日英気候共同研究
UK-Japan Climate Collaboration

Joint Weather & Climate Research Programme
A partnership in climate research

Global Climate Modelling at High Resolution

From UPSCALE to PRIMAVERA and HighResMIP

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With thanks to PRIMAVERA/HighResMIP colleagues from:
AWI, KNMI,ECMWF, MPI, IC3, CMCC, SMHI

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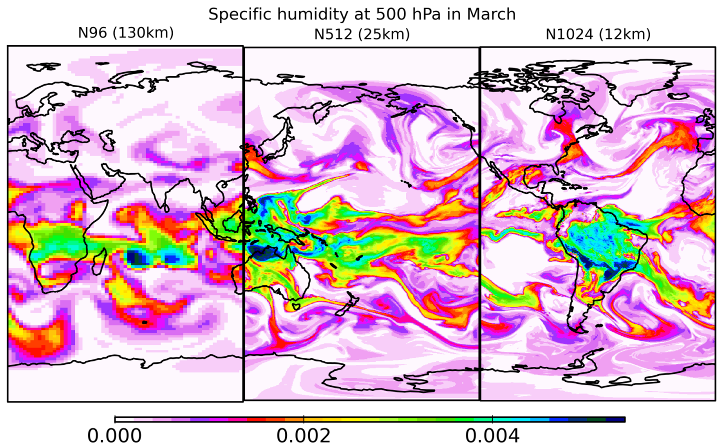
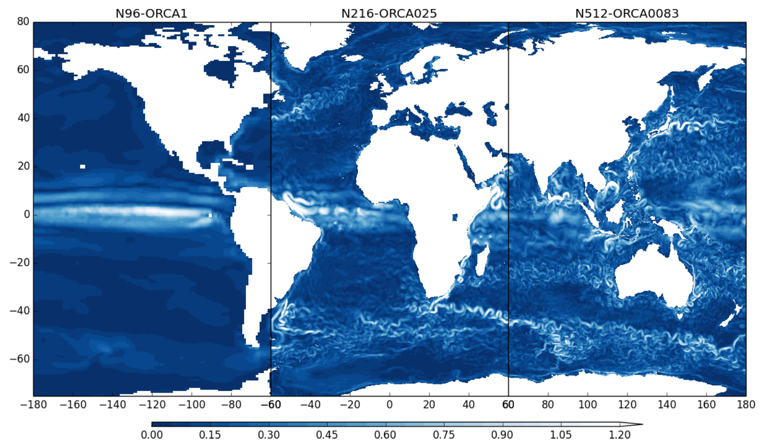
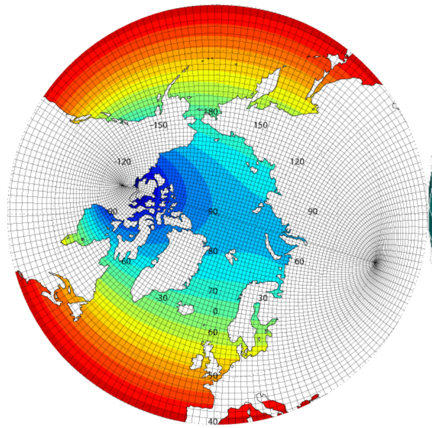


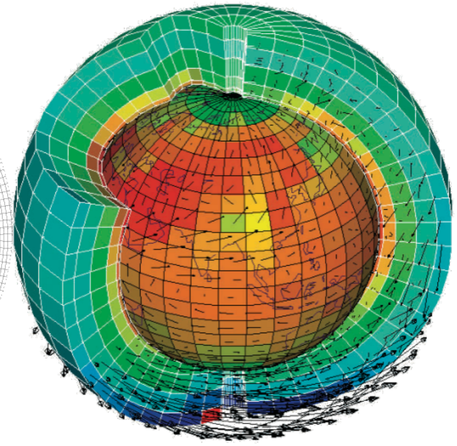


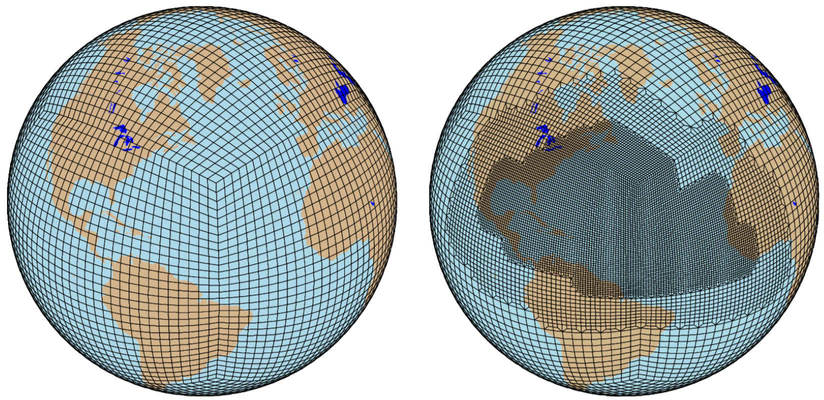
Emerging processes in the atmosphere and ocean as model resolution is increased

Outline

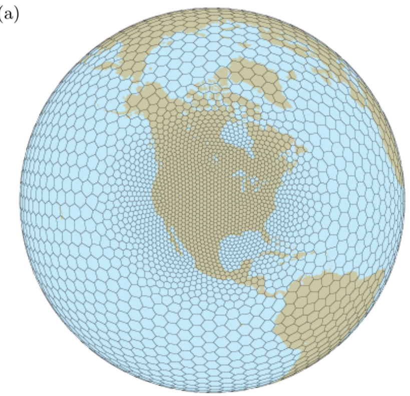
- Scientific motivation for investigating weather and climate at the global scale with high-resolution
    - Why bother with something so expensive and painful?
- A pinch of GCM engineering and aspects of High-Performance Computing
- Examples of multi-scale processes and their interactions in the climate system







(a) (b)



IPCC-type questions

Future of:

- Hydrological cycle: where will it rain, and how much?
- Hurricanes: more intense ones? More overall?
- Weather and Climate Extremes: more and more intense? How are they governed by circulation in the atmosphere and ocean?

Model development question:

what is the role of resolving processes in helping us to understand and reduce systematic model biases?

- Can we see benefits in improving the representation of dynamics and reducing our reliance on physical parameterisation?

WCRP Grand Challenges

Weather and Climate Extremes

1. **Are existing observations sufficient to underpin the assessment of extremes?**
2. What are the relative roles of large-scale, regional and local scale processes, as well as their interactions, for the formation of extremes?
3. Are models able to reliably simulate extremes and their changes, and how can this be evaluated and improved?
4. What are the contributors to observed extreme events and to changes in the frequency and intensity of the observed extremes?

Clouds, Circulation and Climate Sensitivity

1. How do clouds couple to circulations in the present climate?
2. How will clouds and circulation respond to global warming or other forcings?
3. How will they feed back on it through their influence on Earth's radiation budget?

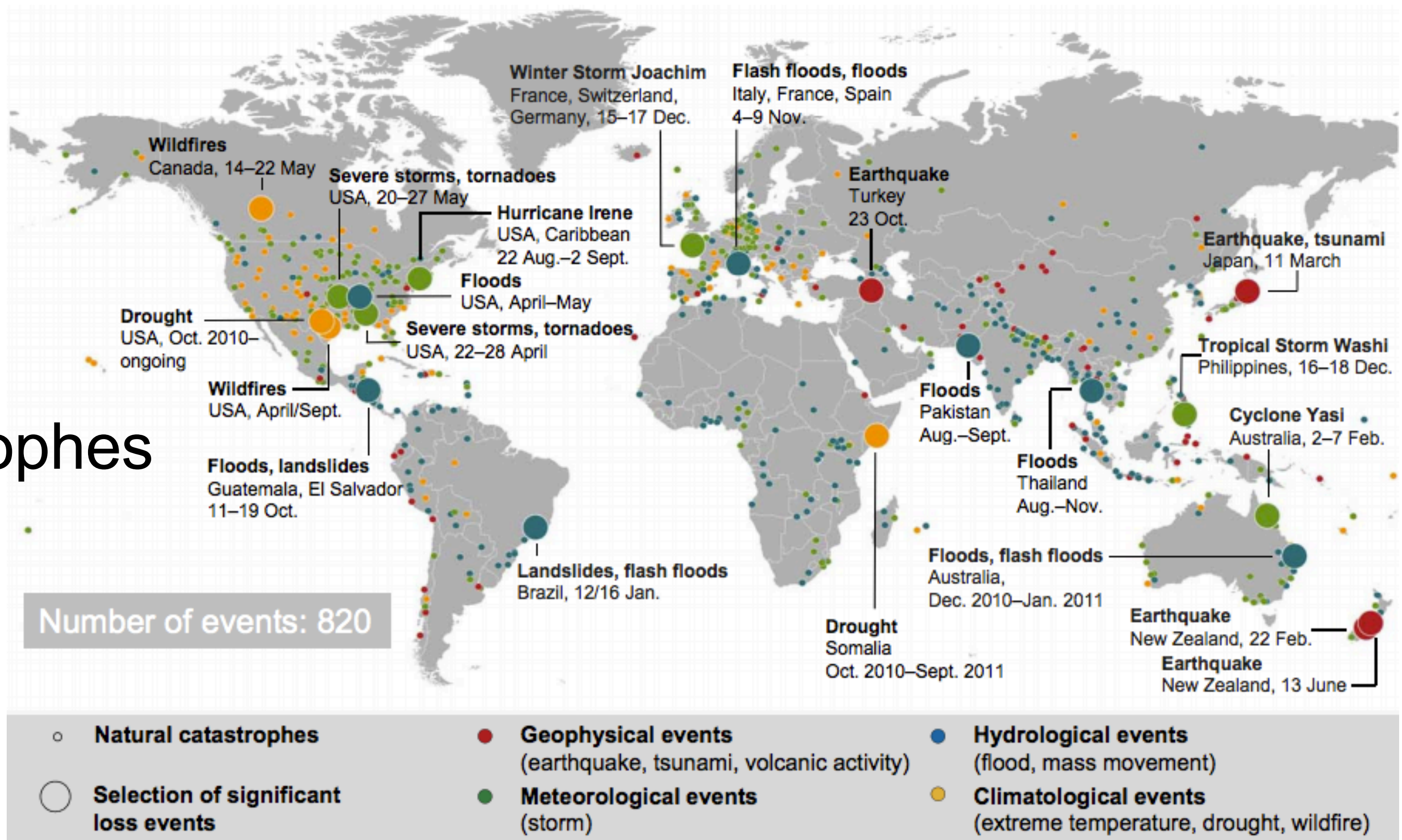
Carbon Feedbacks in the Climate System

1. How will highly-vulnerable land and ocean carbon reservoirs respond to a warming climate, to climate extremes, and to abrupt changes?

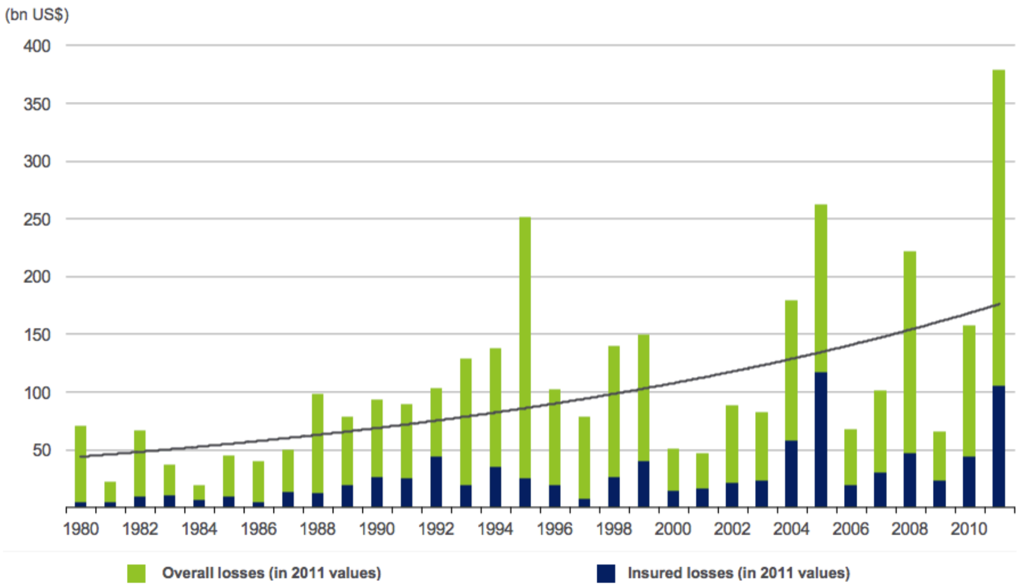
Knowledge
Transfer
Partnerships

Willis Research Network

Natural Catastrophes of 2011



Comparing 2011 with previous years

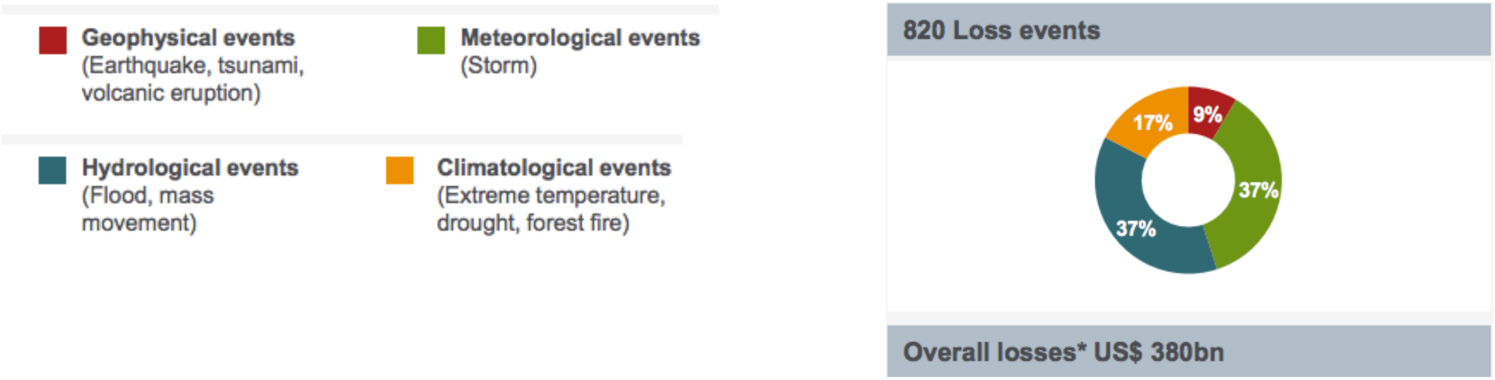


Munich Re 2012

Motivations for modelling **weather and climate as a continuum**

Economic Impact of Weather-related Natural Catastrophes of 2011

- 2011= costliest year ever in terms of natural catastrophe
- **US$380bn** global economic losses (120bn higher than 2005)
  - Of which **only US$105bn** were insured losses
- Although earthquake dominated loss in 2011 (Japan Tsunami prominent), still **90% of the number of natural catastrophes were weather-related**



Munich Re 2012

Observations of extreme events are rare, short, inhomogeneous.

Climate models can provide much needed complementarity: synthetic data sets for W&C extremes.

