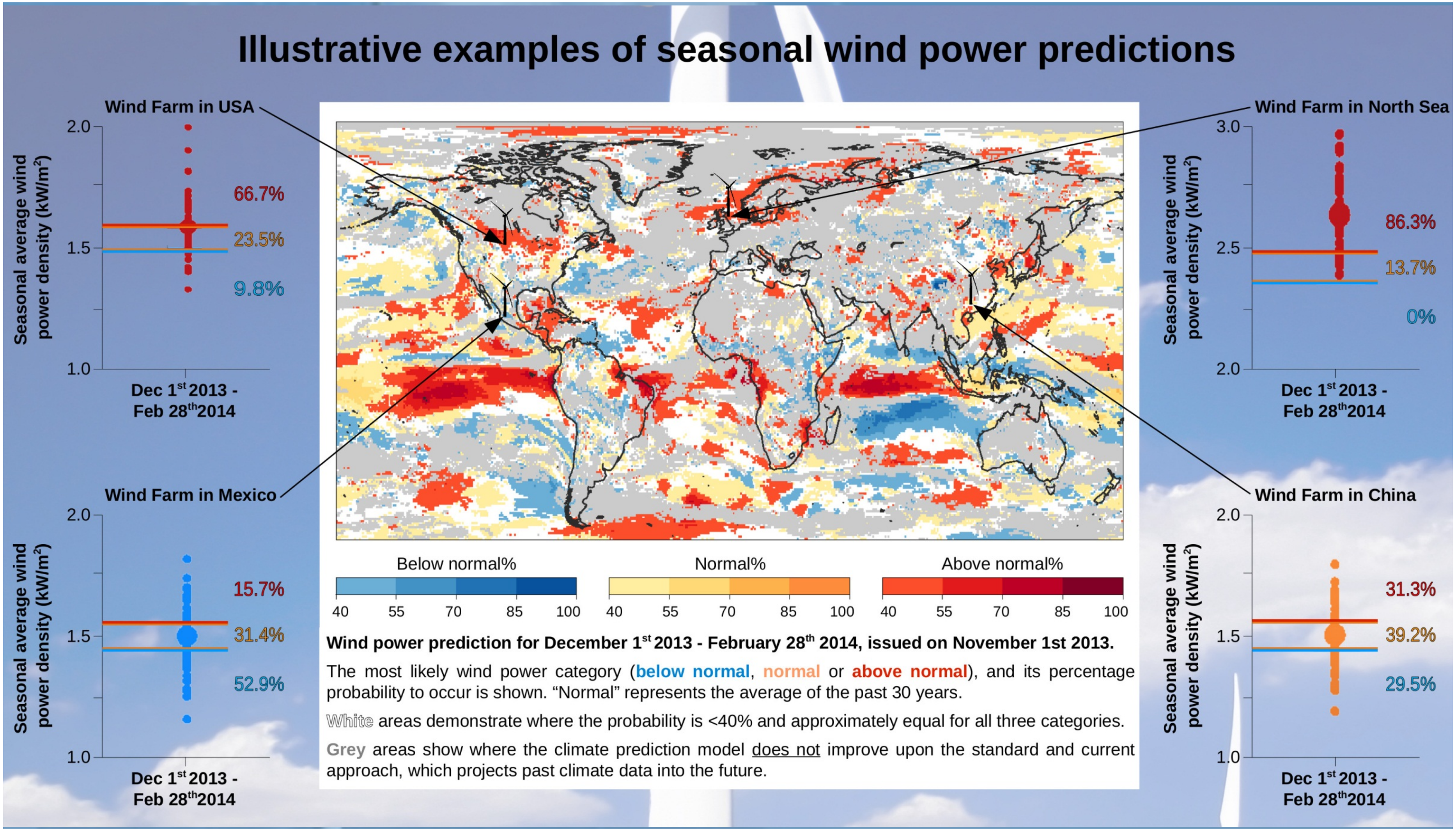
Climate prediction services for energy sector

- Climate predictions, e.g. provide estimate of the wind speed and power over a target period and region
- Wind speed predictions gauge the potential future energy production critical for estimating future energy prices, defining management strategies, planning maintenance, ..
- Whereas short-term meteorological forecasts are a widespread service for the wind energy sector, longer term climate predictions are not yet commonly used

  → Earth System Services group provide seasonal wind speed predictions, based on ECMWF's S4 seasonal prediction system

  → global predictions are run seven months into the future, started every month ⇒ we can provide service information for any location in the world

Seasonal climate prediction of wind power



Wind power prediction for December 1st 2013 - February 28th 2014, issued on November 1st 2013.

The most likely wind power category (**below normal**, **normal** or **above normal**), and its percentage probability to occur is shown. "Normal" represents the average of the past 30 years.

White areas demonstrate where the probability is <40% and approximately equal for all three categories.

Grey areas show where the climate prediction model does not improve upon the standard and current approach, which projects past climate data into the future.

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Climate services for the benefit of renewable energy

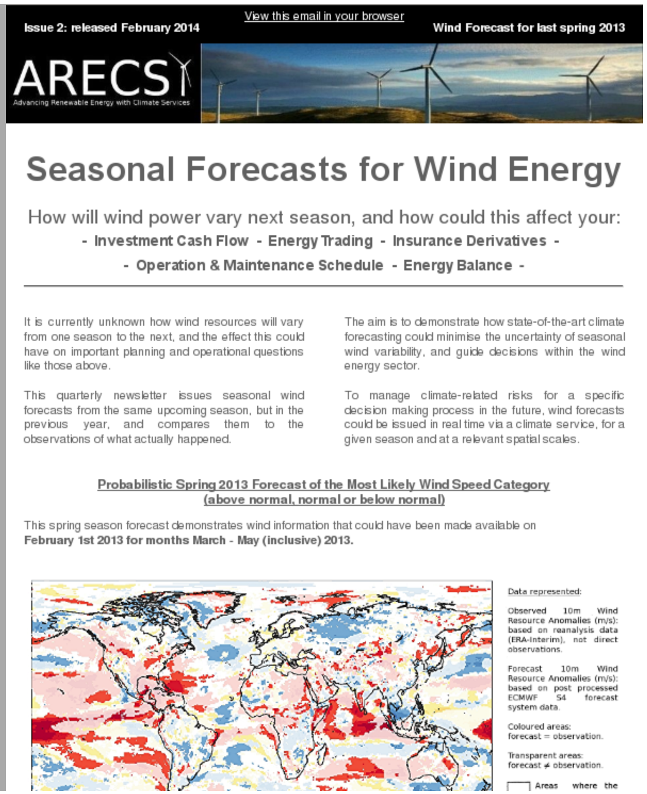
Advancing Renewable Energy with Climate Services (ARECS)

Join the initiative at: **www.arecs.org**

- ✓ Monthly, seasonal and decadal wind and solar forecasts
- ✓ Provide feedback, register your needs
- ✓ Receive a quarterly, seasonal wind forecast newsletter

Website

Newsletter



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Summary and future directions

Key areas of BSC climate prediction and services

- New data assimilation techniques (for single climate component and coupled system) for new reanalyses and initial conditions
- Improving climate model with inclusion of additional processes and increased resolution
- New bias correction, calibration and combination methods
- Forecast quality assessment and development of empirical models
- Expansion of climate services for growing spectrum of stakeholders → climate data is being processed into action-able climate information