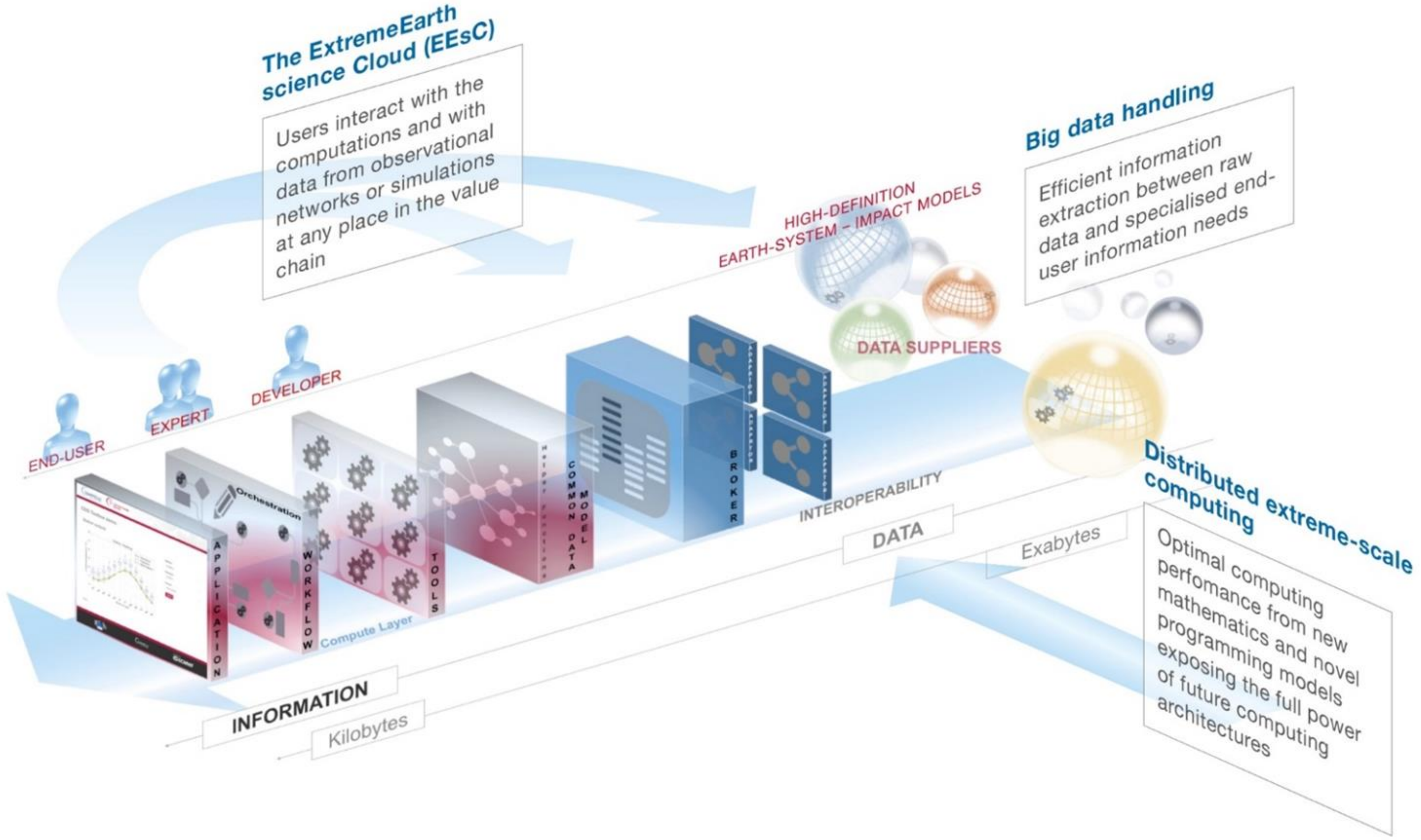
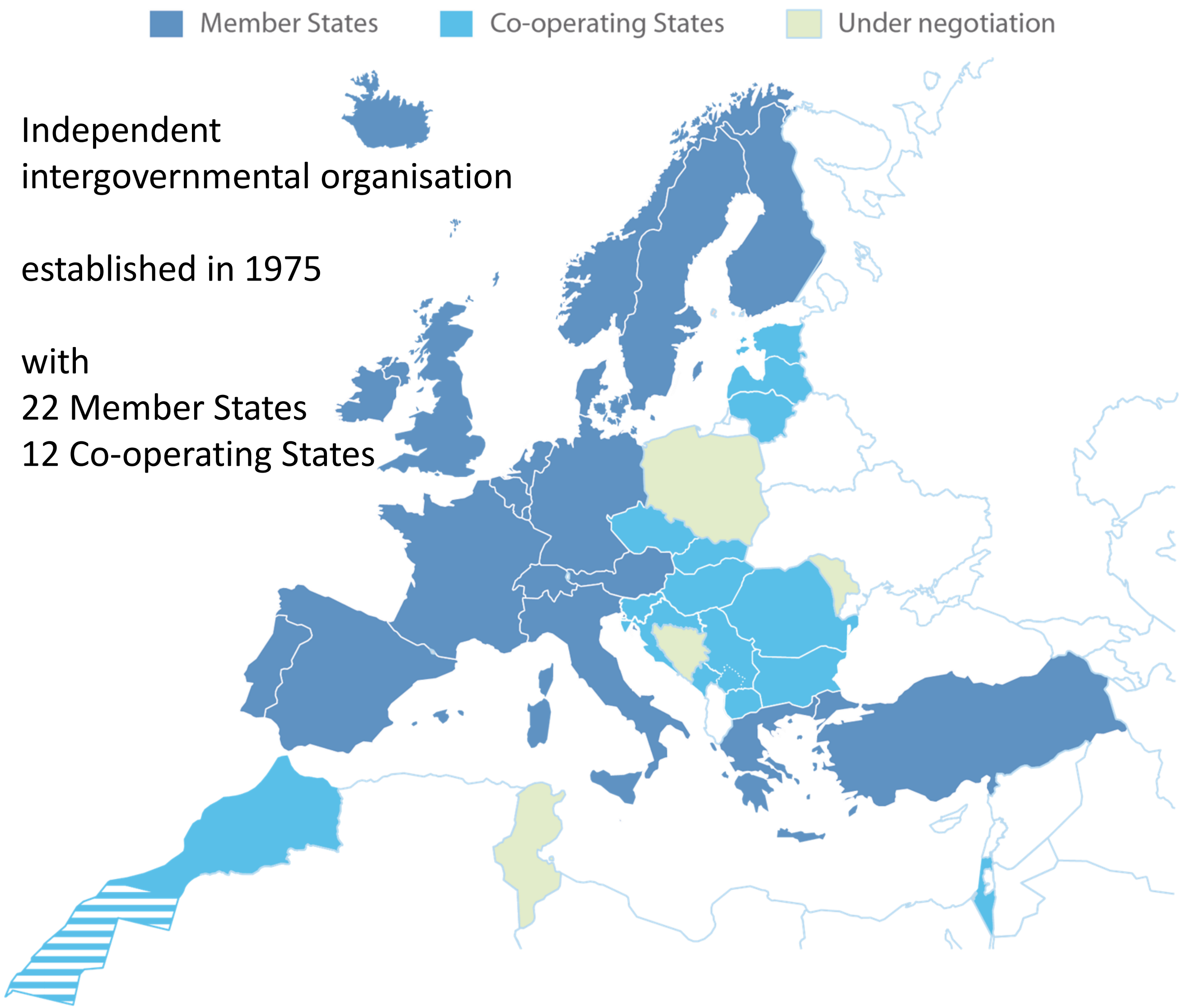
Why the future of weather and climate prediction will depend on supercomputing, big data handling and artificial intelligence

Peter Bauer



ECMWF

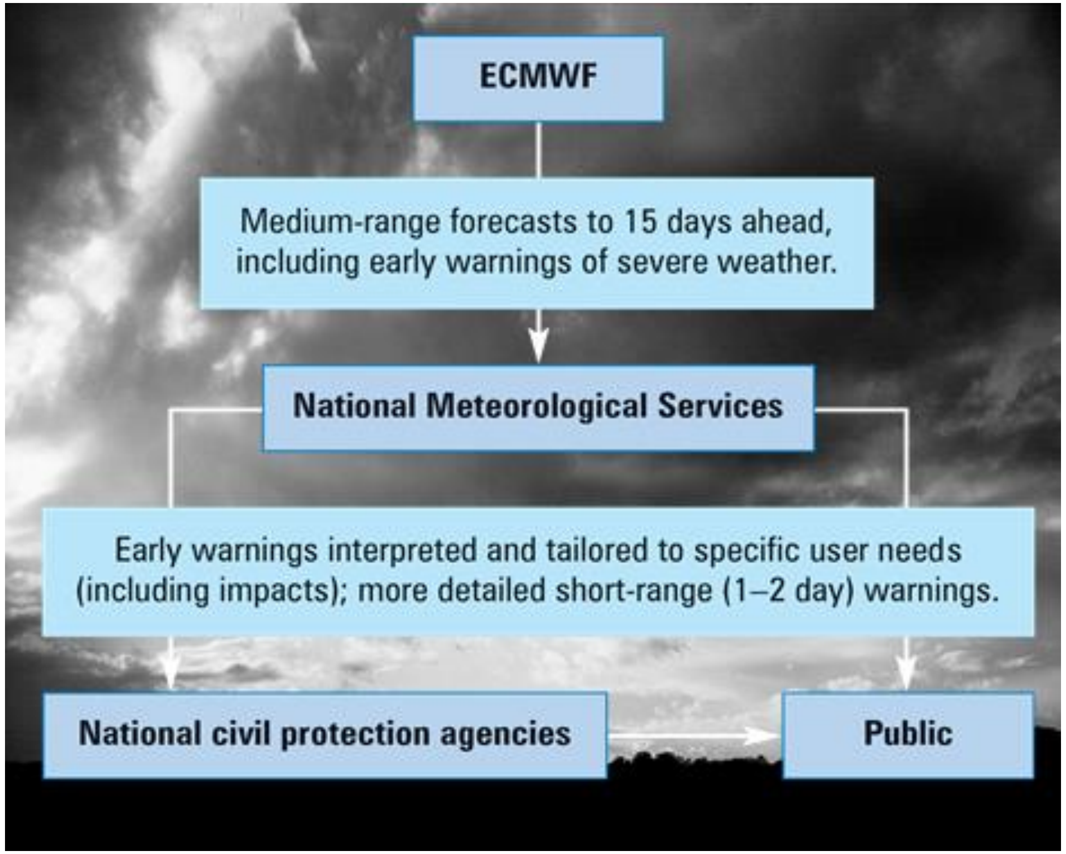
European Centre for Medium-Range Weather Forecasts



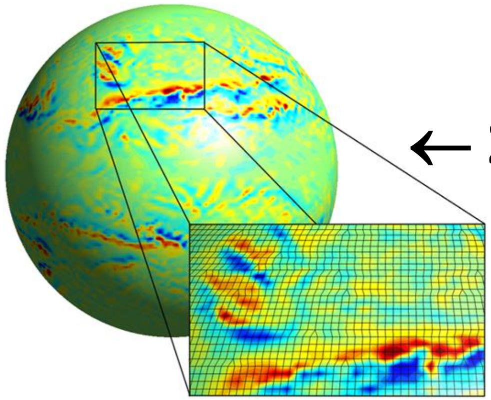
Independent
intergovernmental organisation

established in 1975

with
22 Member States
12 Co-operating States

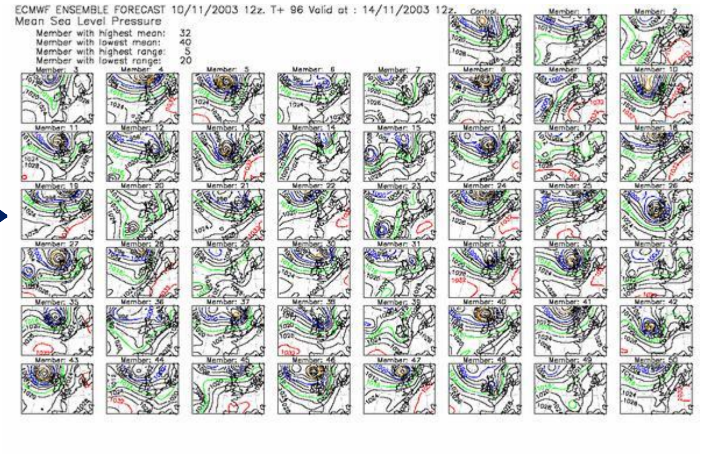


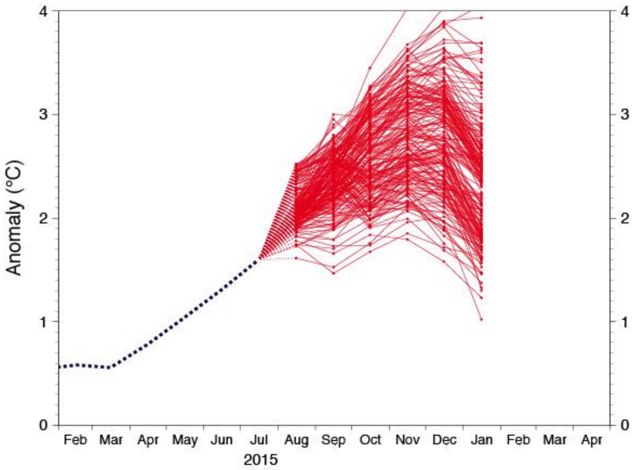
Operational Predictions



← 2x 9-km global high-resolution 10-day forecasts per day

51x 18-km global lower-resolution 15-day forecasts per day… →
… extended to 46 days twice per week at 36 km

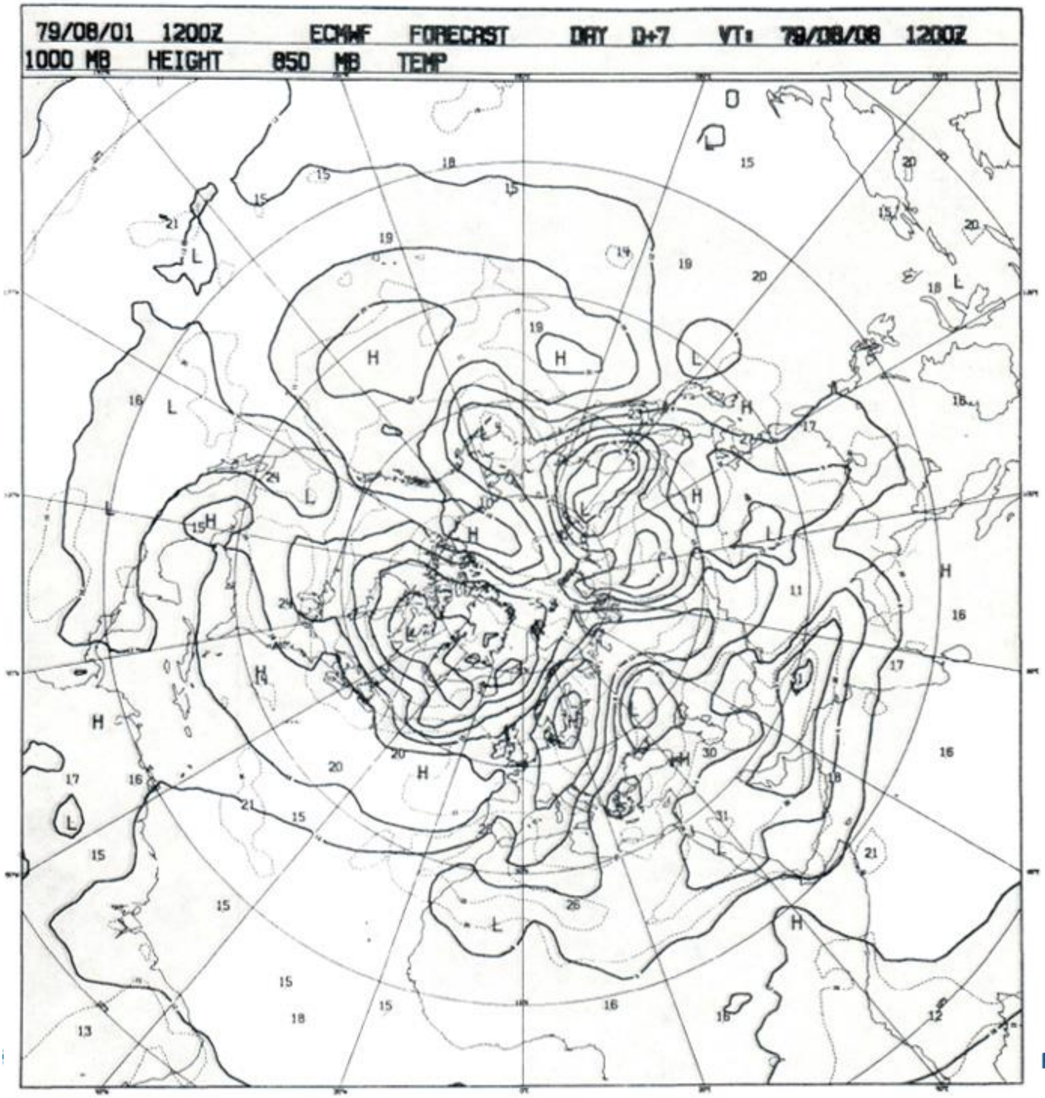




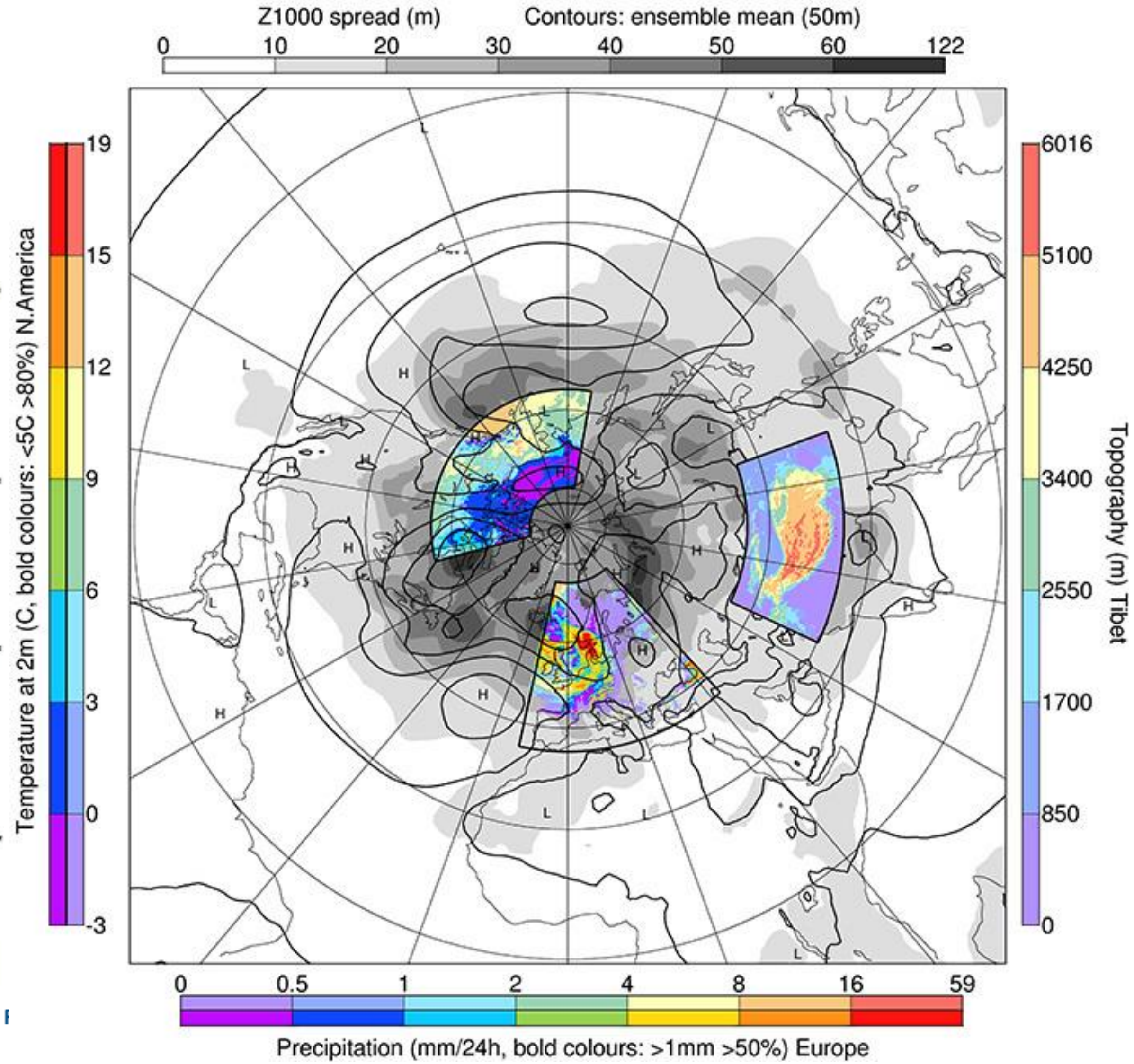
← 51x 64-km global low resolution 7-month forecast per month