- UK insurance and UK science share a need to understand the world around us and to understand how it is changing.
- Need for continuous engagement between the insurance industry and the scientific community to ensure industry has the best possible information to increase its market resilience to W&C risk

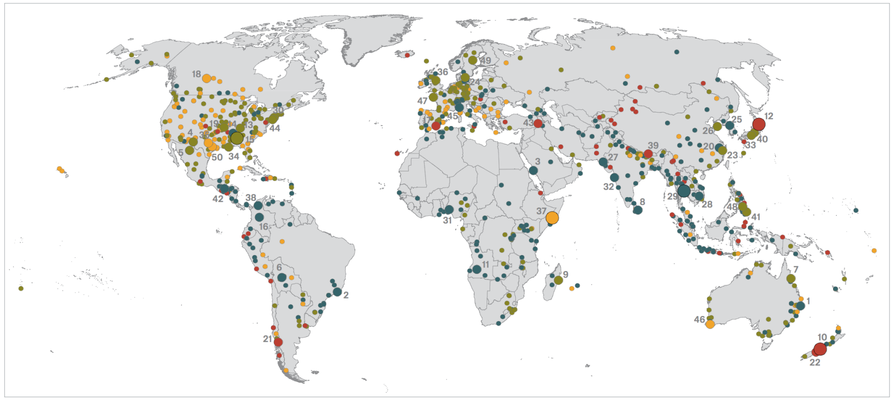
Knowledge Transfer Partnerships

Willis Research Network

Recent natural catastrophes: comparing 2011 with previous years

Topics Geo – World map of natural catastrophes 2011

Munich RE



820 natural hazard events, thereof

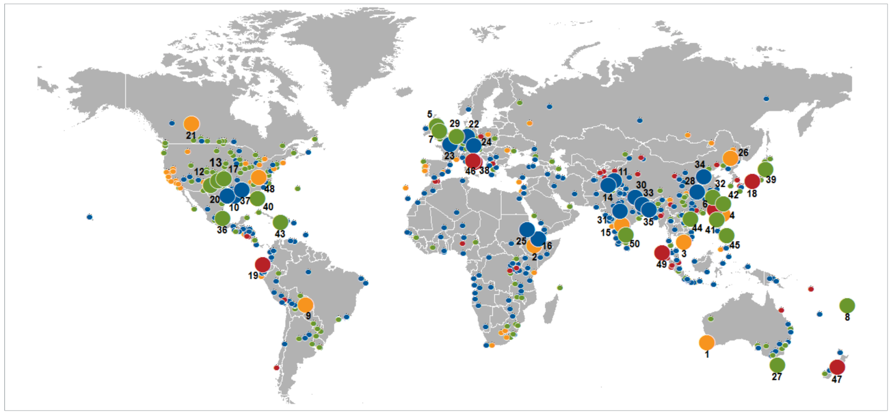
50 major events (selection)

In 2011, five events fulfilled the criteria applicable to a great natural catastrophe.

- **Geophysical events:** Earthquake, volcanic eruption
- **Meteorological events:** Tropical storm, winter storm, severe weather, hail, tornado, local storm
- **Hydrological events:** River flood, flash flood, storm surge, mass movement (landslide)
- **Climatological events:** Heatwave, cold wave, wildfire, drought

Topics Geo – World map of the 50 major loss events 2016

Munich RE

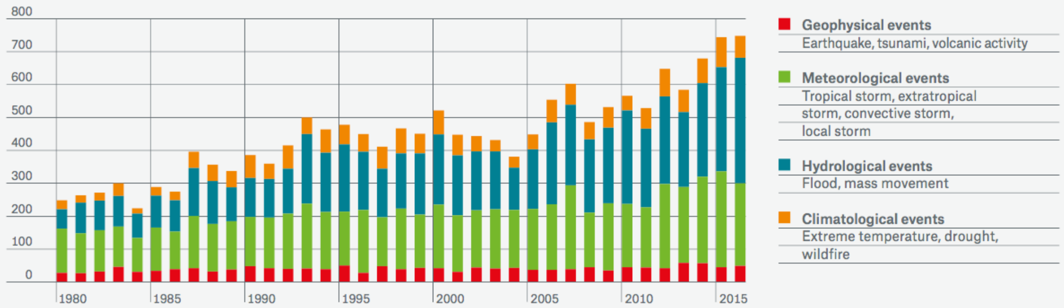


1,060 natural hazard events, thereof

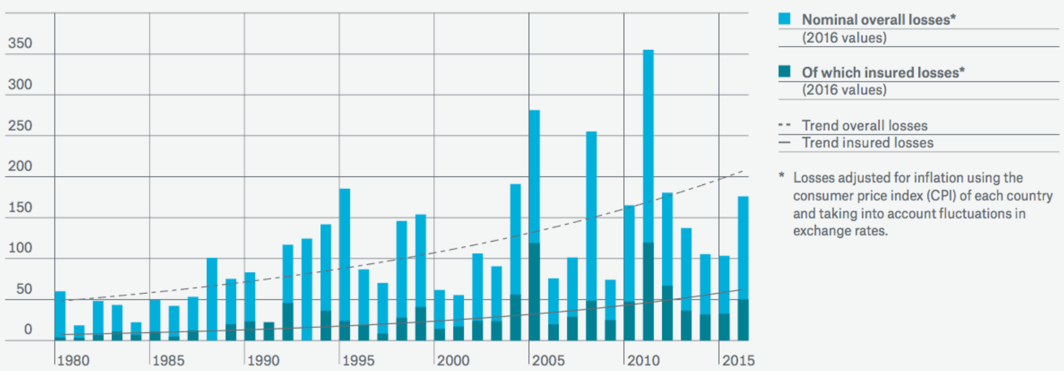
50 major events (details overleaf)

- **Geophysical events:** Earthquake, tsunami, volcanic activity
- **Meteorological events:** Tropical storm, extratropical storm, convective storm, local storm
- **Hydrological events:** Flooding, mass movement
- **Climatological events:** Extreme temperatures, drought, wildfire

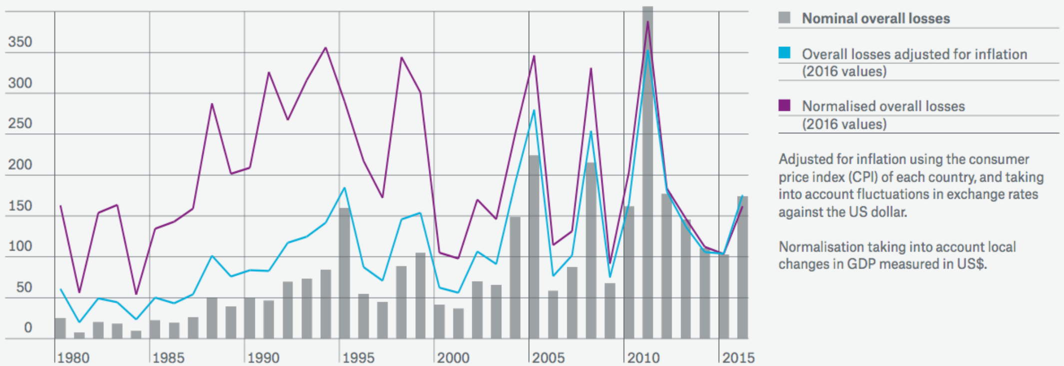
Number of loss events 1980–2016



Overall losses and insured losses 1980–2016 (in US$ bn)



Loss events worldwide 1980–2016



Source: Munich Re NatCatSERVICE

Munich Re 2011-2016

A case study for the weather and climate continuum: the 2011 Thailand floods

To understand interactions between large scale, remote features and local extreme events

- Thailand floods = the main weather-related economic loss event in 2011
- Worst flooding for 50 years
- Flooded 7 major industrial areas with production facilities

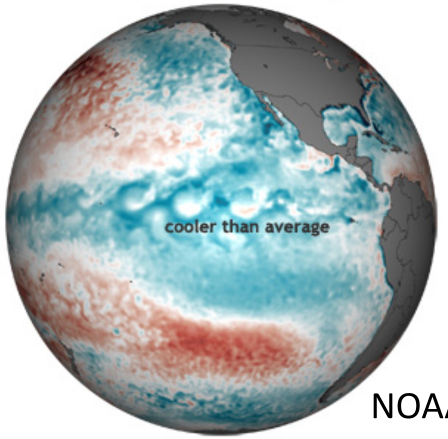
⇒ Production delays, disruption of client businesses

- Multinational companies insured by international insurance companies: **impacts and losses not 100% co-located**
  - ⇒ Biggest loss event for Lloyds of London who had £4.6bn catastrophe claims for 2011

- **La Niña event** likely a contributing factor
  - Successful+robust simulation depends on resolving oceanic eddies in the East Pacific

2011 Thailand Floods

Sea surface temperature anomaly (Jan 2011)



NOAA

The value of high resolution GCMs

Question: how much does it really rain on Earth?

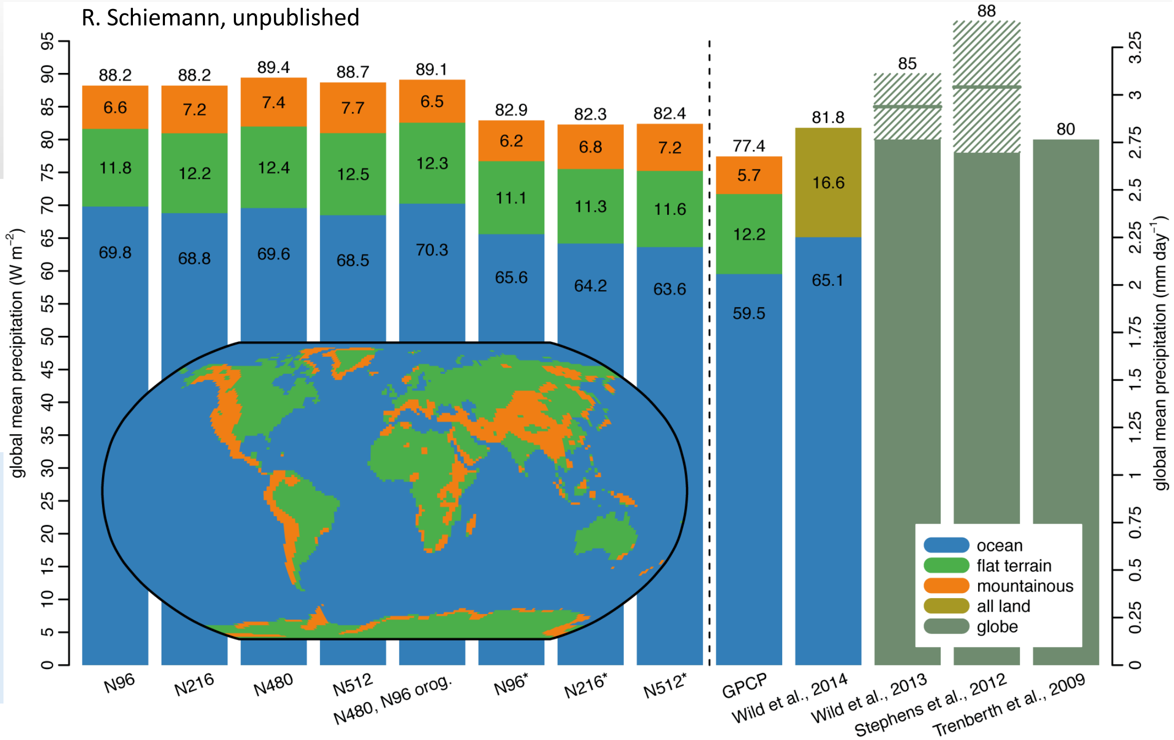
Mission

Understand mechanistic chains

Develop fleet of models with increasing mesh refinement

<u>Challenge observations</u>

Examples:
Allan et al. 2014
Liu et al. 2015
Hodges et al. 2017
Liu et al. 2017



Robustness?

