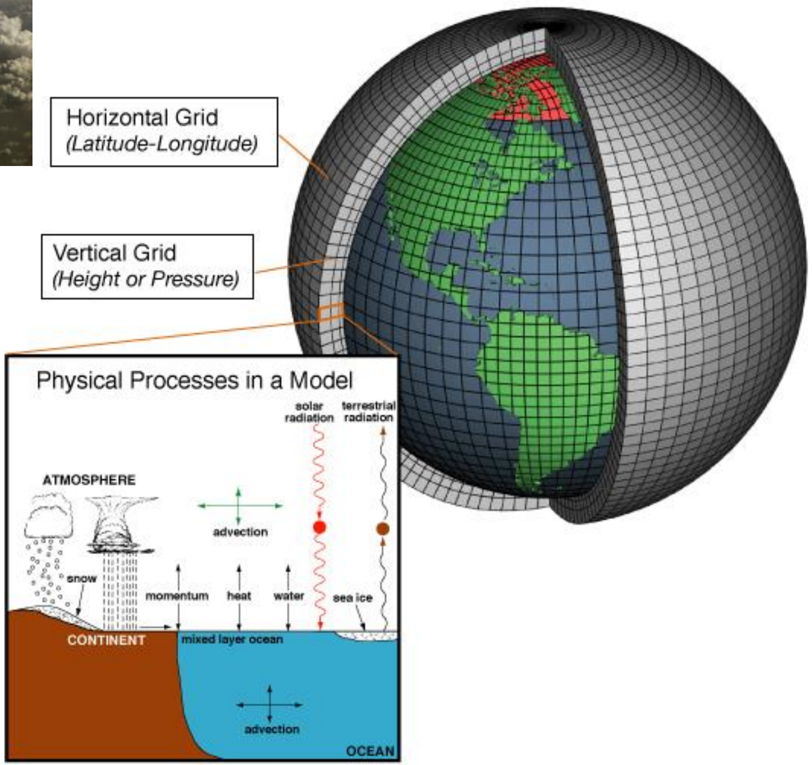
Numerical Weather Prediction

John Marsham (Leeds & NCAS)



doi:10.1038/nature14956

The quiet revolution of numerical weather prediction

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

Advances in numerical weather prediction represent a quiet revolution because they have resulted from a steady accumulation of scientific knowledge and technological advances over many years that, with only a few exceptions, have not been associated with the aura of fundamental physics breakthroughs. Nonetheless, the impact of numerical weather prediction is among the greatest of any area of physical science. As a computational problem, global weather prediction is comparable to the simulation of the human brain and of the evolution of the early Universe, and it is performed every day at major operational centres across the world.

At the turn of the twentieth century, Abbe[1] and Bjerknes[2] proposed that the laws of physics could be used to forecast the weather; they recognized that predicting the state of the atmosphere could be treated as an initial value problem of mathematical physics, wherein future weather is determined by integrating the governing partial differential equations, starting from the observed current use of observational information from satellite data providing global coverage.

More visible to society, however, are extreme events. The unusual path and intensification of hurricane Sandy in October 2012 was predicted 8 days ahead, the 2010 Russian heat-wave and the 2013 US cold spell were forecast with 1–2 weeks lead time, and tropical sea surface

Knowing the future
Mans aim for millennia…

(Asterix and the Soothsayer, Uderzo & Goscinny, 1972)

A Mid-latitude centric view?

(Bauer et al., 2015)

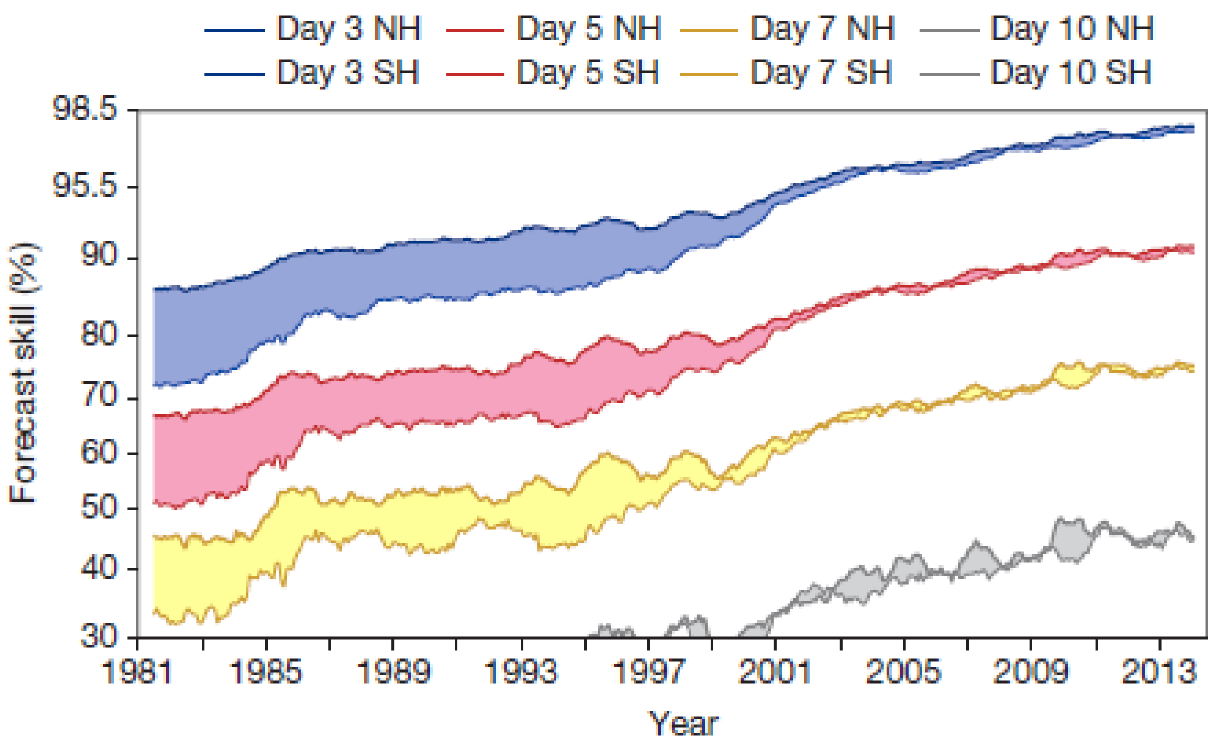
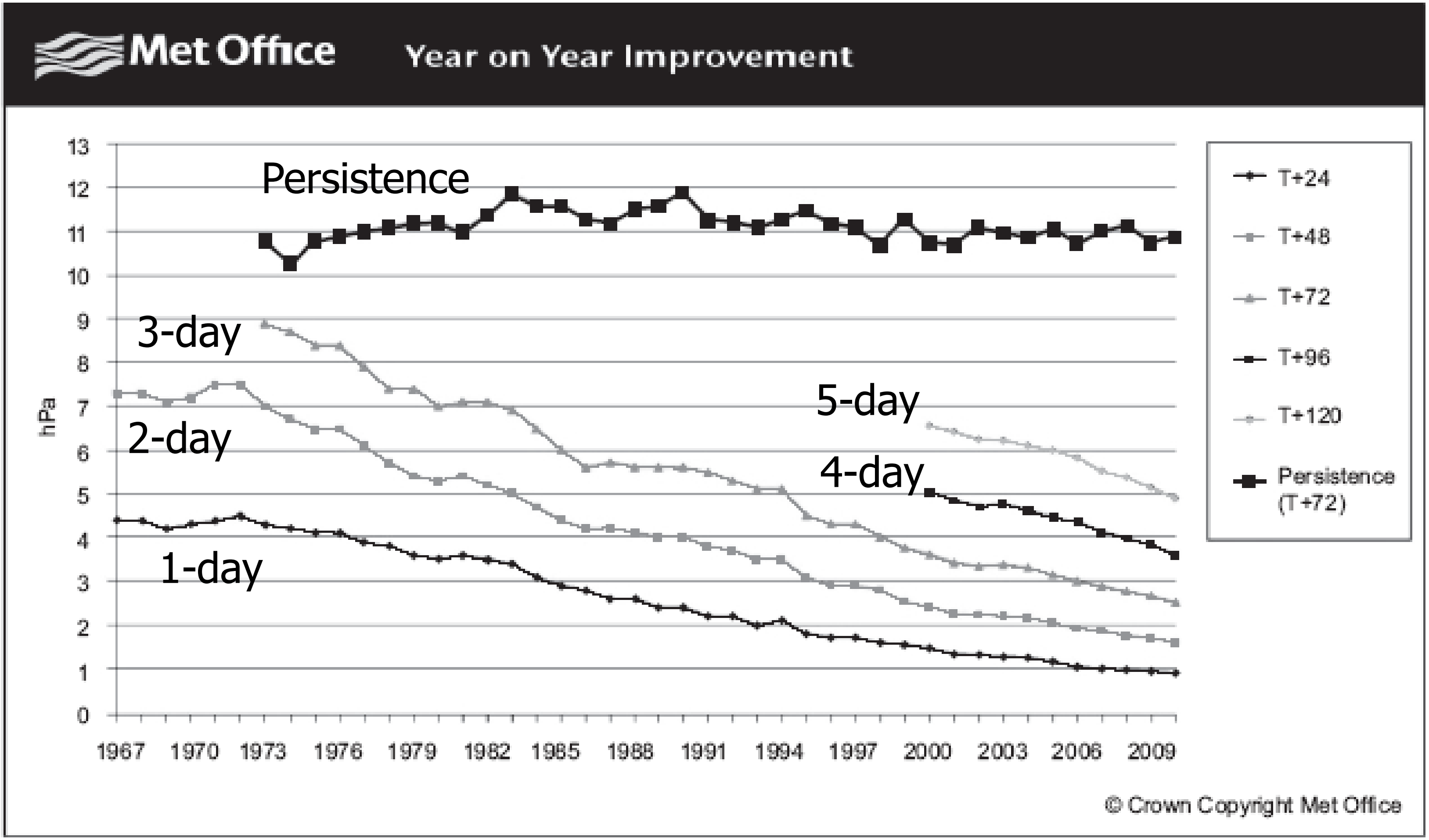


Figure 1 | A measure of forecast skill at three-, five-, seven- and ten-day ranges, computed over the extra-tropical northern and southern hemispheres.

Continual improvement over more than 5 decades

A 4-day forecast in 2010 was as good as a 1-day forecast in 1980

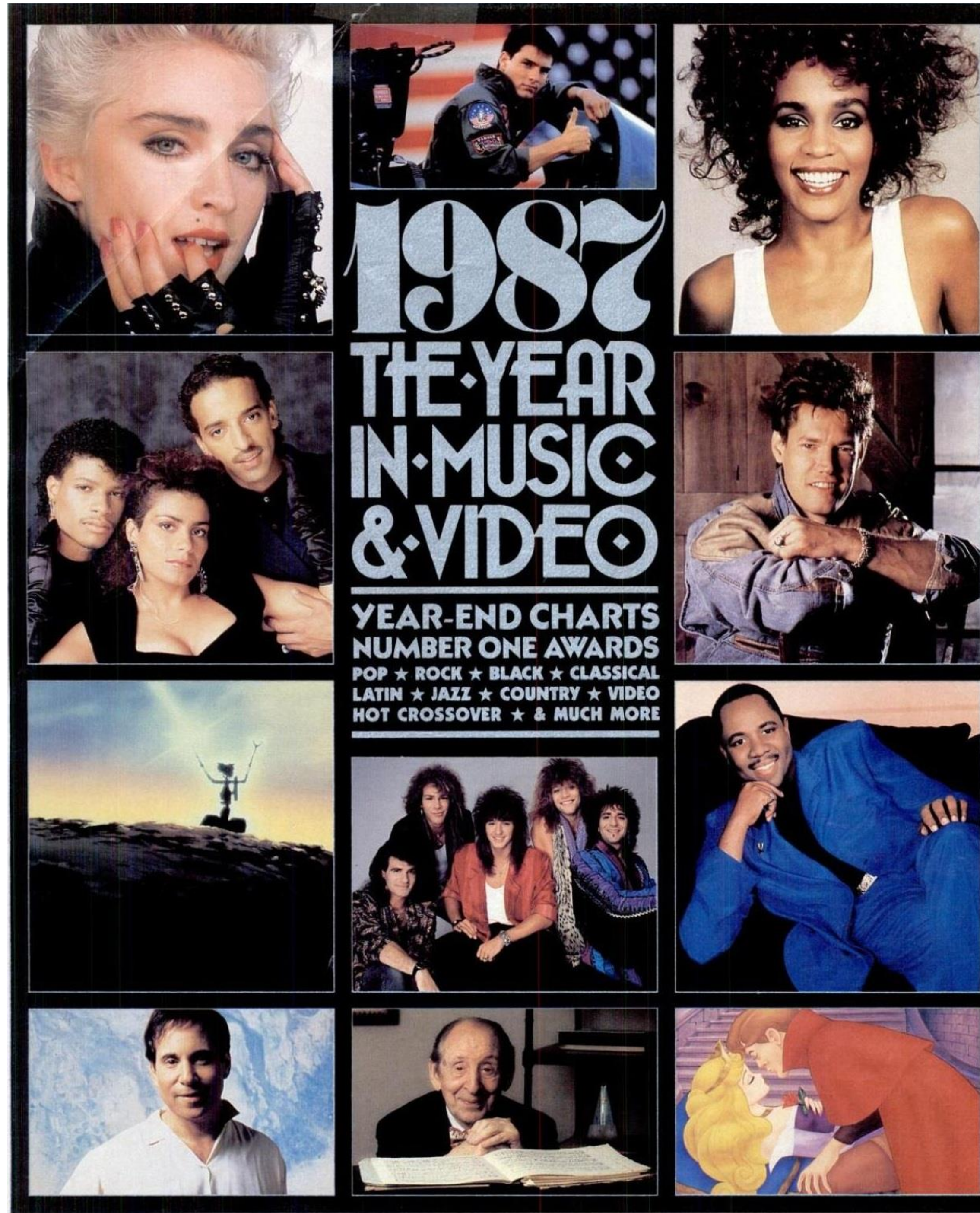


- We have "gained one day per decade"
- But note this is in hPa!

Great Storm of 1987

- A "one in 200 year storm"
- Damage on night of 15/16 October 1987
- First gale warnings at 06:30 15 October
- 22:35 winds of Force 10 were forecast
- 01:40 on 16 October, warnings of Force 11
- 01:35 warning was "that civil authorities might need to call on assistance from the military".

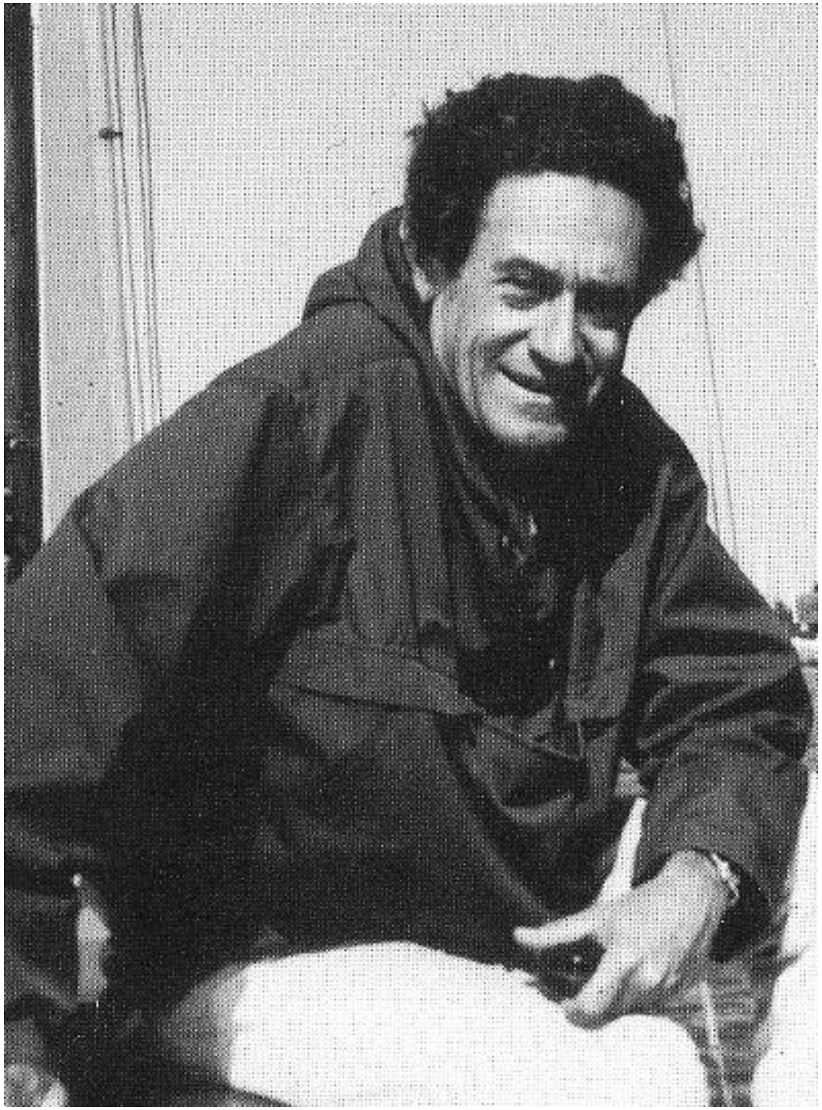
- I remember this



1957

- 5Mb of storage in 1957
- My mum remembers this

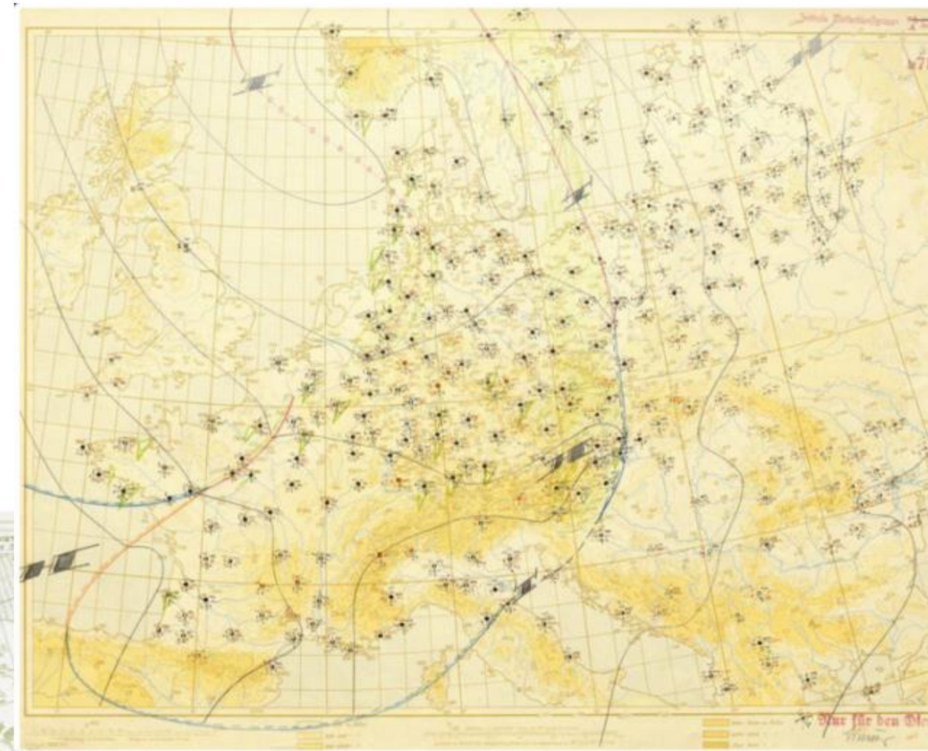
History of NWP: The start of computing for NWP