1st medium-range forecast 1 August 1979

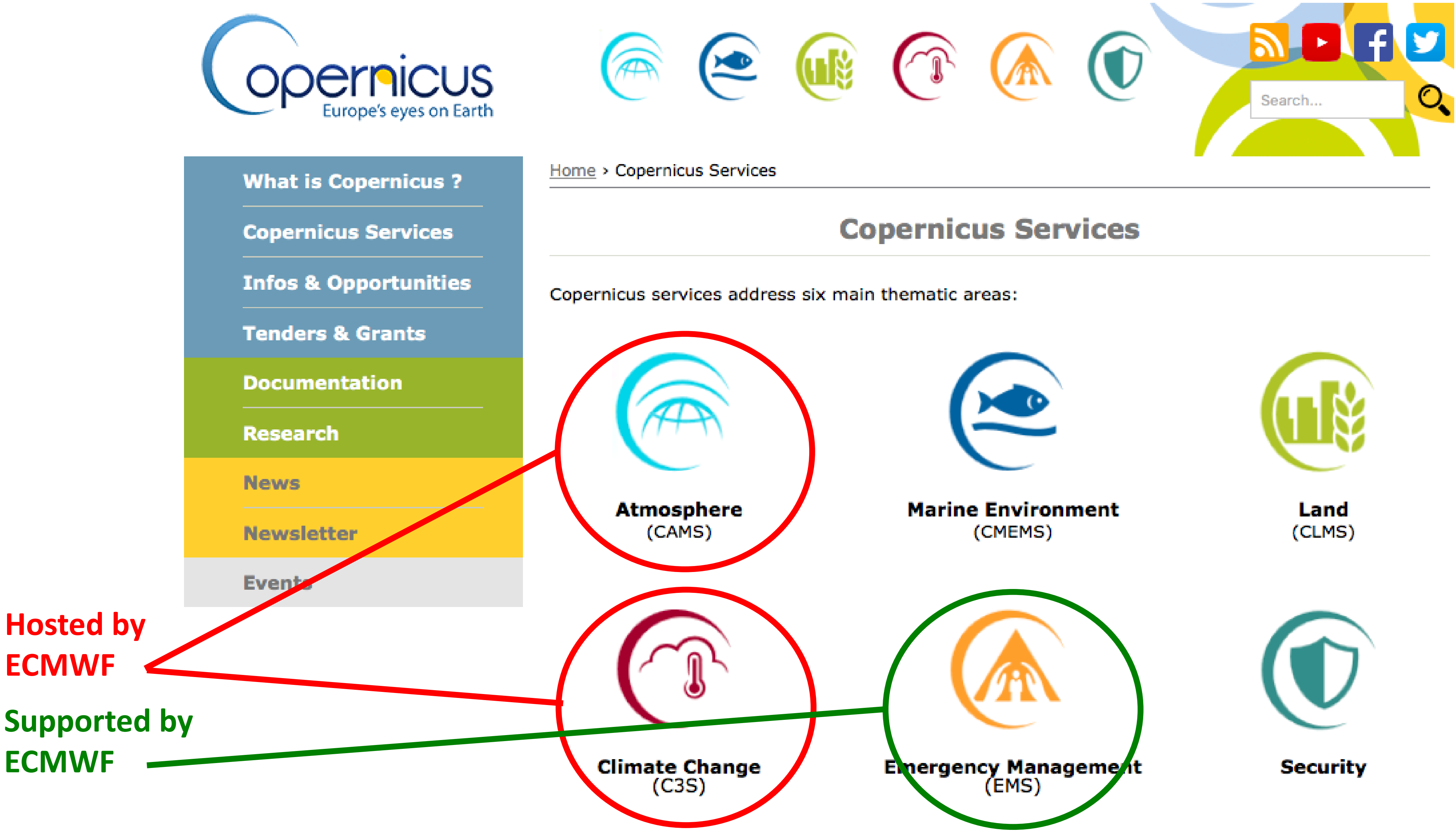
Then: 01/08/1979 12z, z1000, t850



Now: ERA-5+50M ENS, 01/08/1979 12z, z1000, t2m, tp

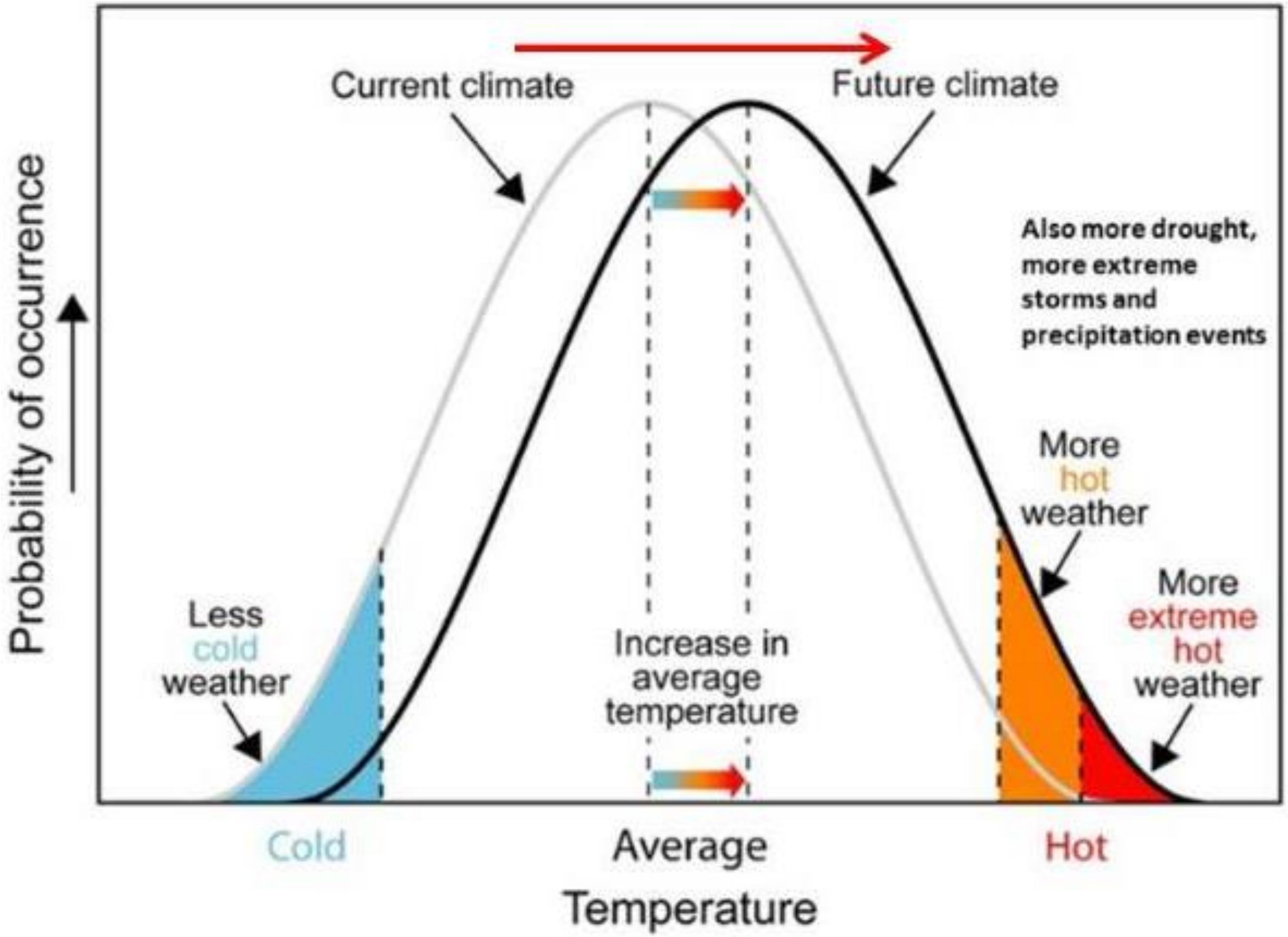


European Commission Copernicus Services



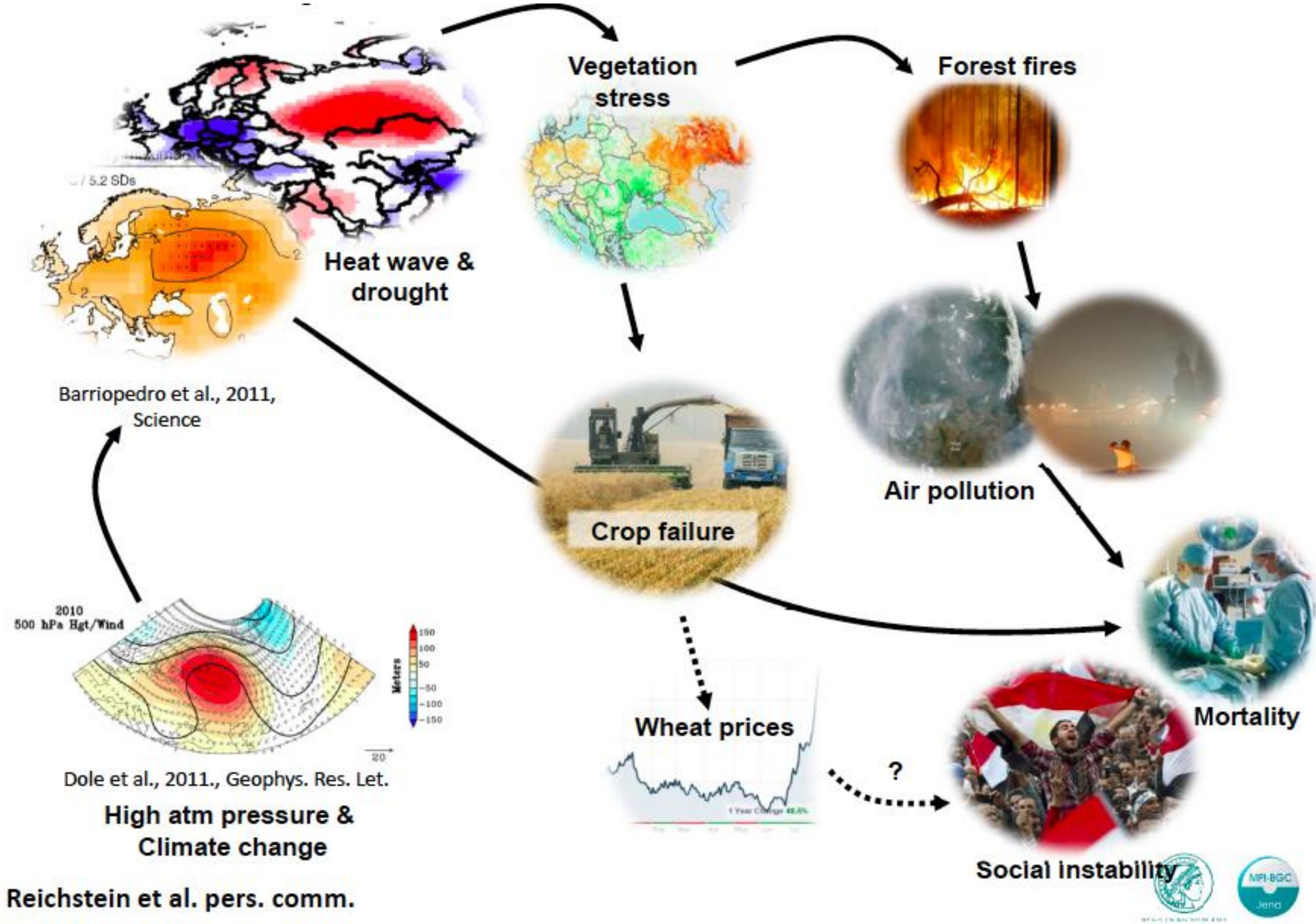
Weather & Climate

“weather decides what clothes you wear, climate decides what clothes you buy”



Impacts are an integral part of prediction

Example Russian heat wave 2010:



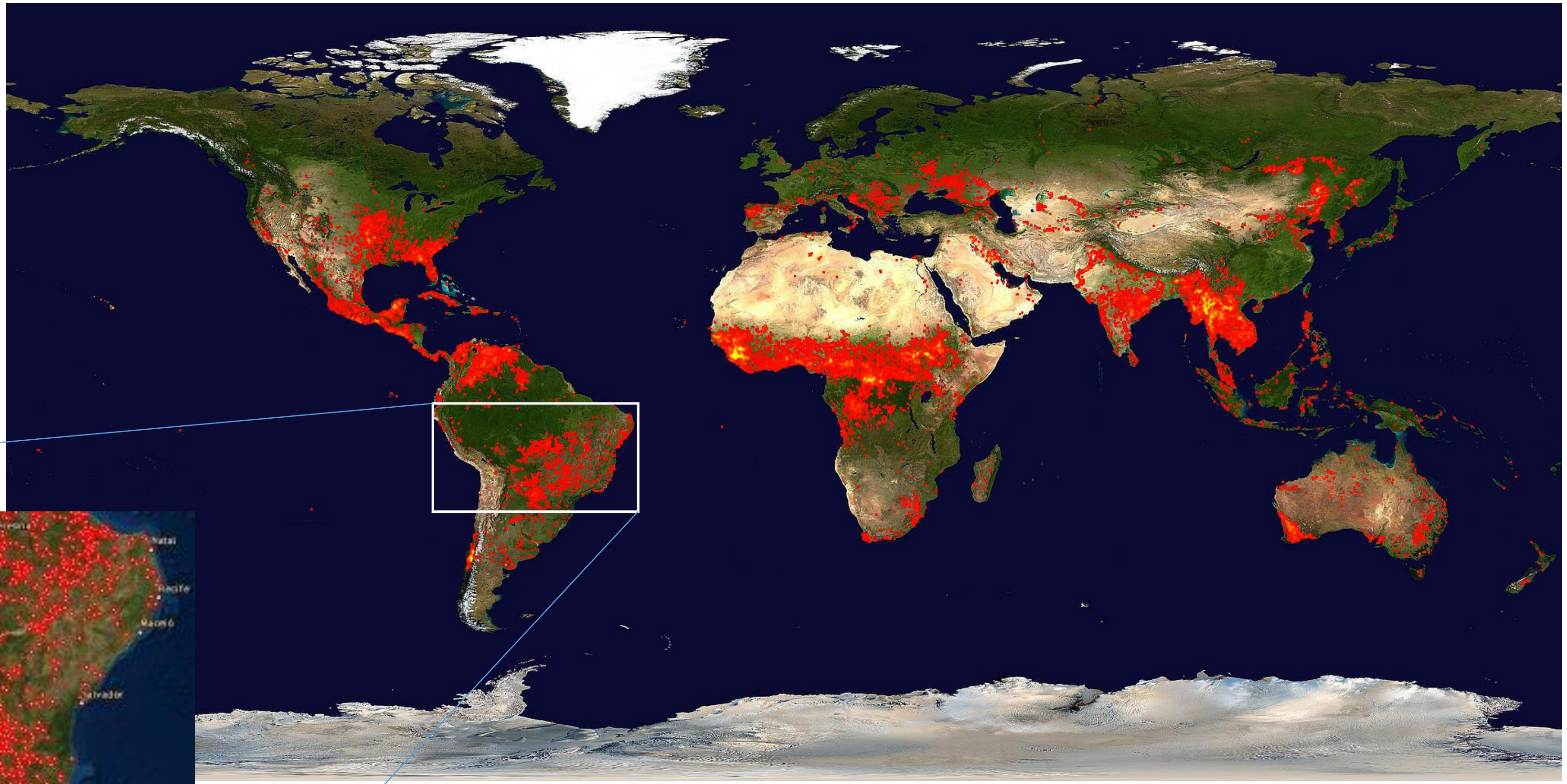
[Courtesy M. Reichstein]

Fire extremes

The grand forecasting challenge:

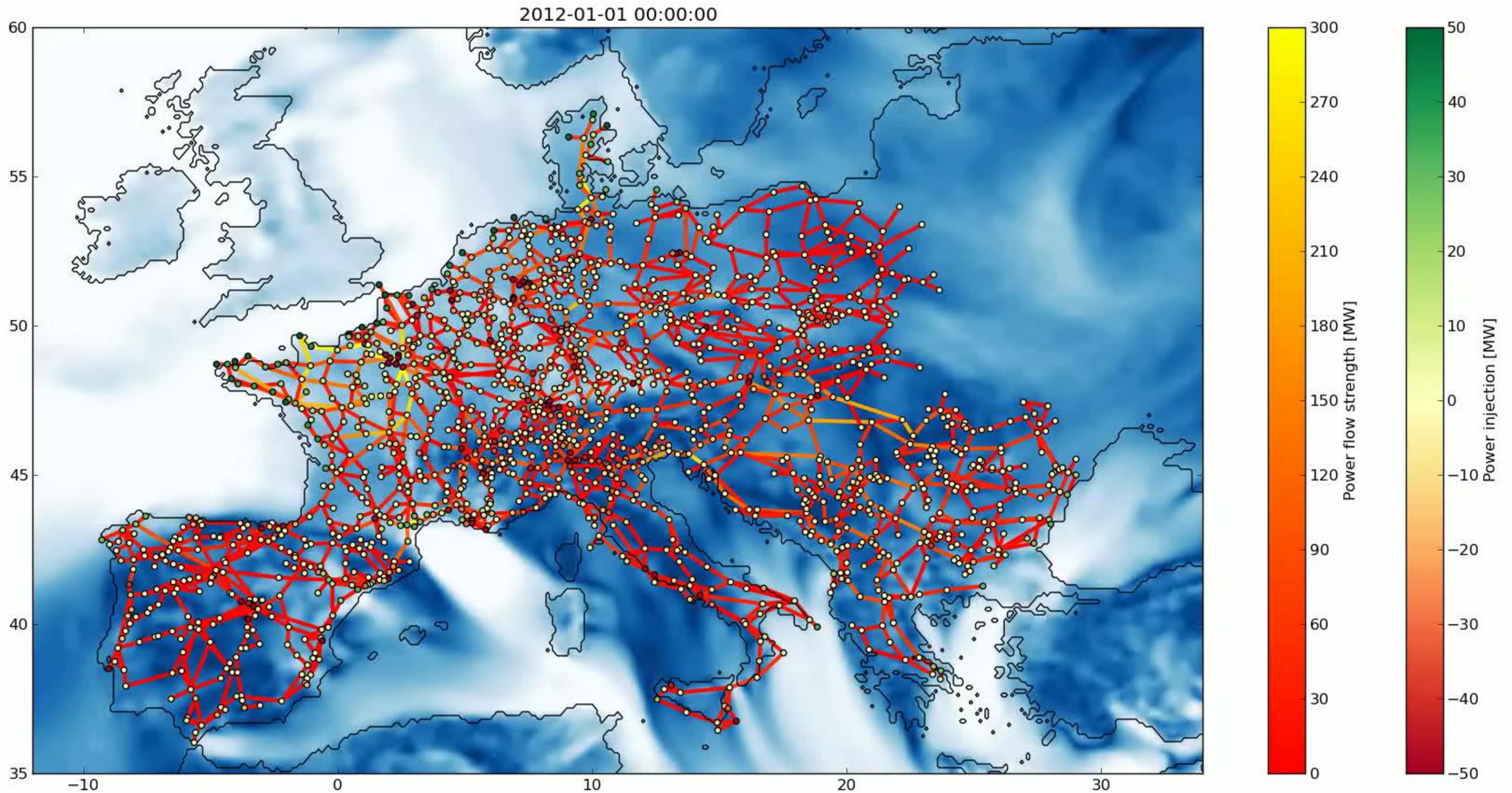
Predict loss of carbon uptake, CO_2+ release and impact on climate

A few years ago…



Now…

Energy extremes



[Courtesy Pierre Pinson DTU]

The grand forecasting challenge:
Predict renewable power generation, dynamic uncertainties, and space-time dependencies at once for Europe

(…with a changing climate?)

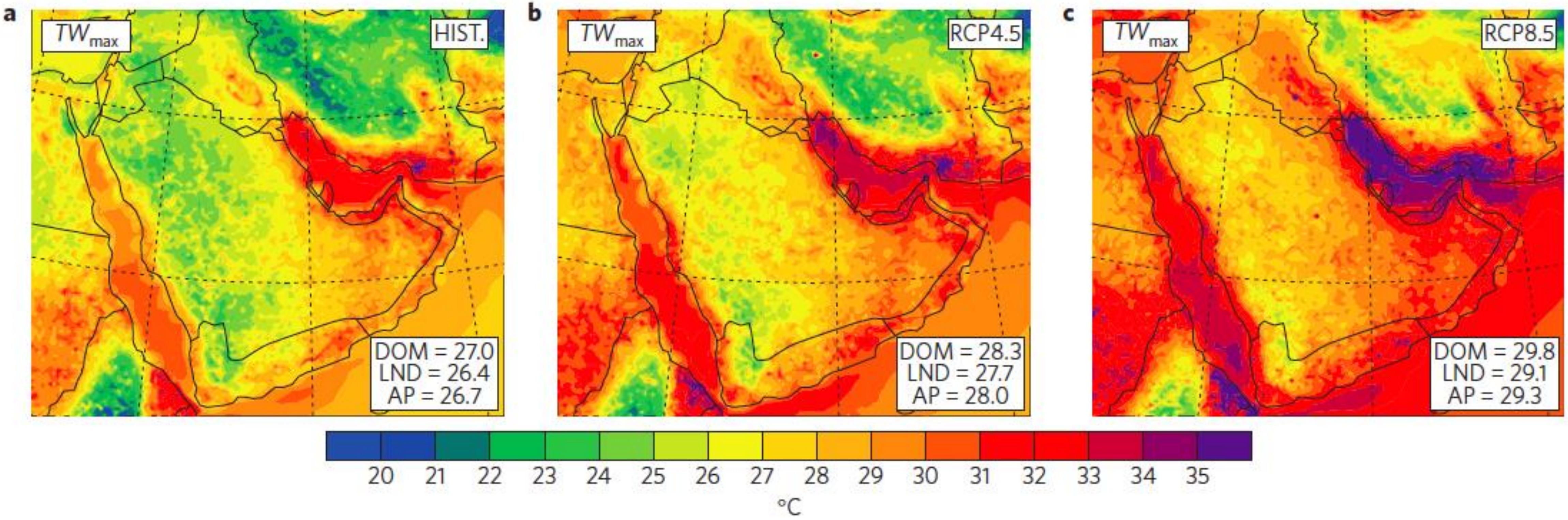
Health extremes

Future temperature in southwest Asia projected to exceed a threshold for human adaptability

Jeremy S. Pal[1,2] and Elfatih A. B. Eltahir[2*]

nature climate change
LETTERS
PUBLISHED ONLINE: 26 OCTOBER 2015 | DOI: 10.1038/NCLIMATE2833

RCP8.5 ensemble predictions cause life threatening wet bulb temperature regimes



The grand forecasting challenge:
Predict location of future uninhabitable regions (…with a changing climate)

A bit of history: First attempts

Among other appointments, captain of HMS Beagle, hosting Charles Darwin on his South American voyages

Vice-Admiral **Robert Fitzroy** (1805-1865)

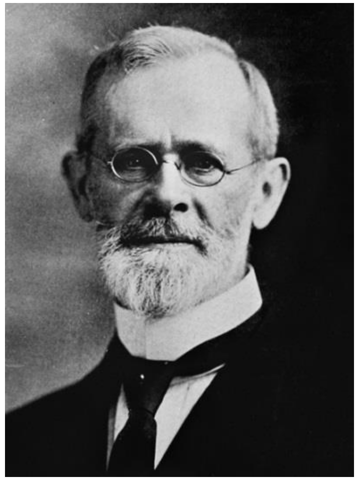
“Man cannot still the raging of the wind, but he can predict it. […]
He cannot appease the storm, but he can escape its violence, and […] the effects of these awful visitations might be wonderfully mitigated”

(Letter to the *Times*, 1859)

“I need not repeat, Sir, what has been so often explained, that the ‘forecasts’ are expressions of probabilities – and not dogmatic predictions”

(Letter to the *Times*, addressed to “those whose hats have been spoiled by umbrellas having been omitted”)

A bit of history: Numerical



Cleveland Abbe (1838-1916), Meteorologist:
- Weather observation and basics of prediction

1901: "The physical basis of long-range weather forecasting ". *Monthly Weather review*.

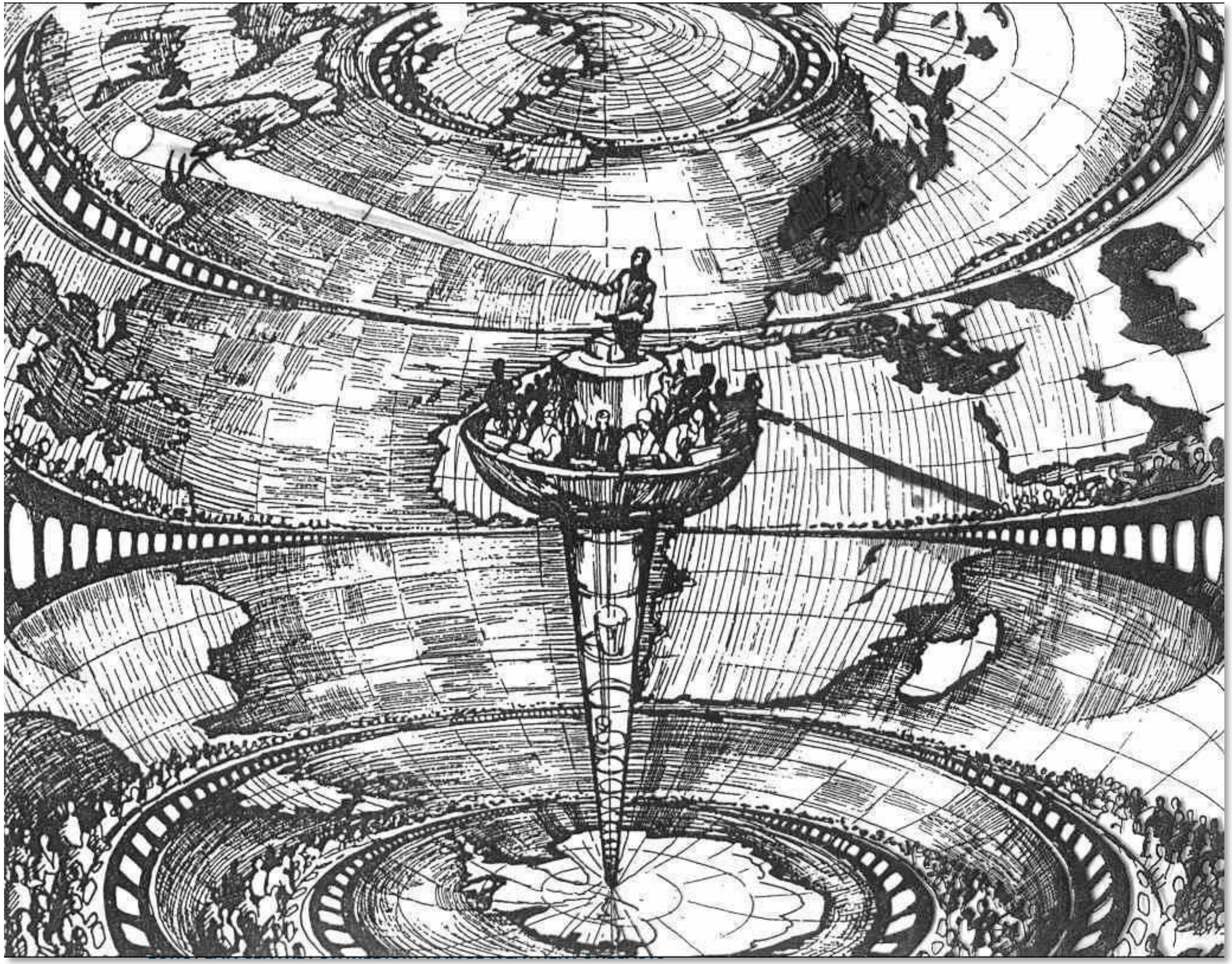
Vilhelm Bjerknes (1862-1951), Physicist und Meteorologist:
- Interaction between dynamics und thermodynamics
- Weather diagnostics, followed by prognoses

1904: "Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik". *Meteorologische Zeitschrift*.

Lewis Fry Richardson (1881-1953), Physicist, Meteorologist, Psychologist, Pacifist:
- Basics of <u>numerical</u> weather prediction
- First explicit calculation of weather on 20 May 1910

1922: "Weather prediction by numerical process". Cambridge University Press.

A bit of history: Richardson's weather factory



ECMWF

A bit of history: Helmholtz lecture

Wirbelstürme und Gewitter

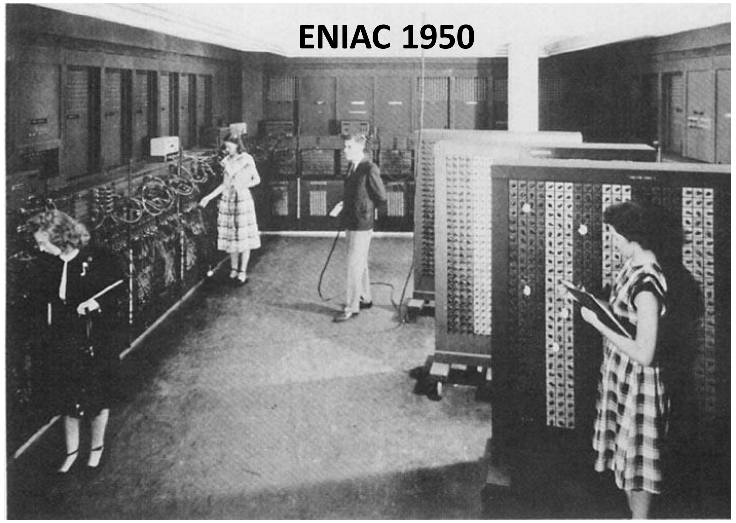
Vortrag
gehalten in Hamburg
1875

des Gesetzes zu fangen. Wenn der Astronom entdeckt, dass eine Sonnenfinsterniss 600 Jahre vor Christo um fünf Viertelstunden falsch aus seiner Rechnung hervorgeht, so verräth ihm dies bisher noch nicht gekannte Einflüsse von Ebbe und Fluth auf die Bewegung der Erde und des Mondes. Der Schiffer auf fernem Meere controlirt seine Uhr nach den ihm vorausgesagten Augenblicken, wo die Verfinsterungen der Jupiterstrabanten eintreten werden. Fragt man dagegen einen Meteorologen, was morgen für Wetter sein werde, so wird man durch die Antwort jedenfalls erinnert an Bürger's „Mann, der das Wenn und das Aber erdacht“, und man darf es den Leuten kaum verdenken, wenn sie bei solchen Gelegenheiten lieber auf Hirten und Schiffer vertrauen, denen die Achtsamkeit auf die Vorzeichen der Witterung durch manchen Regen und Sturm eingepeitscht worden ist [1]).

A bit of history: Computing

John von Neumann (1903-1957), Mathematician:
- Function theory, abstract algebra, quantum physics
- Leader of Electronic Computer Project (1946-52)

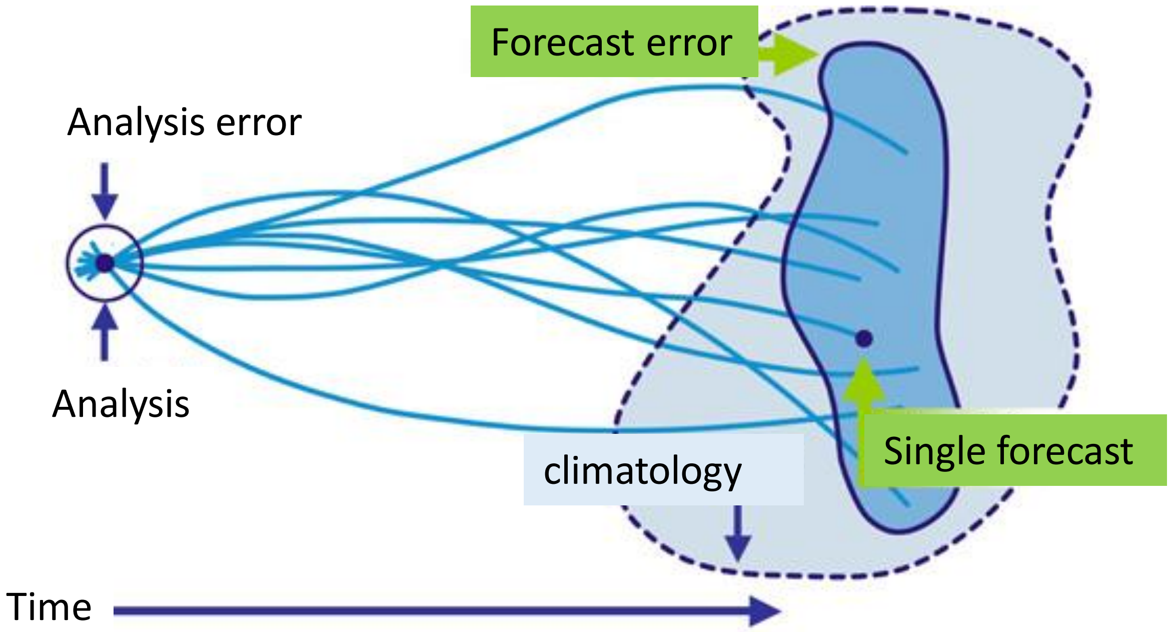
Jule Charney (1917-1981), Meteorologist:
- Set of equations for numerical prediction of planetary waves
- Founder of theory of baroclinic instability



Electronic Numerical Integrator and Computer (ENIAC)
- 140 kW, 30 tons, 18000 thermo-ionic valves
- 1-layer model, resolution 400-700 km, over North America
- Single 24-hour forecast needed 24 hours compute time

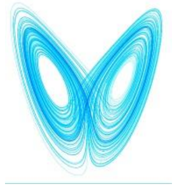
The same prediction needed **1 second** on a Nokia 6300 mobile phone (2006)!