International collaborations

CMIP6 HighResMIP

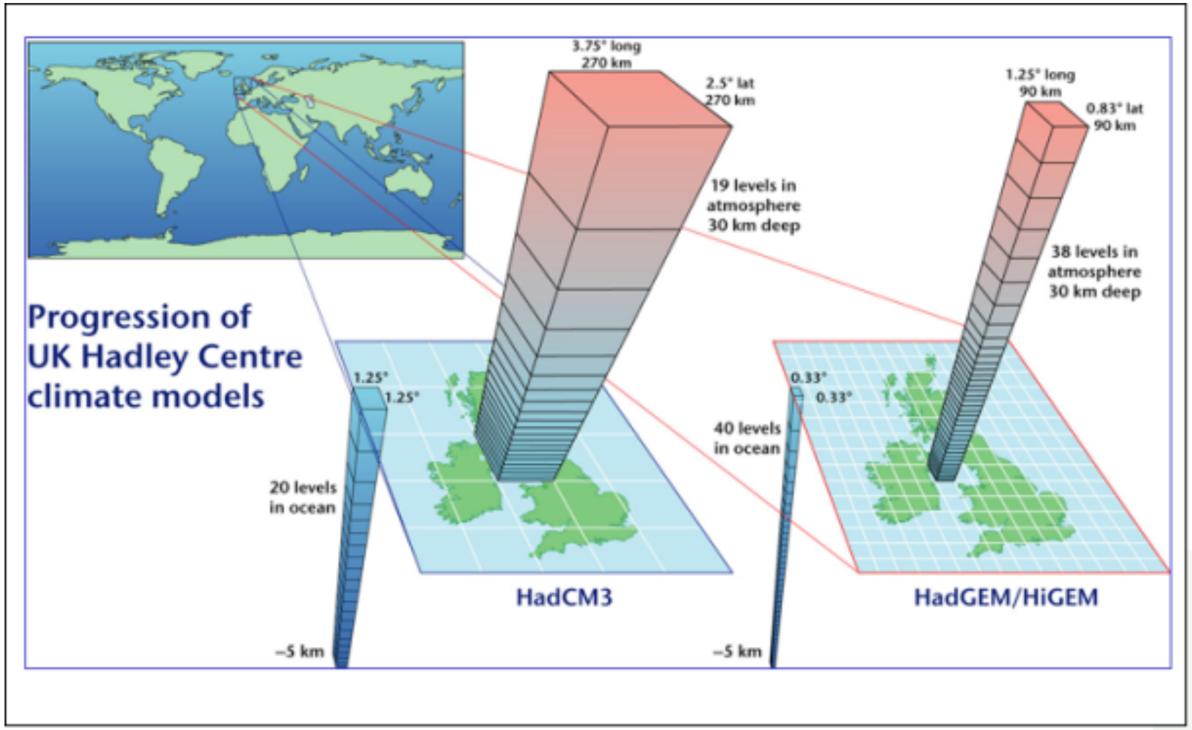
US CLIVAR Hurricane Working Group

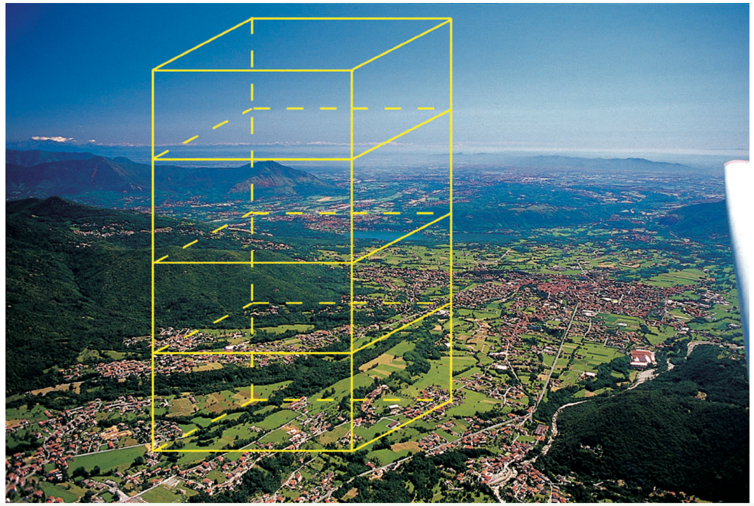
GEWEX

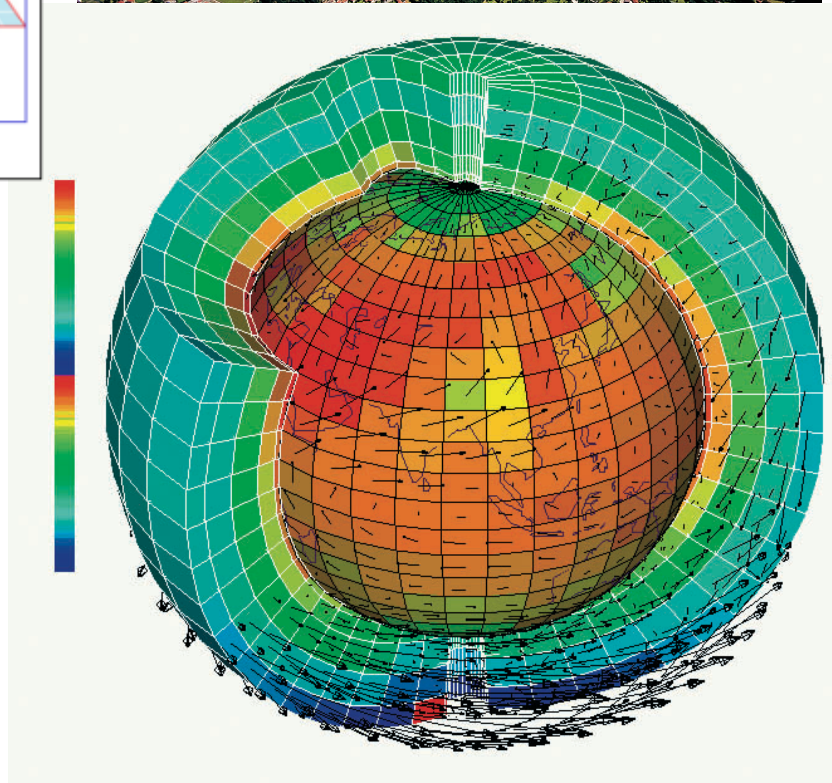
GCMs produce more precipitation than what is found in observations (still within range of uncertainty).

Some of this discrepancy is consistent with excessive radiative forcing, but some of it may be explained by the fact that, <u>as we increase resolution</u>, **GCMs produce more precipitation over rough terrain**, exactly where observations are sparse.
Our process study strengthens the hypothesis (Stephens et al., Waliser et al.) that station sampling is indeed a factor.

GCM engineering



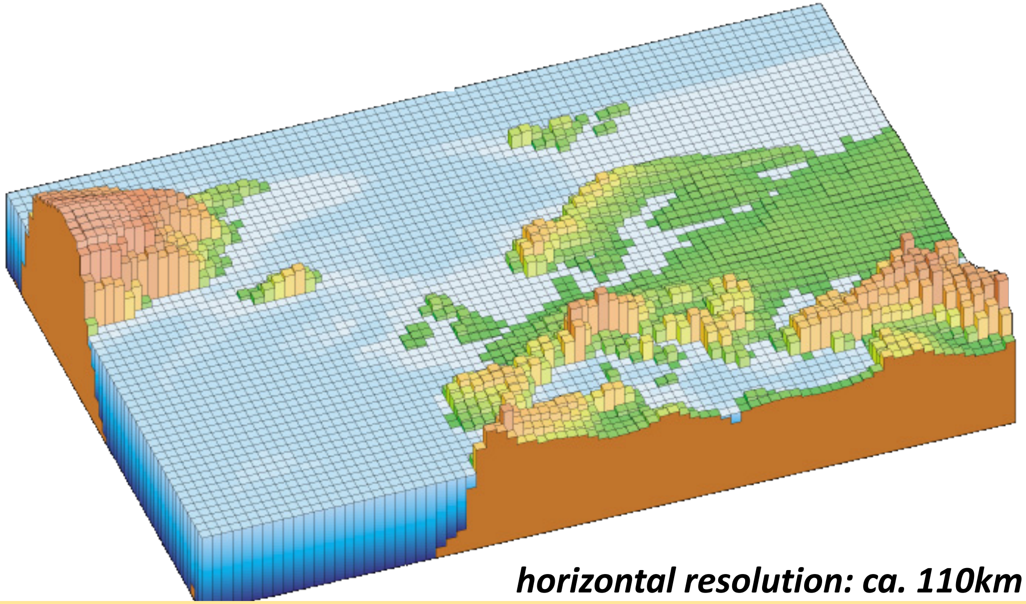




At every box location we compute radiation, winds, pressure, precipitation, temperature, using the laws of physics (gravitation, electromagnetism, thermodynamics, fluid dynamics, turbulence), chemistry, biology, ecology, etc.

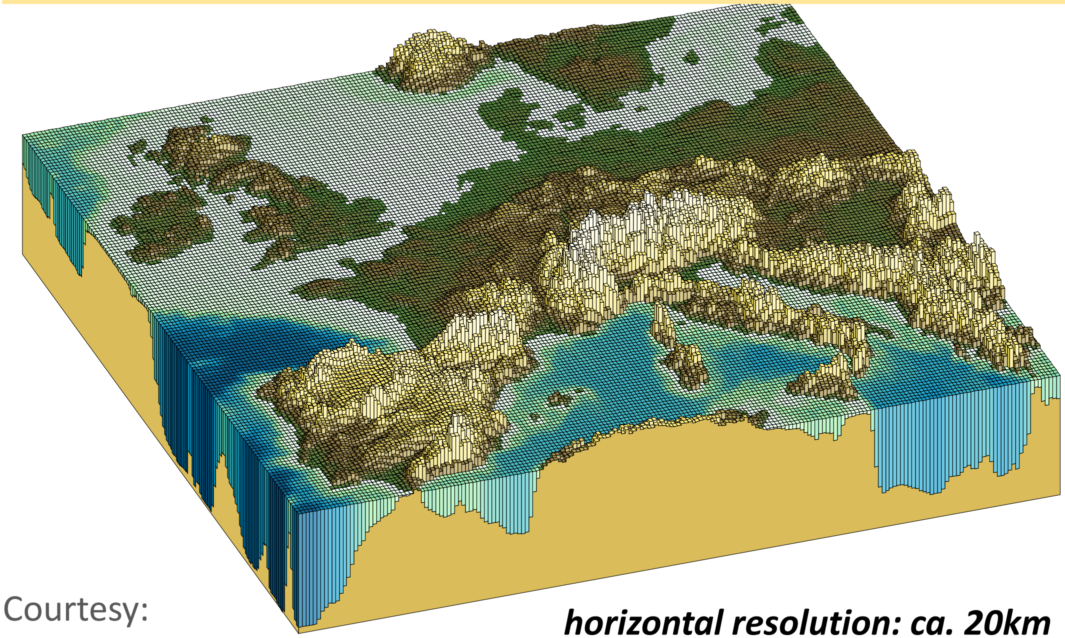
We perform all these computations every 5-30 minutes, for every single box. **We need very large computers !**

Global Modelling at RCM resolutions: Europe as seen by a GCM



horizontal resolution: ca. 110km

Cost of doubling resolution: a factor of 10!



horizontal resolution: ca. 20km

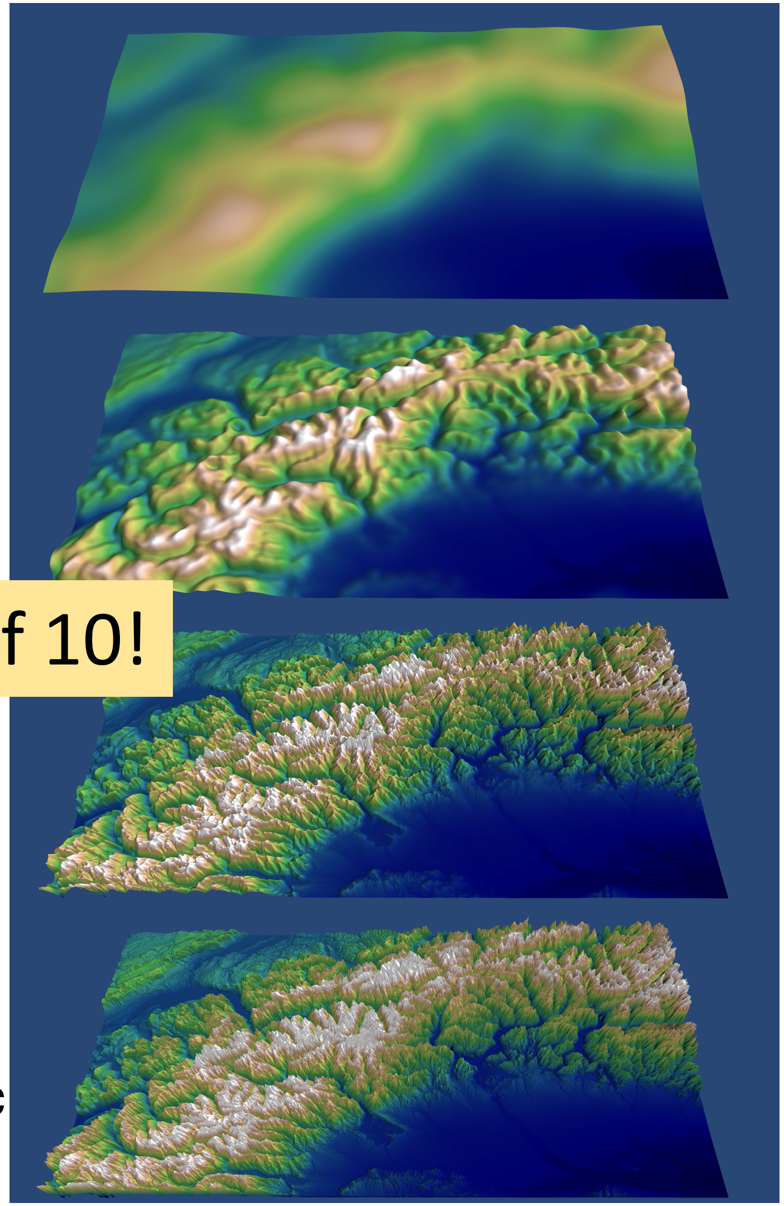
Courtesy:
Uwe Schulzweida, MPI-M

150km

25km

5km

SAR
30sec



The Alps in our GCMs (P.L. Vidale)

Where it all started: the advent of Numerical Weather Prediction

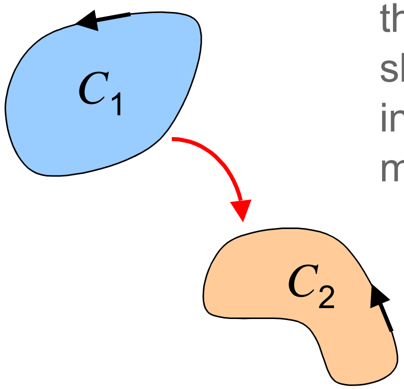
Circulation Theorem:

Circulation:

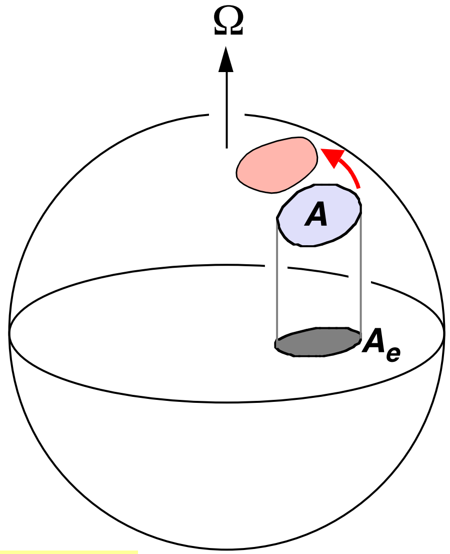
$$C = \oint \mathbf{v} \cdot \mathbf{ds}$$

Kelvin's Theorem:

$$\frac{dC}{dt} = 0$$



In 1904, Bjerknes proposed that „weather forecasting should be considered as an initial value problem of mathematical physics".

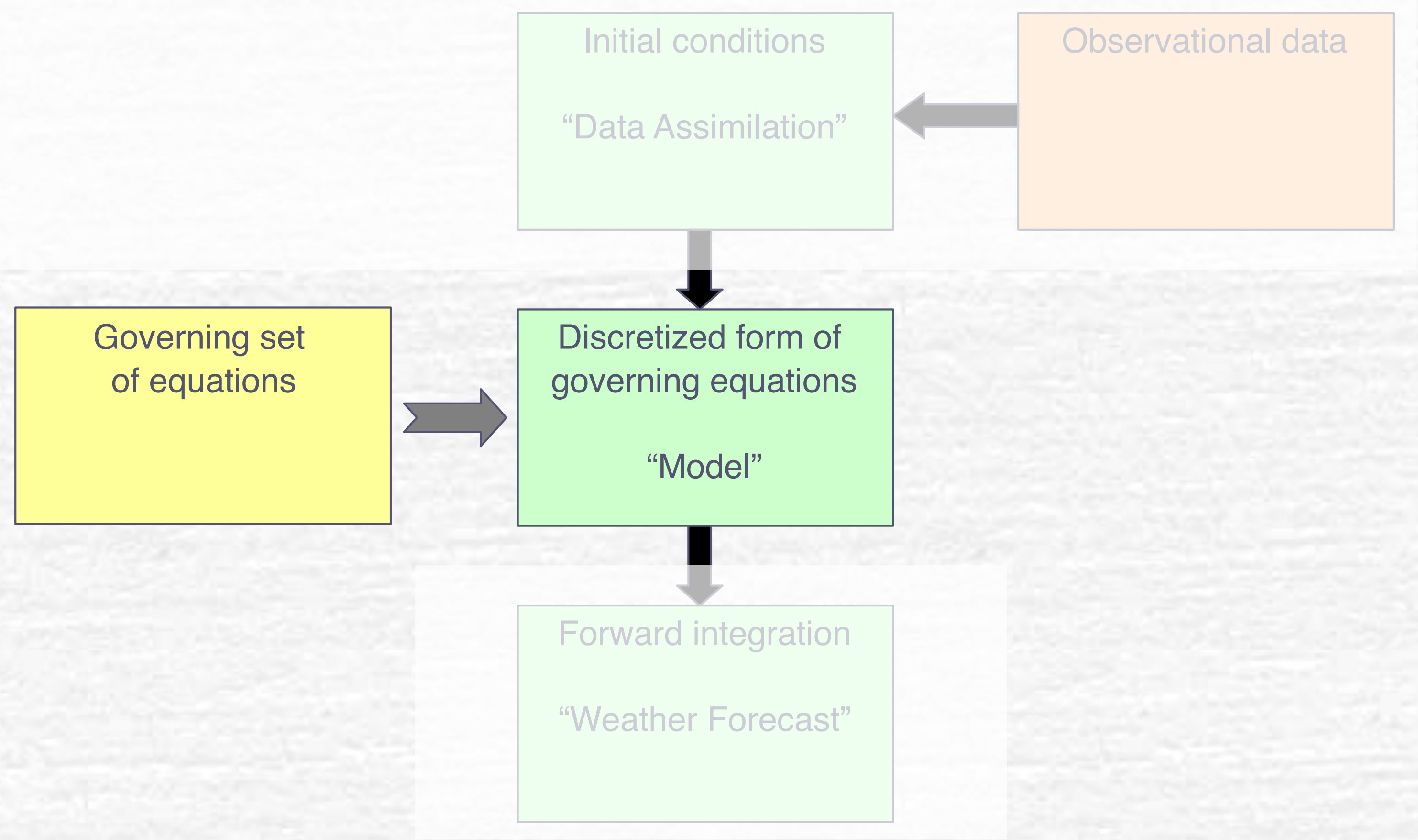


Vilhelm Bjerknes (1862-1951)