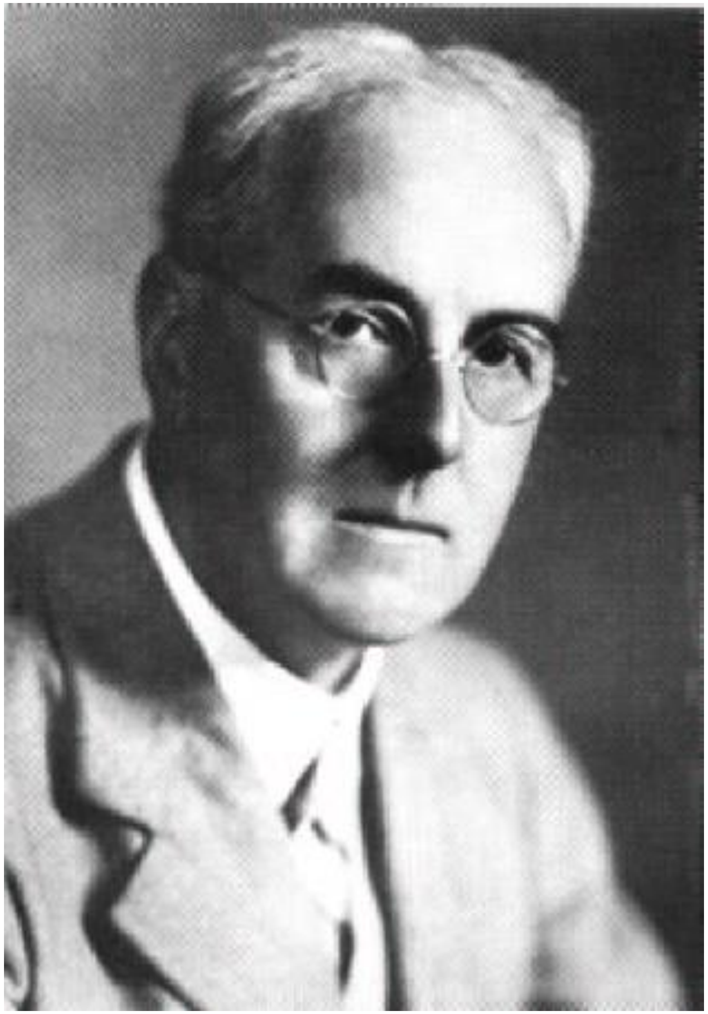
Jule Charney
John von Neumann
Ragnar Fjørtoft
1950

"weather forecasting as a problem *par excellence* for an automated computer"

D Day 1944
(perhaps a million in the UK remember this)



History of NWP: Manual computation



Lewis F. Richardson 1922

Numerical integration of equations of motion

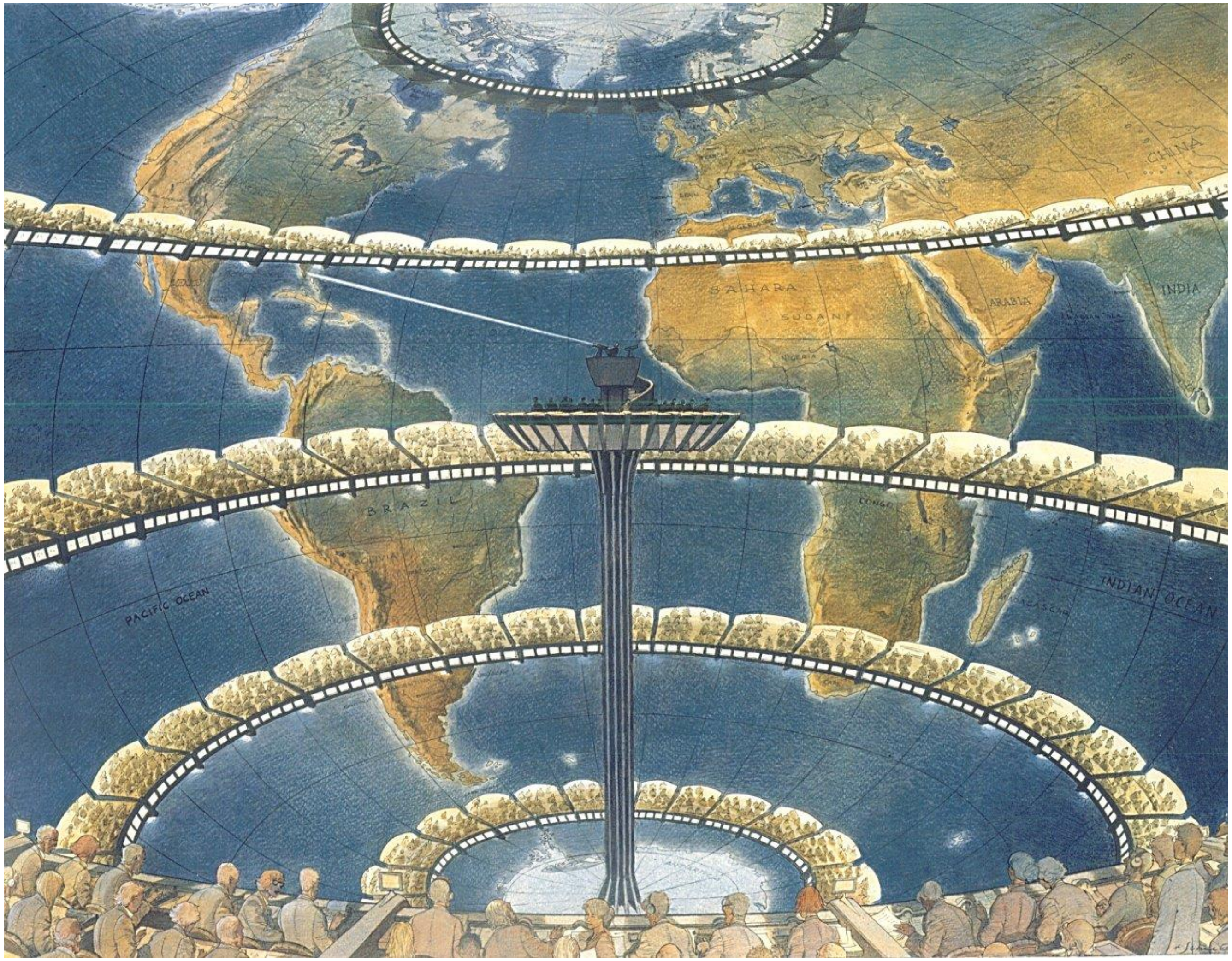
Manual computation of pressure change over England based on discretized equations

Result: 145 hPa in 6 hours …

→ NWP was considered impossible for the decades to come...

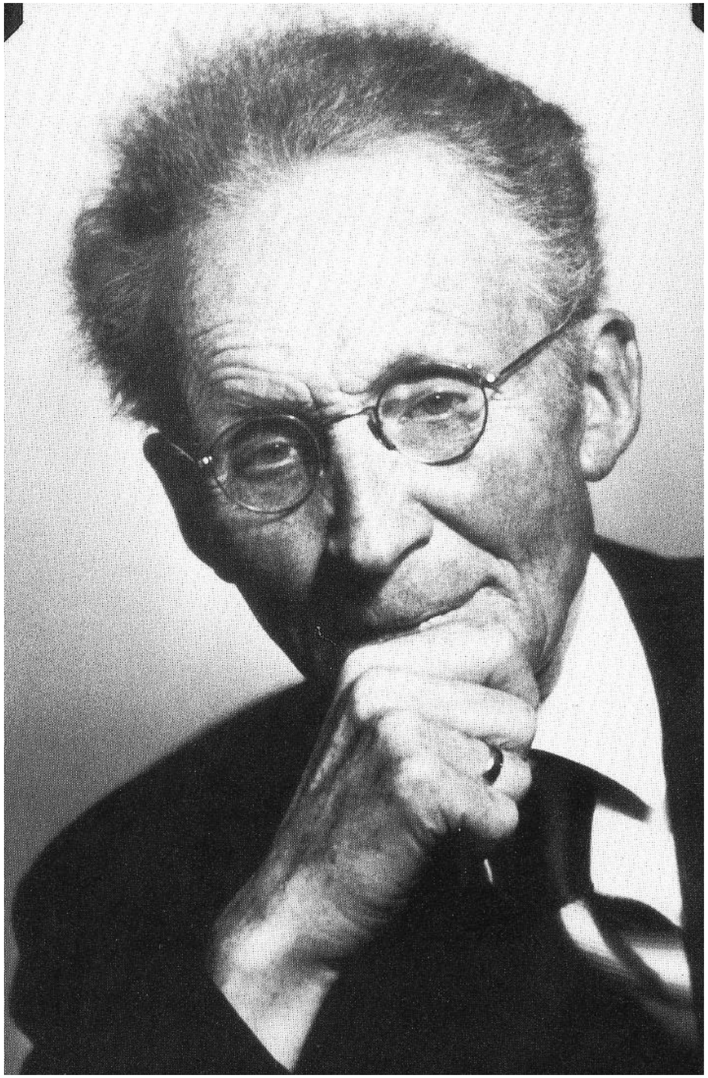
BUT: we still use this concept today

Richardson’s dream



“Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream.”

How did we get to this Point? The history of NWP



Vilhelm Bjerknes 1904

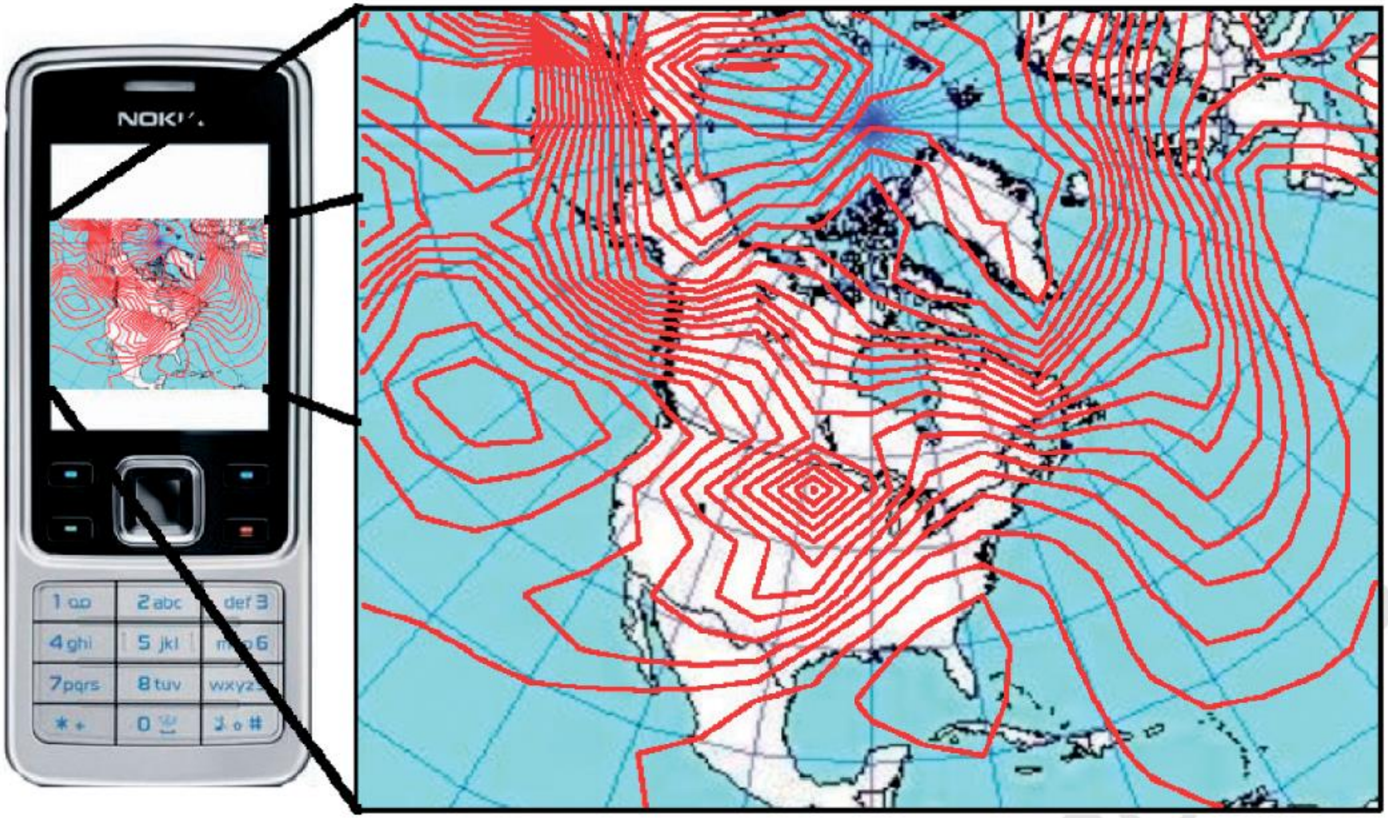
Weather prediction as an initial value problem based on physical equations

→ Weather forecasting becomes a physical science

Historical numerical weather prediction “now” (6 Jan. 1949)

Reproduction with a mobile phone (Java script)

Computational time: < 1 sec



from *Lynch & Lynch, 2008, Weather*

http://mathsci.ucd.ie/~plynch/eniac/phoniac.html

How does numerical weather prediction work?

Mathematically, weather prediction is an initial value problem

time

initial condition → prediction

physical laws
(equations of motion, continuity equation, thermodynamic equation etc.)

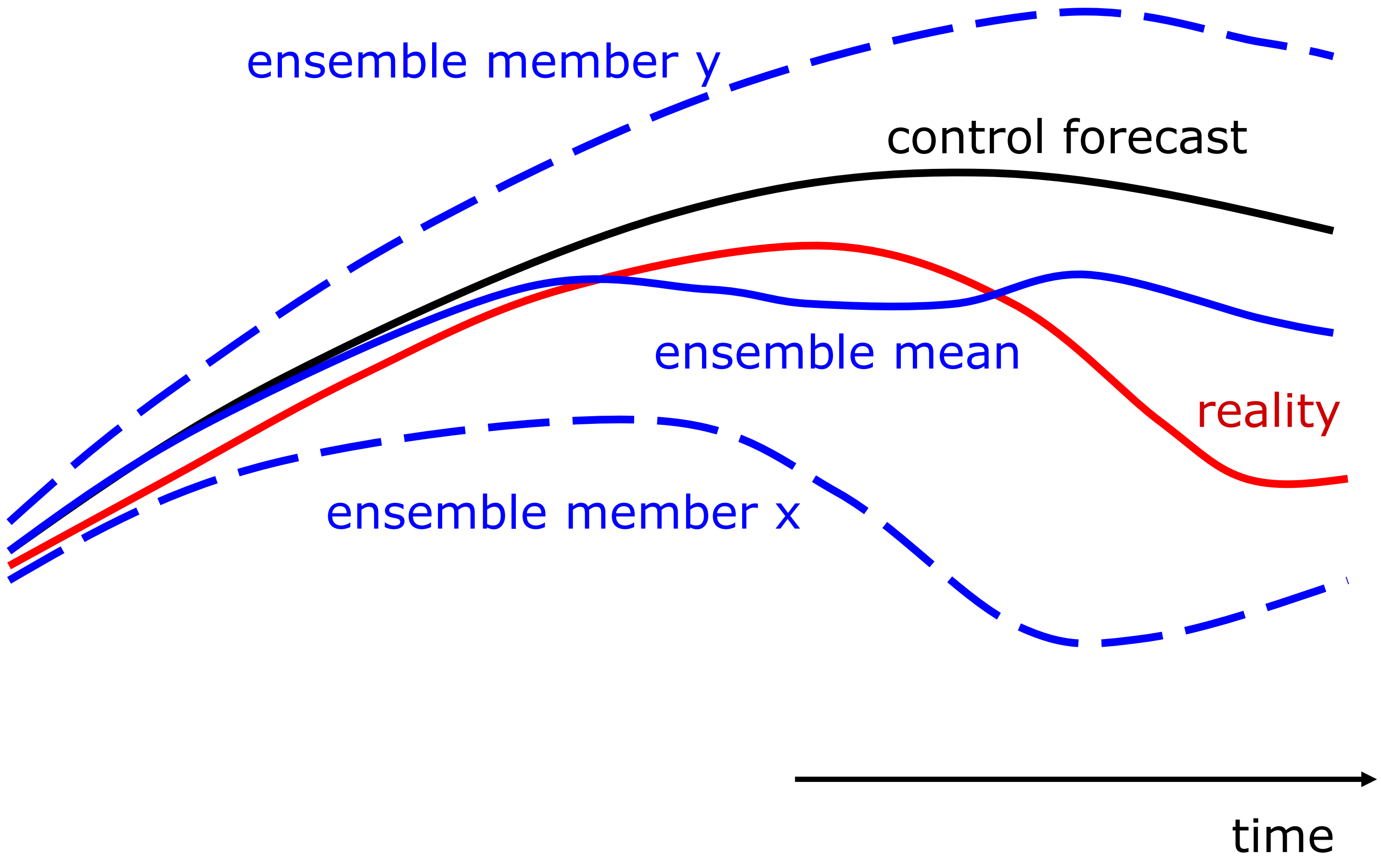
Physical laws form a system of coupled equations

Analytical solution exists for trivial cases only
→ numerical weather prediction (NWP) models, supercomputers

The 4 big challenges for NWP are:
1) discretisation & parametrisation, 2) initialisation, 3) predictability, 4) computing

Construction of ensemble predictions

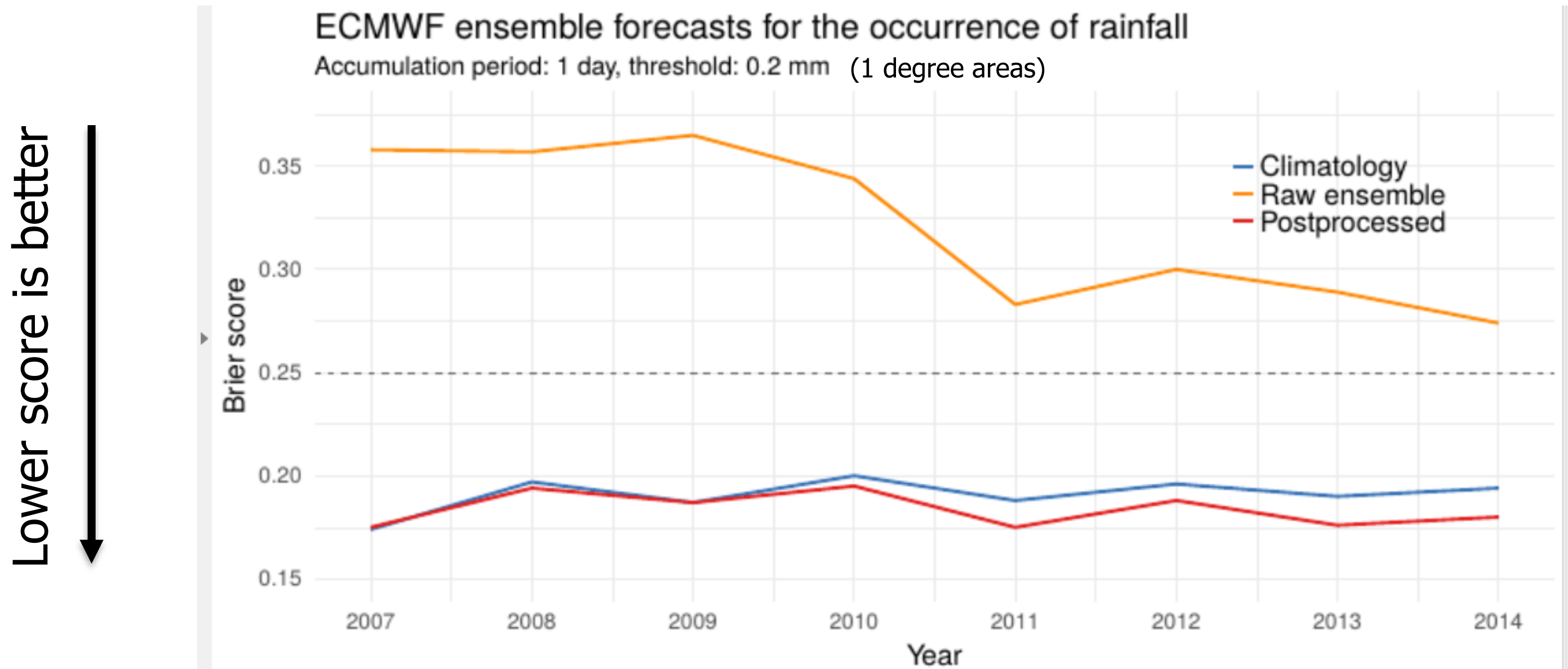
Typical size of an operational ensemble 50 (ECMWF)



Weather is always uncertain – need probabilistic forecasts

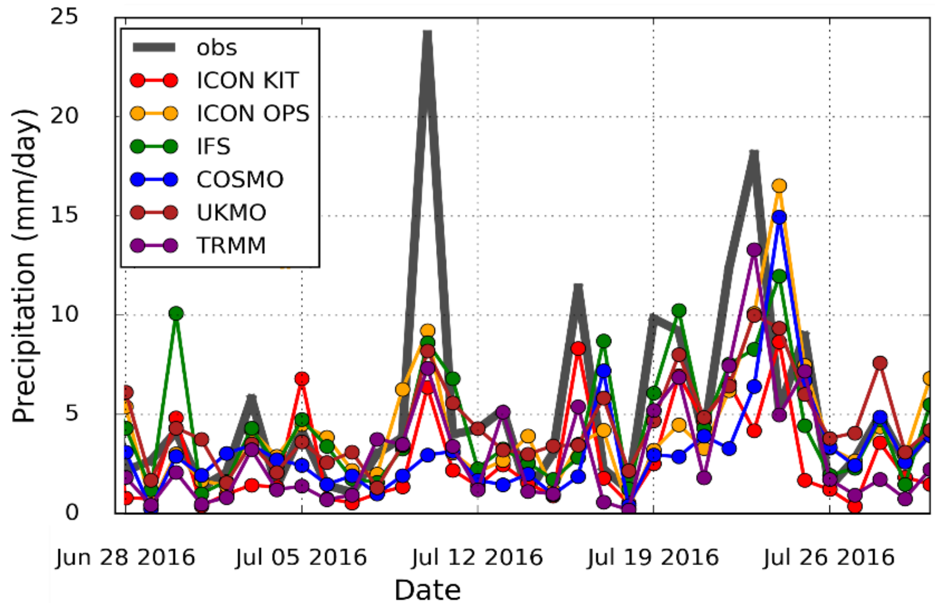
Predicting rainfall in Africa

Based on Vogel et al, 2018



- Post-processed forecasts just beat climatology
    - Raw forecasts do not

Synoptic-forcing does give model skill



(From "Key lessons from the DACCIWA project for operational Meteorological services")

One-day precipitation forecasts and corresponding observations *(derived from 155 stations in southern West Africa). Adapted from Kniffka et al. [2019, in prep.].*

- Synoptic events lead to predictable increases and decreases in rainfall
  - Some issues with timing and magnitude

How good are precipitation forecasts in the tropics?