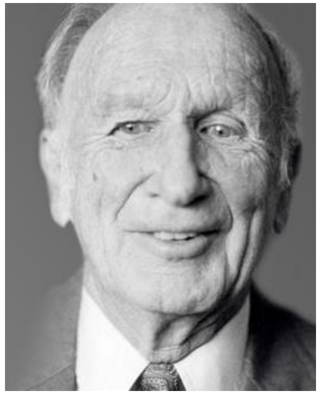
A bit of history: Foundation of Chaos Theory



Ed Lorenz (1917-2008), Mathematician, Meteorologist:

- Impact of initial conditions on forecasts in non-linear systems
- Founder of chaos-theory

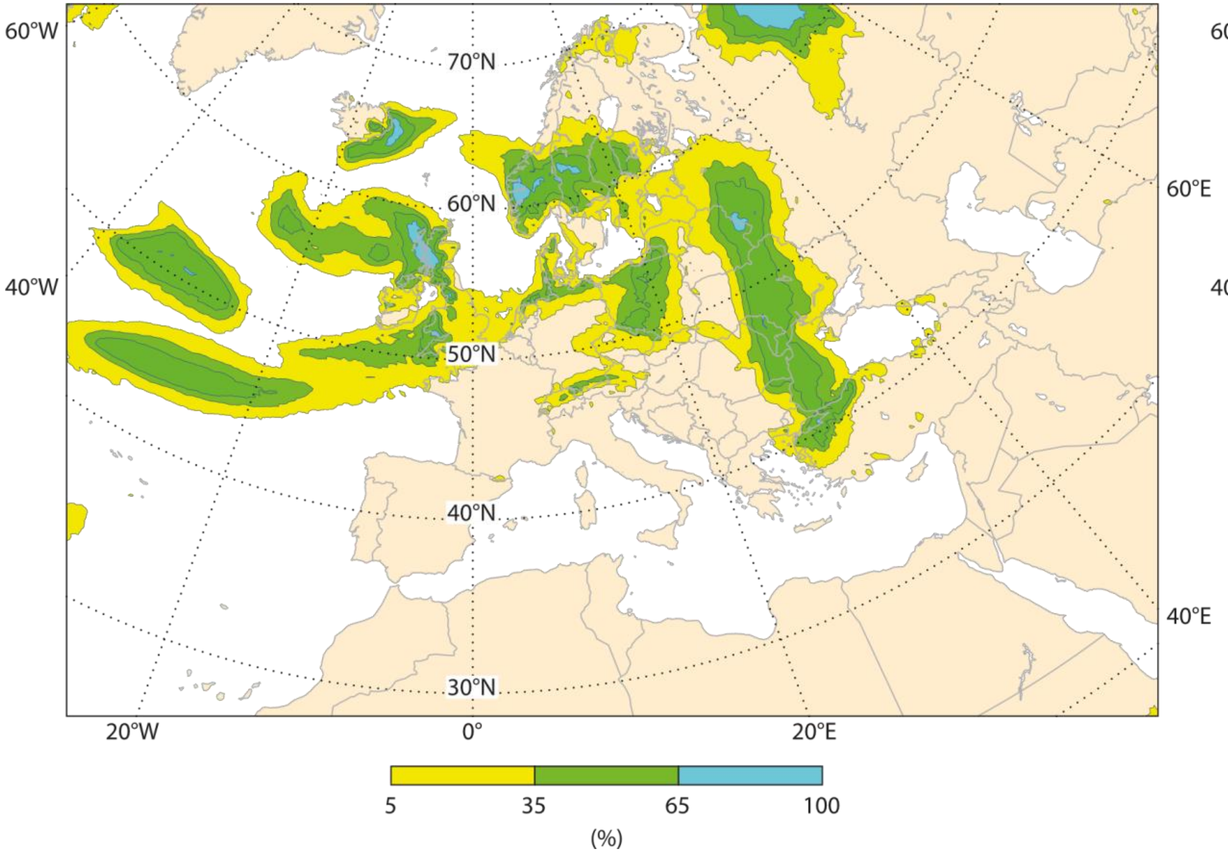




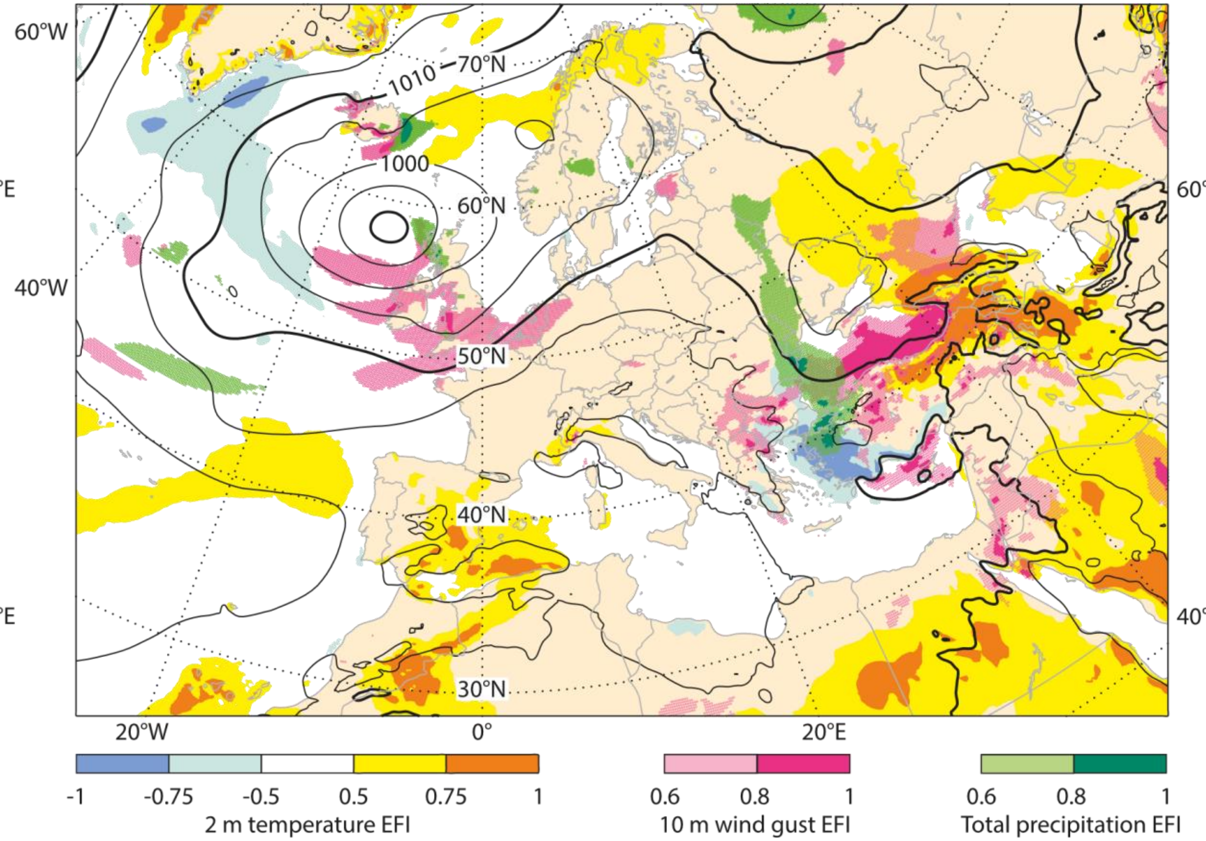
Shakespeare:
“for want a nail, the shoe was lost.
for want a shoe, the horse was lost.
for want a horse, the rider was lost.
for want a rider, the battle was lost.
for want a battle, the kingdom was lost.”

Reliable prediction of extremes 2 weeks ahead

Ensemble-based probability of 24-hour precipitation in excess of 5 mm

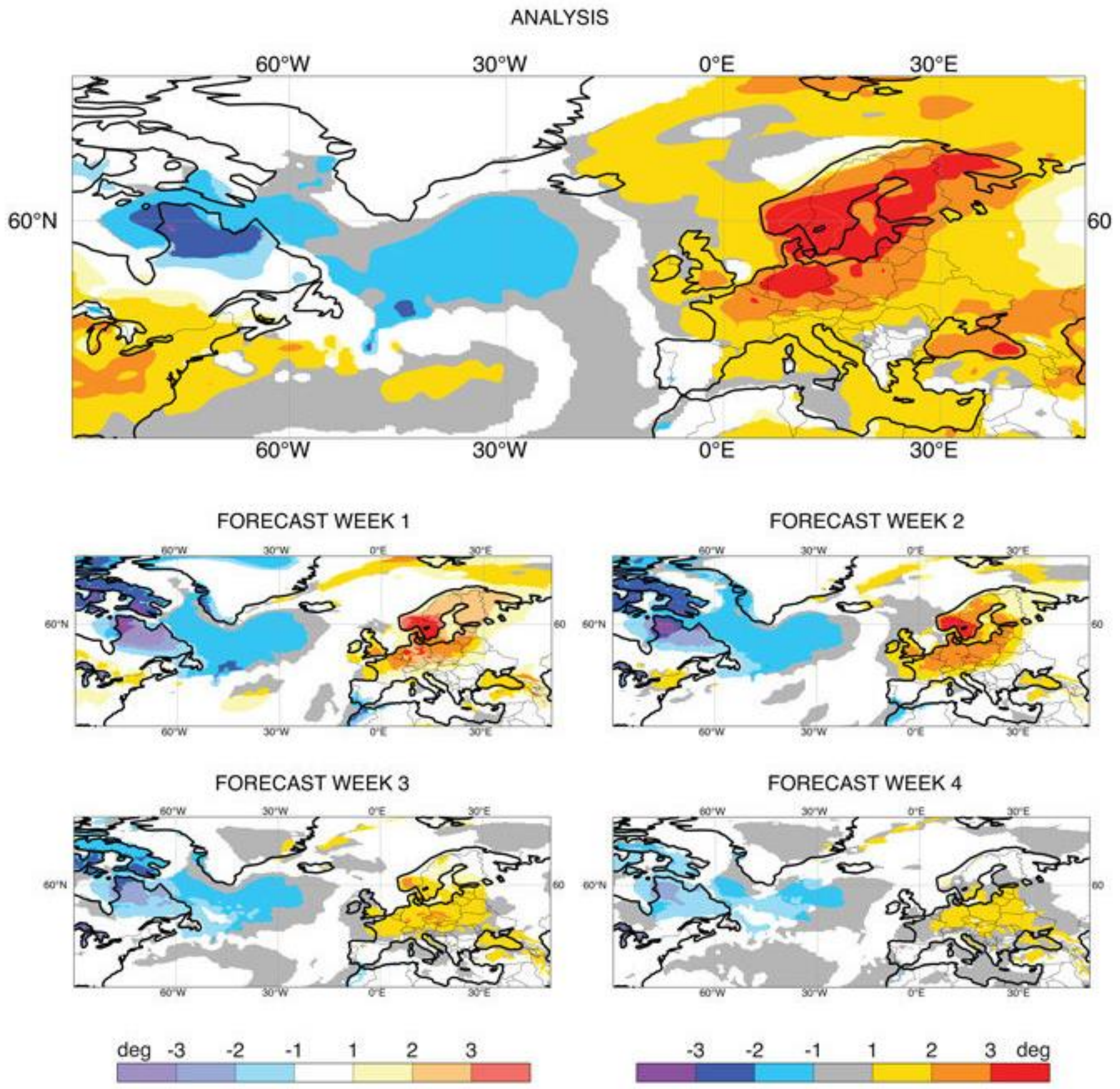


Ensemble-based Extreme Forecast Index (EFI) forecast where the ensemble forecast distribution differs substantially from the model climatological distribution for 2-metre temperature, 10-metre wind gusts and precipitation



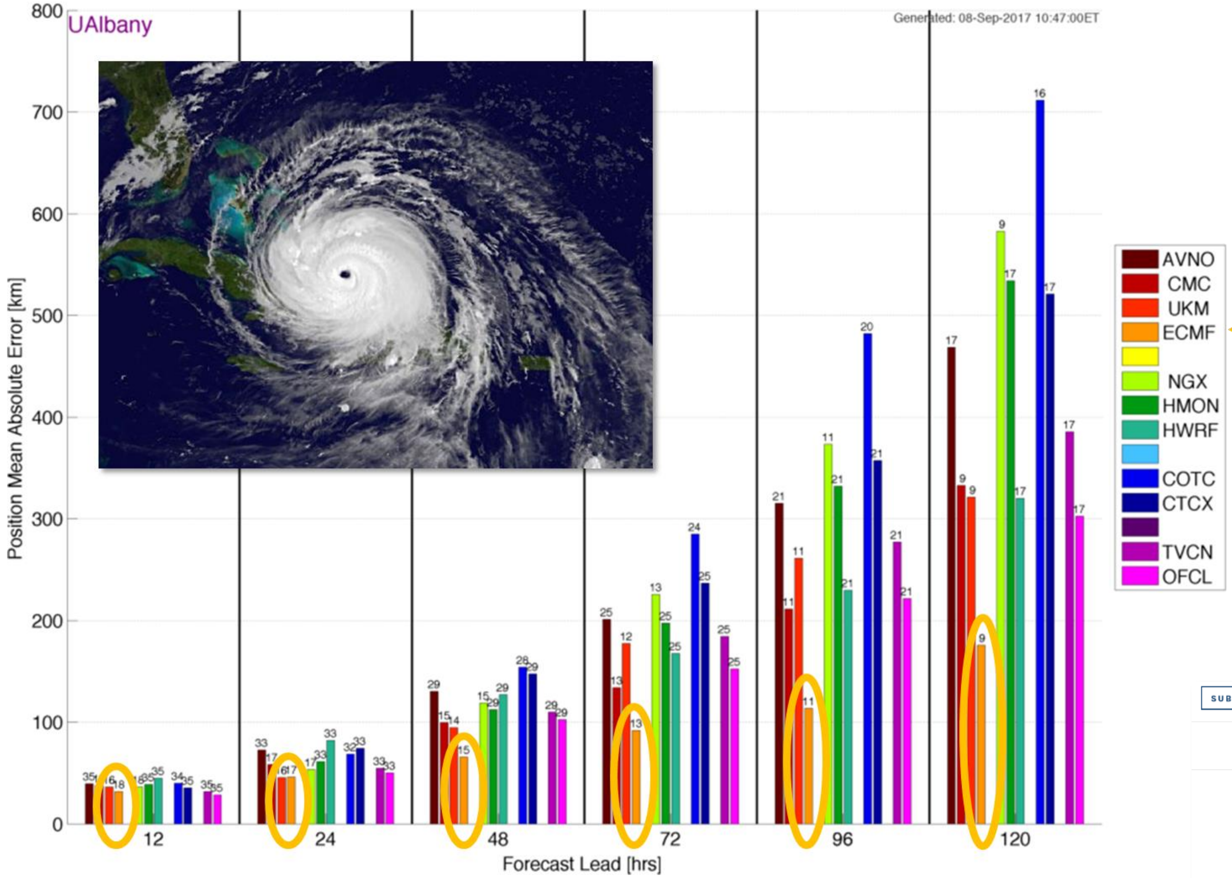
Reliable prediction of extremes 4 weeks ahead

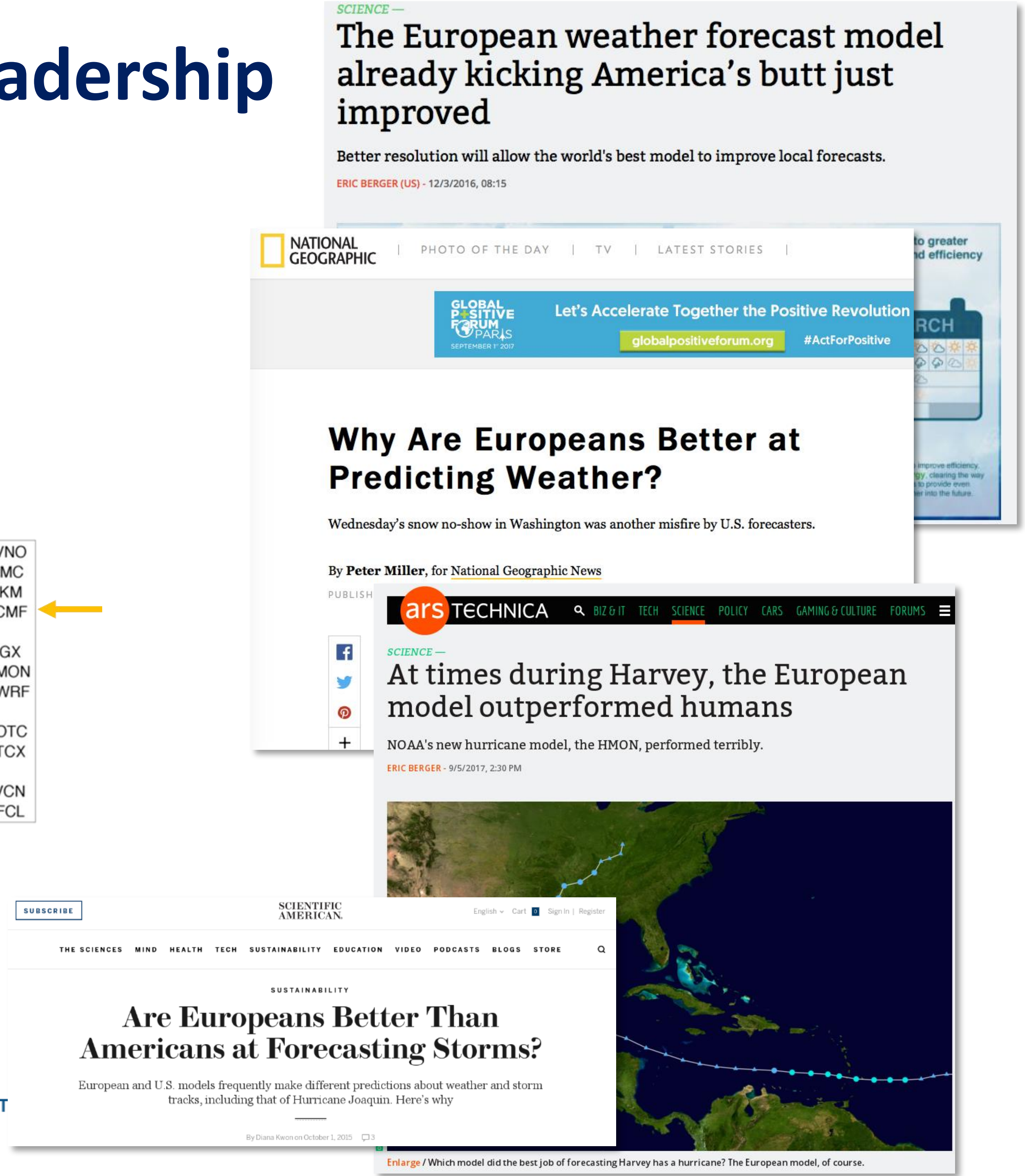
Summer heatwave over Europe:
2m Temperature,
7 May – 12 August 2018



European leadership

World leadership in Europe – but still far away from sufficient accuracy and reliability!





SCIENCE —

The European weather forecast model already kicking America's butt just improved

Better resolution will allow the world's best model to improve local forecasts.

ERIC BERGER (US) - 12/3/2016, 08:15

NATIONAL GEOGRAPHIC | PHOTO OF THE DAY | TV | LATEST STORIES |

GLOBAL POSITIVE FORUM PARIS SEPTEMBER 1st 2017 — Let's Accelerate Together the Positive Revolution — globalpositiveforum.org — #ActForPositive

Why Are Europeans Better at Predicting Weather?

Wednesday's snow no-show in Washington was another misfire by U.S. forecasters.

By Peter Miller, for National Geographic News

ars TECHNICA — BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE FORUMS

SCIENCE —

At times during Harvey, the European model outperformed humans

NOAA's new hurricane model, the HMON, performed terribly.

ERIC BERGER - 9/5/2017, 2:30 PM

Enlarge / Which model did the best job of forecasting Harvey has a hurricane? The European model, of course.

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THE SCIENCES MIND HEALTH TECH SUSTAINABILITY EDUCATION VIDEO PODCASTS BLOGS STORE

SUSTAINABILITY

Are Europeans Better Than Americans at Forecasting Storms?