Bjerknes' Theorem:

$$\frac{dC}{dt} = \underbrace{-2\Omega \frac{dA_e}{dt}}_{\text{Earth's rotation}} \underbrace{- \oint \rho^{-1} dp}_{\text{baroclinic effects}}$$

Ingredients of Weather Forecasting



"Euler Equations"
in Cartesian Coordinates

Newton

Momentum equations

$$\boxed{\begin{aligned}&\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F_x\\&\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F_y\\&\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_z\end{aligned}}$$

With:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

Equation of state

$$\boxed{p = \rho R T}$$

Ideal gas law

Thermodynamic equation

$$\frac{DT}{Dt} - \frac{1}{c_p \rho}\frac{Dp}{Dt} = H$$

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial x} + \frac{\partial (v\rho)}{\partial y} + \frac{\partial (w\rho)}{\partial z} = 0$$

Equations for specific water vapor and cloud water content

$$\frac{Dq_{vap}}{Dt} = S_{vap} \qquad \frac{Dq_{cld}}{Dt} = S_{cld}$$

Externally specified quantities

$$(F_x, F_y)/\rho \qquad H/c_p$$

"Euler Equations" in Cartesian Coordinates

Momentum equations

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F_x \qquad \frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F_y$$

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_z$$

with $\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$

Equation of state

$$p = \rho$$

diabatic

Thermodynamic equation

$$\boxed{\frac{DT}{Dt} - \frac{1}{c_p \rho}\frac{Dp}{Dt} = H}$$

adiabatic

Continuity equation

$$\frac{\partial \rho}{\partial t} \quad \frac{}{\partial x} \quad \frac{}{\partial y} \quad \frac{}{\partial z} = 0$$

Equations for specific water
Vapor and cloud water content

$$\frac{Dq_{vap}}{Dt} = S_{vap} \qquad \frac{Dq_{cld}}{Dt} = S_{cld}$$

Externally specified quantities

$(F_x, F_y)/\rho \qquad H/c_p$

Sadly, there are no analytical solutions to the Euler equations.
How can we solve the governing equations with a digital computer?

Finite Difference Method

Example: linear one-dimensional transport equation for quantity $\phi(x,t)$ and velocity u.

partial differential equation $$\frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x} = 0 \qquad (u = const)$$

Discretization in space; grid spacing Δx: $$\phi_j(t) := \phi(j\Delta x, t)$$

coupled system of ordinary differential equations $$\frac{\partial \phi_j}{\partial t} + u \frac{\phi_{j+1} - \phi_{j-1}}{2\ \Delta x} = 0$$

Discretization in time; time step Δt:

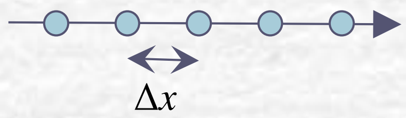
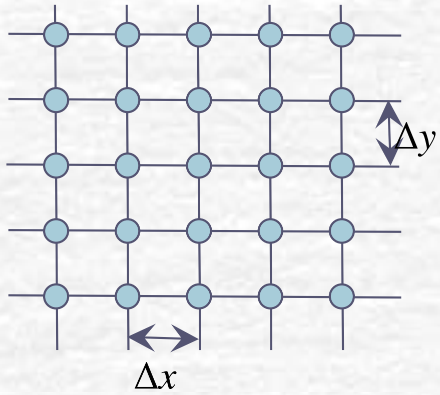
coupled system of finite difference equations $$\frac{\phi_j^{n+1} - \phi_j^{n-1}}{2\ \Delta t} + u \frac{\phi_{j+1}^n - \phi_{j-1}^n}{2\ \Delta x} = 0$$

Solve for ϕ^{n+1}

time-stepping algorithm $$\phi_j^{n+1} = \phi_j^{n-1} - \frac{u\ \Delta t}{\Delta x}\left[\phi_{j+1}^n - \phi_{j-1}^n\right]$$

What numerical scheme is the one above?

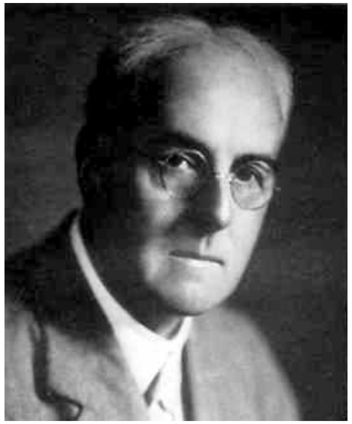
Discretisation in Cartesian Coordinates: going from 1D to 2D domains

Continuous	Discretized	Schematics
$T(x)$	$T(x_i)$ with $x_i = i\Delta x$	
$T(x,y)$	$T(x_i, y_j)$ with $x_i = i\Delta x$, $y_j = j\Delta y$	

This is why the **computational costs arise with model resolution** (10x for each doubling):
Increasing resolution (decreasing mesh size) requires:

1 a shorter time step (so, more frequent computations)
2 a larger number of computations (more points)
3 more memory and more access to memory (bottleneck)
4 more storage and more + more frequent access to storage (slow and expensive)

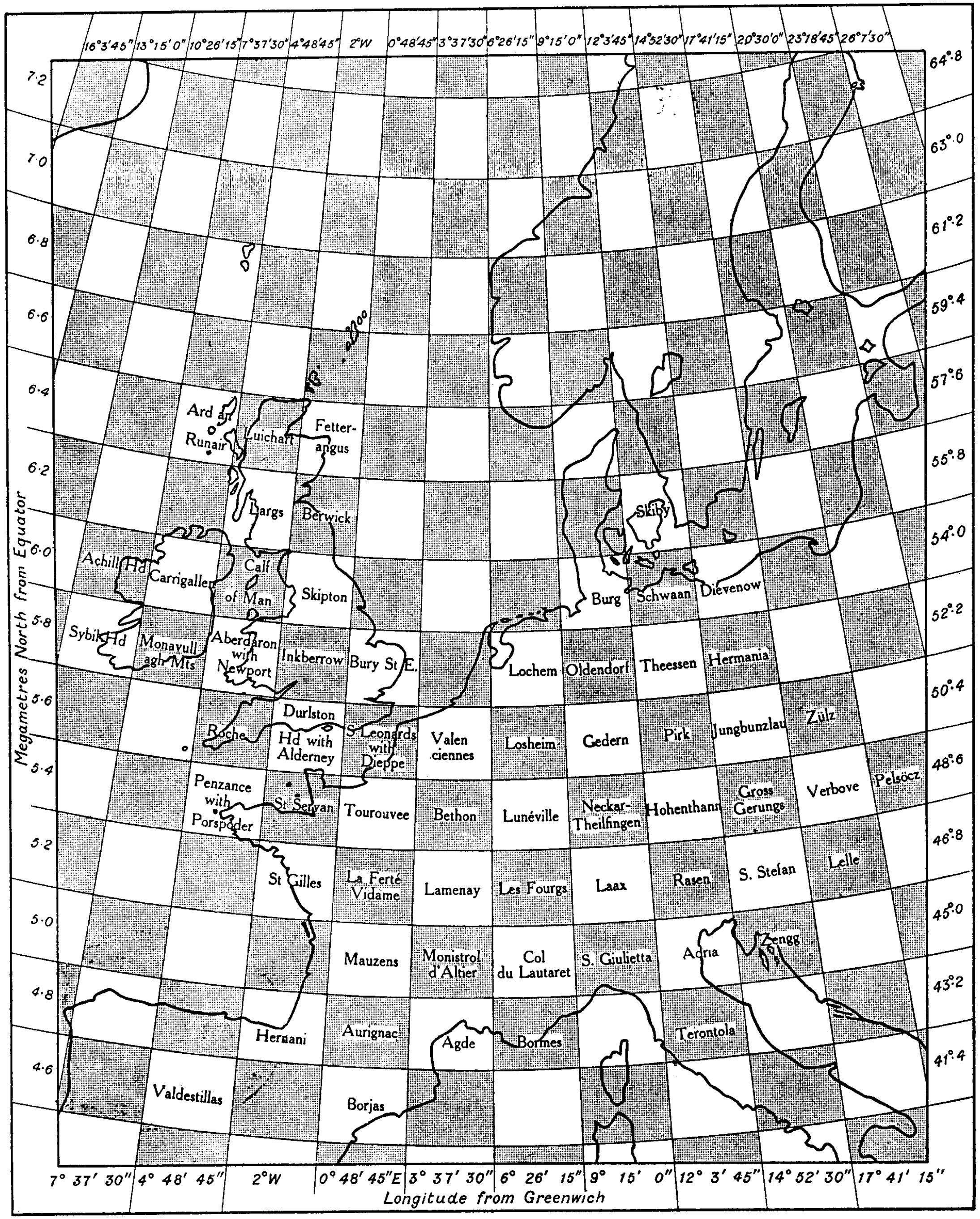
Making it practical to weather forecasting: Lewis F. Richardson (1881-1953)



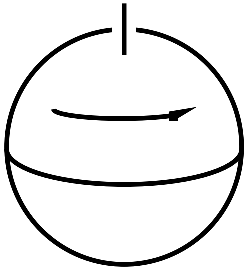
In 1922, Richardson provided the first formulation of the atmospheric equations on a computational grid.

"If the coordinate chequer were 200 km square in plan, ... 64'000 computers would be needed to race the weather. In any case, the organisation indicated is a central forecast-factory."

His one attempt, between two grid points, failed because of poor initial data and computational instability. FILTERED equations were necessary.



Anisotropy of Earth's Atmosphere



Diameter: 12'700 km
Depth of
troposphere: 10 km

requires $\Delta z \ll \Delta x, \Delta y$

Diameter: ~5 cm
Depth: 0.04 mm

Critical velocities

~300 m/s	sound propagation
~100 m/s	horizontal wind velocity
~20 m/s	vertical gravity-wave (buoyancy-wave) propagation

Numerics: Courant-Friedrichs-Levy (CFL) stability criterion $\left|\frac{U \quad \Delta t}{\Delta z}\right| \leq 1$

where U denotes largest velocity in system

would require $\Delta t \leq 0.1$ s

- Here is the first hint of the trouble with Richardson's calculations: he used an unfiltered (primitive eqns.) system

Example of filtering approach for large-scale models: Hydrostatic approximation

Vertical momentum equation:

$$\cancel{\frac{dw}{dt}} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + \cancel{F_z}$$

Balance between pressure-force and gravity,
neglect vertical acceleration

Implications:

- Suppresses vertical sound propagation
- w must be diagnosed from continuity equation (diagnostic variable)
- much easier to maintain time-step criterion
- BUT: only valid for $\Delta x >\sim 10$ km

Second bit of trouble: system of coupled differential equations, even heavily filtered, has strong sensitivity to initial conditions AND the fact that a large range of scales are treated as "sub-grid" makes it so that our initial conditions contain a lot of uncertainty

Stability of discretized solutions

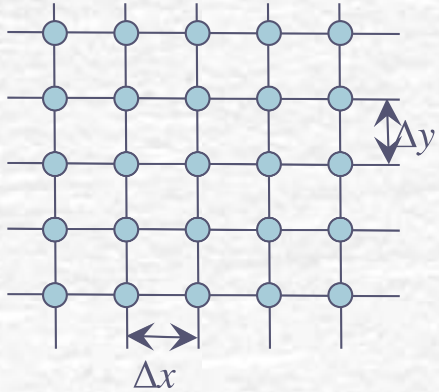
Time-stepping algorithm

$$\phi_j^{n+1} = \phi_j^{n-1} - \underbrace{\frac{u \ \Delta t}{\Delta x}}_{\alpha \text{ = Courant Number}} \left[\phi_{j+1}^n - \phi_{j-1}^n\right]$$

The Courant number is a dimensionless parameter that depends upon the (somewhat arbitrary) choice of Δx and Δt. For most numerical time-stepping algorithm, it determines the numerical stability of the algorithm.

Courant-Friedrichs Levy (CFL)
<u>stability</u> criterion

$$\left|\frac{u\Delta t}{\Delta x}\right| \leq 1$$



Thus, the information must travel not further than one grid-point per time-step.
Changing the grid-spacing requires changing the time-step!