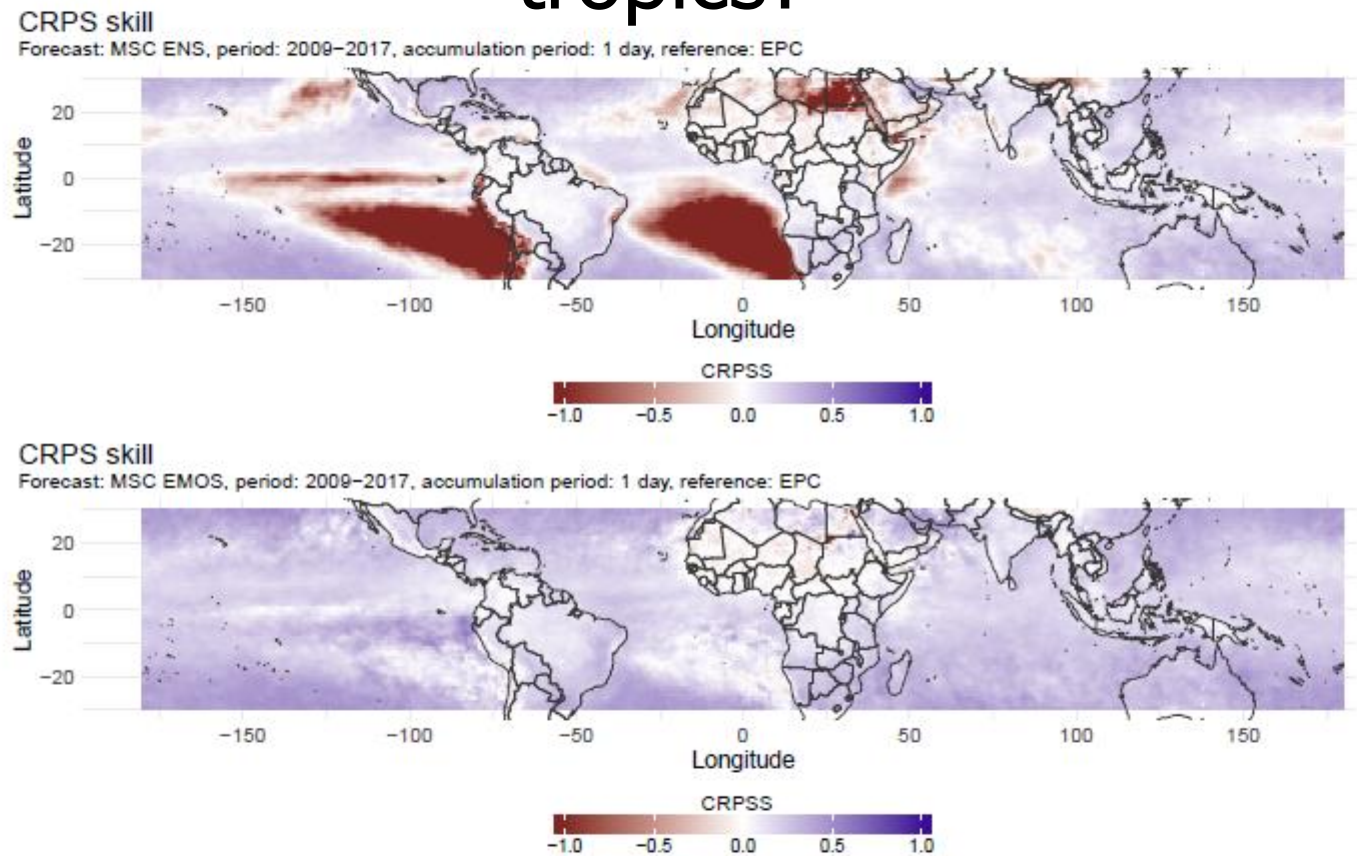


FIG. 7. CRPS skill of MSC raw and postprocessed ensemble forecasts for 1-day accumulated precipitation.

- Forecast model performance in Africa is amongst worst in the world
  - Due to both the challenges for paramerisation and initialisation

How does numerical weather prediction work?

Mathematically, weather prediction is an initial value problem

initial condition $\xrightarrow{\text{time}}$ prediction

physical laws
(equations of motion, continuity equation, thermodynamic equation etc.)

Physical laws form a system of coupled equations

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The 4 big challenges for NWP are:
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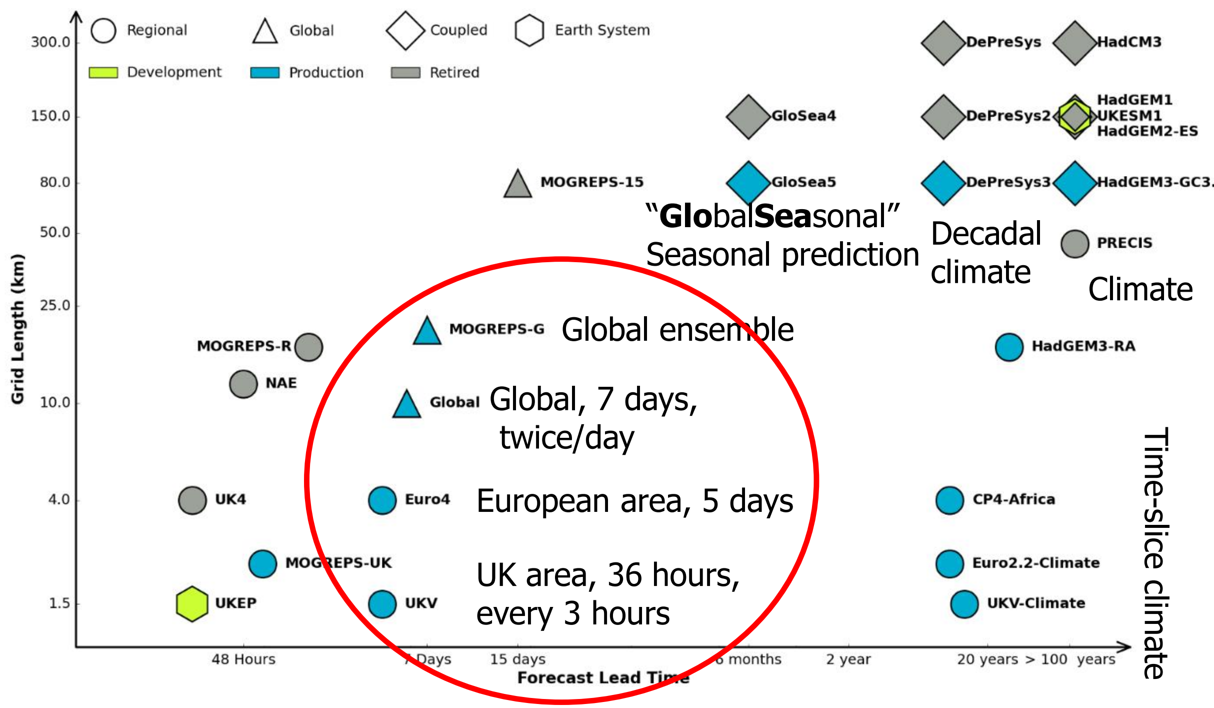
Discretisation:

Current state of the art, e.g. The UK Met Office Unified Model (UM)

Computer resources put limits on:
– the number of ensemble members
– the domain
– the resolution

NWP: The Met Office runs 3 versions of the UM at different resolution over different domains ("nesting")

The European Centre for Medium-Range Weather Forecasting (ECMWF) runs 15-day global forecasts



Need high resolution for the "basic building block" of tropical weather: convection

Parametrisation

radiation

cloud physics

convection

turbulence

evaporation of rain

unresolved topography

fluxes of heat, moisture

snow melt

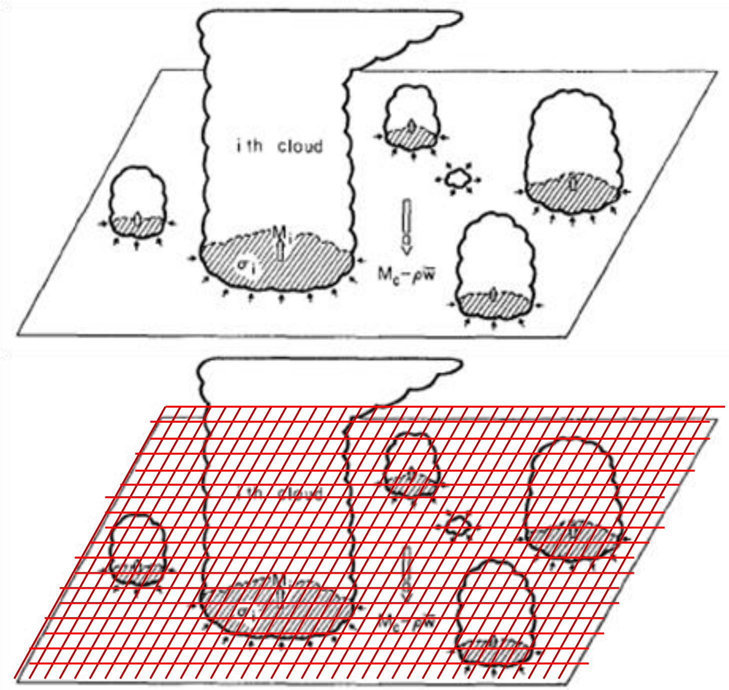
evaporation

soil moisture

Parametrisations estimate effects of these processes on gridscale fields

- All challenging for Africa, especially convection, clouds, aerosols, surface fluxes

Convection in Models



Parameterised:

- Δx > 100km, many clouds in a grid cell
- Assume:

(1) All up and down draughts occur within the grid-box.
(2) Updraughts occupy a small area of the grid-box.
(3) Quasi-equilbrium

- Parameterised convection has no memory beyond impacts of the parameterised convection on the profile.
- No representation of self-organisation

Convection-permitting:

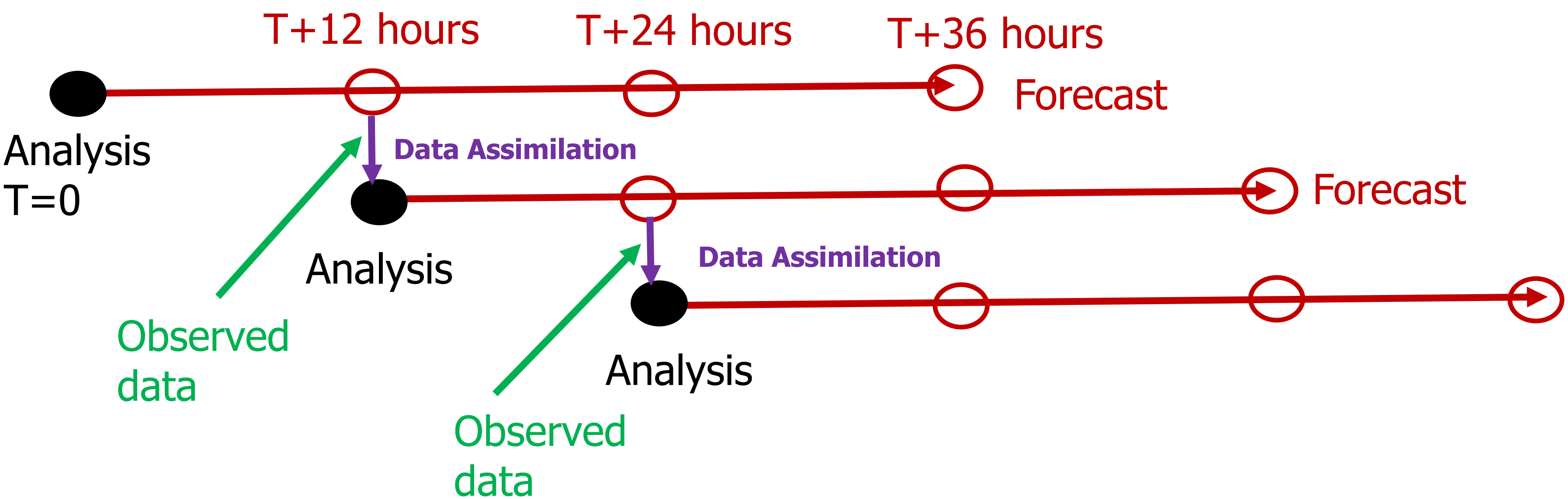
- Many cells for each cloud
- Cloud circulation captured by grid-scale flow
- Turbulence paarmetrised
- Δx ~100m needed to resolve convection, but 1 to 4km often used in explicit models

- Convection delivers the vast majority of rain in Africa, and most heat to the atmosphere
- In places organised MCSs deliver 90% of the rain
- Failures of convection-parameterisation have both direct and indirect impacts on forecast quality

Initialisation

- We do not know the **initial state** of the atmosphere for weather forecasting with high accuracy.

- Measurements have errors and limited coverage.

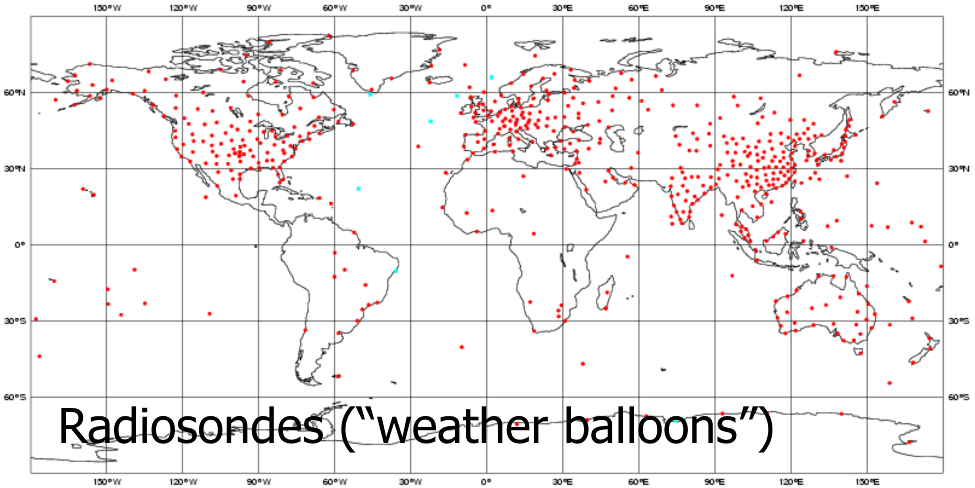


- **Data assimilation** techniques generate analysis fields by combining **observations** and **short-term predictions** from NWP models $\rightarrow$ physically consistent data set

- More challenging in tropics as flow less geostrophic

Initialisation

- We do not know the initial state of the atmosphere for weather forecasting with high accuracy.

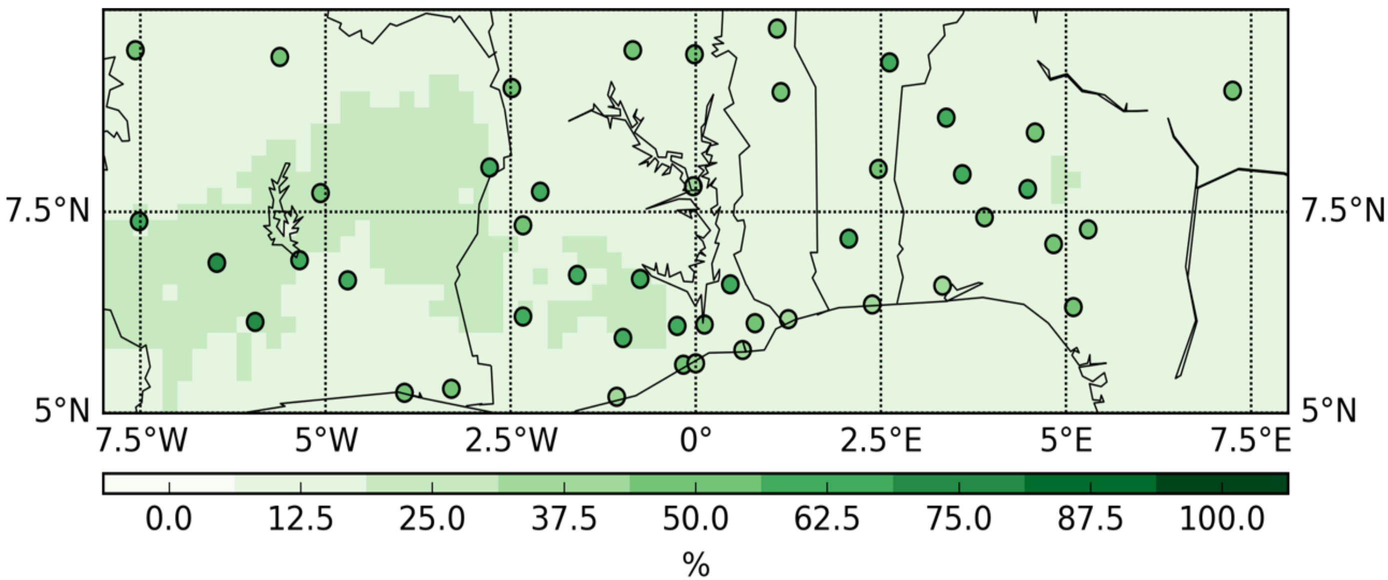


Radiosondes ("weather balloons")

- Few measurements over the ocean, in the Southern Hemisphere and at upper levels.
- Measurements have errors.
- Some observations are quantities not directly used in NWP models (e.g. radiances from satellites).
  - Calculating what the satellite would see from the model improves assimilation

- Africa has some of sparsest in-situ observations reaching the GTS in the world

An (over) reliance on satellite products



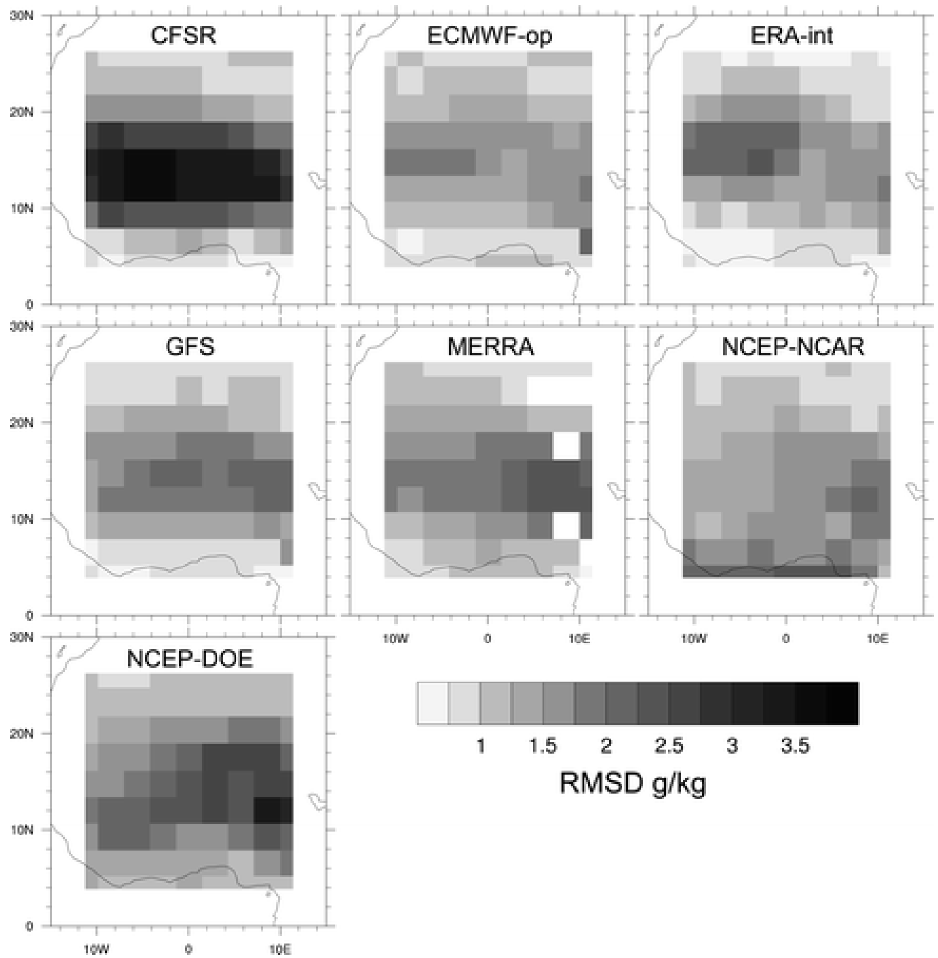
(From "Key lessons from the DACCIWA project for operational Meteorological services")

Daily mean cover of low clouds: Optimal Cloud Analysis (OCA) satellite product (shading) and surface observations (spots) for June+July 2016 (from Kniffka et al., 2019, in prep.)