European and U.S. models frequently make different predictions about weather and storm tracks, including that of Hurricane Joaquin. Here's why

By Diana Kwon on October 1, 2015

ECMWF

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECAST

Euro Vs. GFS: The Weather Model Wars Take A New Turn In March

Marshall Shepherd Senior Contributor
Science

I still don't get it. If you follow the meteorological community or weather enthusiasts on Twitter, there is a level of hyperventilation (and vitriol) at times when it comes to the debate about what weather model is better: European "Euro" or American. It is well documented that t[...] model (run by the European Center for Medium-[...] Weather Forecasts or ECMWF) has historically p[...] better than the American model, Global Forecast [...] System (GFS), run by NOAA. In 2013, Jason Sam[...] this in the *Washington Post* after Hurricane San[...]

> Last year, criticism began to emerge concern[...] inferior accuracy of the NWS's Global Foreca[...]

ERIC NIILER SCIENCE 02.19.19 08:00 AM

THE GOVERNMENT'S NEW WEATHER MODEL FACES A STORM OF PROTEST

ECMWF

The New York Times

A Software Upgrade (After 40 Years) Aims to Improve U.S. Weather Forecasts

A view of H[...] 2012. Norma[...]

"We are confident the upgrade will provide an overall improvement," Dr. Gross said. Specifically, he added, it should help produce more accurate forecasts of temperature and the amount of rain and snow.

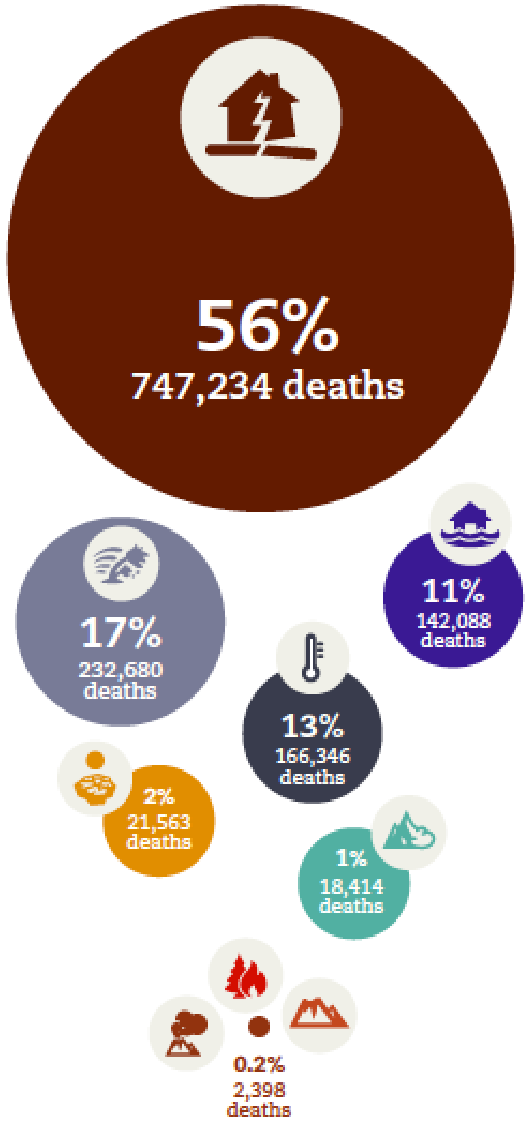
Among other improvements, he said, the new model should more accurately reflect changes that occur between daytime and nighttime. As for hurricanes, he said, the upgrade should help improve forecasts both of a storm's track and its intensity.

The upgrade is part of a series of improvements that were undertaken after Sandy. In addition to improving the software, more computing power was added. The European model also had the advantage of vastly greater number-crunching capacity.

For more news on climate and the environment, follow @NYTClimate on Twitter.

"Economic losses, poverty and disasters 1998-2017"

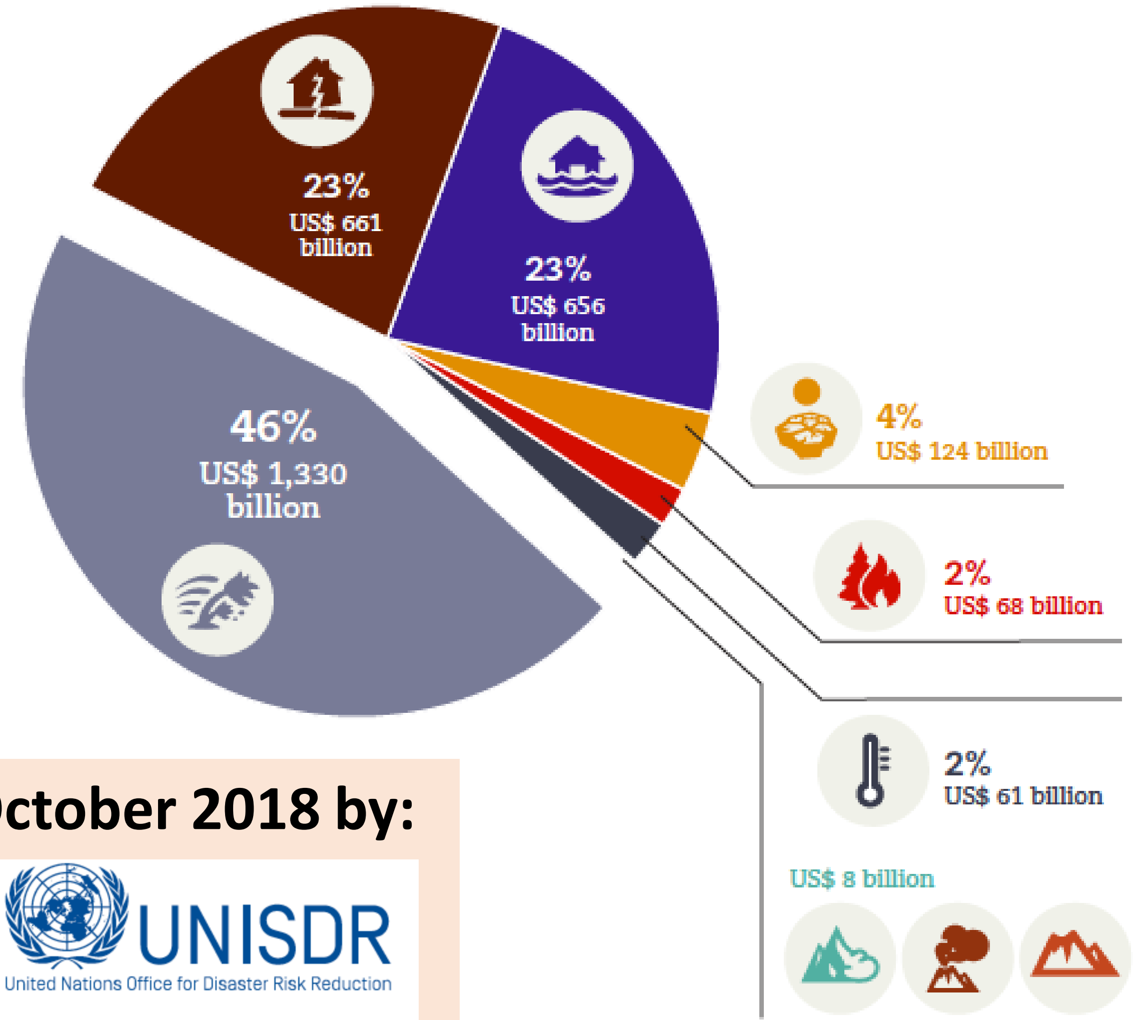
Number of deaths
per disaster type 1998-2017



- Earthquake
- Storm
- Extreme temperature
- Flood
- Drought
- Landslide
- Wildfire, Volcanic activity, Mass movement (dry)

> 1.3 million fatalities
> 2.9 trillion US$ losses

Breakdown of recorded economic losses (US$)
per disaster type 1998-2017



UN Report published on 10 October 2018 by:

Centre for Research on the Epidemiology of Disasters CRED

UNISDR
United Nations Office for Disaster Risk Reduction

“The 2019 Global Risks Report”

WORLD ECONOMIC FORUM

COMMITTED TO IMPROVING THE STATE OF THE WORLD

Top 10 risks in terms of
Likelihood

1. Extreme weather events
2. Failure of climate-change mitigation and adaptation
3. Natural disasters
4. Data fraud or theft
5. Cyber-attacks
6. Man-made environmental disasters
7. Large-scale involuntary migration
8. Biodiversity loss and ecosystem collapse
9. Water crises
10. Asset bubbles in a major economy

Top 10 risks in terms of
Impact

1. Weapons of mass destruction
2. Failure of climate-change mitigation and adaptation
3. Extreme weather events
4. Water crises
5. Natural disasters
6. Biodiversity loss and ecosystem collapse
7. Cyber-attacks
8. Critical information infrastructure breakdown
9. Man-made environmental disasters
10. Spread of infectious diseases

Categories

- Economic
- Environmental
- Geopolitical
- Societal
- Technological

Reliable prediction of extremes decades ahead?

npj | Climate and Atmospheric Science

www.nature.com/npjclimatsci

EDITORIAL OPEN

Extreme weather and climate

npj Climate and Atmospheric Science (2018)1:45 ; https://doi.org/10.1038/s41612-018-0057-1

Humans and ecosystems struggle to cope with extreme weather and climate conditions. The articles in this collection examine a range of weather and climate phenomena that are extreme either in their rarity, intensity, or both. Such research aims to help societies better anticipate and manage the challenges of the most impactful future weather and climate events, be they weeks or decades from now.

...

Weather and climate extremes pose scientific challenges as well as societal ones. Much of the recent progress can be traced back to improvements modeling and simulation. Extremes such as heavy rainfall depend on physical processes that occur on short time scales and small spatial scales. Increased computational power has allowed higher time and space resolution that provide more realistic depictions of extremes for numerical weather prediction and climate change projections. Nonetheless, uncertainties remain, especially at regional scales, as to how a changing climate will change the frequency and intensity of extremes, and continued efforts are needed to better understand the wide range of time and space scales that are involved in weather and climate extremes.

RANGE WEATHER F

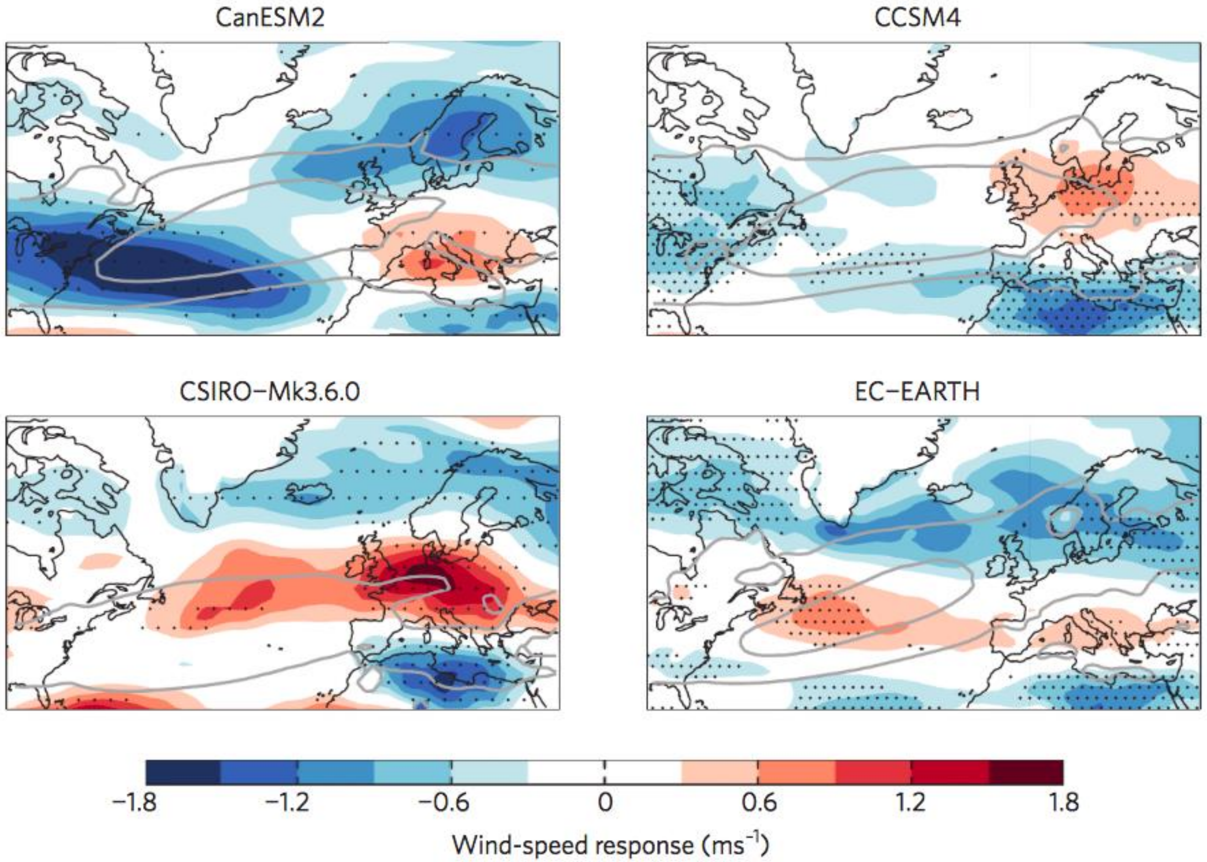
nature geoscience

PERSPECTIVE

PUBLISHED ONLINE: 21 SEPTEMBER 2014 | DOI: 10.1038/NGEO2253

Atmospheric circulation as a source of uncertainty in climate change projections

Theodore G. Shepherd



850 hPa wind speed response to RCP8.5 forcing by 2100

Resolved or not resolved?

Conservation of momentum, energy, mass and moisture:

$$\frac{\partial \vec{V}}{\partial t} = -(\vec{V}\cdot\nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega}\times\vec{V} + \nabla\cdot(k_\omega \nabla \vec{V}) + \vec{F}_d$$

$$\rho c_p \frac{\partial T}{\partial t} = -\rho c_p(\vec{V}\cdot\nabla)T - \nabla\cdot\vec{R} + \nabla\cdot(k_\tau \nabla T) + C + S$$

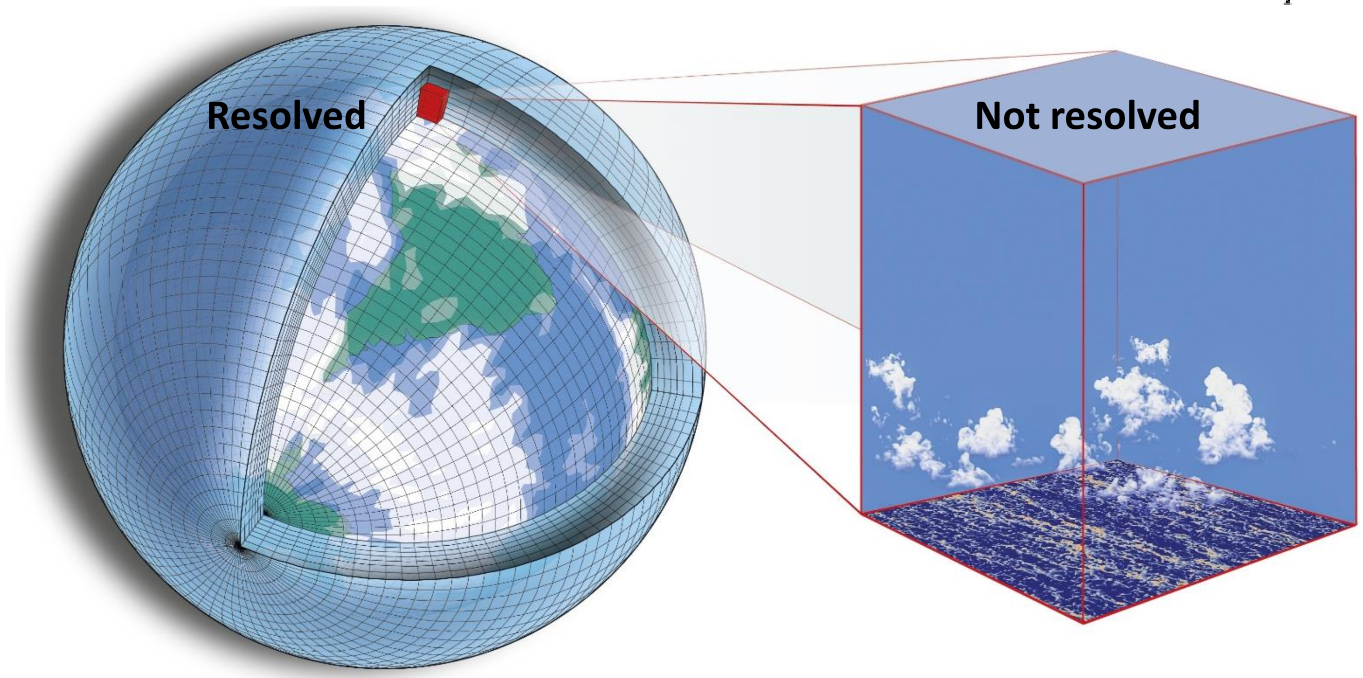
$$\frac{\partial \rho}{\partial t} = -(\vec{V}\cdot\nabla)\rho - \rho(\nabla\cdot\vec{V})$$

$$\frac{\partial q}{\partial t} = -(\vec{V}\cdot\nabla)q + \nabla\cdot(k_q \nabla q) + S_q + E$$

Equation of state:

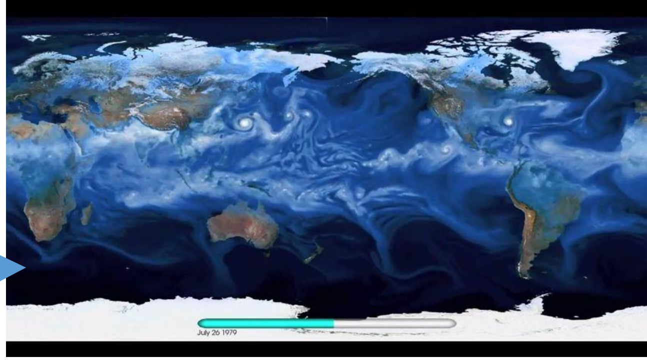
$$p = \rho R_d T$$

V = velocity
T = temperature
p = pressure
ρ = density
q = specific humidity
g = gravity
Ω = rotation of Earth
F_d = drag force of Earth
R = radiation vector
C = conductive heating
c_p = heat capacity, constant p
E = evaporation
S = latent heating
S_q = phase change source
k = diffusion coefficients
R_d = dry air gas constant