This is one of the primary reasons why high-resolution numerical models are so expensive

Model Grid Size (km) & Computing Capability: our 2008 predictions

	Earth Simulator 2002-2009		PRACE-HERMIT 2012-	EU-PRACE ECMWF Met Office 2016-	
Peak Rate:	**10 TFLOPS**	**100 TFLOPS**	**1 PFLOPS**	**10 PFLOPS**	**100 PFLOPS**
Cores	**1,400 (2005)**	**12,000 (2007)**	**80-100,000 (2009)**	**300-800,000 (2011)**	**6,000,000? (20xx?)**
Global NWP^0: 5-10	**18 - 29**	**8.5 - 14**	**4.0 - 6.3**	**1.8 - 2.9**	**0.85 - 1.4**
S 50-100					**1.3**
D 5-1					**.2**
Change^2: 20-50 yrs/day	**120 - 200**	**57 - 91**	**27 - 42**	**12 - 20**	**5.7 - 9.1**

* Core counts above O(10^4) are unprecedented for weather or climate codes, so the last 3 columns require getting 3 orders of magnitude in scalable parallelization

teraFLOPS = 10^{12} (trillion) floating point operations per second
petaFLOPS = 10^{15} (quadrillion) floating point operations per second
exaFLOPS = 10^{18} (quintillion) floating point operations per second

Range: Assumed efficiency of 10-40%
0 - Atmospheric General Circulation Model (AGCM; 100 vertical levels)
1 - Coupled Ocean-Atmosphere-Land Model (CGCM; ~ 2X AGCM)
2 - Earth System Model (with biogeochemical cycles) (ESM; ~ 2X CGCM)

Thanks to Jim Abeles (IBM)

A few dynamical core types currently in use

Finite differences

Simplest conceptually

Often grows in complexity to try and increase efficiency and quality of solution

Cost: O(N)

(Unified Model, IPSL)

Finite volumes

Built to conserve properties

Complexity in flux formulation

Good performance, Cost: O(N)

NCAR CESM (oldish)

Spectral

Efficient, also thanks to fast Legendre transform, despite potential Cost: $O(N^2)$, in reality O(N logN)

Enables scale discrimination

No conservation at all

ECMWF-IFS, ECEarth, MRI, old NCAR CCSM

Finite elements

Efficient, Cost: O(N)

Complex

Conservation can be achieved

New NCAR model, LFRIC

Conservation is important for studying the climate system. However…

The continuity equation implies:

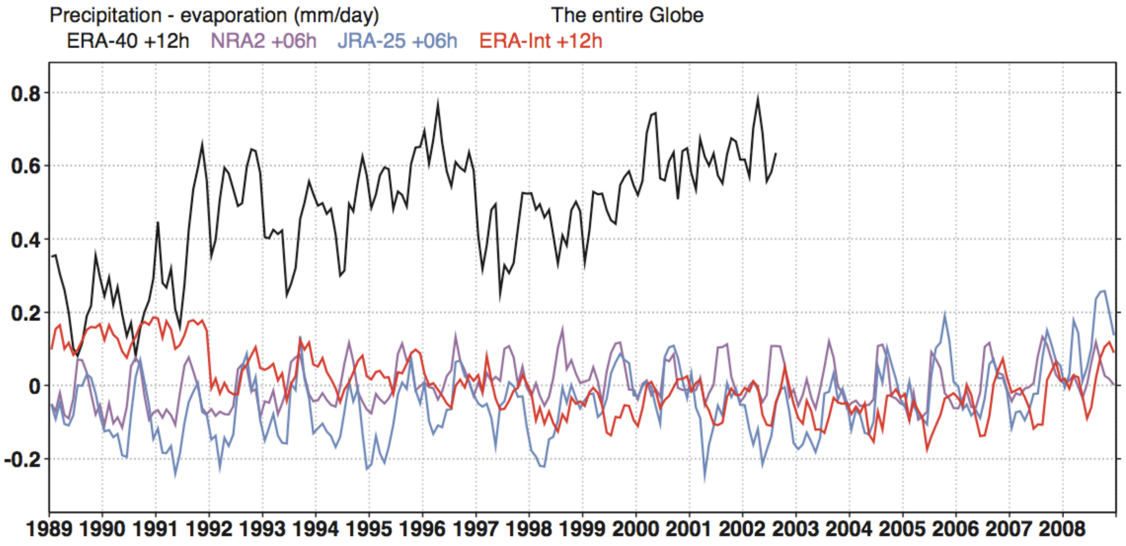
$$\frac{\partial W}{\partial t} = E - P - \nabla \cdot qU$$

Over long time periods, globally:

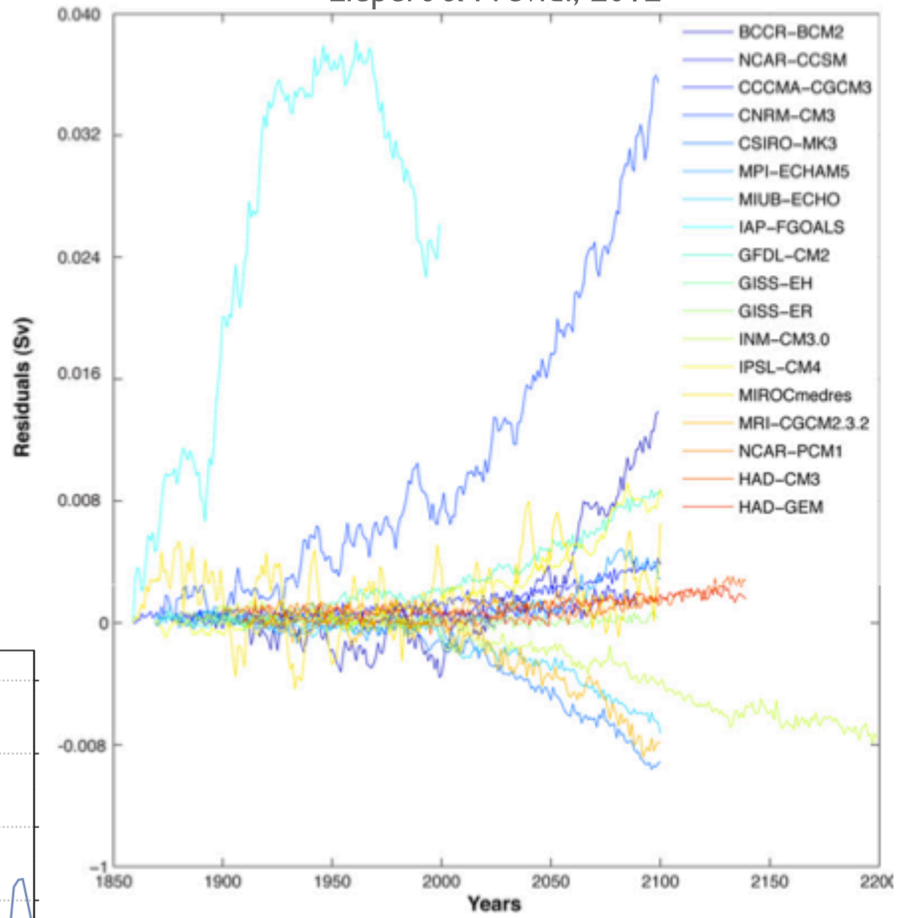
$E - P = 0$

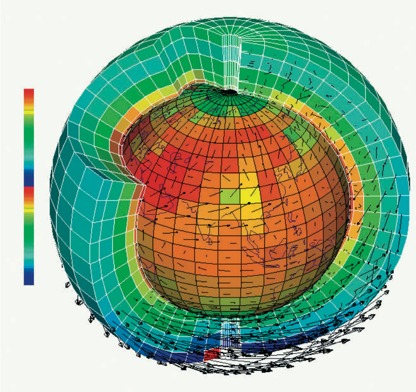
Sadly, not the case in most GCMs…

Re-analyses (Demory et al. 2013)



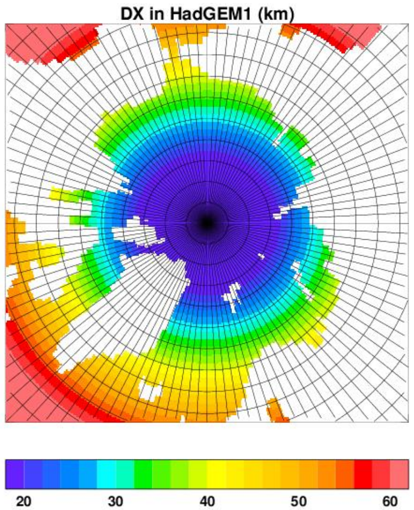
IPCC models
Liepert & Previdi, 2012

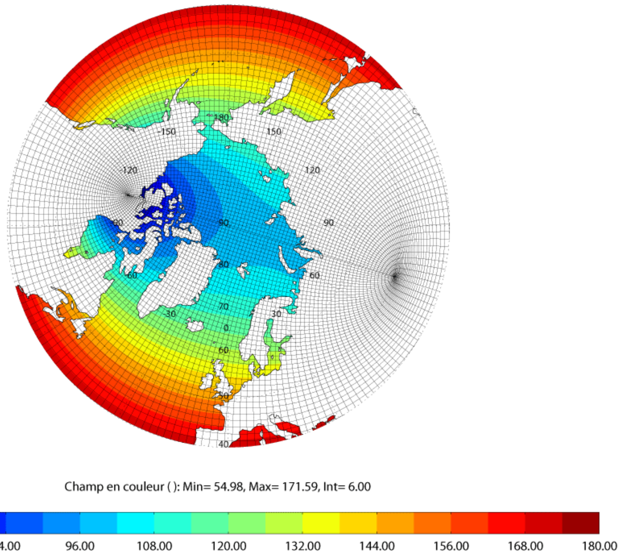


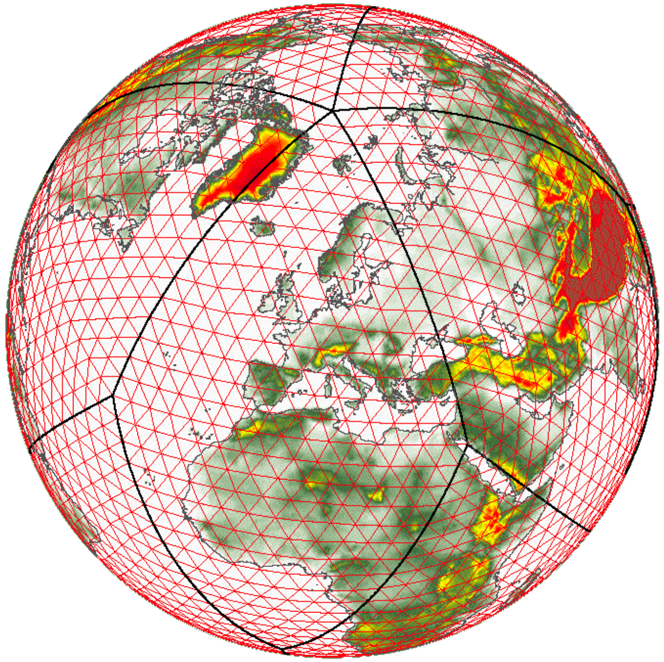


Some popular grid topologies

- UM (HadGOM1, HiGOM) ocean model assumes a regular lat-lon grid which leads to a **singularity at North and South Poles** (and associated numerical costs and instabilities)
- NEMO and CICE models have a generalised grid defined by corners, scale factors (grid sizes) and areas
- The tripolar grid most commonly used in NEMO has two poles in Northern Hemisphere and one at South Pole. Grids using same position for poles are ORCAx grids where x is nominal resolution.







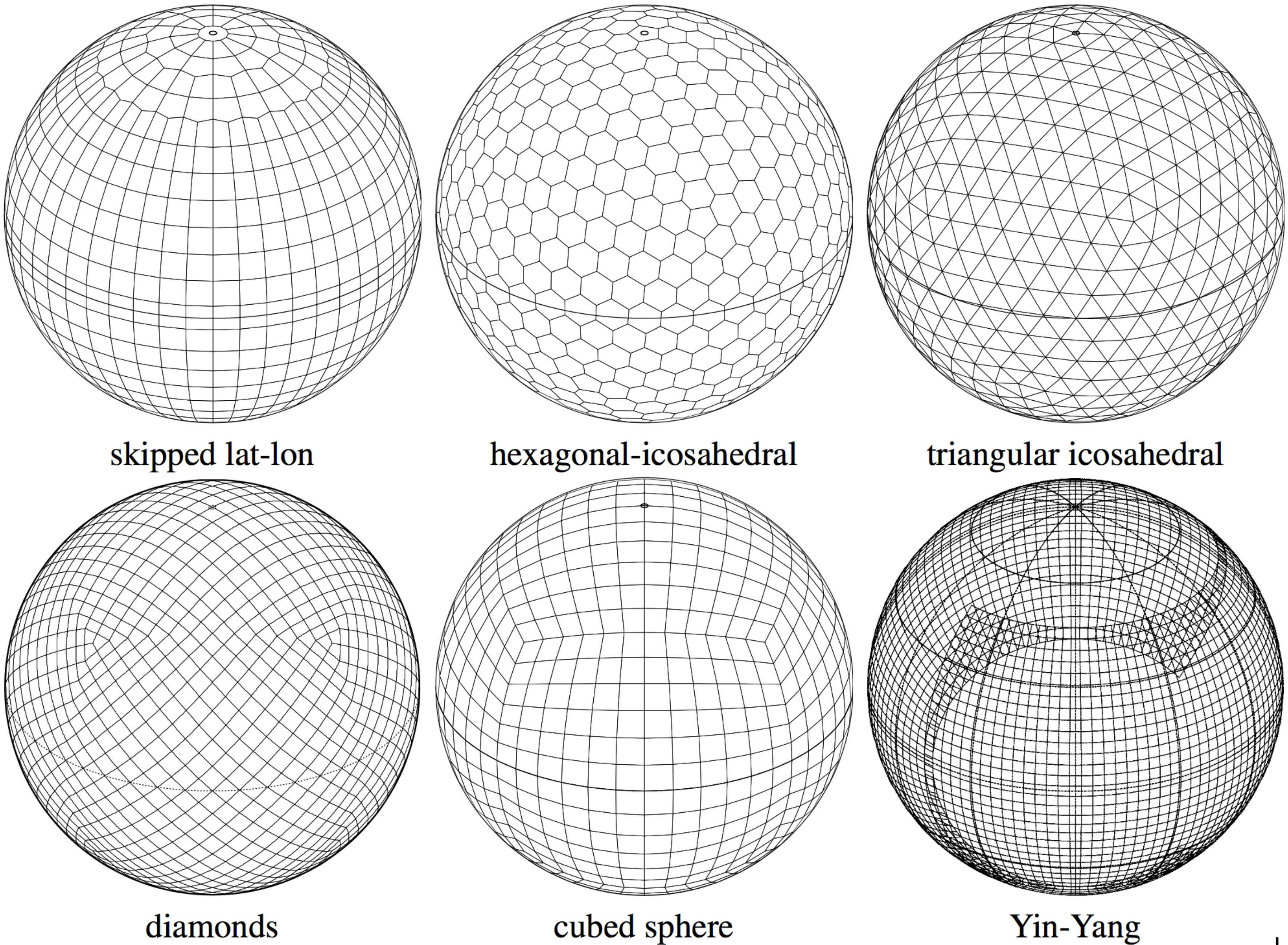
This grid is constructed from a projection of an icosahedron on the sphere, and subsequent refinement of the 20 triangles.

Dynamics not as simple, nor as accurate, as the good old lat/lon grid… but this is less and less important as we increase resolution

Variants used by the German Weather Service, US groups (CSU, NCAR) and Japanese NICAM group.