There is a need to:

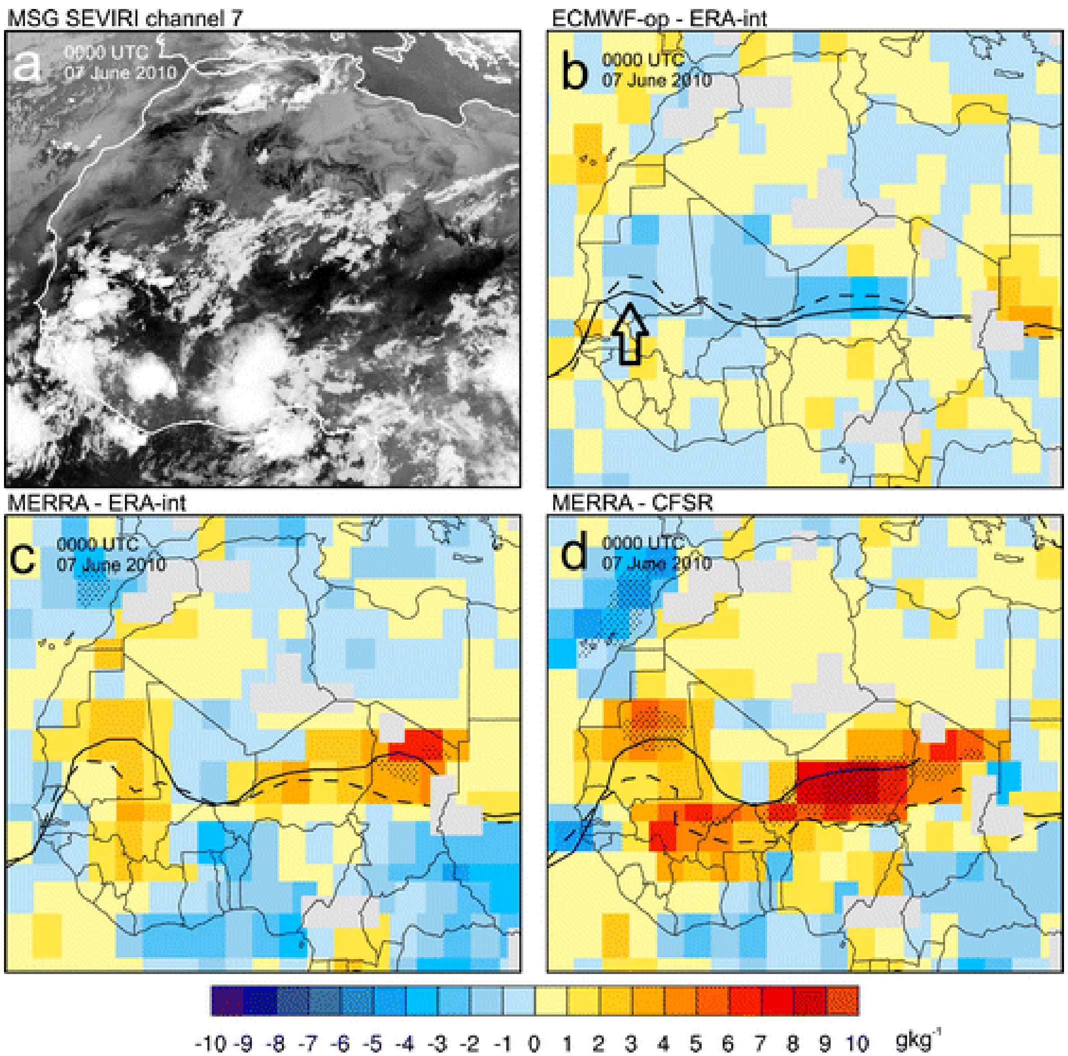
- Evaluate and develop satellite products
- Improve the number of high-quality in-situ observations (routine & non-routine)

Resultant uncertainty in analyses



Root mean square difference between each analysis and multi-analysis mean for 925 hPa specific humidity (Roberts et al., 2015)

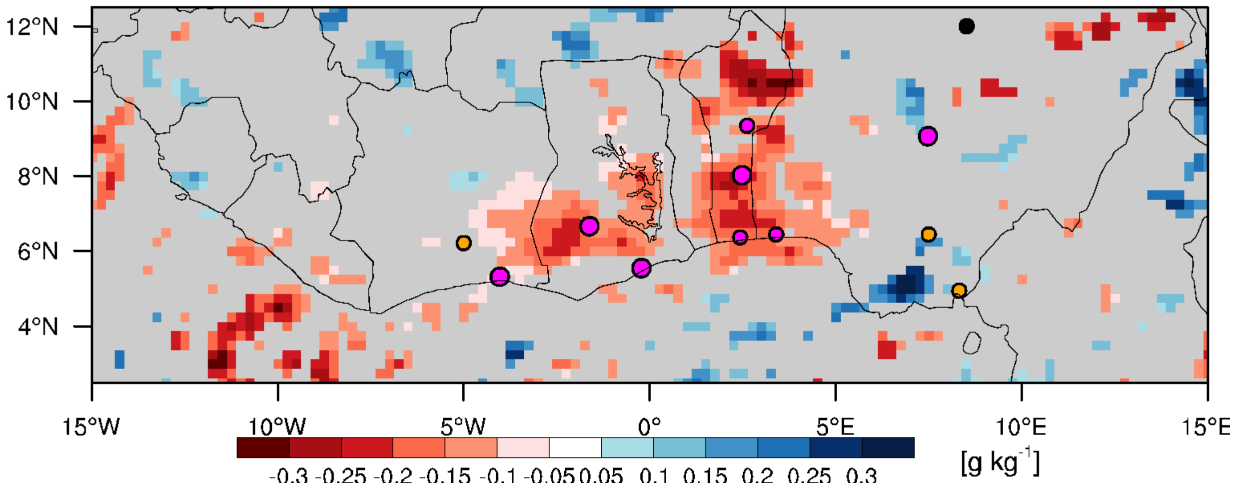
E.g. Uncertainty in analyses



(Roberts et al., 2015)

- Large (8 g/kg!) difference between analyses in this cases

More observations improves forecasts

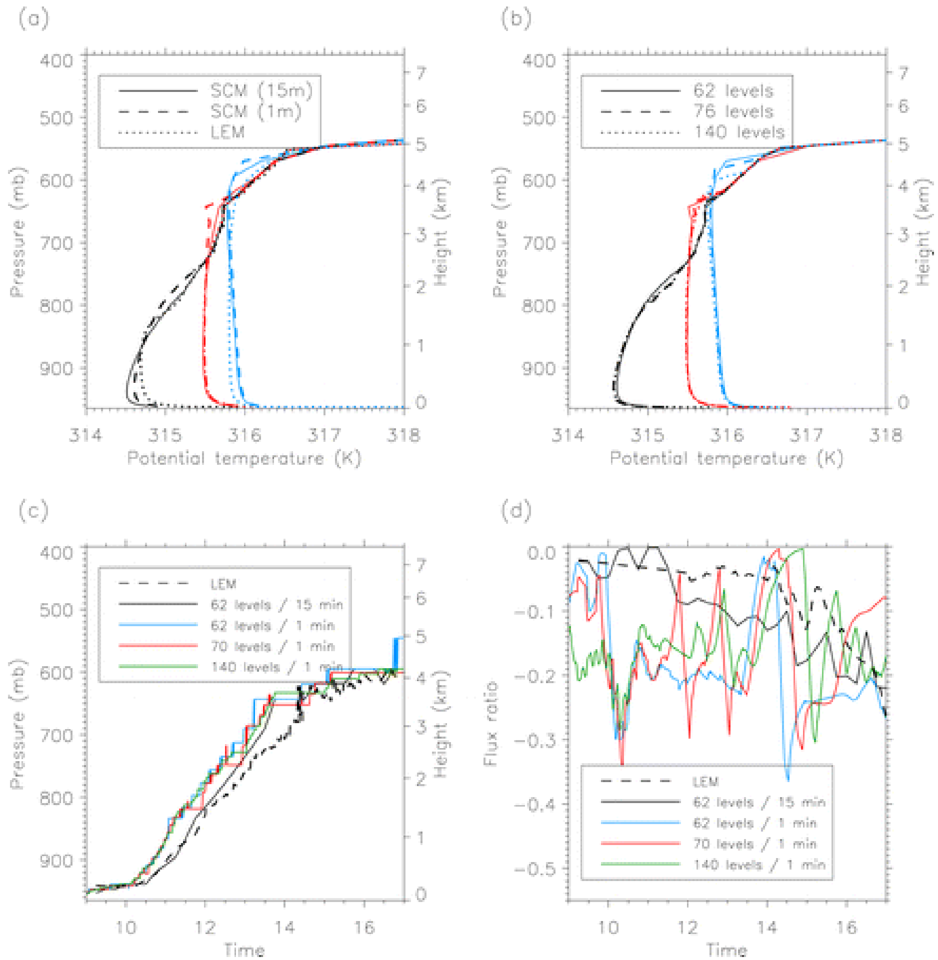


(From "Key lessons from the DACCIWA project for operational Meteorological services")

Bias of ECMWF specific humidity (near 925 hPa) between the "noDACCIWA" and "DACCIWA" analyses at 0600 UTC (regions not statistically significant at the 10% level are shaded in grey). Filled circles indicate the the radiosonde stations with colour and size indicating the amount of data available. Adapted from van der Linden et al. [2019, in prep.].

- But increased observations only improves forecast for 12 hours
- Information lost within one diurnal cycle
  - We need improved model physics

Tropics & convection: dry convection

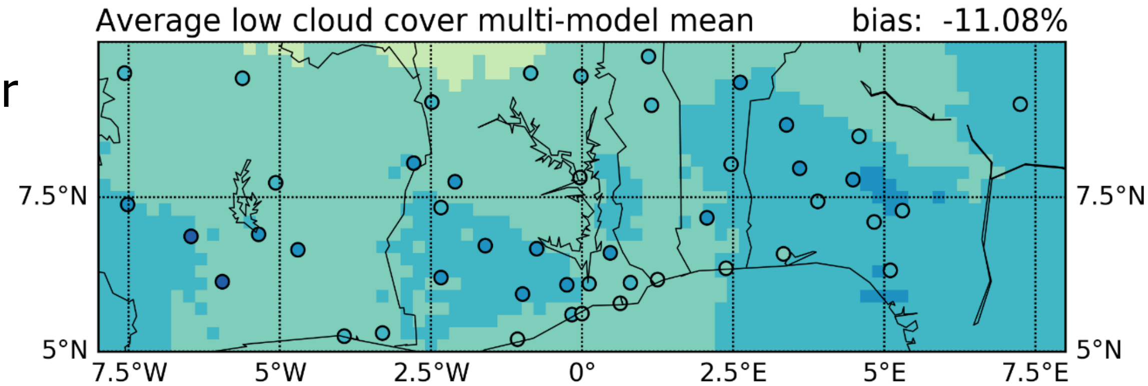


Large eddy model (LEM ·······) parametrised single column model (— — —) Saharan boundary layer profiles, in **morning**, **midday** and **afternoon** (Garcia-Carreras, 2015)

- Even deep dry convection is challenging to parametrisation (Garcia-Carreras, 2015)

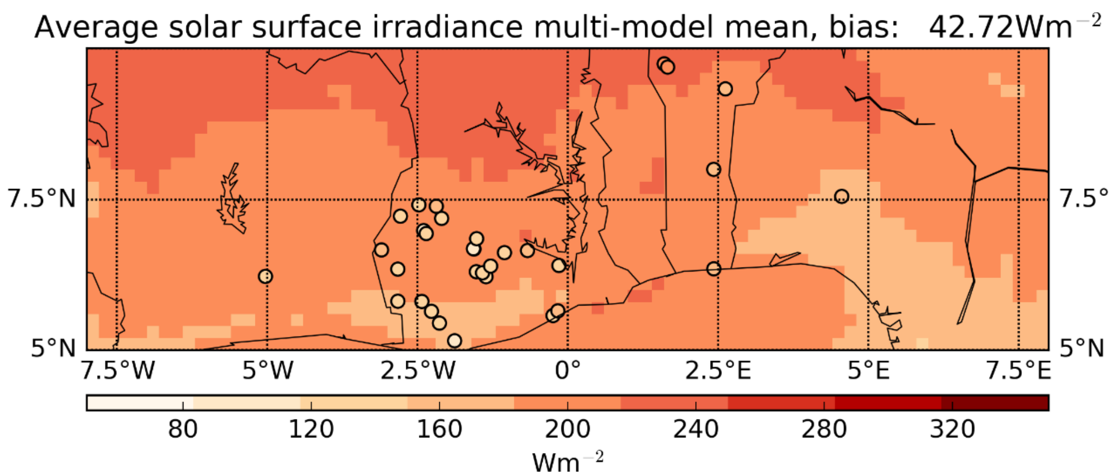
Shallow clouds

Cloud cover



(From "Key lessons from the DACCIWA project for operational Meteorological services")

Surface solar irradiance

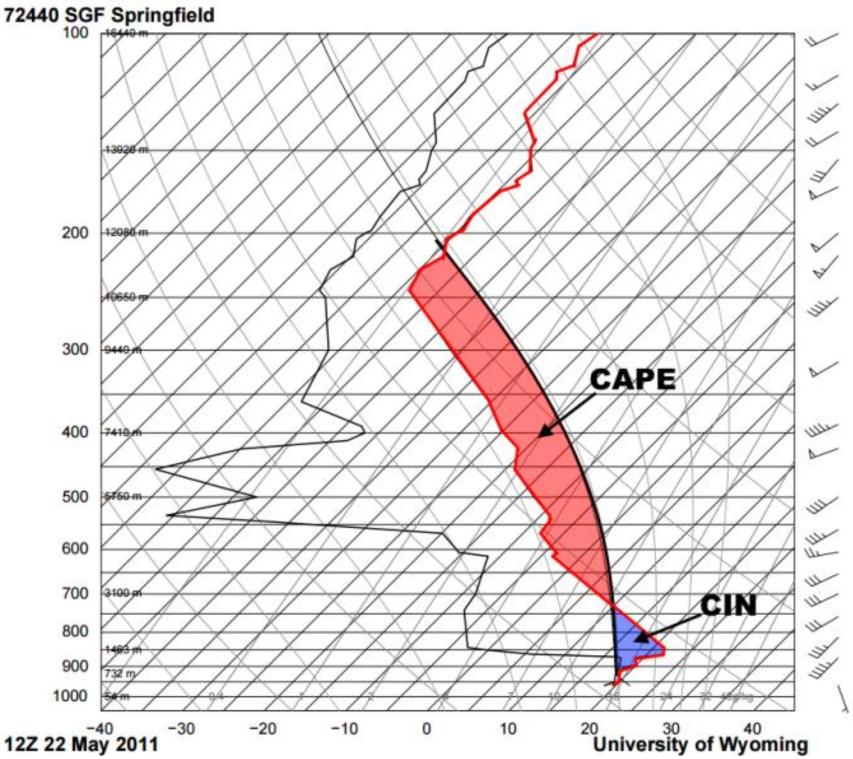


Shading: Average for five NWP models (June+July, 2016) Coloured circles: station observations. Adapted from Kniffka et al. [2019, in prep.].

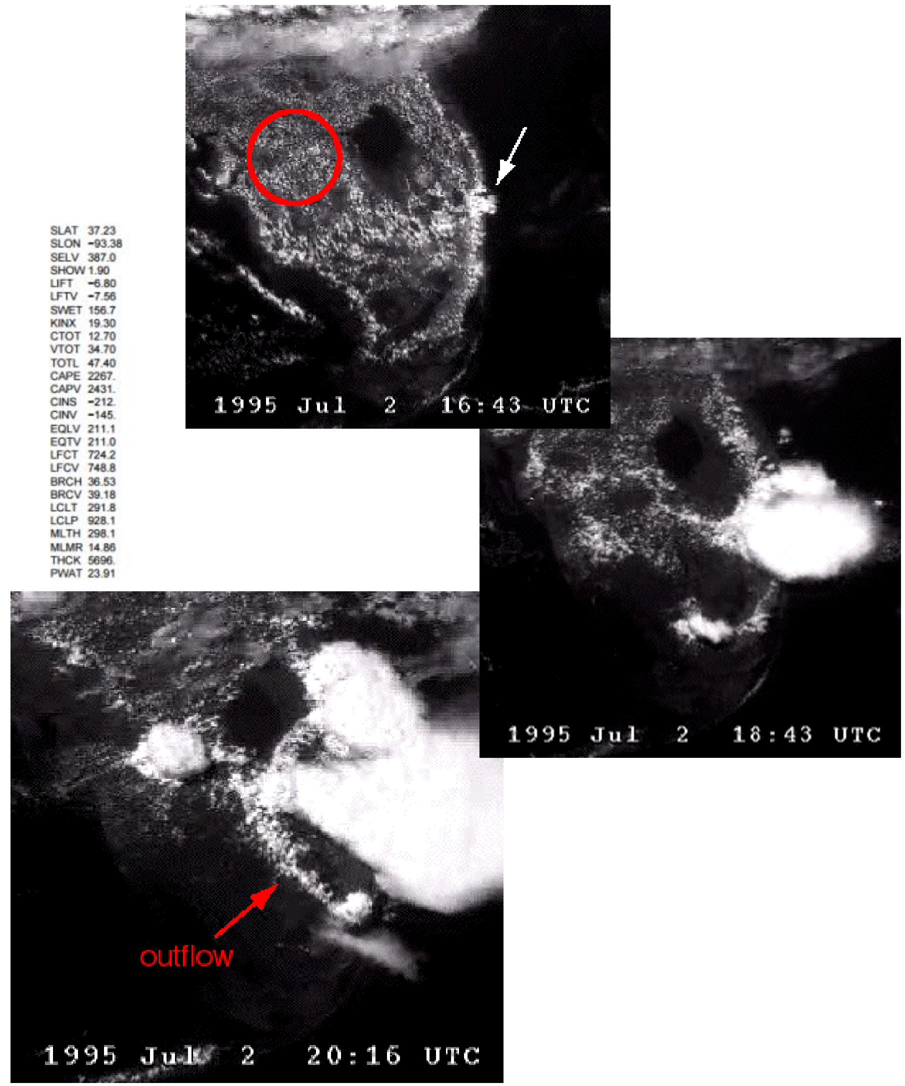
- Models have too little thing low cloud and so far too much surface solar irradiance

Deep moist convection

A bifurcation point in atmospheric evolution: do you trigger a storm or not?