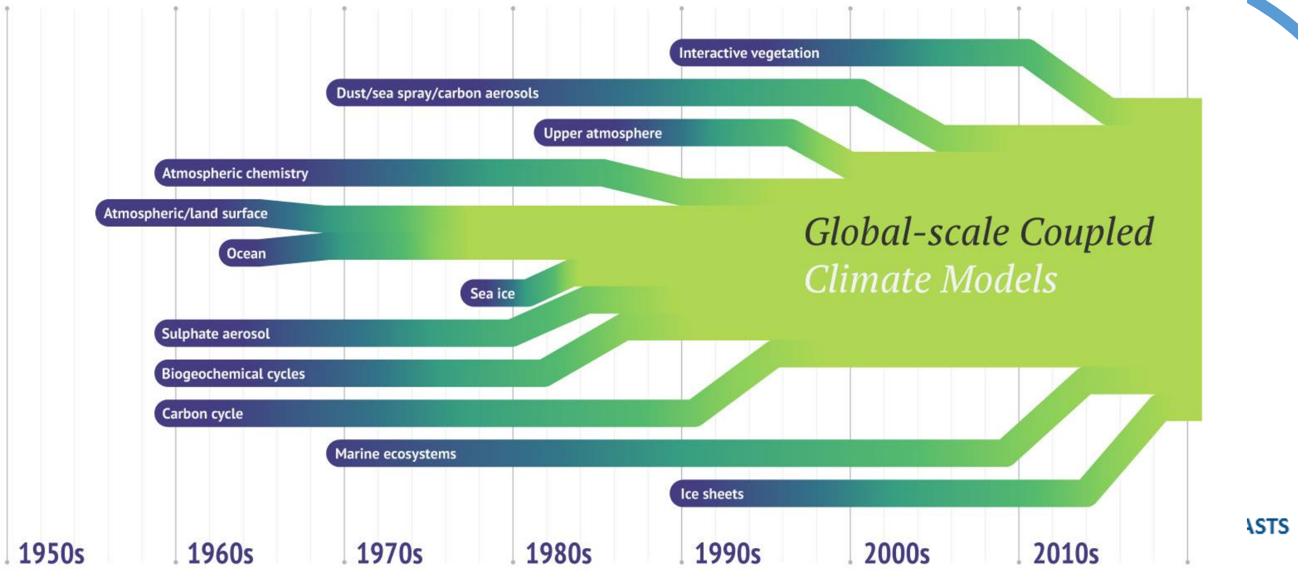
… from **parameterizations** for radiation, cloud, convection, turbulence, waves…

Present schools of thought

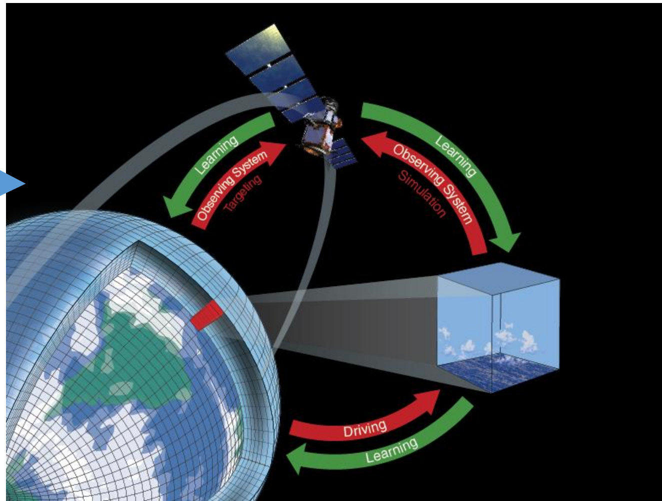


Resolution: Add spatial resolution to eliminate parametrisations
→ ***Computing***?

Traditional: Add model complexity, rely on parametrisations
→ ***Realism***?

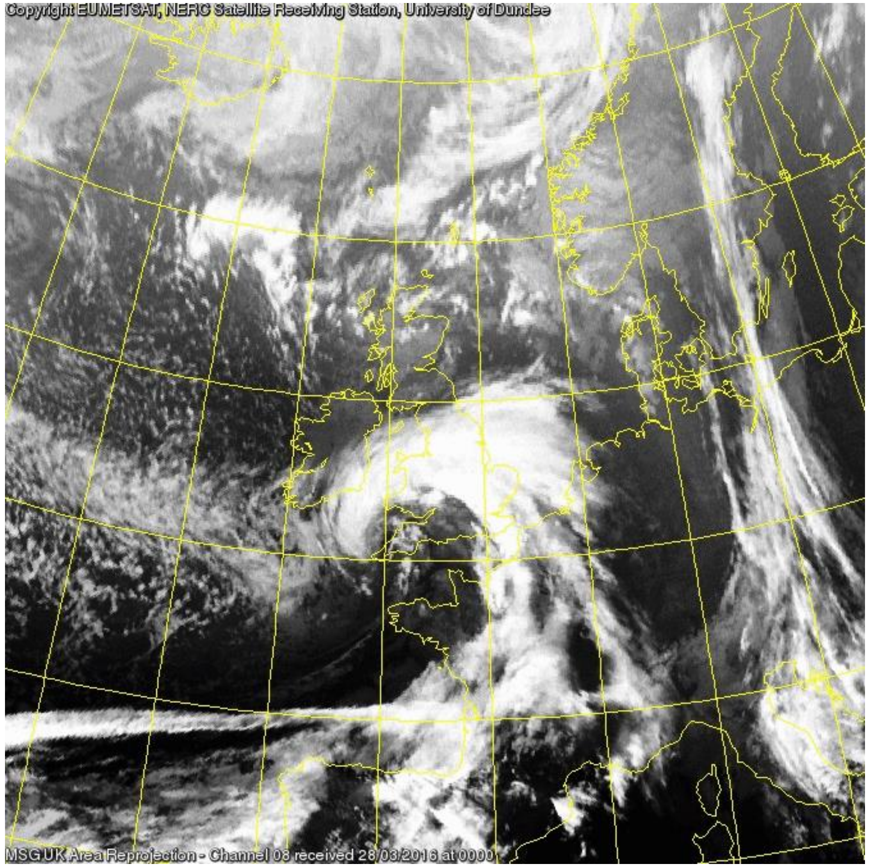


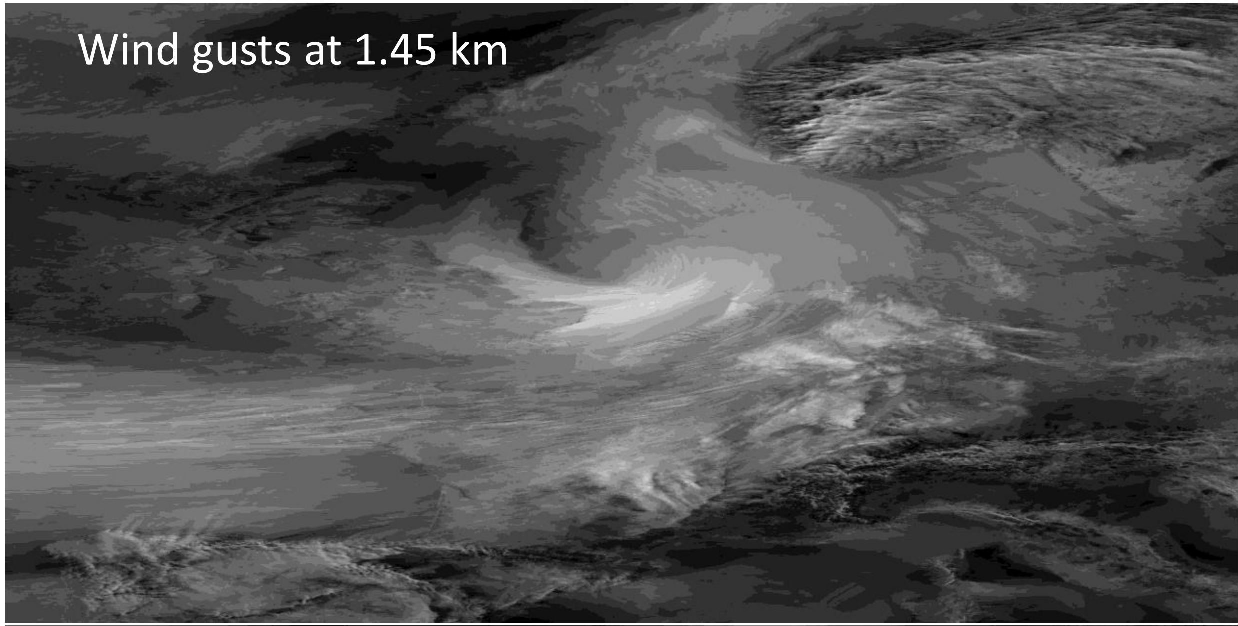
Technology: Use ML to replace parametrisations
→ ***Training***?

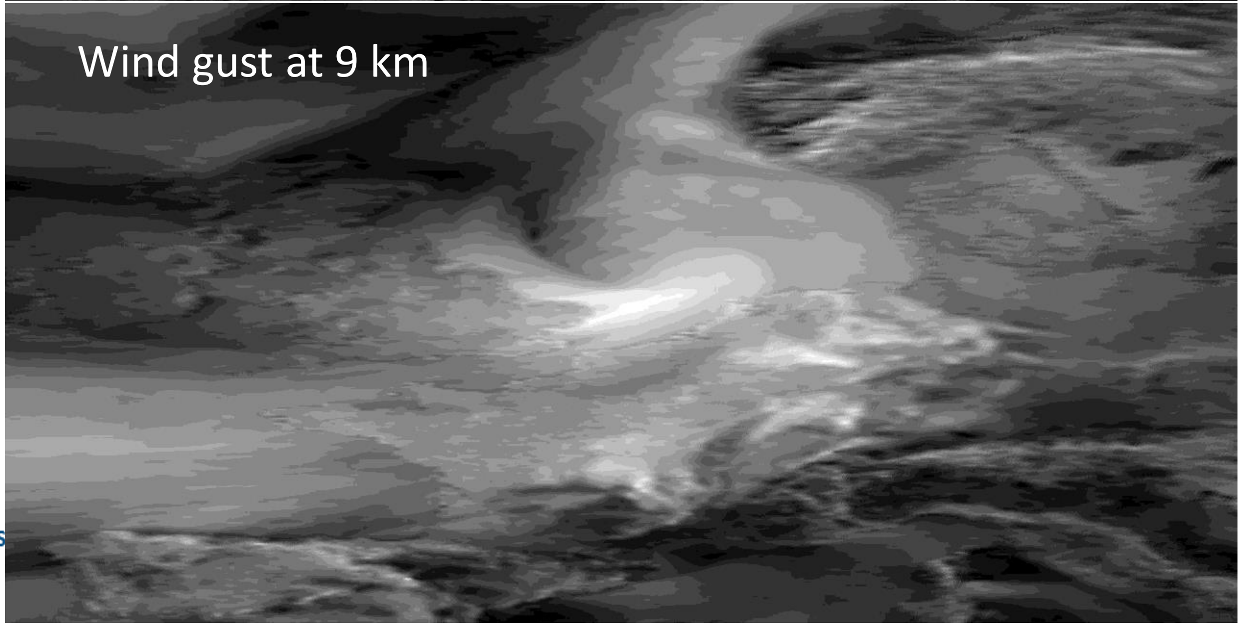


ECMWF model @ 1.45km

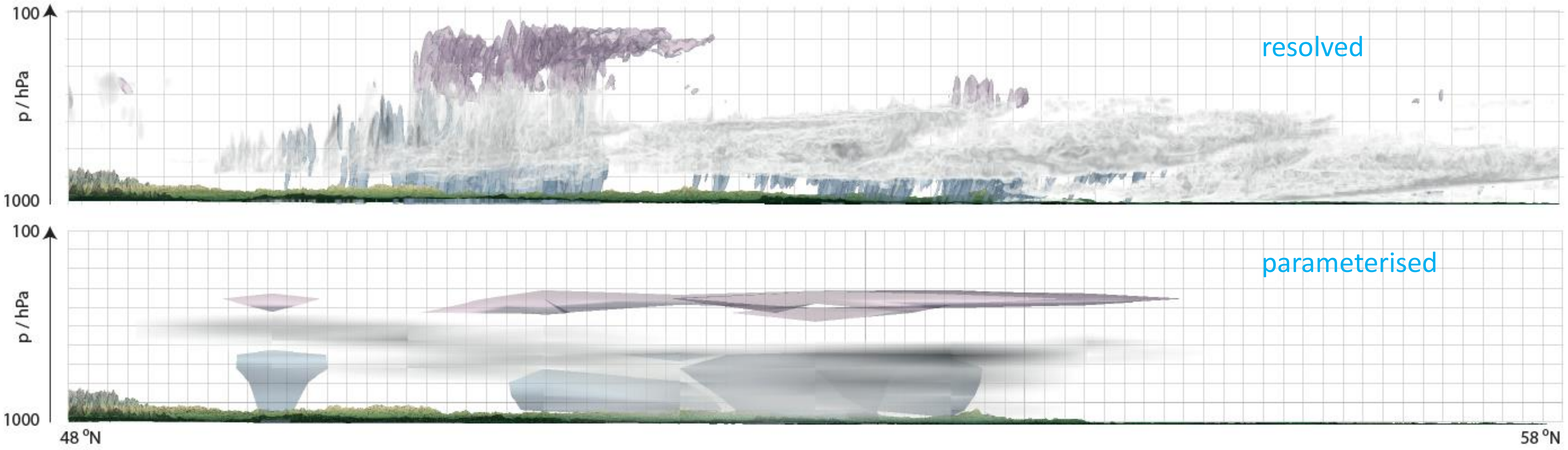
Better orography, better boundary layers





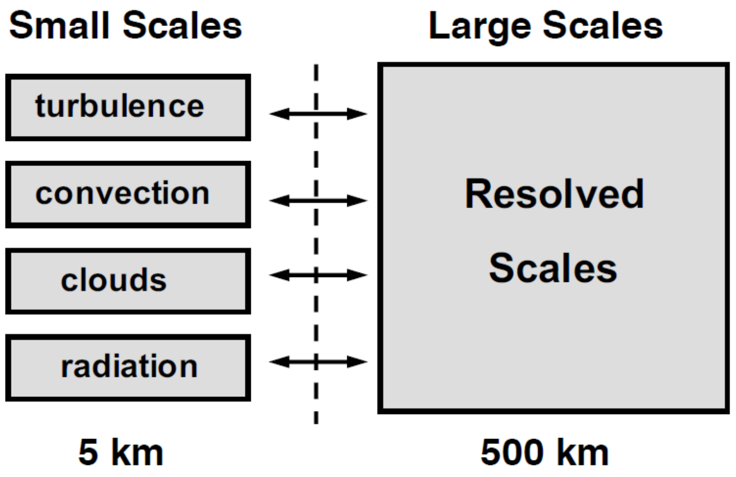


Global storm resolving models

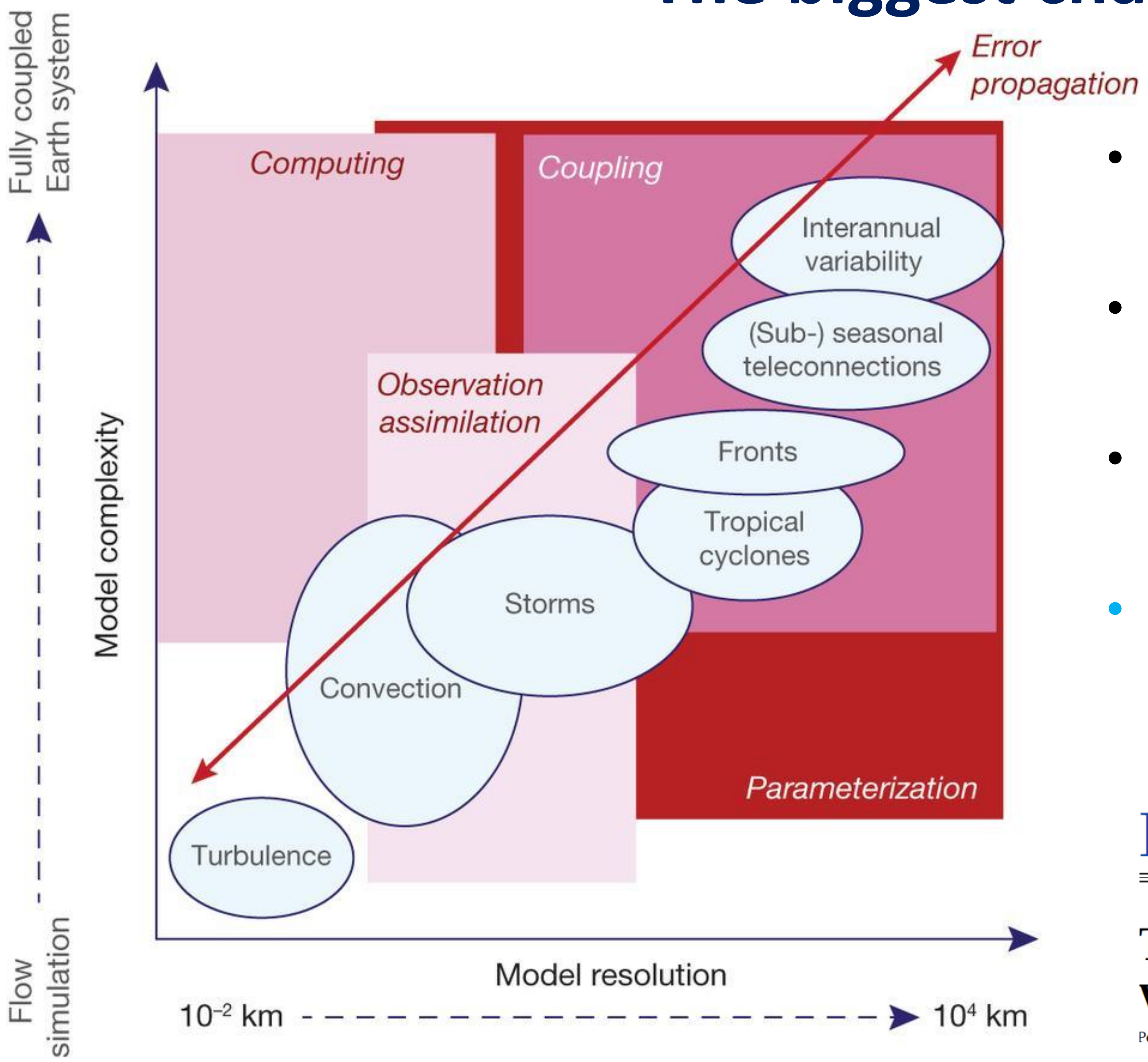


Global Storm Resolving Models ≠ High-resolution General Circulation Models:

[Courtesy Bjorn Stevens]



The biggest challenges



- **Parameterizations**: are in the way of overcoming key sources of model error
- **Coupling**: drives how Earth-system components interact: fluxes, budgets
- **Observation/assimilation**: key to model improvement, initialisation
- **Computing**: key to running realistic models in the future