More popular grid topologies

Quasi-Uniform Horizontal Grids to avoid the Pole Problem

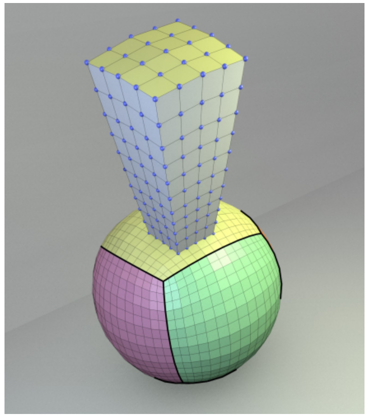


H. Weller

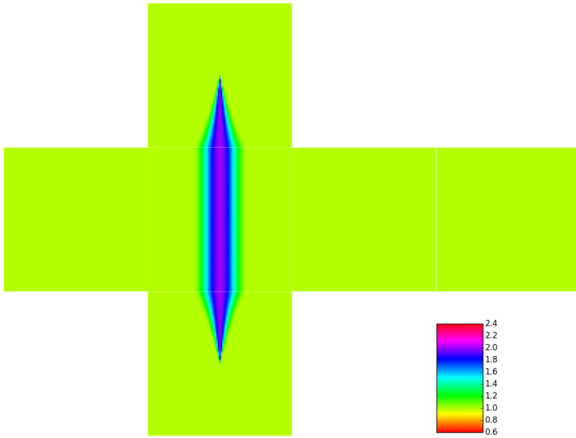
Next-generation UK dynamical core

GungHo: the design

- Quadratic mesh
  - Cubed sphere/diamond mesh

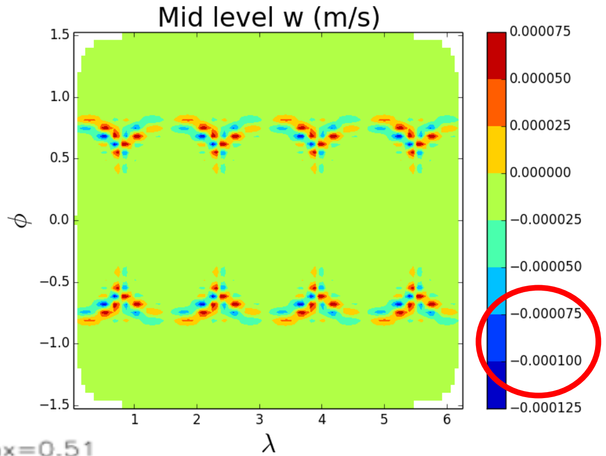


- Mixed finite elements (see next slide)
- Semi-implicit
- Conservative transport

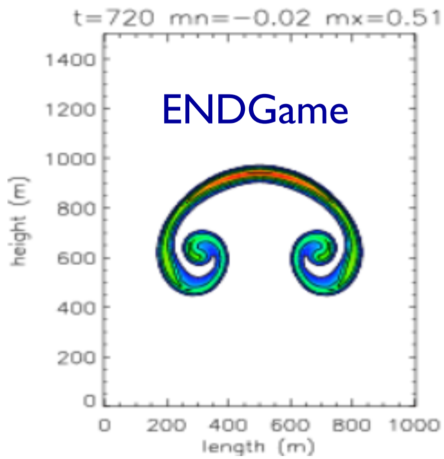


Some early GungHo results

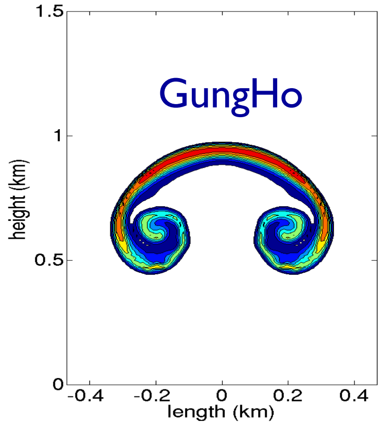
- 20 m/s Solid Body Rotation
- C24L30 (400kmx10km)
- After 20 mins



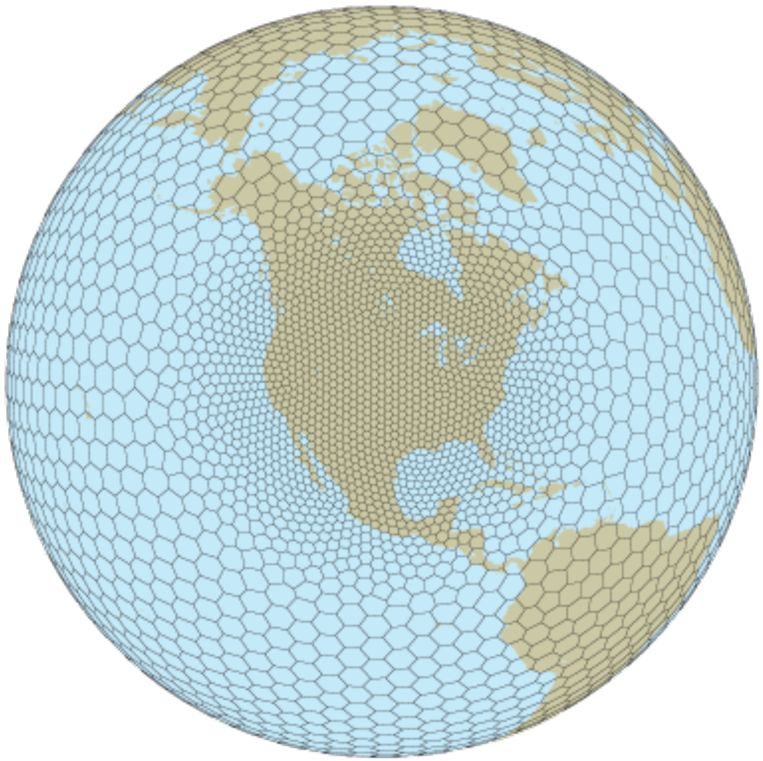
0.1 mm/s



Robert bubble test 10m resolution after 12 mins



Other future trends



A variable resolution MPAS Voronoi mesh

The MPAS atmosphere consists of an atmospheric fluid-flow solver (the *dynamical core*) and a subset of the Advanced Research WRF (ARW) model atmospheric physics. Work is underway to port the MPAS atmospheric dynamical core to the Community Atmosphere Model (CAM) in the Community Earth Systems Model (CESM), which will provide coupling between MPAS Ocean and MPAS Atmosphere and coupling to the CAM physics and other components of the CESM system. Work is also progressing on porting the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) atmospheric physics to MPAS.

CAM-SE uses the spectral element method on a cubed-sphere grid to discretize in the horizontal direction [Dennis et al., 2012]. Cubed-sphere grids provide for quasi-uniform mesh spacing over the entire surface of the globe. This eliminates issues that arise from the use of traditional latitude-longitude grids such as the convergence of meridians in polar regions which requires either extremely short time steps or polar filtering to satisfy numerical stability constraints.

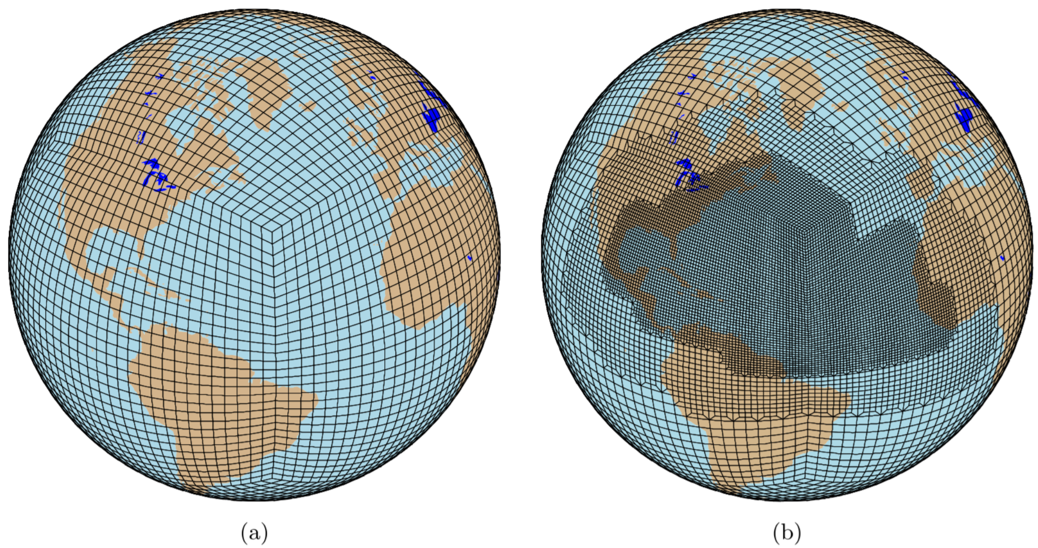


Figure 1. The two meshes used for this study are (a) a uniform 1° resolution mesh and (b) a variable-resolution mesh that ranges from 1° → 0.25°. Note that each element shown in the above plots contains additional 3 × 3 collocation cells.

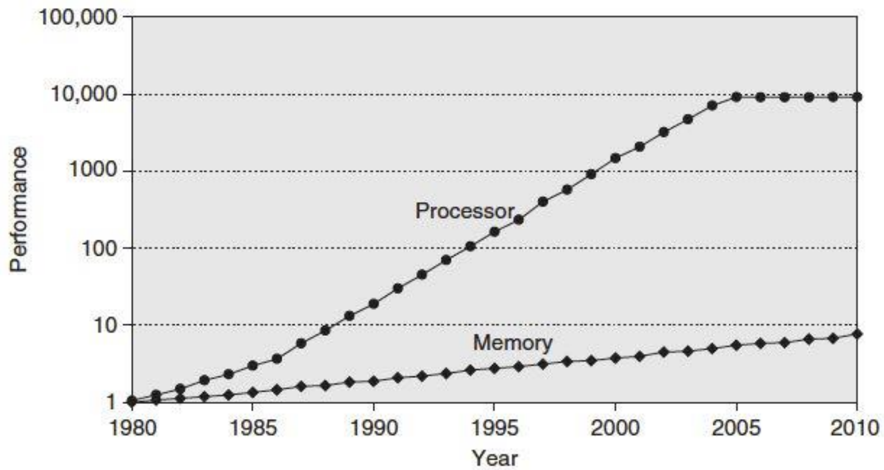
Special CAM-SE set-up to study hurricanes
ZARZYCKI AND JABLONOWSKI, 2014

Moore's law has reached the end of the road… and there is worse

Source: Hennessy & Patterson, 2011

The memory wall

- Off-chip memory bandwidth is not increasing at the same rate as FLOP performance



Moore's law has reached the end of the road… and there is worse

Consequence for climate models

- "Dynamics" code (niter = 48, nwork = 4096000)

```
do j = 1, niter
  do i = 1, nwork
    c(i) = a(i) + b(i) * ( a(i+1) - 2.0d0*a(i) + a(i-1) )
  end do
end do
```

$$\frac{\partial a}{\partial t} = k\frac{\partial^2 a}{\partial x^2}$$

Machine	Cray XT4	Cray XT5	Cray XE6	Cray XK6
# cores	4	6	12	16
Single core	0.80 s	0.84 s	0.63 s	0.65 s
All cores	0.56 s	0.46 s	0.18 s	0.16 s
Speedup	**1.4**	**1.8**	**3.4**	**4.0**
	1.4/4=0.35	1.8/6=0.30	3.4/12=0.28	4/16=0.25

Much much worse

For a 1-year global climate simulation:

A modern simulation's costs are O(MW) hours per simulated year (MWh/SY)
Piz Daintz simulation power draw: 2MW; TaihuLight simulation: 15MW

A conventional **cloud-resolving simulation** would cost about 3000 MWh/SY, nearly the amount of energy used by 900 households in one year.

A novel, energy-efficient **cloud-resolving simulation (DX=930m)** with COSMO costs about 596 MWh/SY **

$\langle \Delta x \rangle$	#nodes	Δt [s]	SYPD	MWh/SY	gridpoints
930 m	4888	6	0.043	596	3.46×10^{10}
1.9 km	4888	12	0.23	97.8	8.64×10^{9}
47 km	18	300	9.6	0.099	1.39×10^{7}

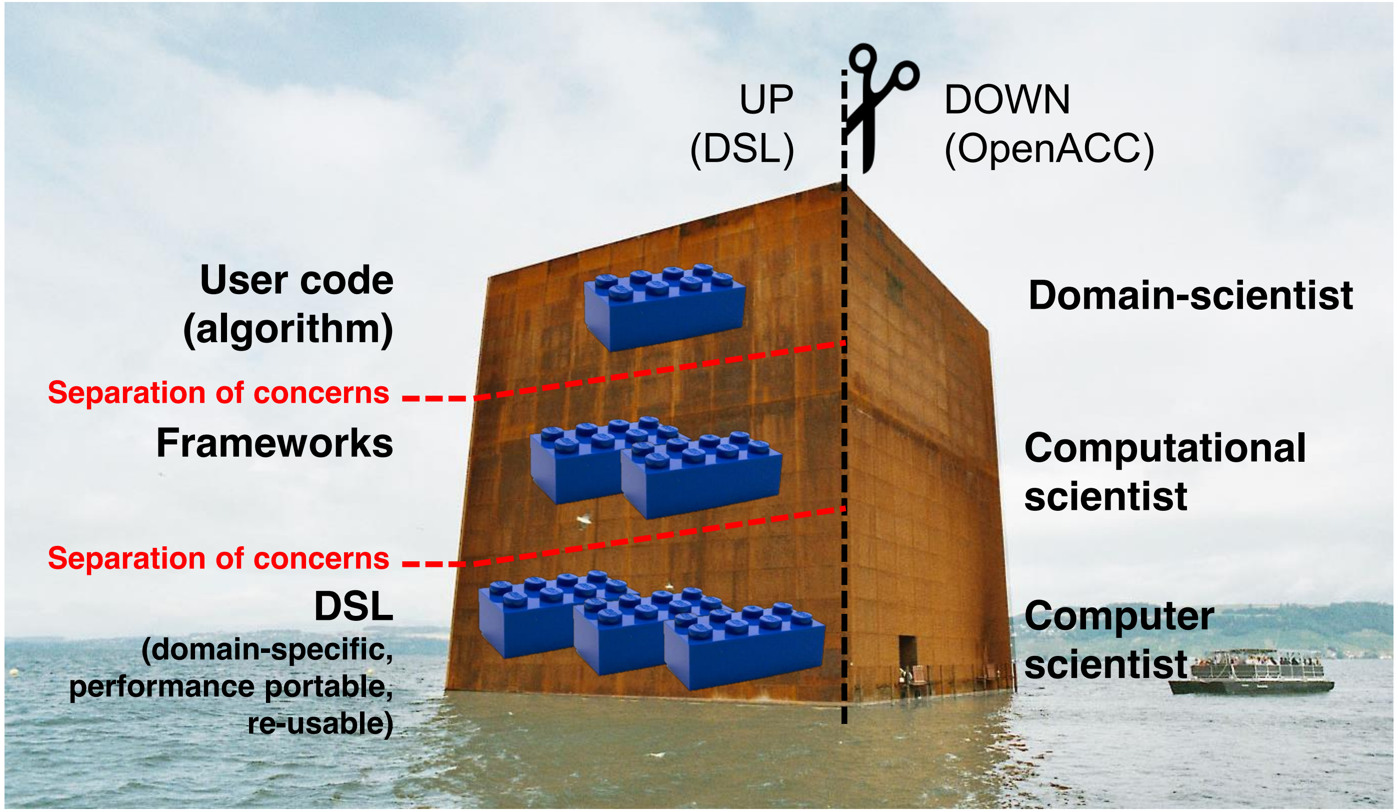
(see Fuhrer et al., GMD Discussions, 2017