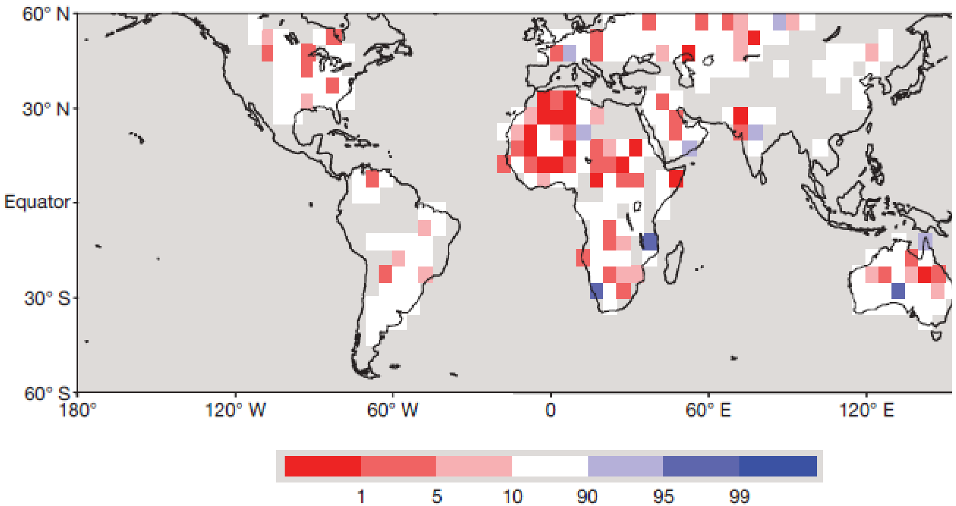


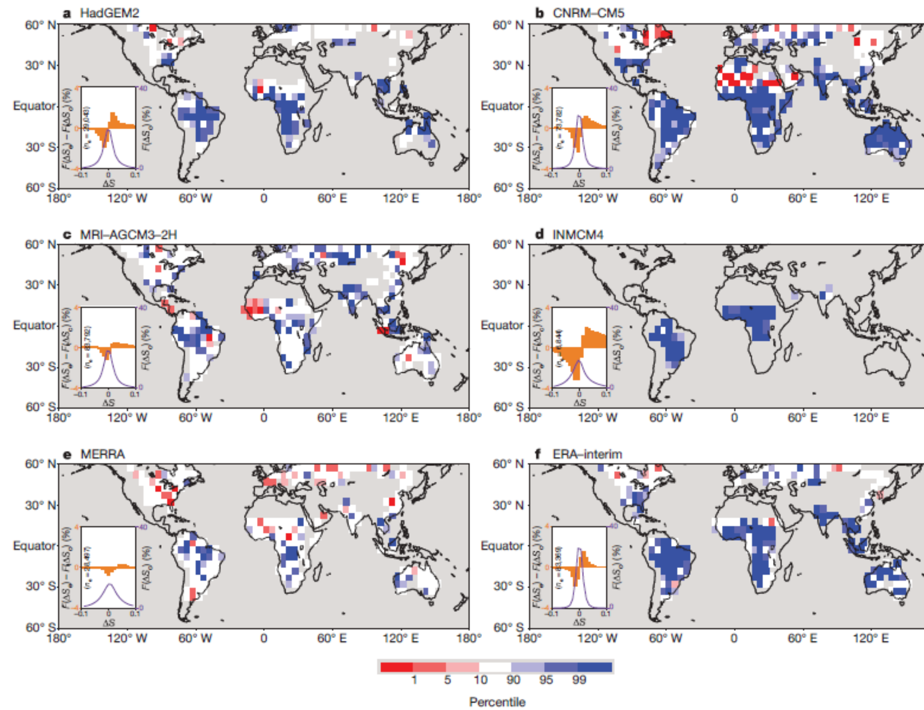
SLAT	37.23
SLON	-93.38
SELV	387.0
SHOW	1.90
LIFT	-6.80
LFTV	-7.56
SWET	156.7
KINX	19.30
CTOT	12.70
VTOT	34.70
TOTL	47.40
CAPE	2267.
CAPV	2431.
CINS	-212.
CINV	-145.
EQLV	211.1
EQTV	211.0
LFCT	724.2
LFCV	748.8
BRCH	36.53
BRCV	39.18
LCLT	291.8
LCLP	928.1
MLTH	298.1
MLMR	14.86
THCK	5696.
PWAT	23.91



Land-atmosphere interaction

(Taylor et al., 2012)





Preference for afternoon precipitation over soil moisture anomalies

- Africa is a hot-spot for land-atmosphere interaction
  - Mesoscale flows from soil moisture contrasts can trigger storms over drier soils
- Models fail to capture this

Upscale impacts: gravity waves

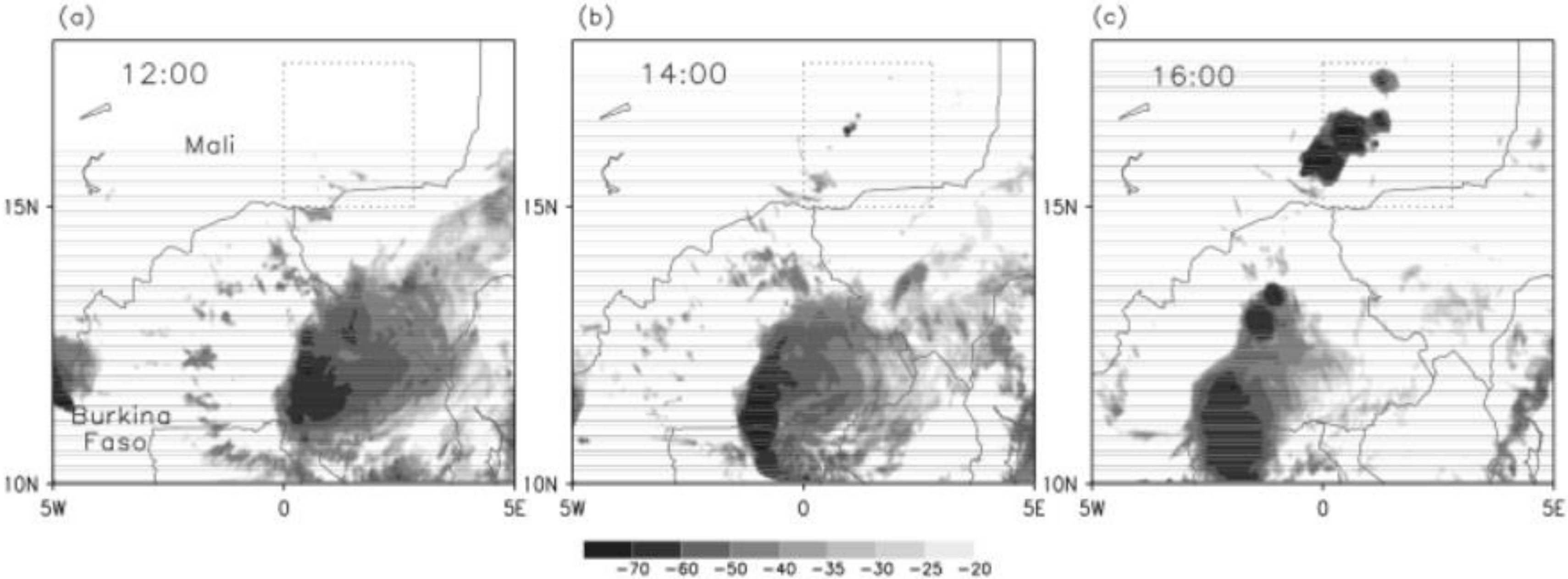
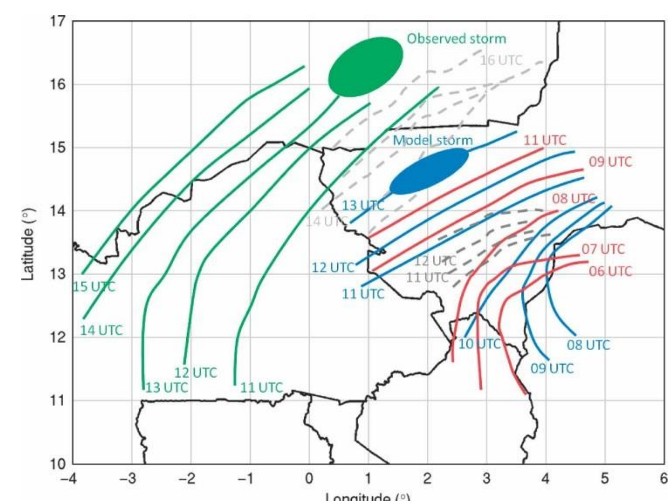
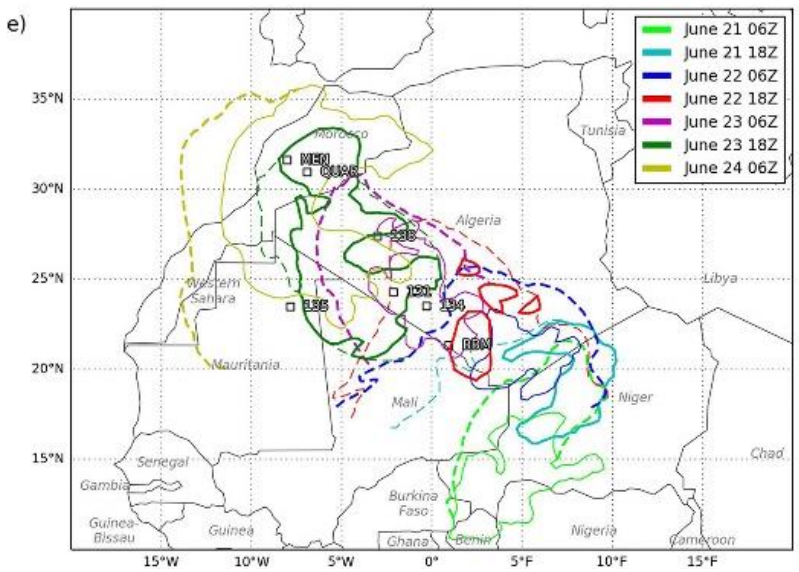


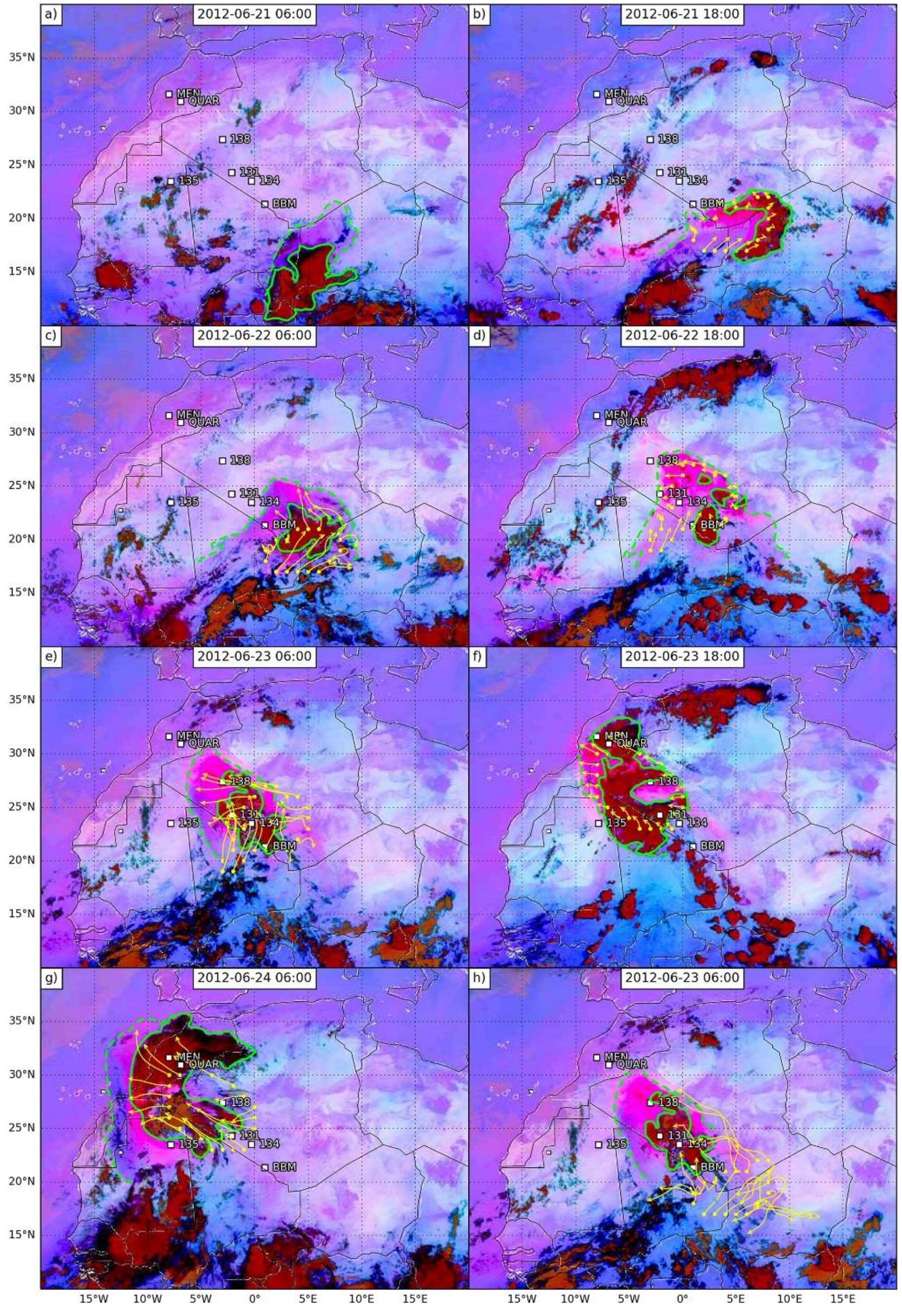
Figure 4. Brightness temperature images (°C) depicting cold cloud at (a) 1200, (b) 1400 and (c) 1600 UTC. The domain in Figure 3 is marked by the dotted lines.

- “Parent storm” triggers gravity wave that triggers storm (on soil-moisture boundary): Taylor et al., 2010; Birch et al., 2012



Upscale impacts: cold pools

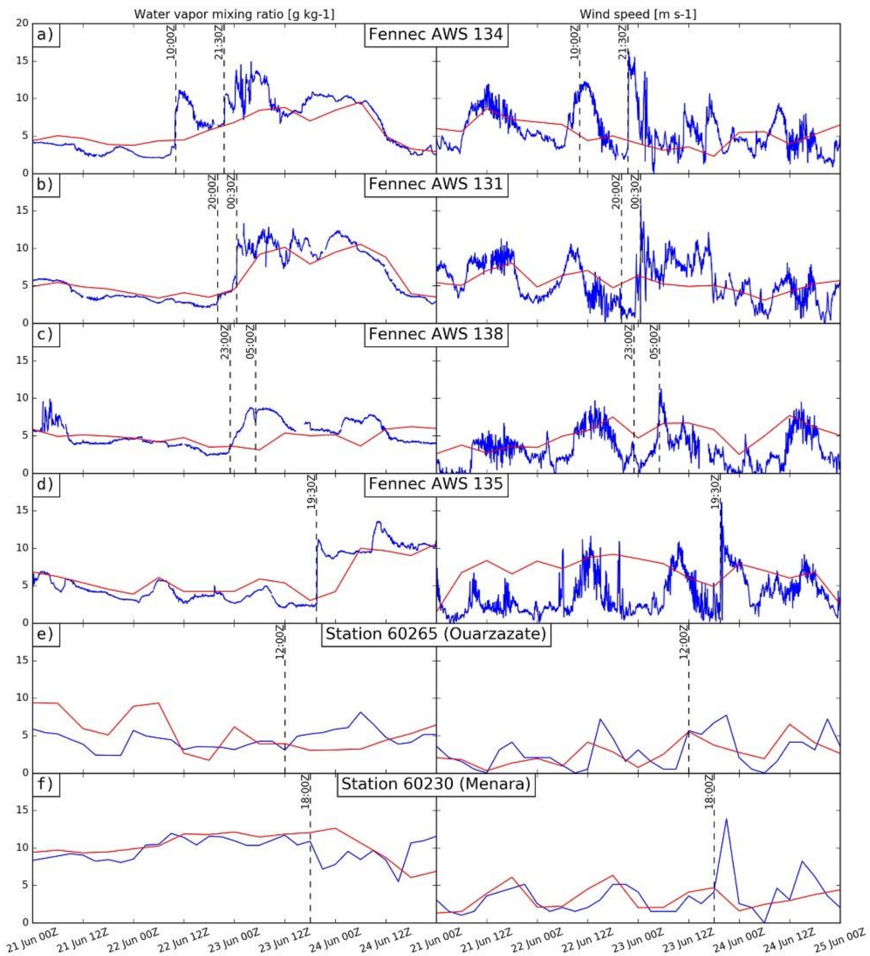




- Trzeciak et al., 2017: Cold pools enhance south-to-north cross-Sahara water vapour transport by one-day (compared with 3.5 days from analyses)
- C.f. cold pools are main cause of global model bias in central Sahar ain summetime Garcia Carreras et al., 2013

Parametrised convection and cold pools

Water vapour mixing ratio (g/kg)

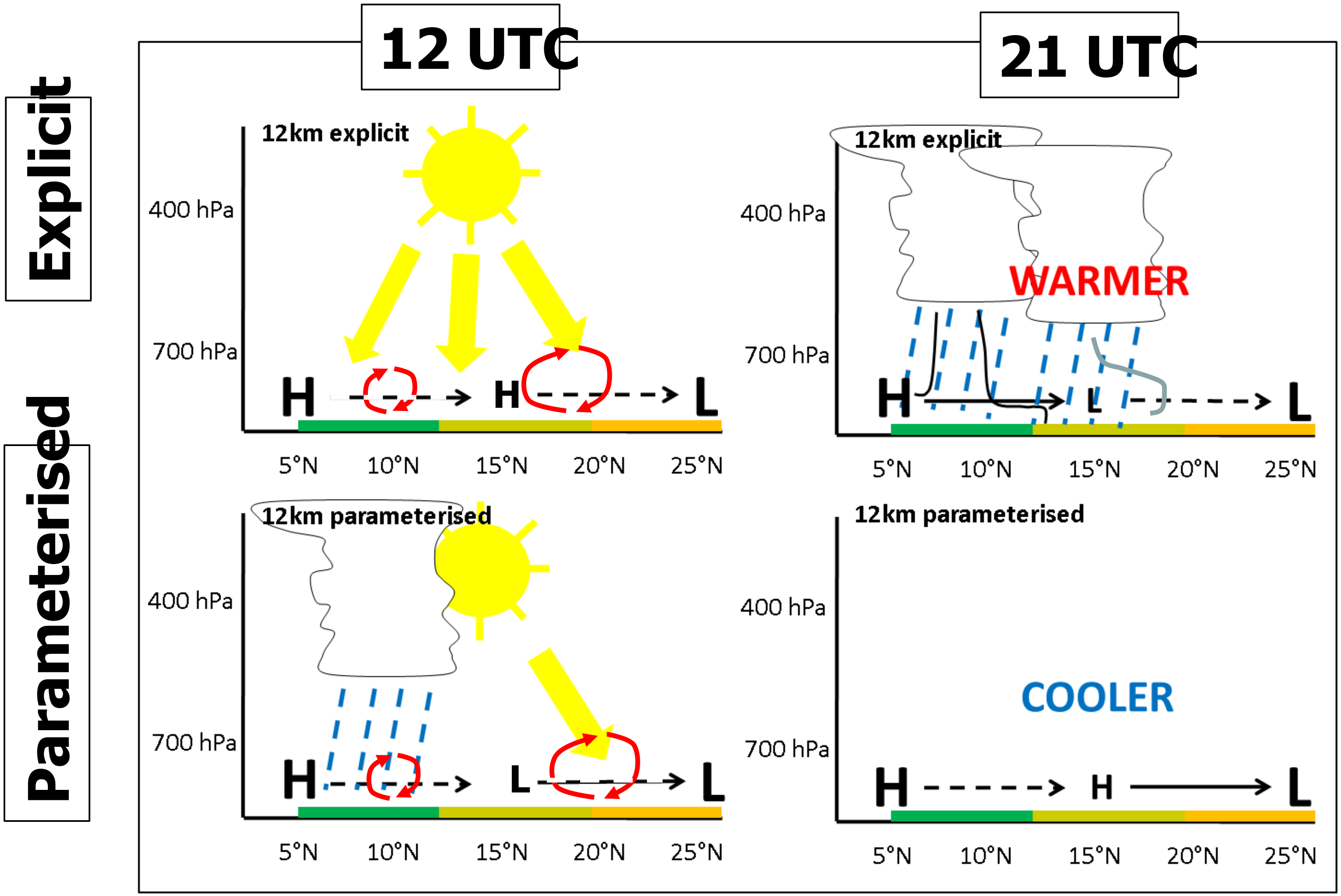


Wind-speed (m/s)