REVIEW

doi:10.1038/nature14956

The quiet revolution of numerical weather prediction

Peter Bauer[1], Alan Thorpe[1] & Gilbert Brunet[2]

nature

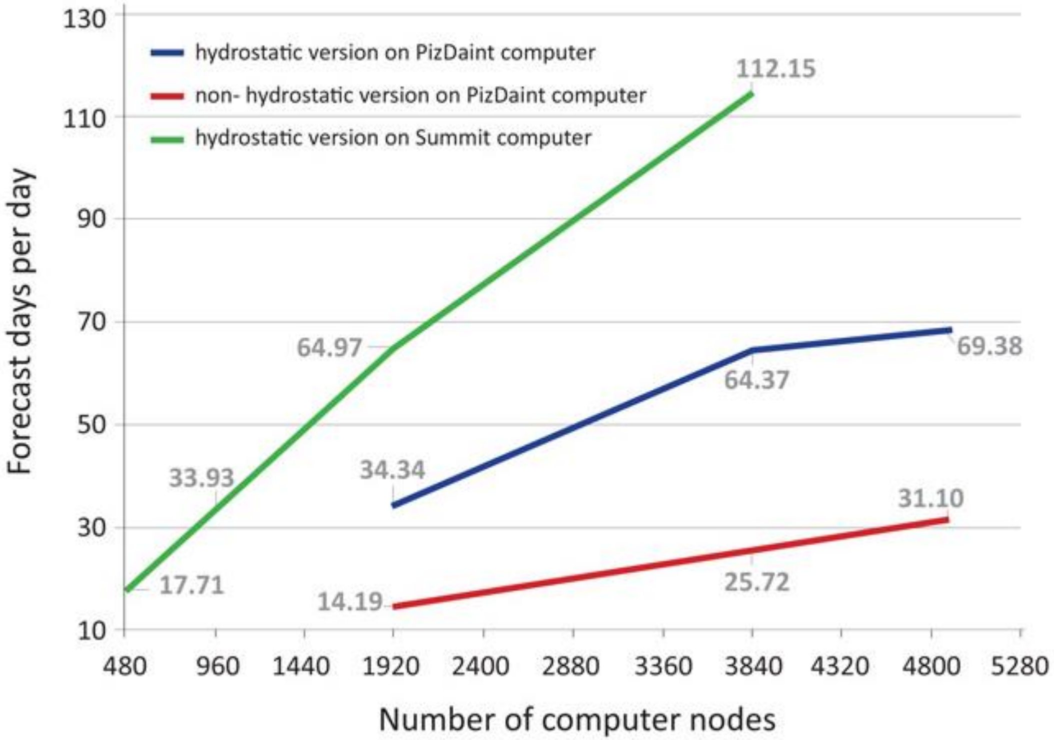
Present capability @ 1 km

Type: New
Title: "Unprecedented scales with ECMWF's medium-range weather prediction model"

Principal Investigator: Nils Wedi, European Center for Medium-Range Weather Forecasts
Co-Investigators: Peter Bauer, European Center for Medium-Range Weather Forecasts

Scientific Discipline: Earth Science: Climate Research

INCITE Allocation:
Site: Oak Ridge National Laboratory
Machine (Allocation): IBM AC922 (102,000 node-hours)



	Near-global COSMO[15]		Global IFS[16]	
	Value	Shortfall	Value	Shortfall
Horizontal resolution	0.93 km (non-uniform)	0.81x	1.25 km	1.56x
Vertical resolution	60 levels (surface to 25 km)	3x	62 levels (surface to 40 km)	3x
Time resolution	6 s (split-explicit with sub-stepping)*	-	120 s (semi-implicit)	4x
Coupled	No	1.2x	No	1.2x
Atmosphere	Non-hydrostatic	-	Non-hydrostatic	-
Precision	Single	-	Single	-
Compute rate	0.043 SYPD	23x	0.088 SYPD	11x
Other (e.g. physics, ...)	microphysics	1.5x	Full physics	-
Total shortfall		101x		247x

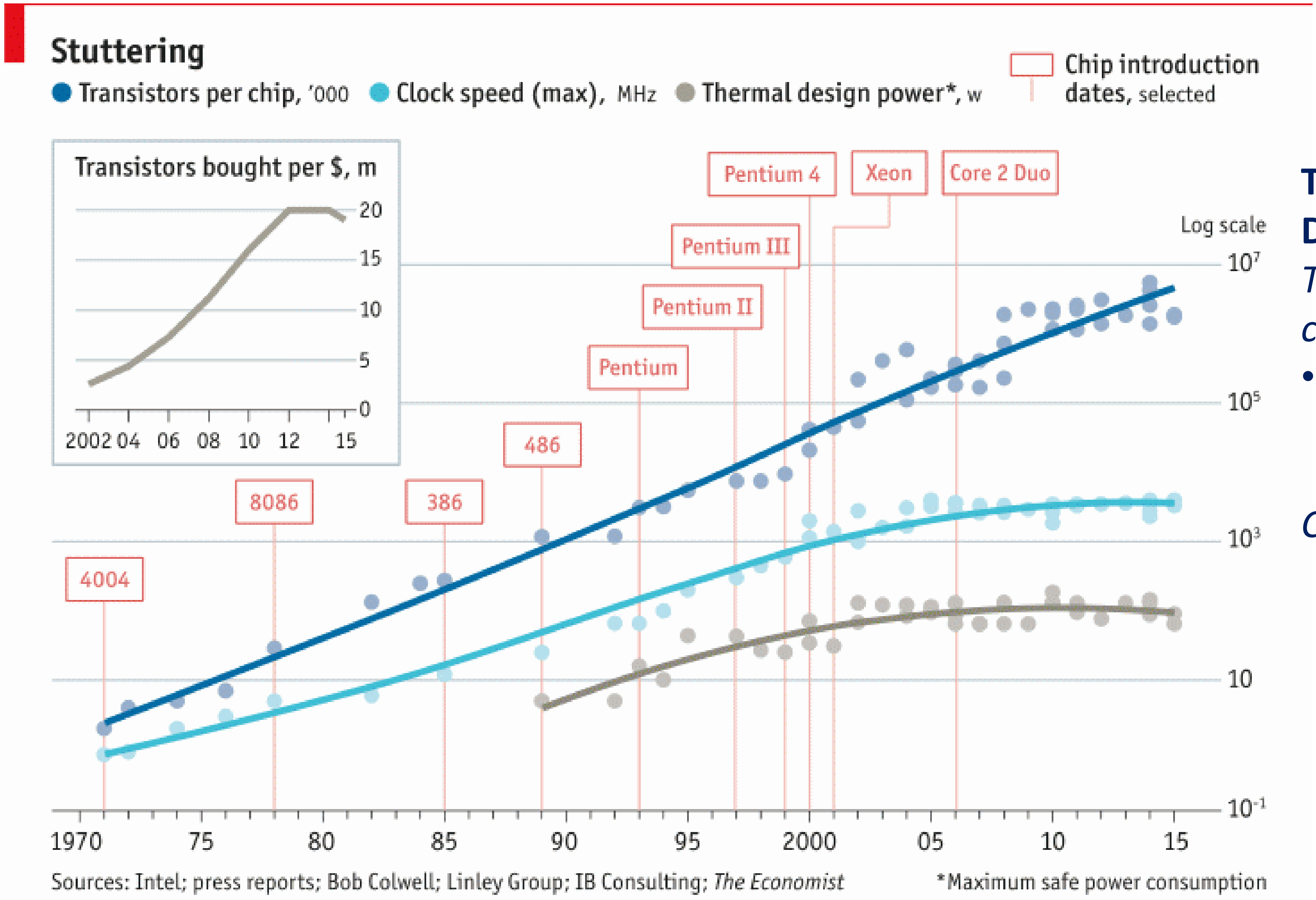
→ O(3-10) too slow (atmosphere only, no I/O)

→ O(100-250) too slow (still no I/O)

→ O(1000) incl. everything (ensembles, Earth system, etc.)

[Schulthess et al. 2019, Computing in Science & Engineering]

The end of Moore’s law and Dennard scaling



Transistor size and clock-cycle (serial, Moore, Dennard):

The smaller the transistor the faster its state can be changed by clock cycles

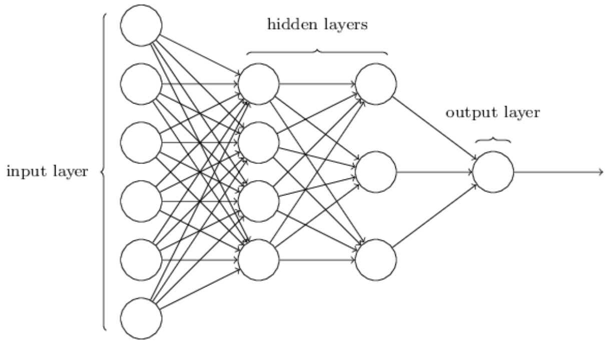
- *Power P = capacitance x voltage^2 x 1/clock-cycle*
  (capacitance area)

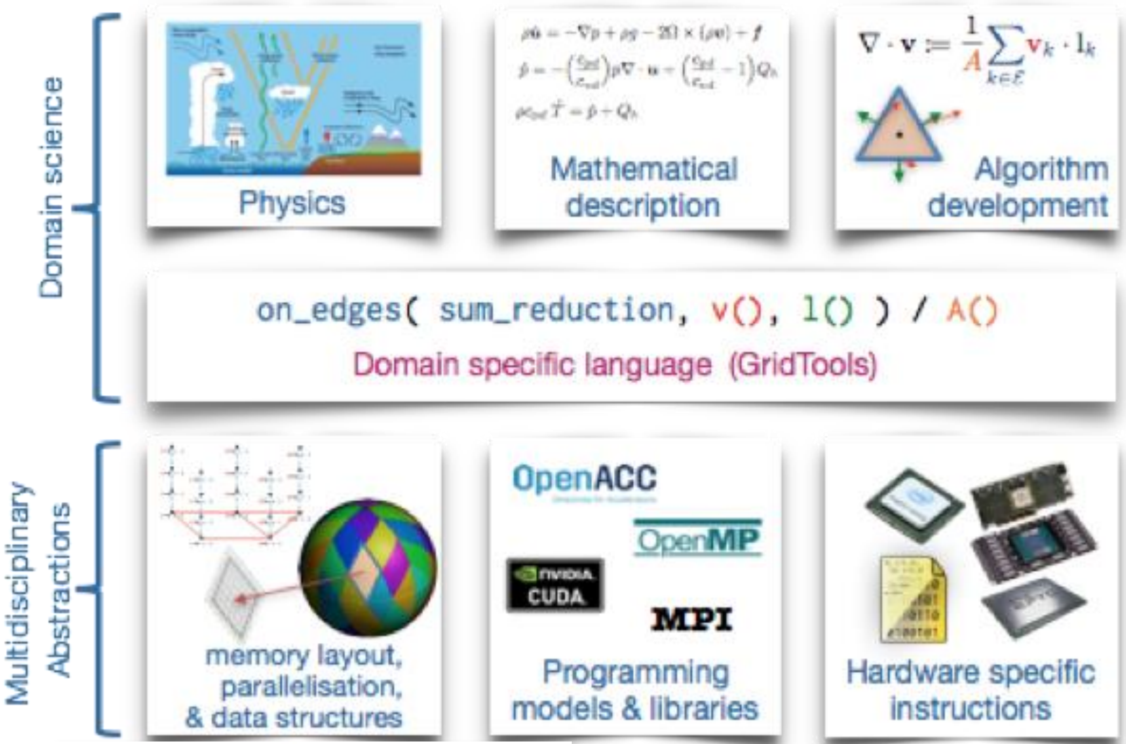
Caveats:

- *transistors cannot become smaller anymore → spontaneous electron leakage*
- *transistor voltage does not scale with size anymore → overall power increases*

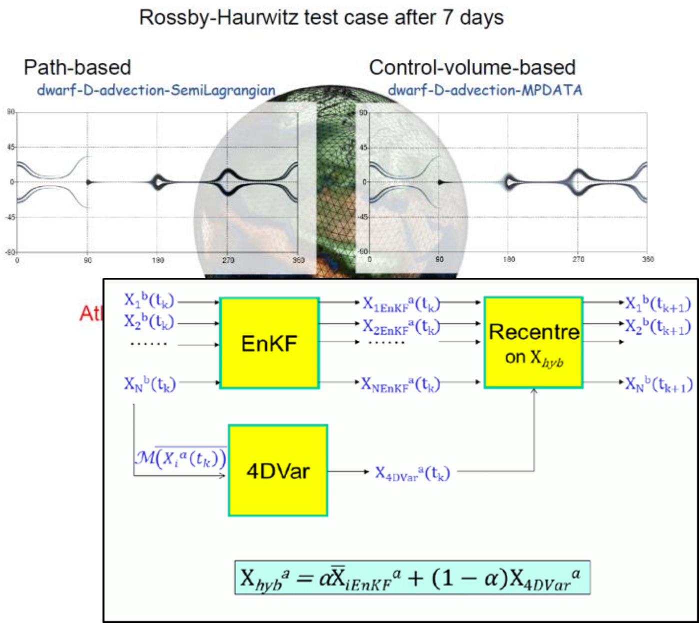
The future – ultimately, touch everything