Power output of the Didcot power plant: 3'360MW

**for AMIP = 22GWh (6500 households for one year)

We can also go for an integrated hardware-software solution

- Example: COSMO



We can also go for an integrated hardware-software solution

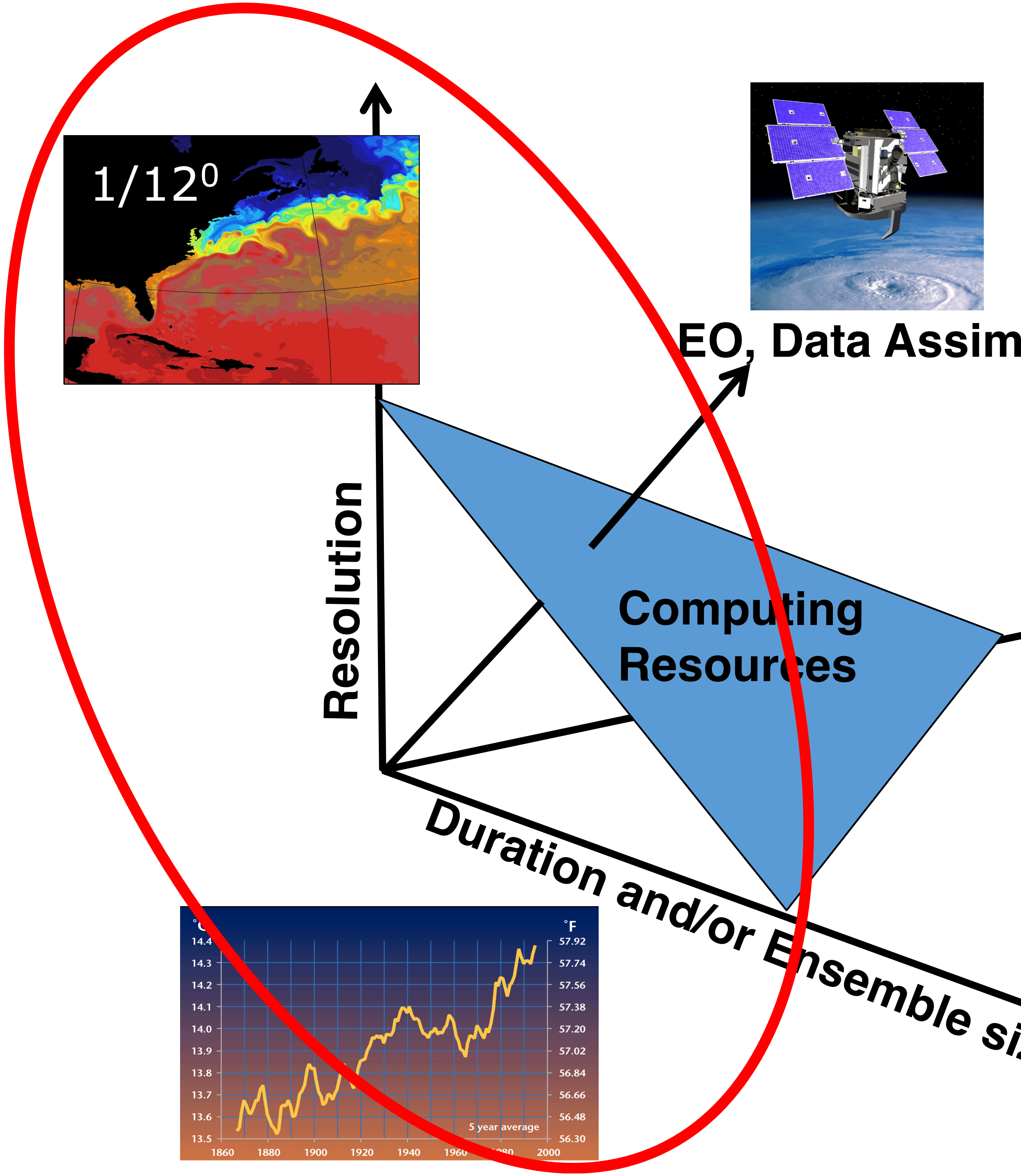
- Traditional vs. next-generation?

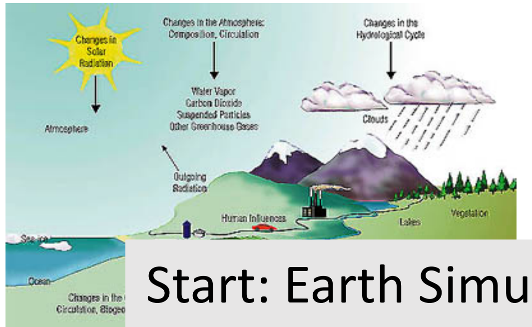
	Piz Dora (old code)	**Piz Kesch (new code)**	Factor
Sockets	~26 CPUs	~7 GPUs	**3.7 x**
Energy	10 kWh	2.1 kWh	**4.8 x**

→ Investment into hardware **and software**!

Hardware	~ 2-3 MCHF
Software (projects, in-kind)	~ 5-7 MCHF

The UK High-Resolution Global Climate Modelling programme



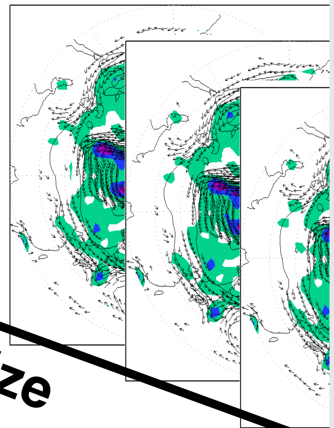


Start: Earth Simulato

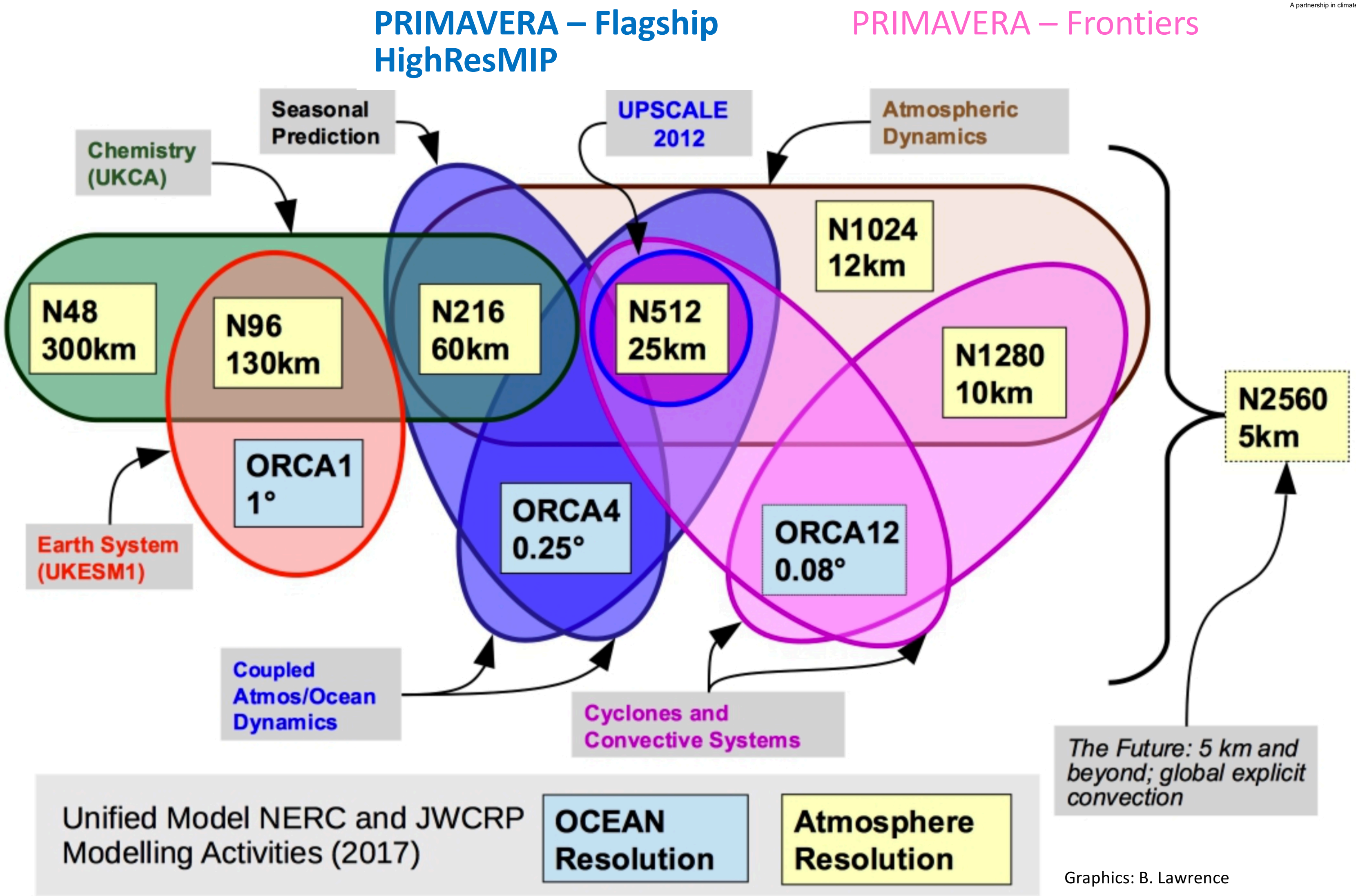
2012 PRACE-**UPSCAL**
resources to do what
rather than trying to
round hole".

144 million core hou

UPSCALE AGCM (GA
5 ensemble member
N216(60k **N5**
future climates.



Our fleet: MetUM global atmosphere / coupled model climate configurations in use



Graphics: B. Lawrence

Essentially <u>the same</u> physics/dynamics parameters used throughout model hierarchy

Main <u>capability</u>:

Seamless prediction, enabling pursuit of traceable chain of mechanisms http://www.primavera-h2020.eu

Strategy:

- Develop a new generation of well-evaluated high-resolution global climate models, capable of simulating and predicting regional climate with unprecedented fidelity
- Coordinated multi-model approach, within Europe and via CMIP6
- Lead and deliver a new protocol: CMIP6-HighResMIP
  - to **develop and run multi-model ensembles of global atmosphere-only and coupled simulations beyond current resolution frontiers**
- Co-design with end-users in 3 key sectors: energy, transportation, insurance

The analysis challenge:

- Minimum HighResMIP set will require 670 million core hours (ARCHER), 8 PB data
  - Our previous project, UPSCALE: 144M core hours (HERMIT) = 260M (ARCHER), 400 TB data
- Fast (parallel), specialised process-based analysis will be a crucial component, in order to extract science in time for CMIP6
  - Need large, dedicated analysis server, e.g. CEDA-JASMIN
  - Need to strongly enhance our parallel analysis capability

PRIMAVERA: open science questions

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather & Climate Research Programme

A partnership in climate research

- What processes emerge as we increase resolution in the ocean and in the atmosphere?
- Do these finer scale processes, missing in IPCC-class GCMs, affect the simulation of the <u>global</u> climate system?
- Can we produce more trustworthy predictions of climate change if we increase our models' resolution?
  - Are unresolved (missing) processes involved in:
    1. **Teleconnections**, e.g. ocean → land water transport, ENSO
    2. **Decadal variability**, e.g. Sahel rainfall recovery
  - Can we compute robust predictions of the risk of extremes?
    - Hurricanes/typhoons, flooding/drought, windstorms, heatwaves

Roadmap:

UK-Japan Climate Collaboration, HiGEM	UK JWCRP **High Resolution Global Climate Modelling**	PRACE EU-PRACE **UPSCALE**	EU-Horizon 2020 **PRIMAVERA**
2005-2007	2008-	2012-2013	PIs: M. Roberts and P.L. Vidale

Malcolm Roberts, Met Office (coordinator)
Pier Luigi Vidale, Univ. of Reading (scientific coordinator)

PRocess-based climate s**IM**ulation: **A**d**V**ances in high resolution modelling and **E**uropean climate **R**isk **A**ssessment

Goal: **to develop a new generation of advanced and well-evaluated high-resolution global climate models, capable of simulating and predicting regional climate with unprecedented fidelity, for the benefit of governments, business and society in general.**

HighResMIP is a key deliverable in PRIMAVERA

Core integrations in PRIMAVERA will form much of the European contribution to CMIP6 HighResMIP, which is led on behalf of WGCM by PRIMAVERA PIs.

PRIMAVERA core experiments (HighResMIP) and "Frontiers" simulations

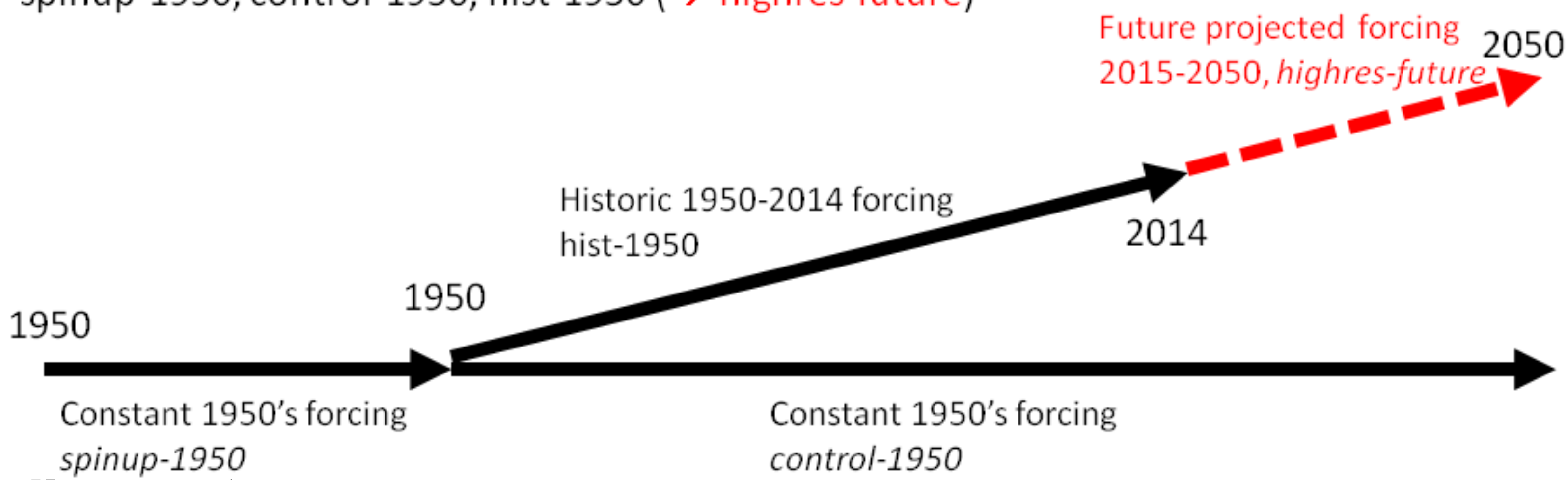
Institution	MO NCAS	KNMI IC3 SMHI CNR	CERFACS	MPI	AWI	CMCC	ECMWF
Model names	MetUM NEMO	ECEarth NEMO	Arpege NEMO	ECHAM MPIOM	ECHAM FESOM	CCESM NEMO	IFS NEMO
Atmosph. Res., core	60-25km	T255-799	T127-359	T63-255	T63-255	100-25km	T319-799
Atmosph. Res., FCM	10-5km						T1279-2047
Oceanic Res., core	¼°	¼°	¼	0.4-¼°	1-¼ spatially variable	¼	¼
Oceanic Res., FCM	1/12°	1/12°	1/12°	1/10°	1-1/14° spatially variable	*(1/16°)*	

PRIMAVERA simulations to be submitted to CMIP6-HighResMIP

Atmosphere-land-only, 1950-2014 (→ 2050)
Forced by observed SST and sea-ice and historic forcings (→ projected)
highresSST-present (→ highresSST-future)

Generating up to 8PB of data, to be analysed for the next IPCC report (AR6)

Coupled climate, 1950-2014 (→ 2050)
Forced by constant 1950 and historic forcings (→ projected)
Initial coupled spin-up period ~ 30-50 years from 1950 EN4 ocean climatology
spinup-1950, control-1950, hist-1950 (→ highres-future)



Summary of Global Climate Modelling at the Petascale

- From High Resolution to High Fidelity: beautiful pictures are not enough.
- Focus on producing and <u>understanding:</u>
  i) trustworthy, ii) traceable and iii) reproducible results.
  - **Emerging processes** and **scale interactions**
    - Intense cyclones (tropical, extra-tropical)
    - Eddies and their transports
    - Convective organisation
  - <u>QUESTION: what is the impact of emerging processes on the larger scales?</u>