- Analyses fail to capture observed impacts of cold pools on moisture & winds

Summary

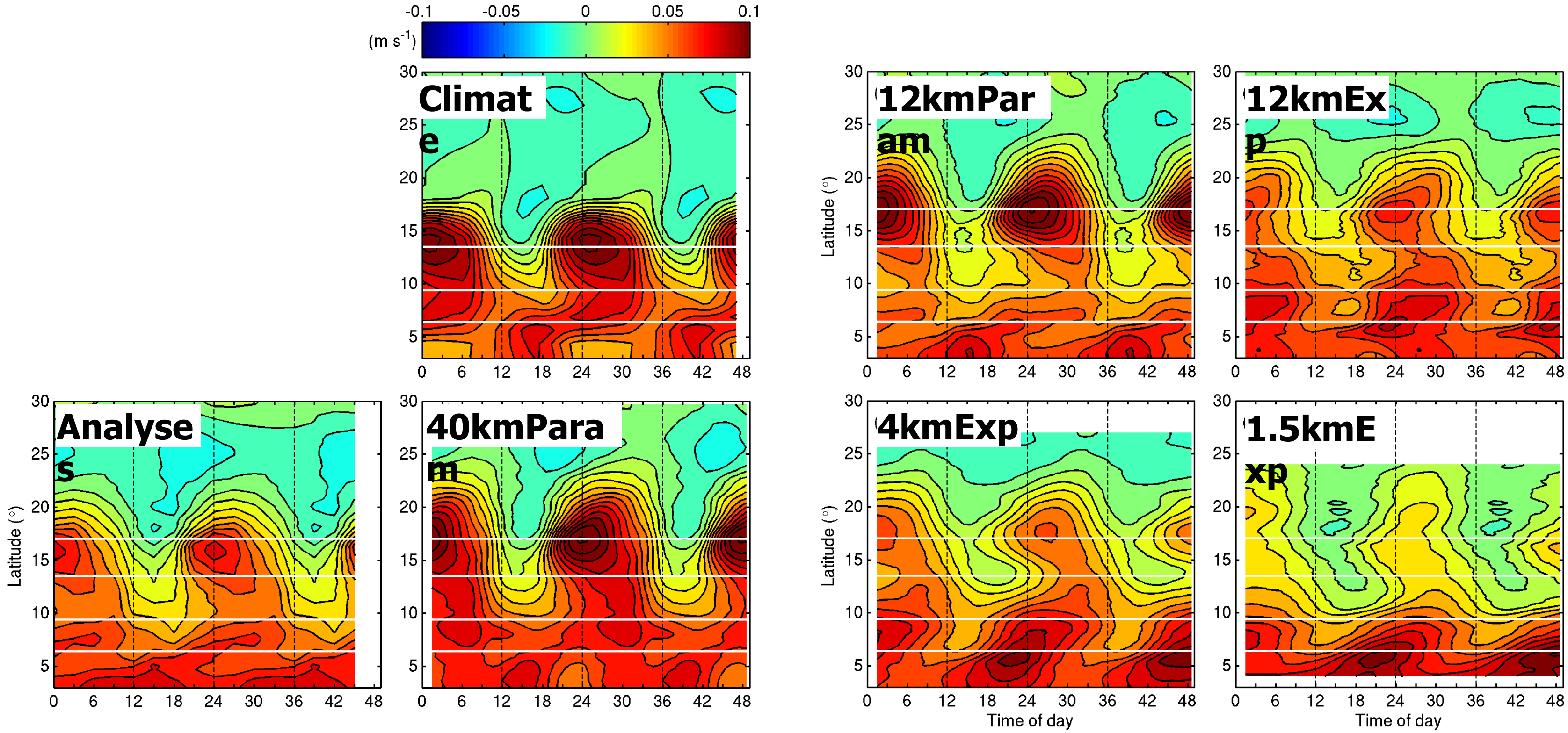
(Marsham et al., GRL, 2013; Birch et al., JGR, 201



Water budget

(Birch et al., JGR, 201

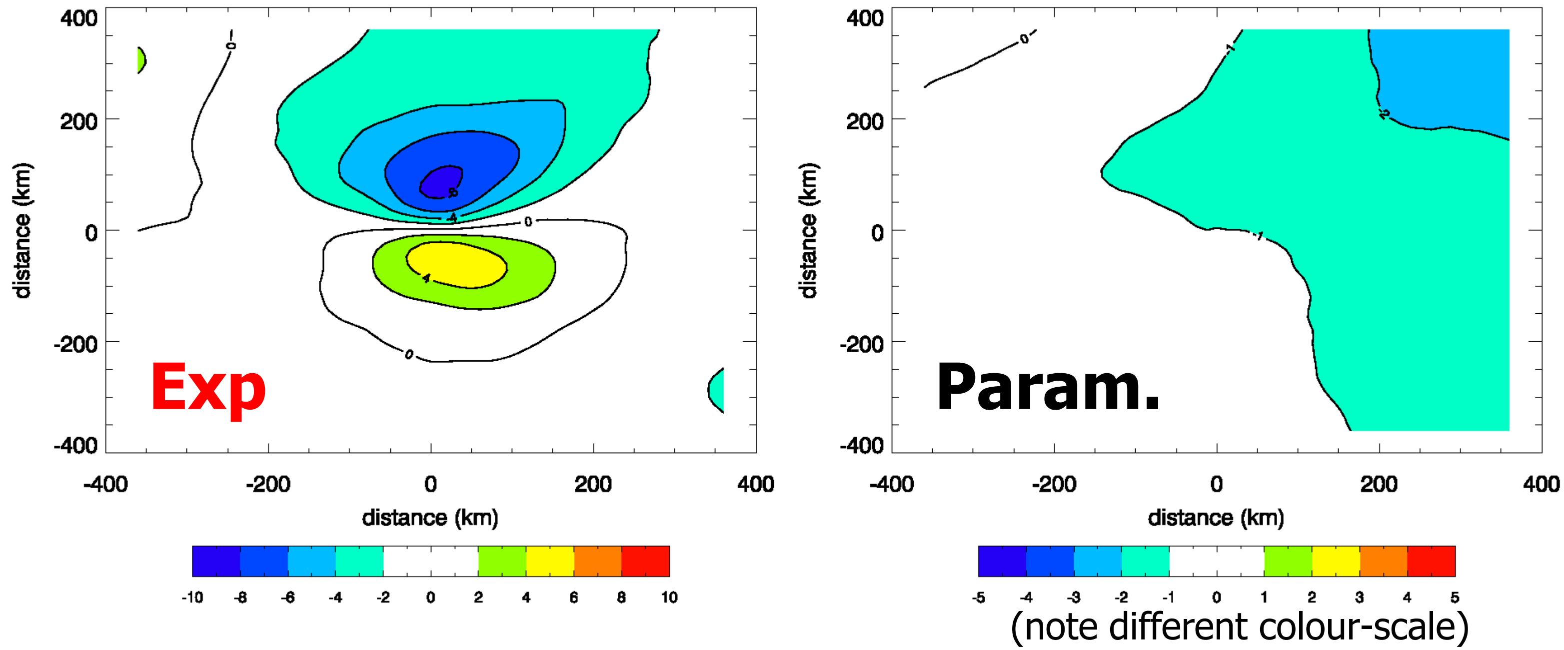
Meridional moisture flux (v*q) at 400 m above ground level



- Parameterised models have too much moisture moving from Sahel to Sahara at night

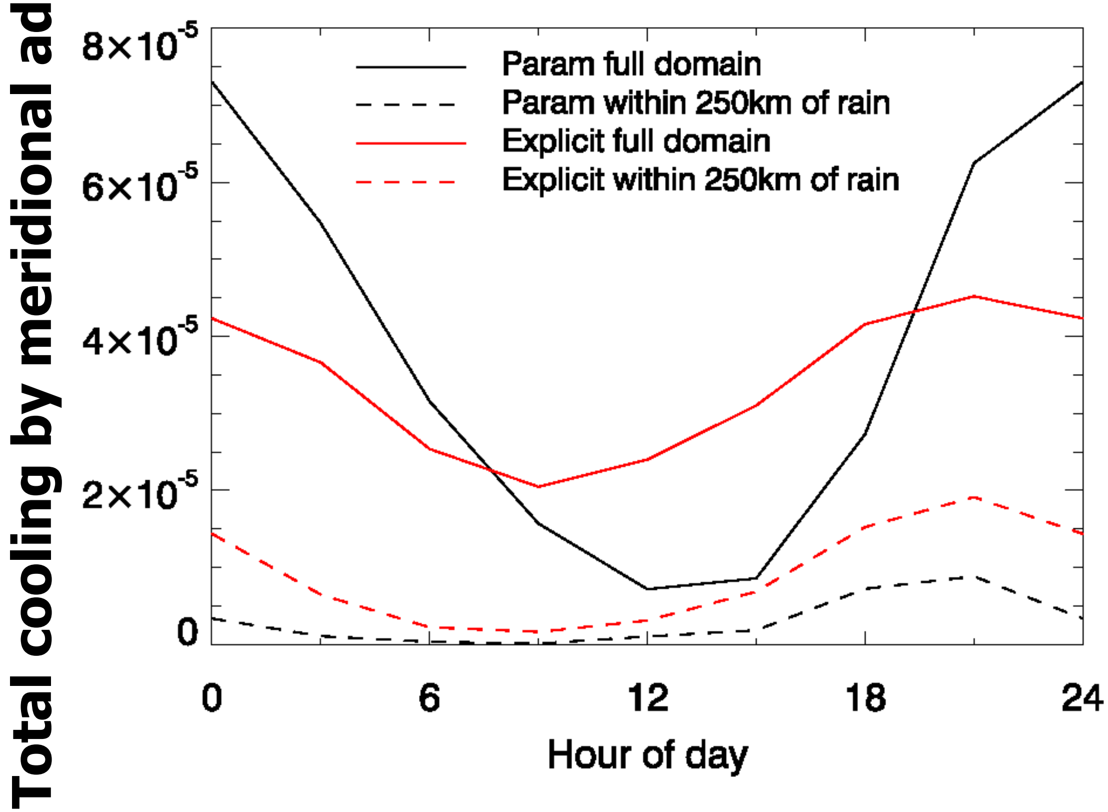
Cold pool outflows

Eddy heat fluxes composited around rain events



- In 12kmExp cold pools transport cold air north, missing in 12kmParam
  - 12kmExp: six times more northwards flux than southwards transport

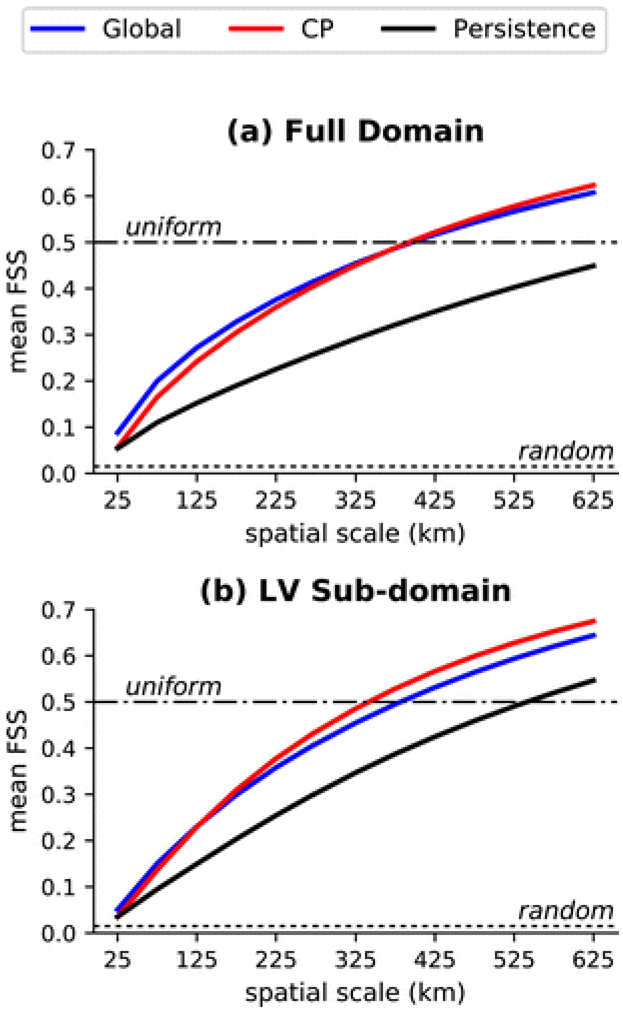
Ventilation by cold pool outflows

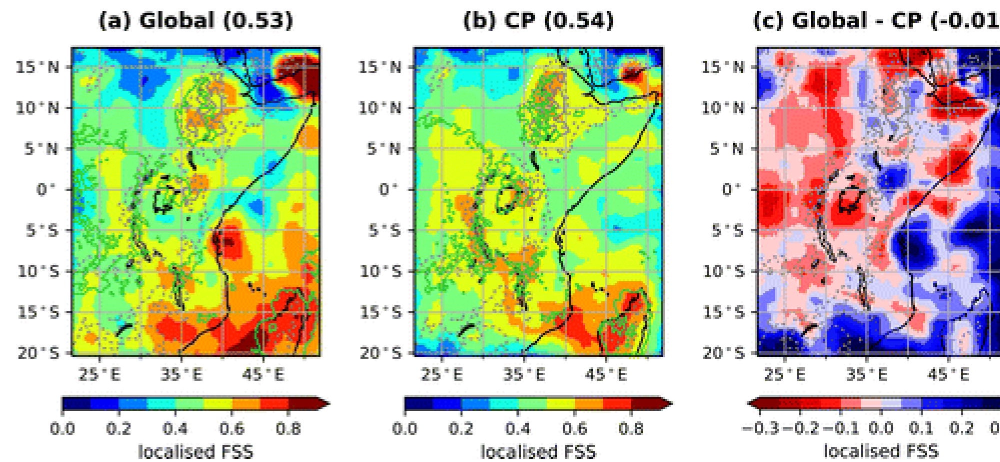


- 18 to 21Z maximum in 12kmExp (cold pools)
- Cold pools missing in 12kmParam, but greater nocturnal synoptically-driven flow

Improved skill from explicit convection

Woodhams et al., 2018
(East Africa, Met Office UM)

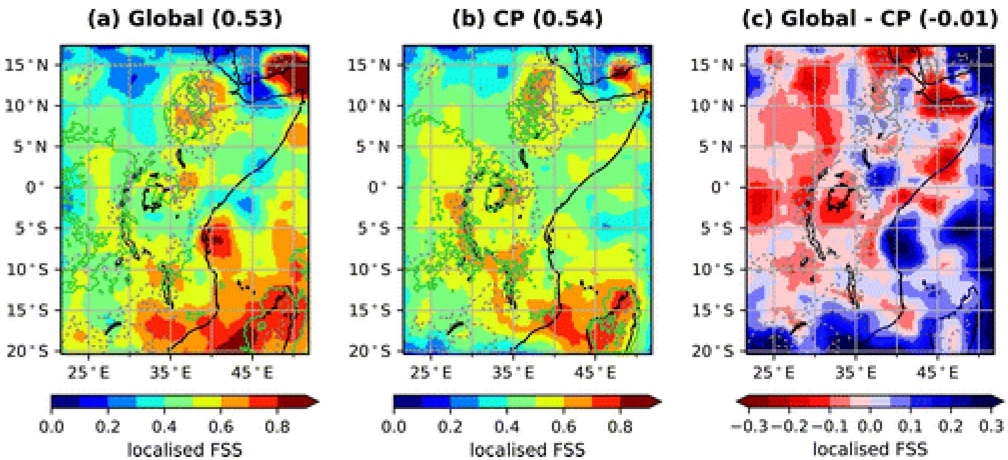


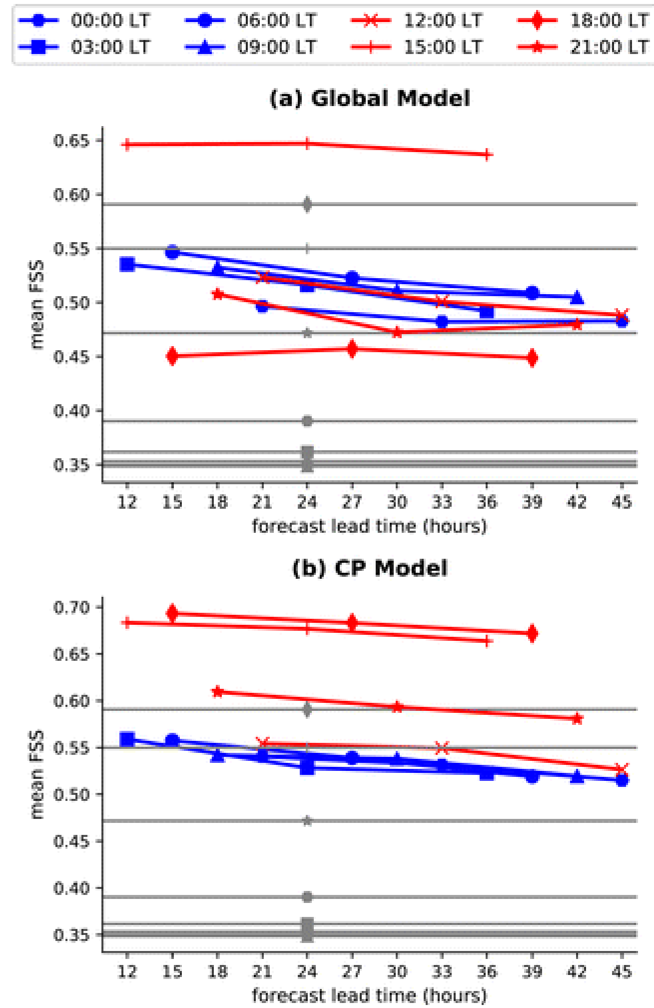


- Some improved skill from convection-permitting (CP), especially over coasts and mountains
  - Need an ensemble (we now have that for SWIFT – a huge opportunity!)

Improved skill from explicit convection

Woodhams et al., 2018
(East Africa, Met Office UM)



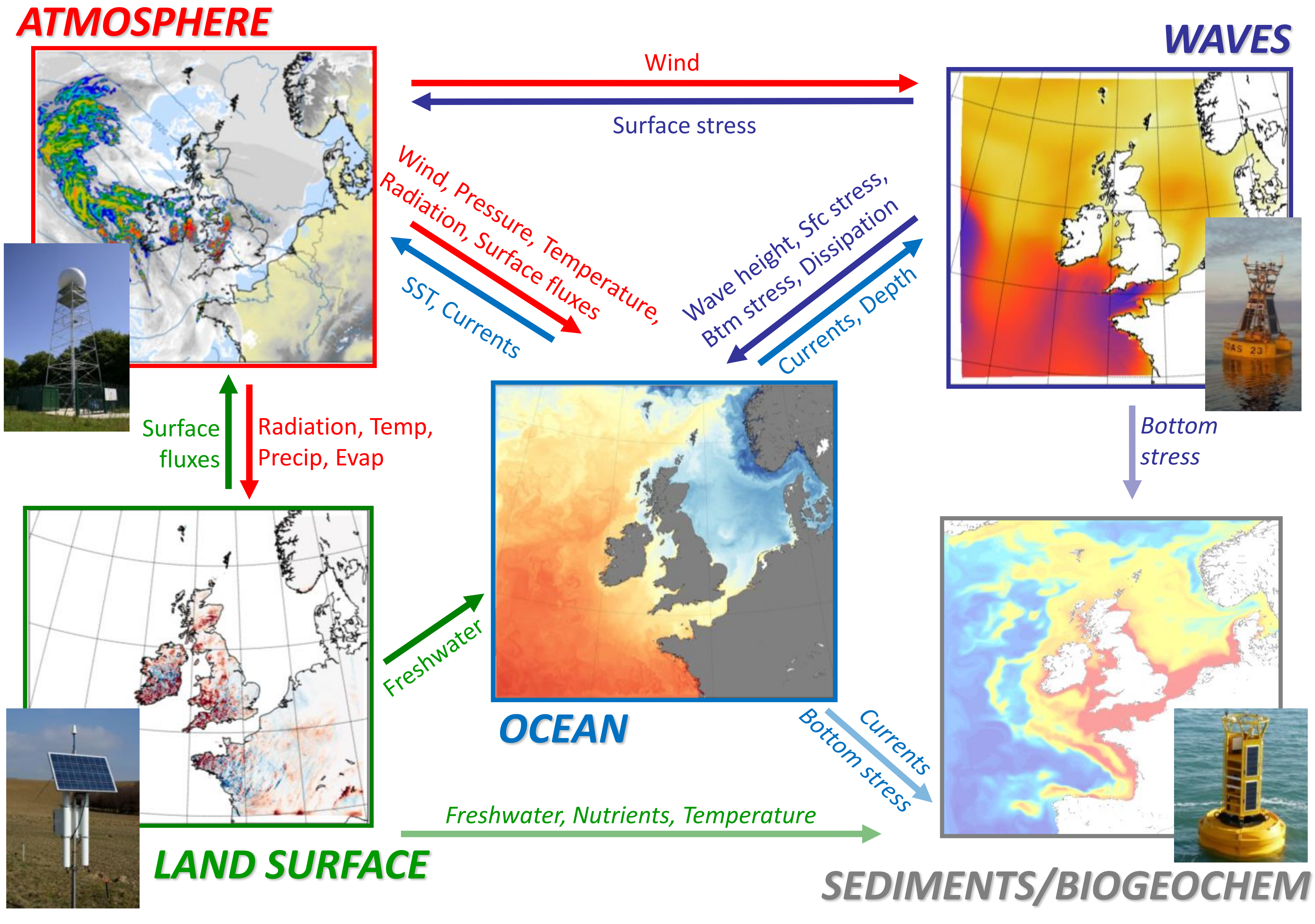


- Skill is highest at time of initiation
- Explicit convection responds better to convergence (c.f. Birch et al., 2014 GRL) from coasts & mountains

Conclusions

- NWP has been a phenomenal success in predicting mid-latitude weather over past 7 decades
  - Skill in tropics still limited, especially Africa
- Major opportunity now we have convection-permitting models, and ensembles of these
  - They resolve this basic “building block” of tropical weather
- Many challenges remain, especially parametrisation of sub-grid clouds, fluxes, turbulence, aerosols
- Errors in parametrised processes rapidly upscale to regional and indeed global-scale errors
- This is a fantastic time to be working in African NWP!