Neural networks

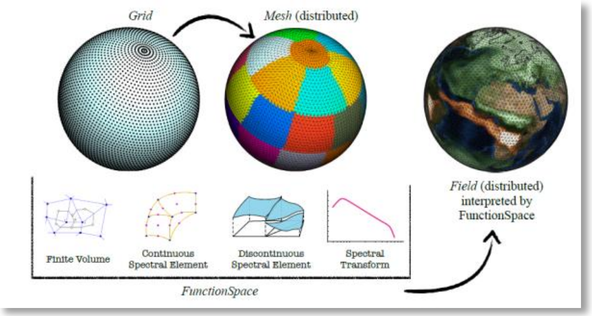




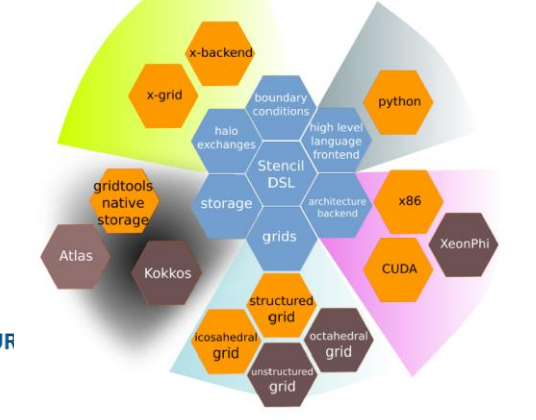
Mathematics&algorithms



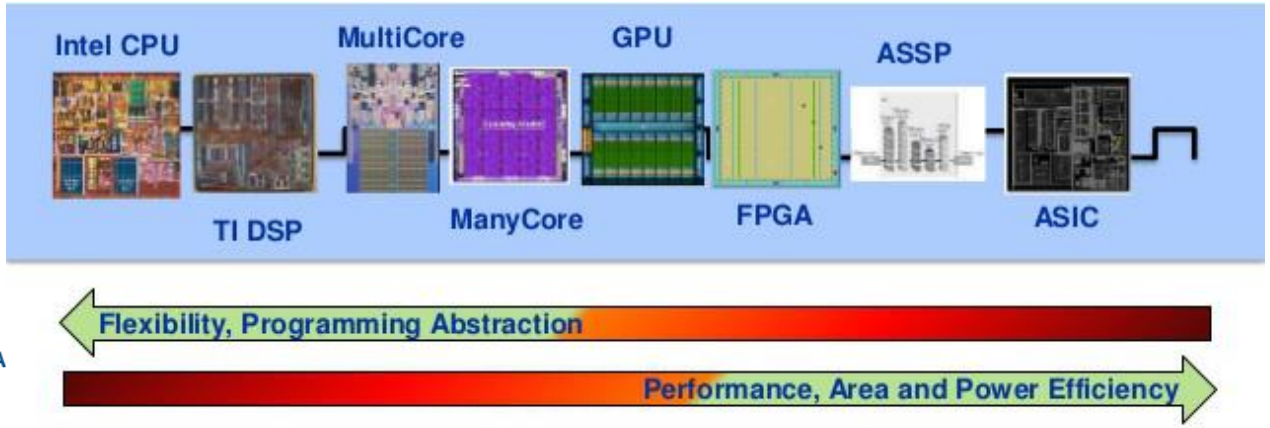
Data structures: Atlas



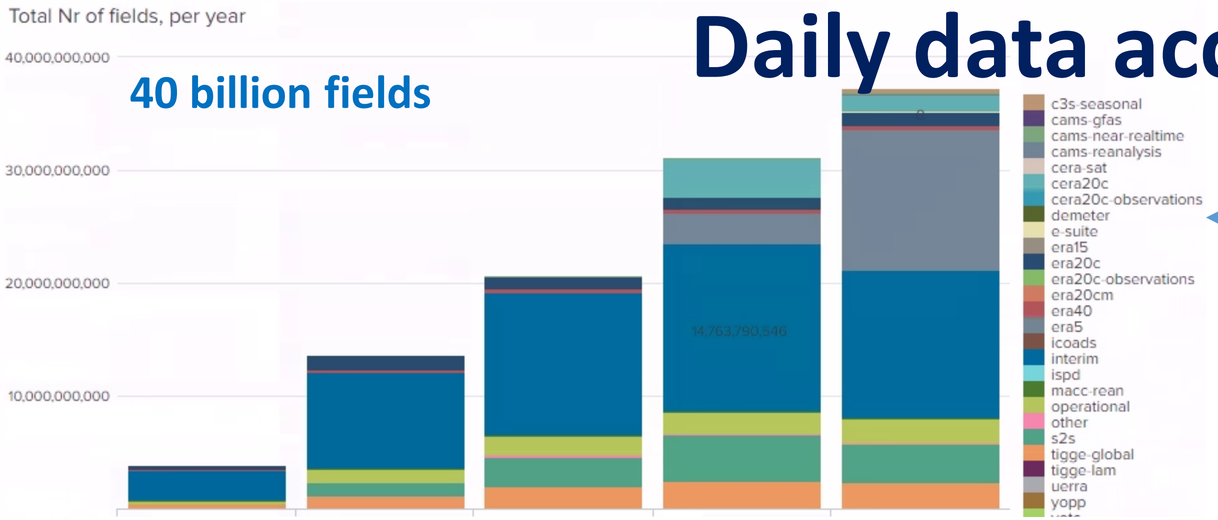
Back-end: GridTools



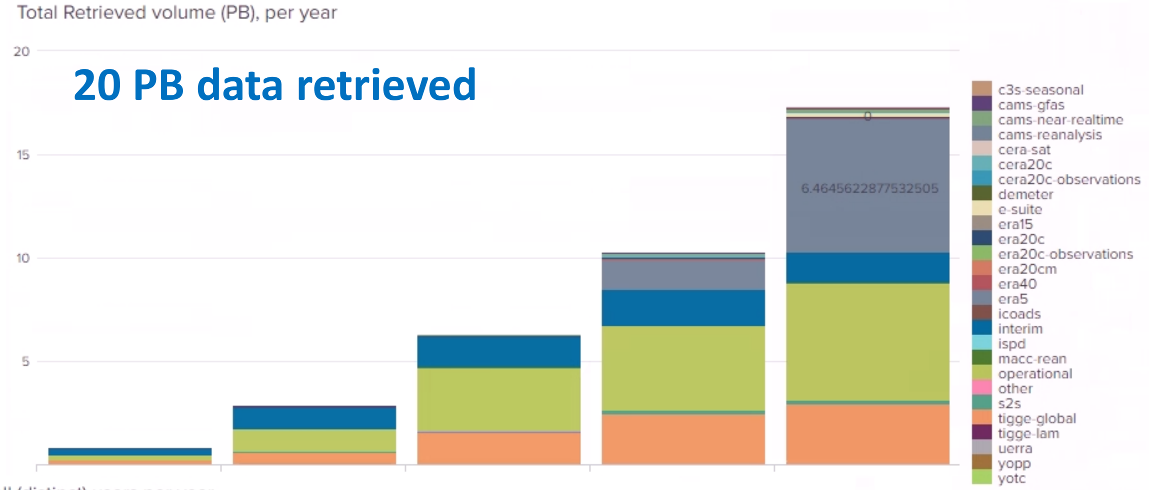
Processors

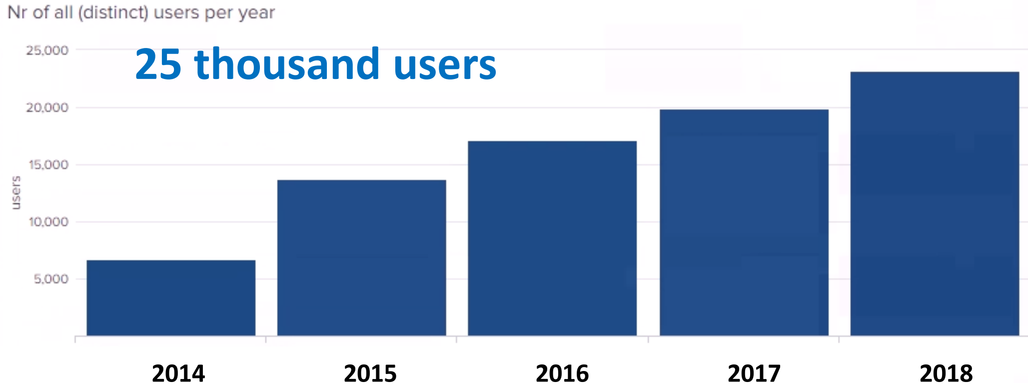


Daily data access at ECMWF



Public





Total **activity (Member States and commercial customers) per day:**

- **450 TBytes retrieved**
- **200 TBytes archived**
- **1.5 million requests**

Total volume in MARS: 220 PiB

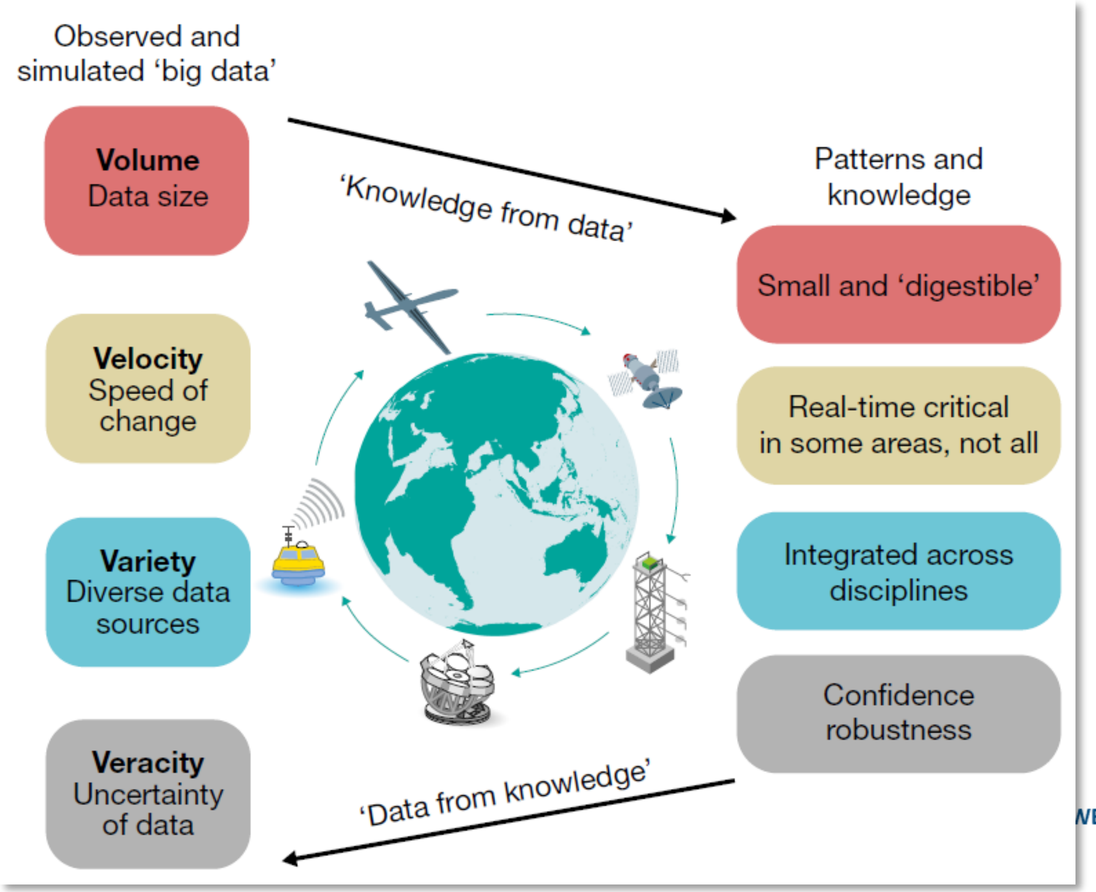
Deep learning and Earth-system sciences


PERSPECTIVE

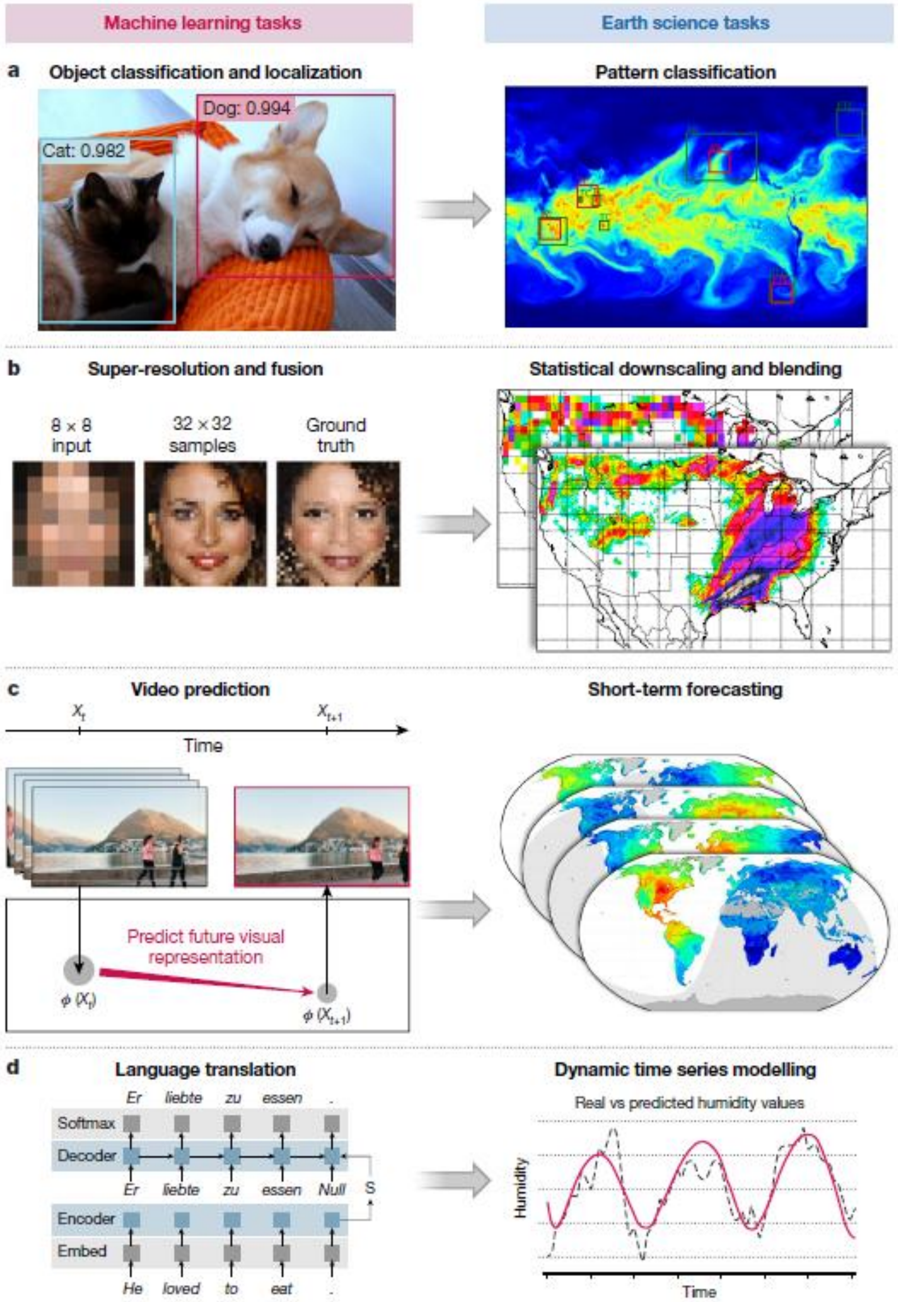
https://doi.org/10.1038/s41586-019-0912-1

Deep learning and process understanding for data-driven Earth system science

Markus Reichstein[1,2*], Gustau Camps-Valls[3], Bjorn Stevens[4], Martin Jung[1], Joachim Denzler[2,5], Nuno Carvalhais[1,6] & Prabhat[7]



WEATHER FORECASTS



Application areas in workflow

Observational data processing *(edge & cloud &HPC)*:

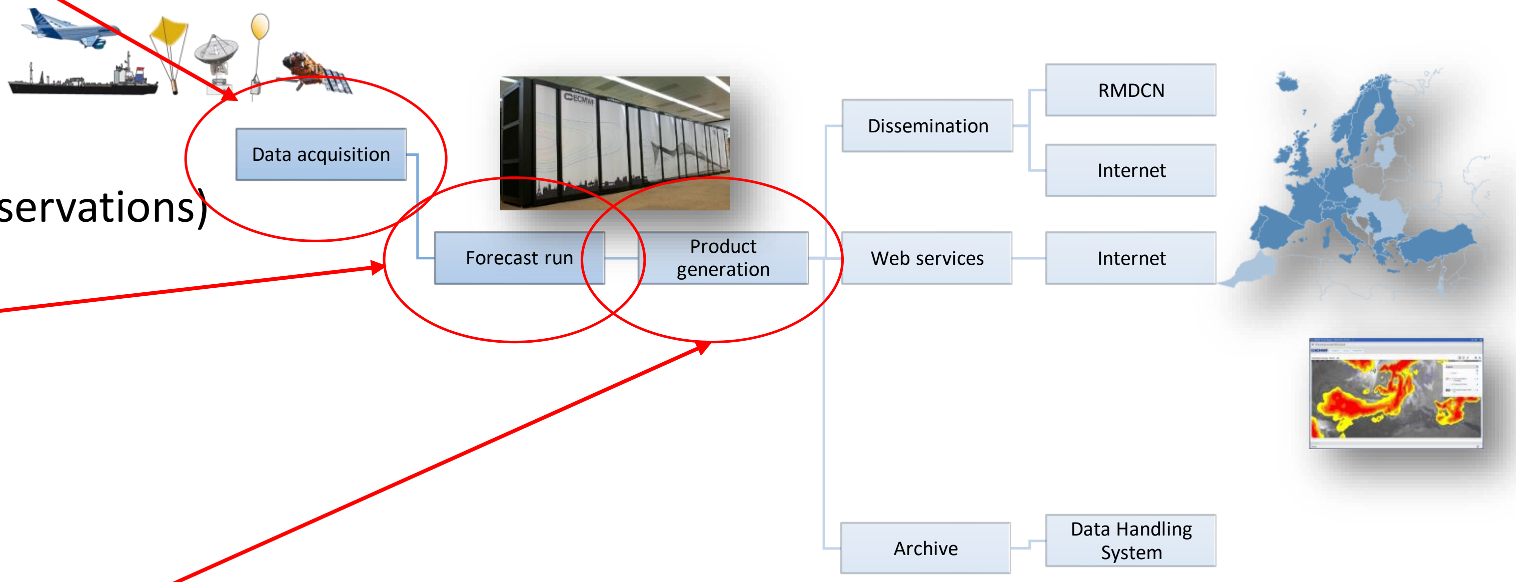
- Quality control and bias correction
- Data selection
- Inversion (=retrieval)
- Data fusion (combining observations)
- …

Prediction models *(cloud & HPC)*:

- Data assimilation (combining models w/ observations)
- Surrogate model components
- Prediction itself
- Model error statistics
- …

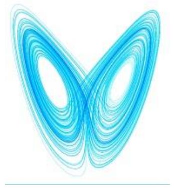
Service output data processing *(cloud &HPC)*:

- Product generation and dissemination
- Product feature extraction (data mining)
- Product error statistics
- Interactive visualisation and selection
- Data handling (access prediction)
- …



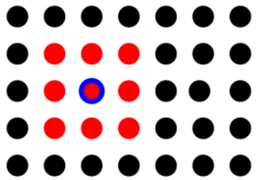
But can we predict the weather?

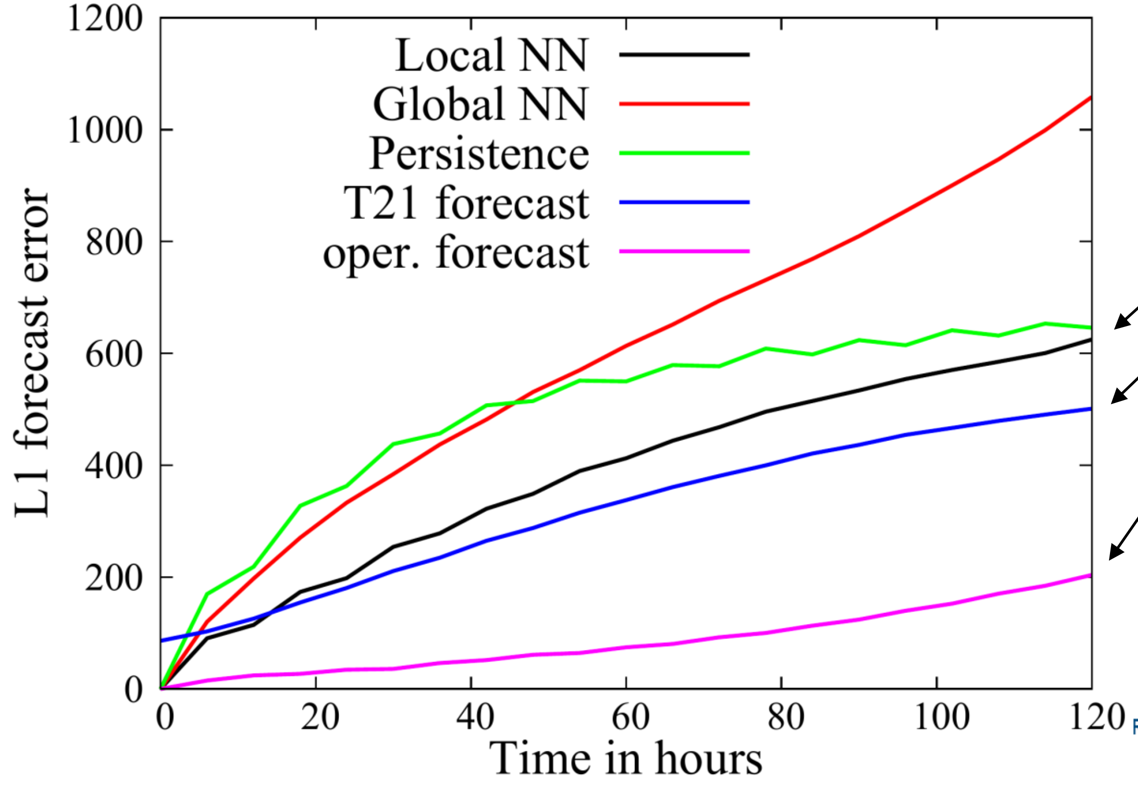
An attempt to test if Neural Networks could replace weather forecast models that are based on physics principles:



→ Use Ed Lorenz's 1996 simplified model that captures chaotic and non-linear interaction between scales, just like in the real atmosphere

→ Use real ECMWF model forecasts at (much) reduced resolution, local stencil





RECASTS

- **Local NN only slightly worse than**
- **T21 forecast model**
- **This is the real target: T1279 (9km) forecast mode**

Geosci. Model Dev., 11, 3999–4009, 2018
https://doi.org/10.5194/gmd-11-3999-2018

Geoscientific Model Development
Open Access

Challenges and design choices for global weather and climate models based on machine learning

Peter D. Dueben and Peter Bauer
European Centre for Medium-range Weather Forecasts, Shinfield Rd, Reading, RG2 9AX, UK

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EARTH

Climate Forecast: World Is "Sleepwalking into Catastrophe"

In an annual World Economic Forum report, climate change, extreme weather and biodiversity loss were named among the highest global risks

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ExtremeEarth

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

Learn More

https://www.extremeearth.eu

https://sites.google.com/view/climatemodelingcentre

Sign the Petition

The climate science community must join forces to provide the most accurate predictions and make their results publicly accessible.

As described in our Scientific American OpEd, we call for an international centre for climate models supported by dedicated (and not simply shared) exascale supercomputing to:

- reduce the grid spacing of models to around 1km (0.6 mi)
- implement modern techniques of software development as they arise
- explore novel computer technologies and hardware architecture
- bring together scientists and technologists of diverse disciplines
- develop an open data interface for projecting changes in future weather and climate

This initiative is part of a programme called Extreme Earth which seeks to improve our ability to predict a range of natural and human-induced hazards. The petition will send a clear message to politicians and funding agencies to come together to address one of the biggest challenges for our society'.

Authors

Tim Palmer, University of Oxford

Bjorn Stevens, Max-Planck-Institute for Meteorology

Peter Bauer, European Centre for Medium-Range Weather Forecasts

There are new career opportunities for computational scientists in weather and climate prediction – an opportunity to create impact for society!