  $\Rightarrow$ need high-resolution global climate simulations over centennial time scales

- International collaboration on the workflow from simulation to analysis is key to scientific outputs:
  - From PRACE-UPSCALE to PRIMAVERA and HighResMIP
  - WCRP, US CLIVAR Hurricane Working Group, ENES
  - EPECC
- Scientific leadership:
  - Now leading a new protocol for CMIP6: HighResMIP

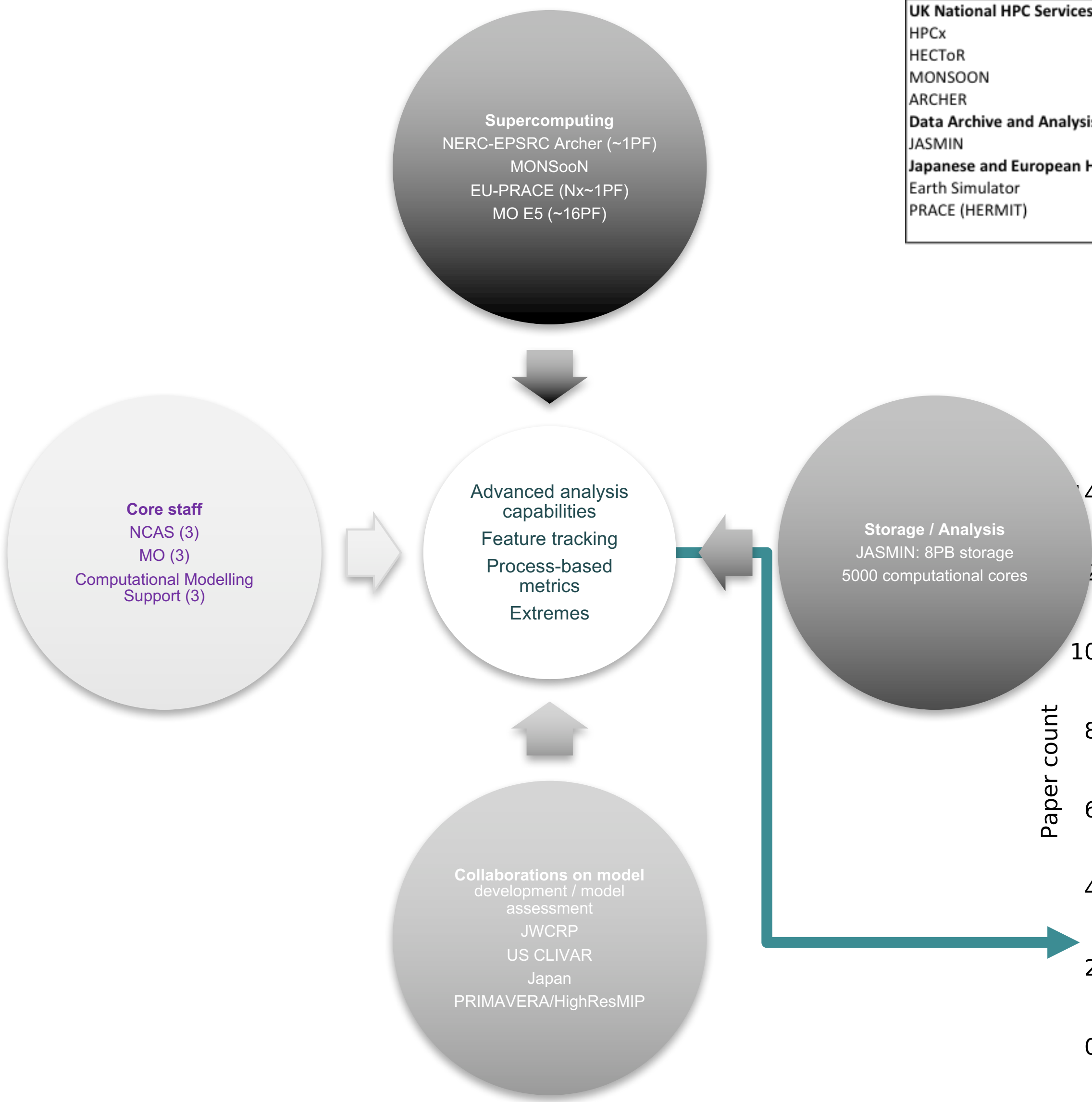
Resources / Investments

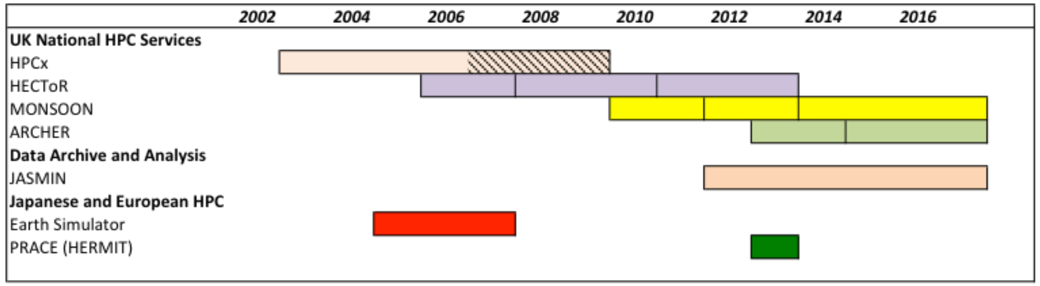
The UK's JWCRP High Resolution global Climate Modelling has required large, sustained investments over decadal time scales

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

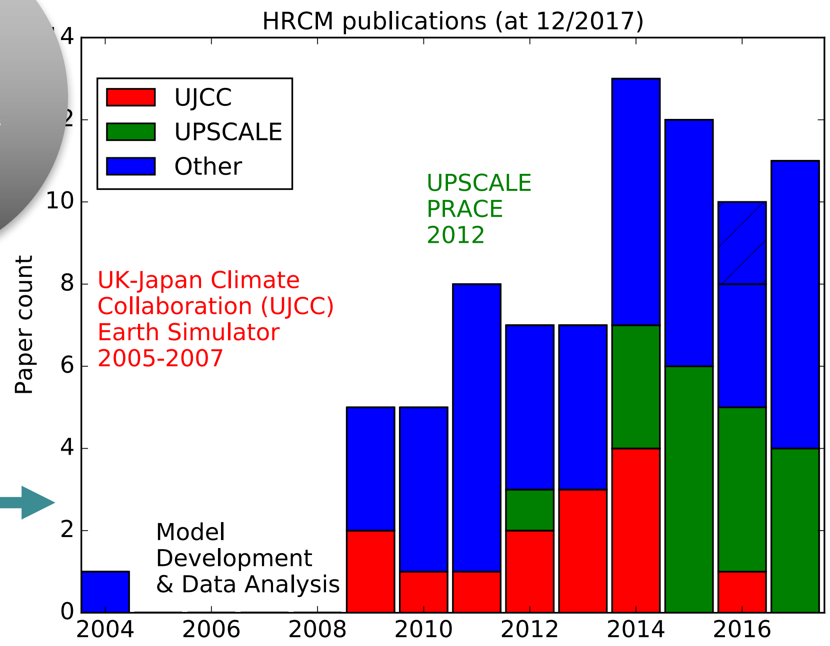
Joint Weather and Climate Research Programme

A partnership in climate research





Publication timing lags experimental design/execution by several years, which is a challenge for University academics. Publication impact, however, is high.



The future

Joint Weather and Climate Research Programme

A partnership in climate research

1. Continue to exploit the data produced in our numerical campaigns: we have about 5 years of paper-writing ahead of us.
   – Engage the observational community with evidence for the need for better (e.g. higher resolution in time and space) observations
   – Engage in other world-leading programmes, such as the CLIVAR Hurricane Working Group (which we are!)
2. PRIMAVERA follow-on (2020 call in H2020)
3. Re-engage in LFRIC/Exascale design, testing, etc., and <u>make preparations for coupling (JULES!) and analysis</u>
4. Continue to Engage in EPECC

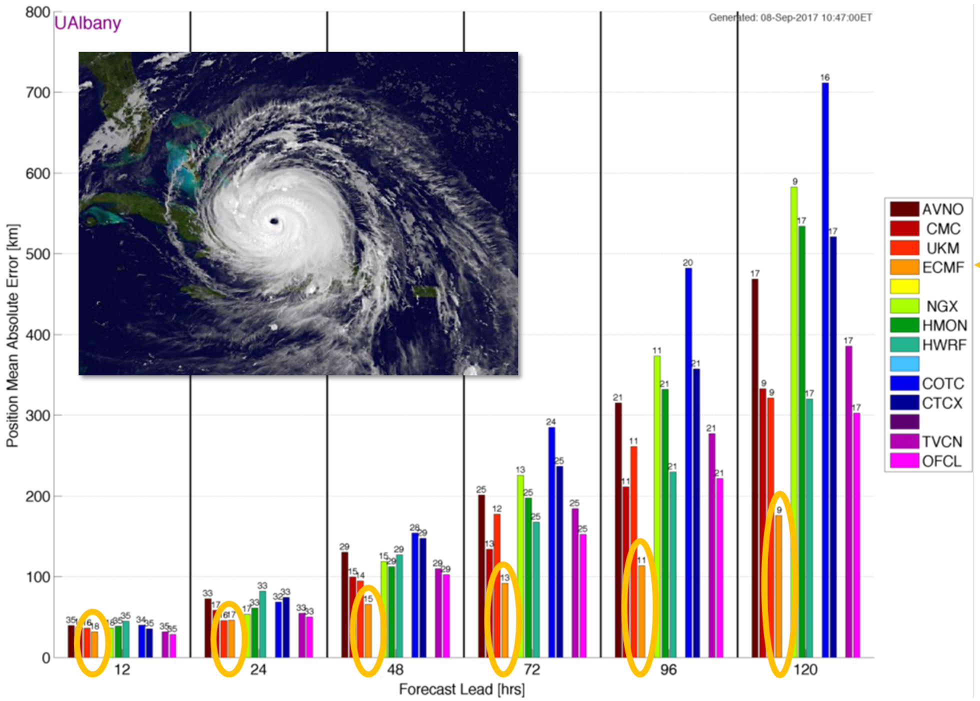
ExtremeEarth for FETFLAG-01-2018

Vision: ExtremeEarth *will revolutionize Europe's capability to predict and monitor environmental extremes and their impacts on society enabled by the imaginative integration of edge and exascale computing and beyond, and the real-time exploitation of pervasive environmental data*

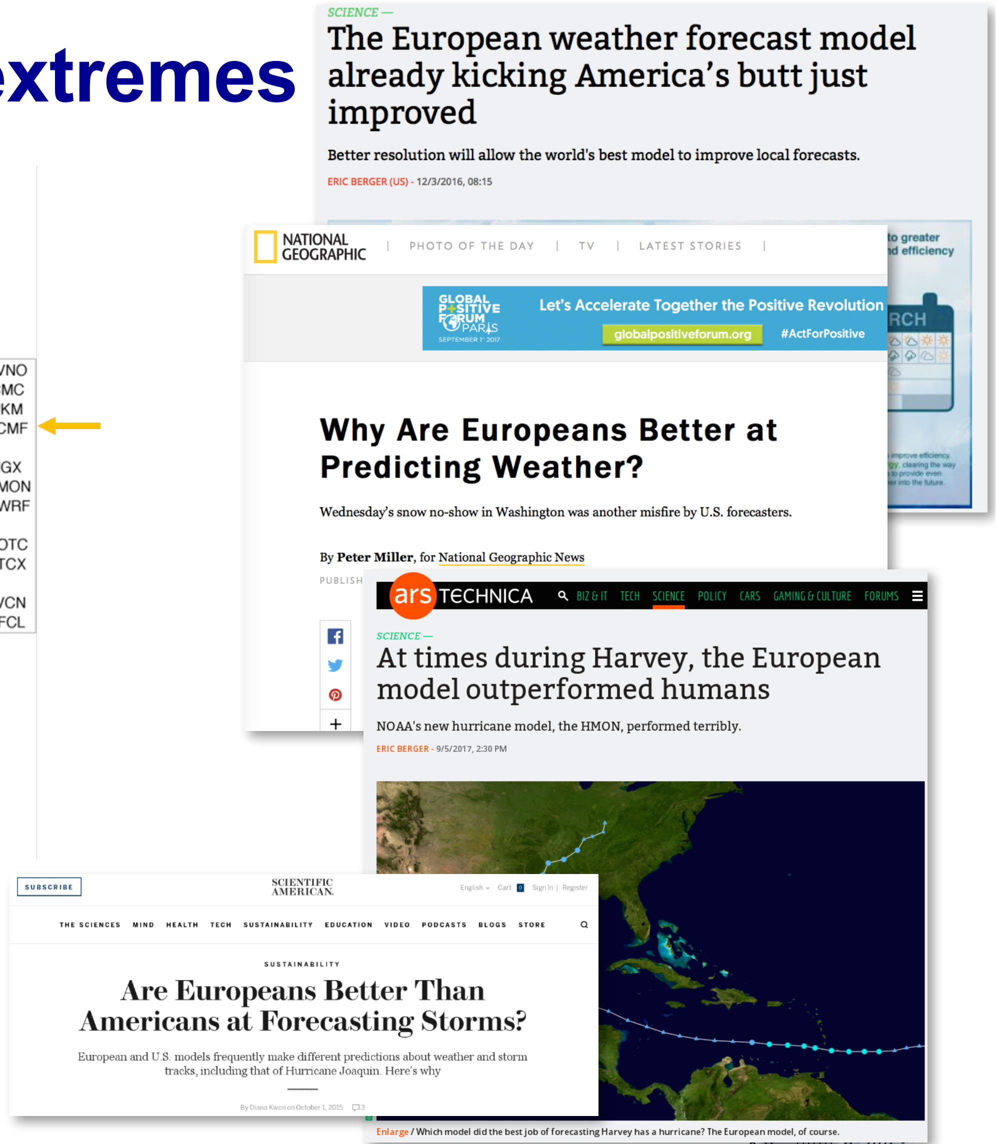
Coordination team:

Peter Bauer (ECMWF Int'l)
Tim Palmer (U Oxford UK)
Harald Bolt, Thomas Jung, Alex Rudloff (FZ Jülich DE)
Wilco Hazeleger (eScience Center NL)
Sylvie Joussaume (IPSL FR)
Steven Mobbs (NERC UK)
Antonio Navarra (CMCC IT)
Thomas Schulthess (ETHZ CH)
Bjorn Stevens (MPG DE)

Weather extremes



European world leadership – but far away from sufficient accuracy and reliability!



EPECC

ECMWF

ExtremeEarth in a Nutshell

1. Dealing responsibly with extremes at national and international level requires much (!) enhanced predictive capabilities along the entire value chain of:
   Climate – Weather – Water – Food – Energy – Health – Risk management
2. Achieving much enhanced predictive skill requires:
   a. Very high-resolution Earth-system ensemble modeling <u>capabilities</u>
   b. Domain specific extreme-scale computing <u>capabilities</u> (software & hardware)
   c. Domain specific extreme-scale data handling and workflow <u>capabilities</u>
   d. Domain specific Earth system information system <u>capabilities</u>
3. Integrating downstream applications in above steps is mandatory

European science leadership will spawn technology leadership

ECMWF

EPECC