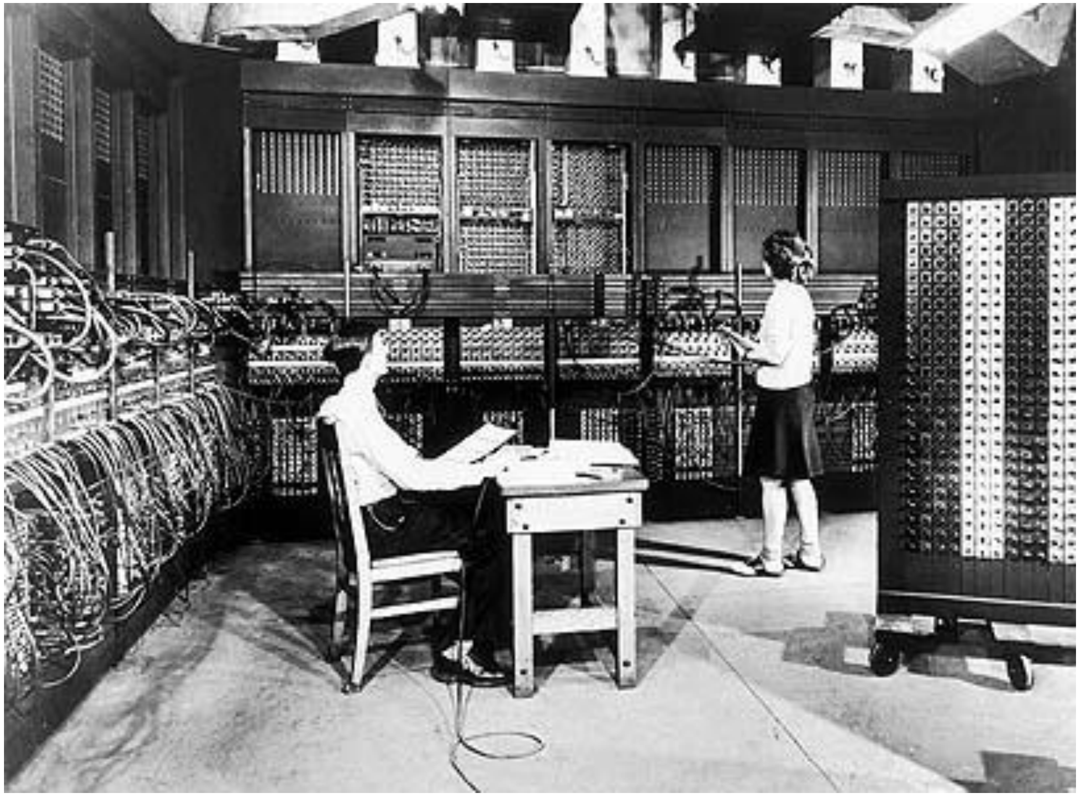
Towards coupled prediction? Met Office plans



Spare slides

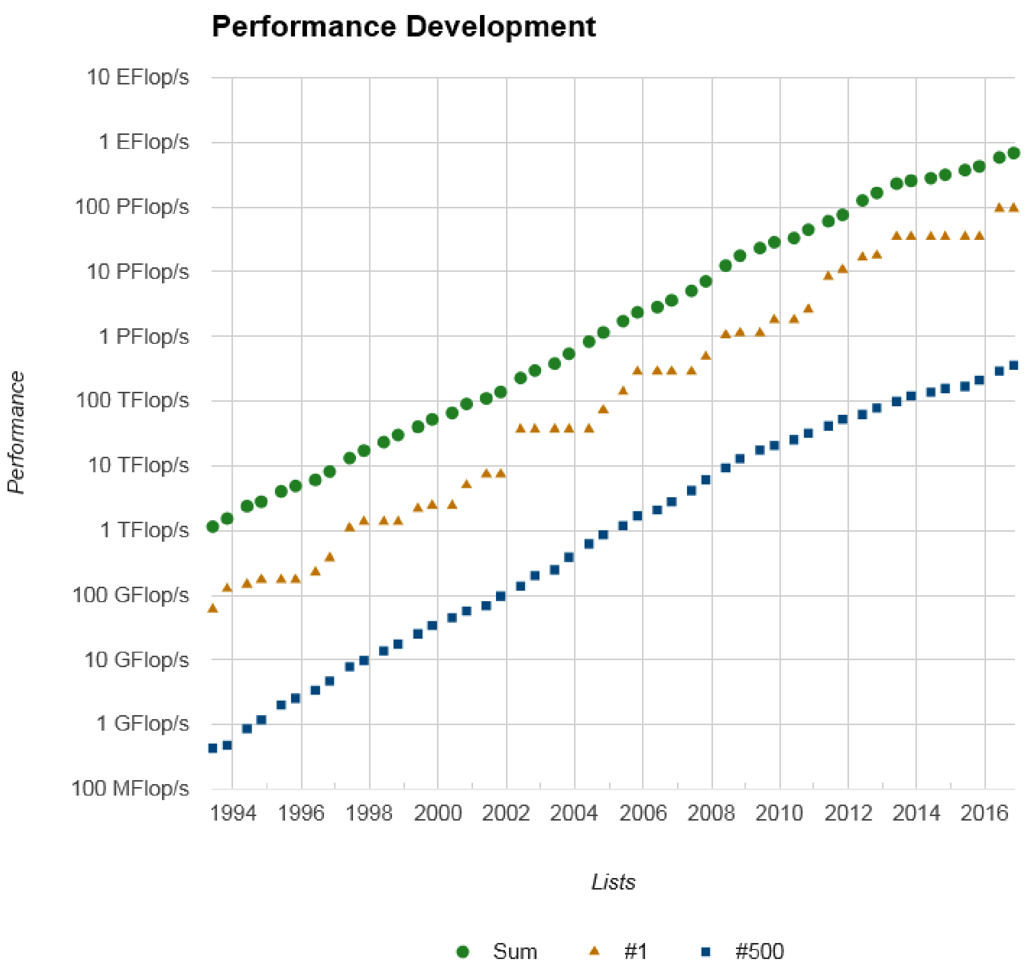
The first "supercomputer" for weather forecasting

– First numerical weather prediction with the ENIAC
– Highly simplified physical equations
– 24-hour forecast took 24 hours to compute



Limited computational resources

Despite exponential increases in the last decades, computer time is still a limiting factor in operational NWP



From top500.org

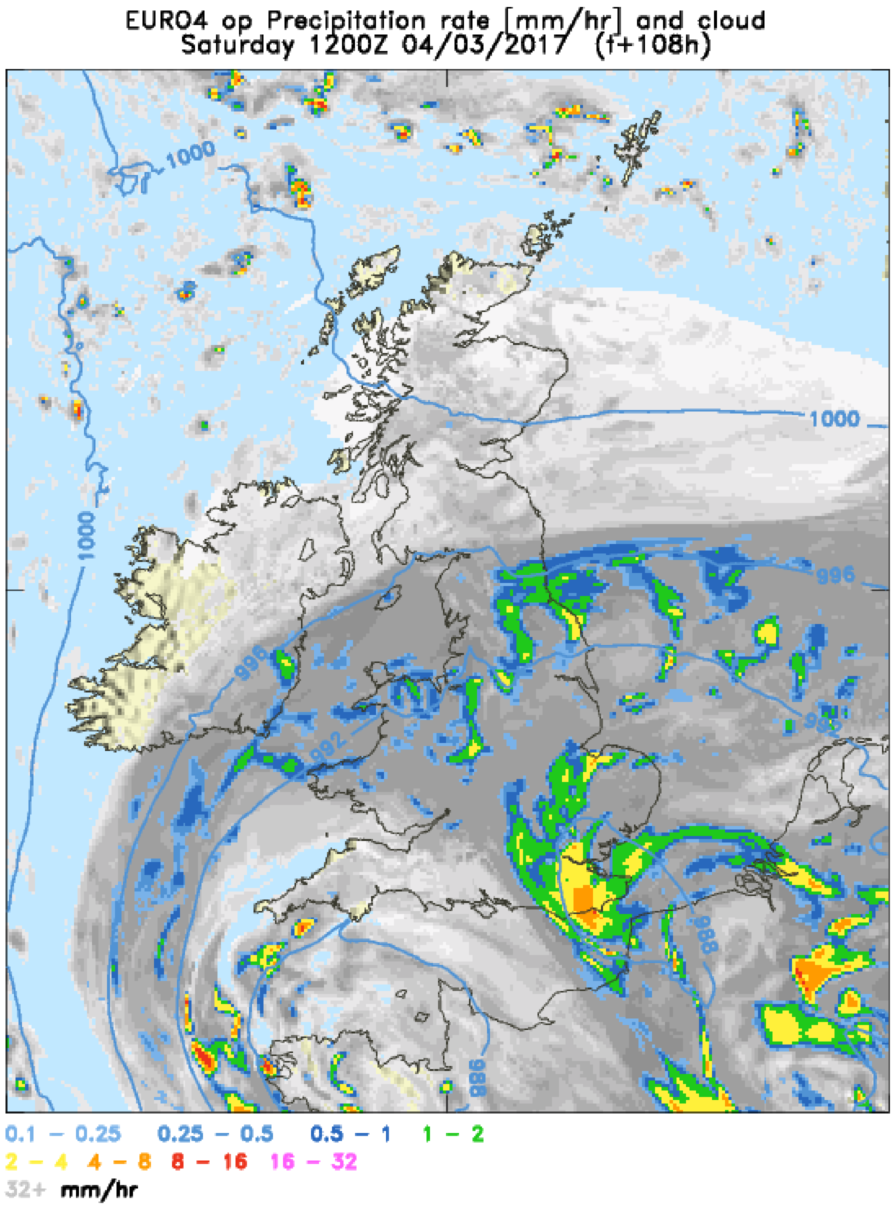
The timeline towards modern NWP

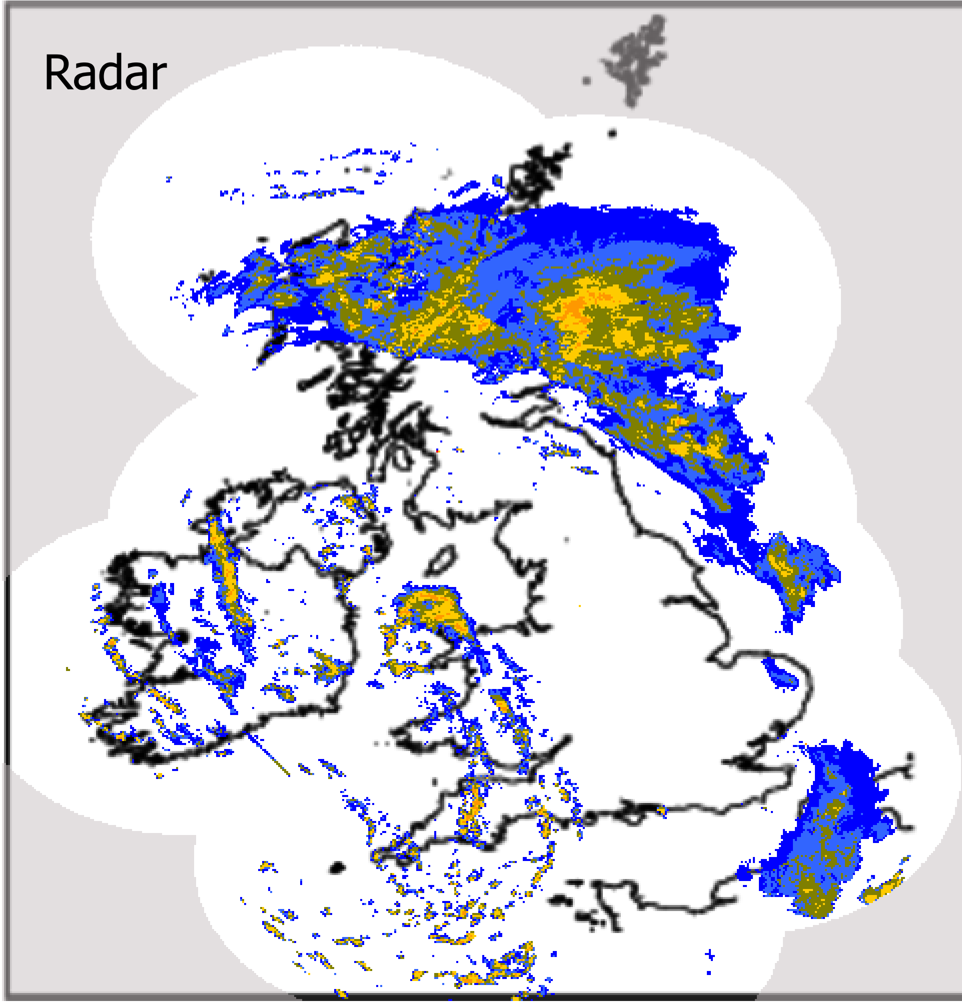
- 1954-55: First operational numerical weather prediction in Sweden & USA
- 1958: First generation of initial conditions with objective analysis method
- 1966: First usage of full physical equations for NWP
- 1971: First nested regional model.
- 1979: Establishment of European Centre for Medium-Range Weather Forecasts (ECMWF; now 31 member states)
- 1992: First ensemble prediction system at ECMWF
- Since 1995: Development of non-hydrostatic regional models (horizontal resolution < 5km)
- 2012 Met Office non-hydrostatic ensemble

2014/2015 first time I've seen trains cancelled/ticket restrictions lifted based on weather forecast, not on weather.

- 2019 UK coupled environmental prediction under development

There's still a long way to go …

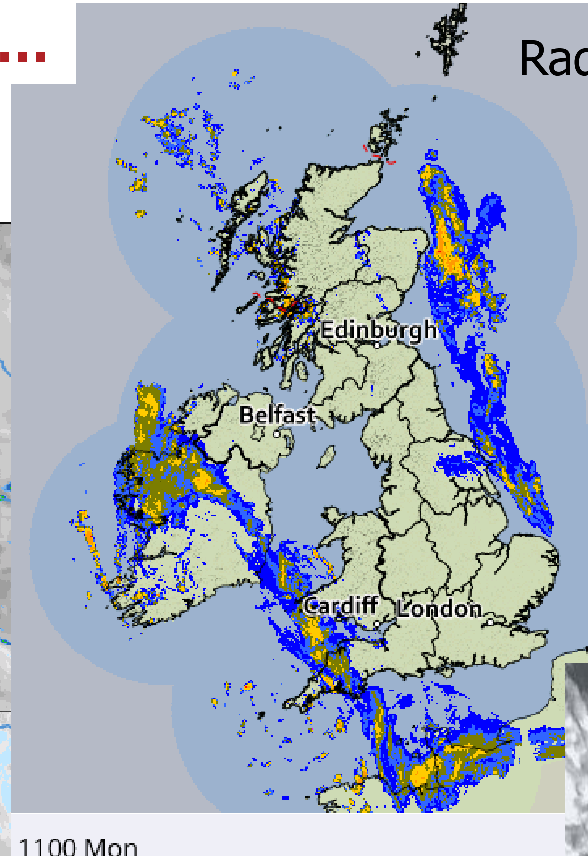


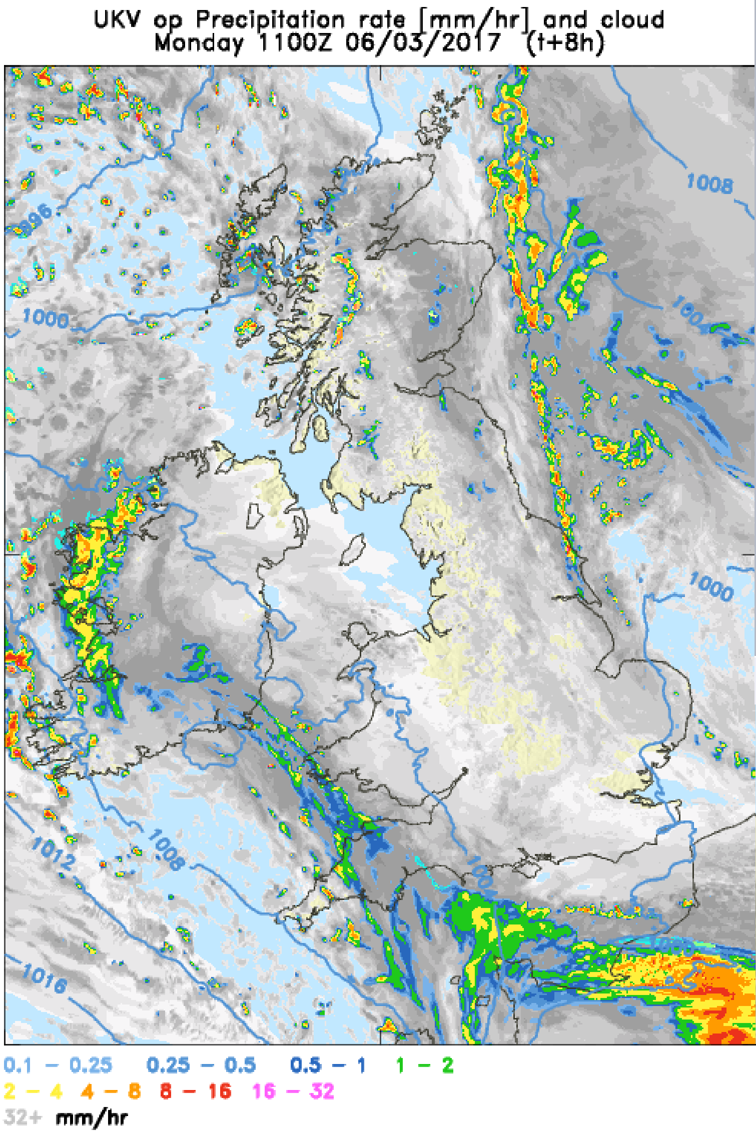


Model (forecast for Sat midday, at +4.5 days)

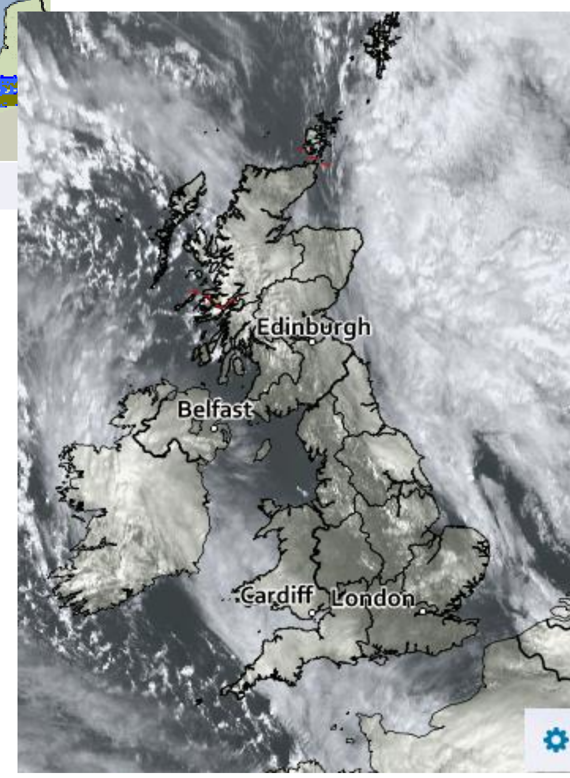
There's still a long way to go …

Radar





Model (forecast for 11 am (GMT) today, at +8 hours)



Visible satellite

Summary of this lecture

- Numerical Weather Prediction (NWP) is a highly complex initial value problem
- The four main challenges for NWP are:
  – discretisation
  – initialisation
  – predictability
  – computational resources
- The history of NWP is a fascinating success story
- The UK MetOffice currently uses a model chain that links global longer-term simulations with 1.5-km resolution forecasts over the UK
- Increasingly – not just weather prediction, but environmental hazard prediction: Rain, rivers, storm surge, ocean waves, flooding, soil moisture drought, fires, vegetation, crops….

Further Reading

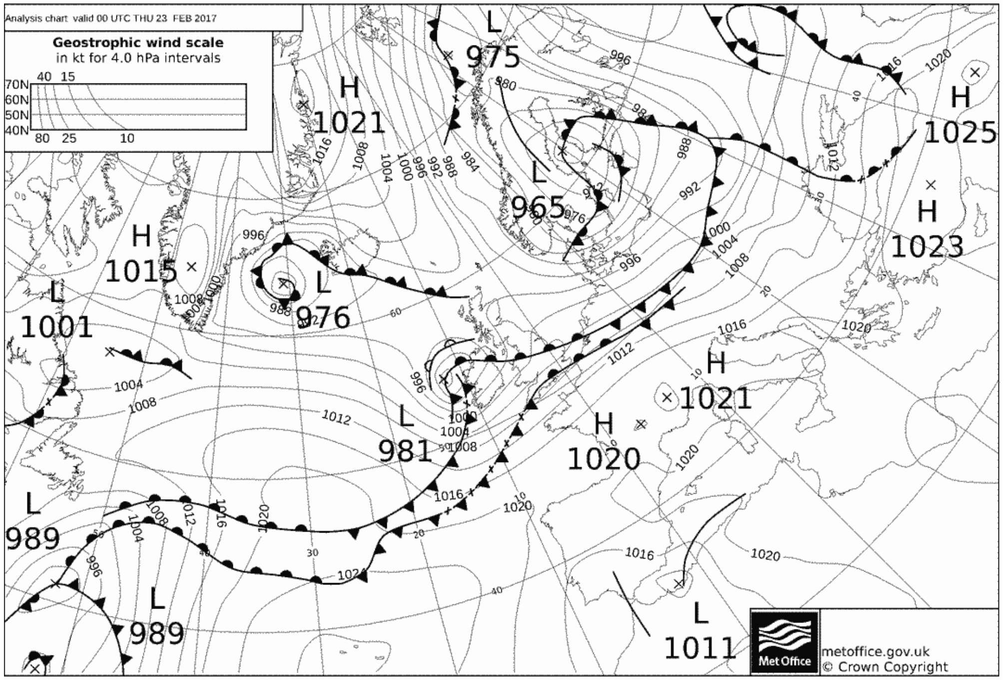
The quiet revolution of numerical weather prediction, Peter Bauer, Alan Thorpe and Gilbert Brunet, Nature, 525,47–55, 2015, doi:10.10381947/nature14956

The emergence of numerical weather prediction: Richardson's dream by Lynch, Peter

Weather by the numbers: the genesis of modern meteorology
by Harper, Kristine

Operational weather forecasting by Inness, Peter and Dorling, Steve

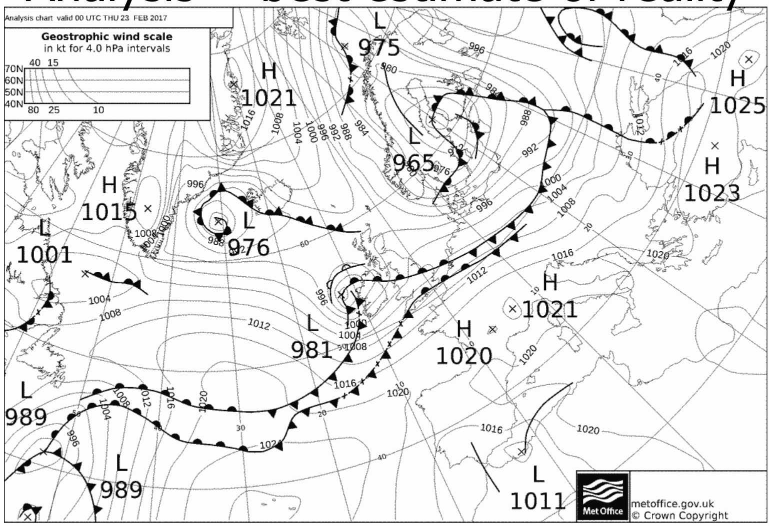
Storm Doris (2017)



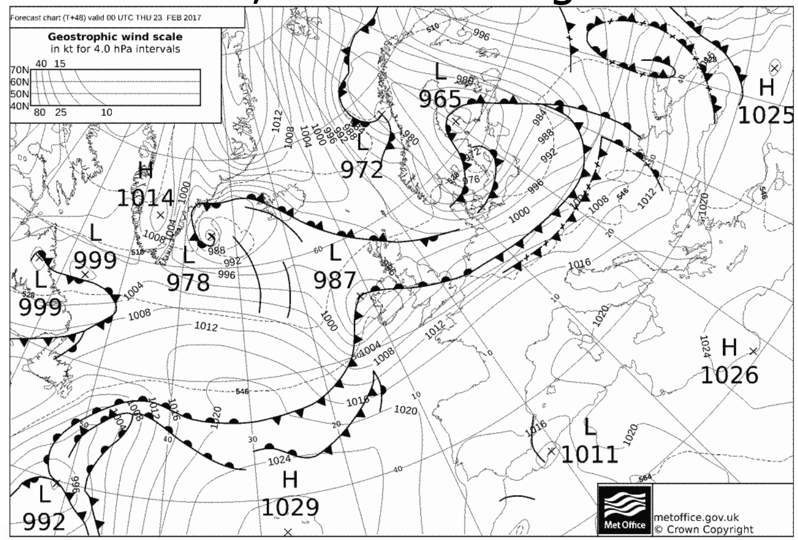
- 21 February: yellow and amber warnings for wind, snow and rain were issued Night/morning of 22/23 Doris underwent explosive cyclogenesis moved rapidly across northern England and out into the North Sea by the early afternoon.
- Heavy snow to Scotland during the morning rush hour causing widespread disruption, including the closure of the M80
- Strong winds and gusts (gust of 199), > £160M damage

Storm Doris Forecasts

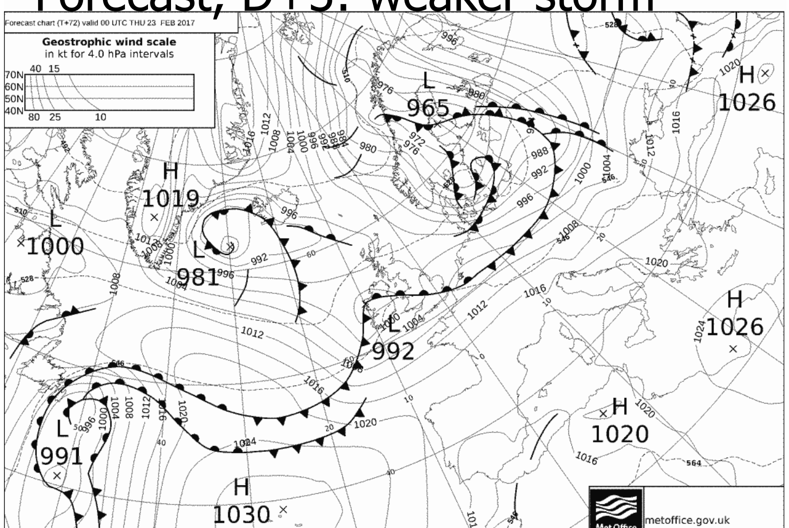
Analysis = best estimate of reality



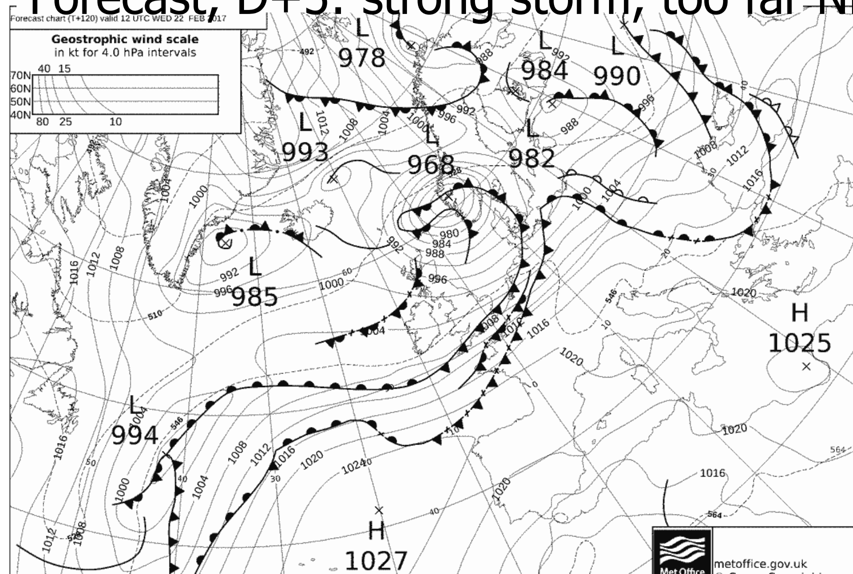
Forecast, D+2: warning issued



Forecast, D+3: weaker storm

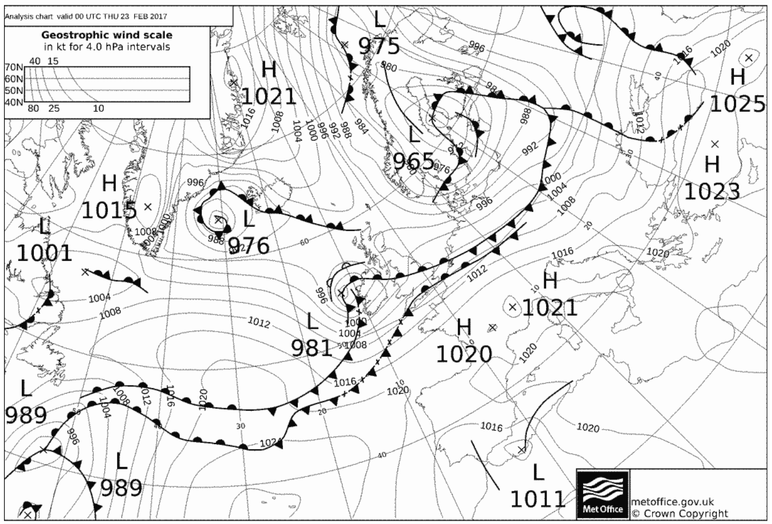


Forecast, D+5: strong storm, too far NE

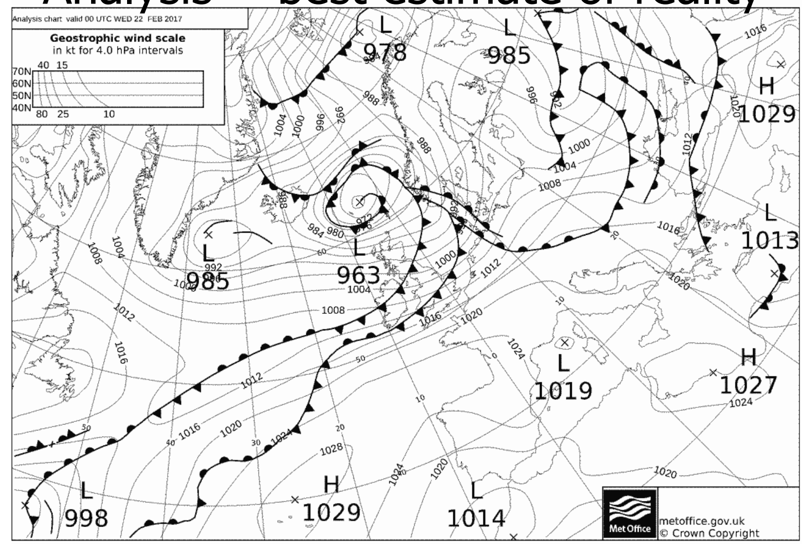


Storm Doris, the day before

23 Feb
Analysis = best estimate of reality

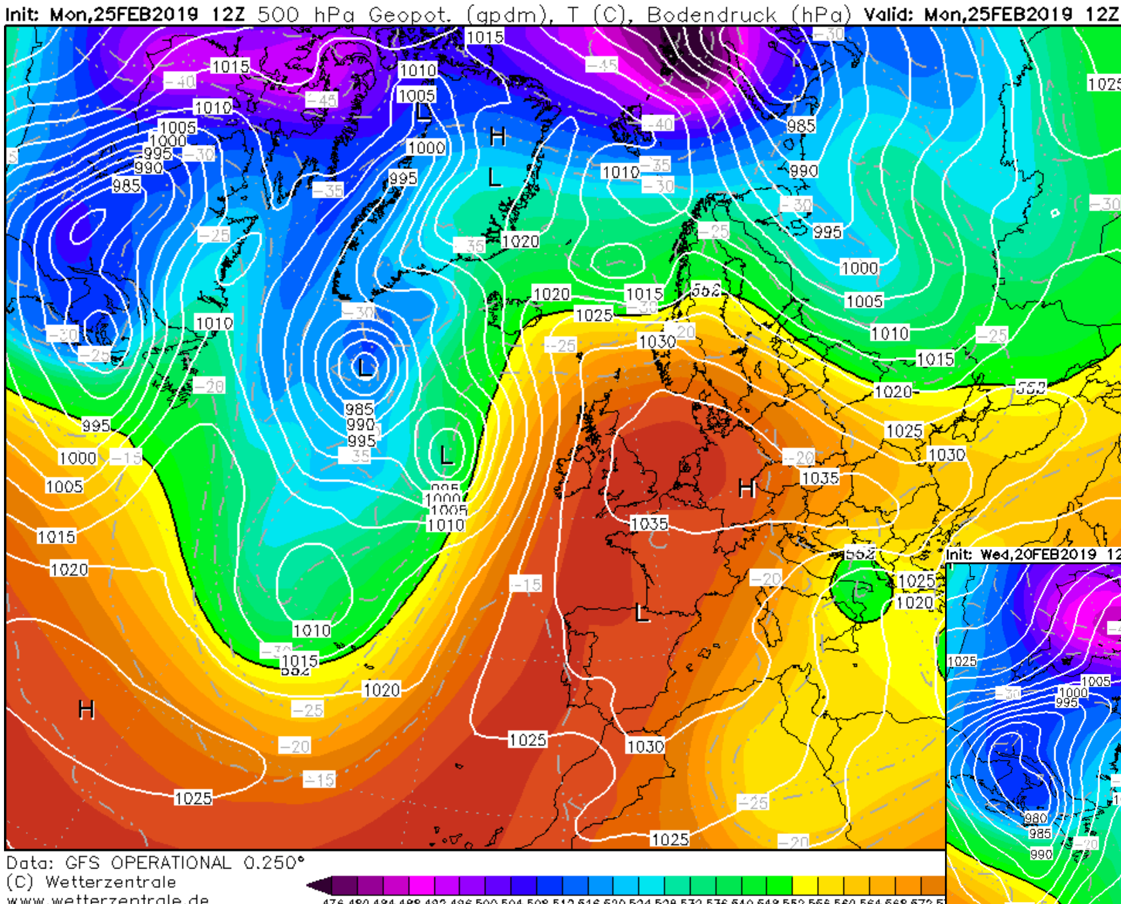


22 Feb
Analysis = best estimate of reality

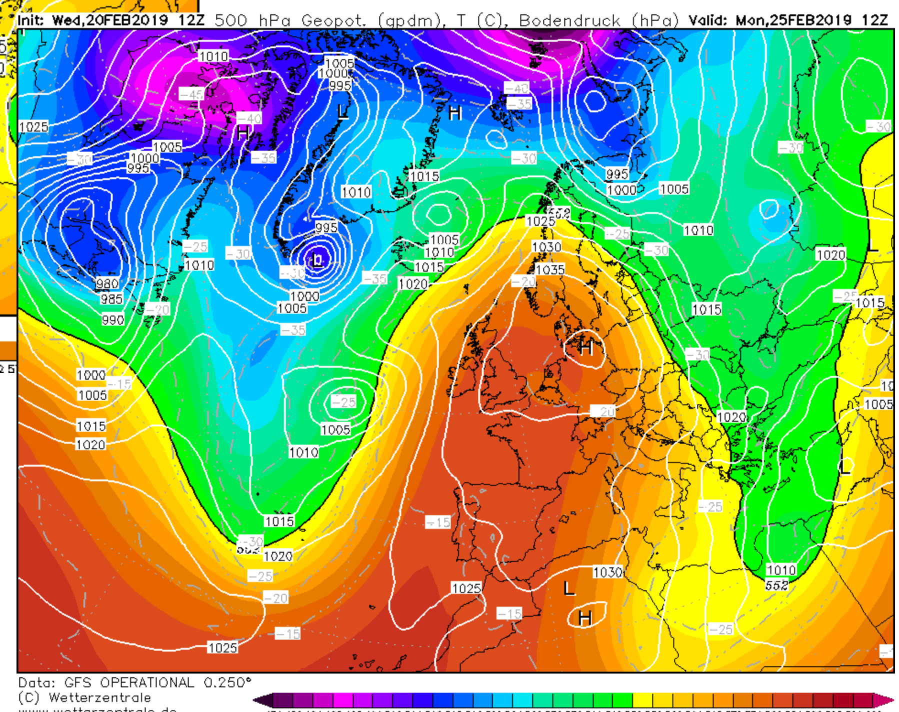


- It is not that it was there in the Atlantic and we could just see it coming
- NWP allowed us to predict the future!

Warmest recorded UK February day



Analysis



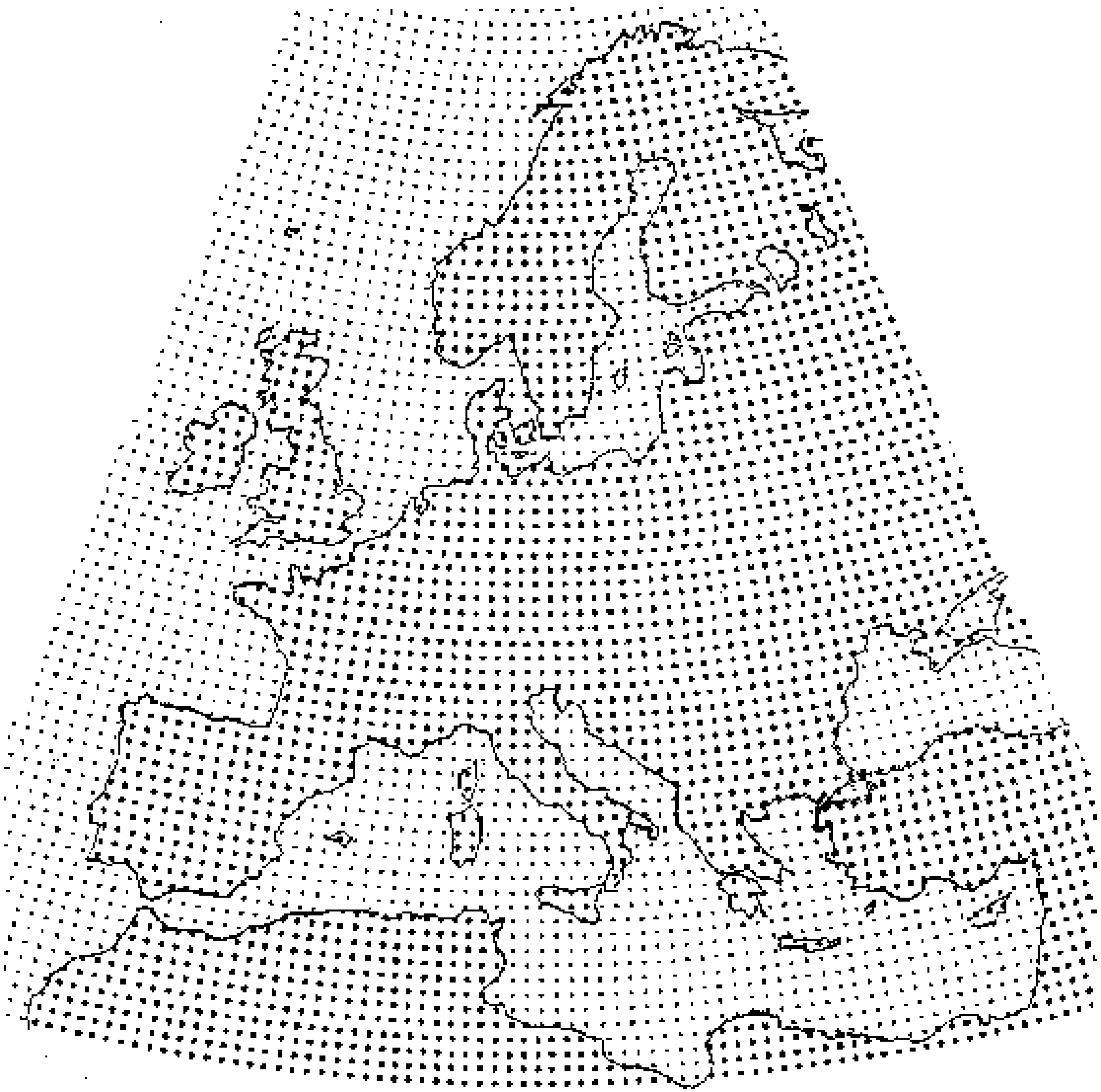
5-day forecast

Discretisation

For numerical treatment, we have to approximate the continuous atmosphere with values on a discrete grid

Typical distance between gridpoints 1–30 km. For climate models often ~100 km

State of the art models have >10^7 gridpoints

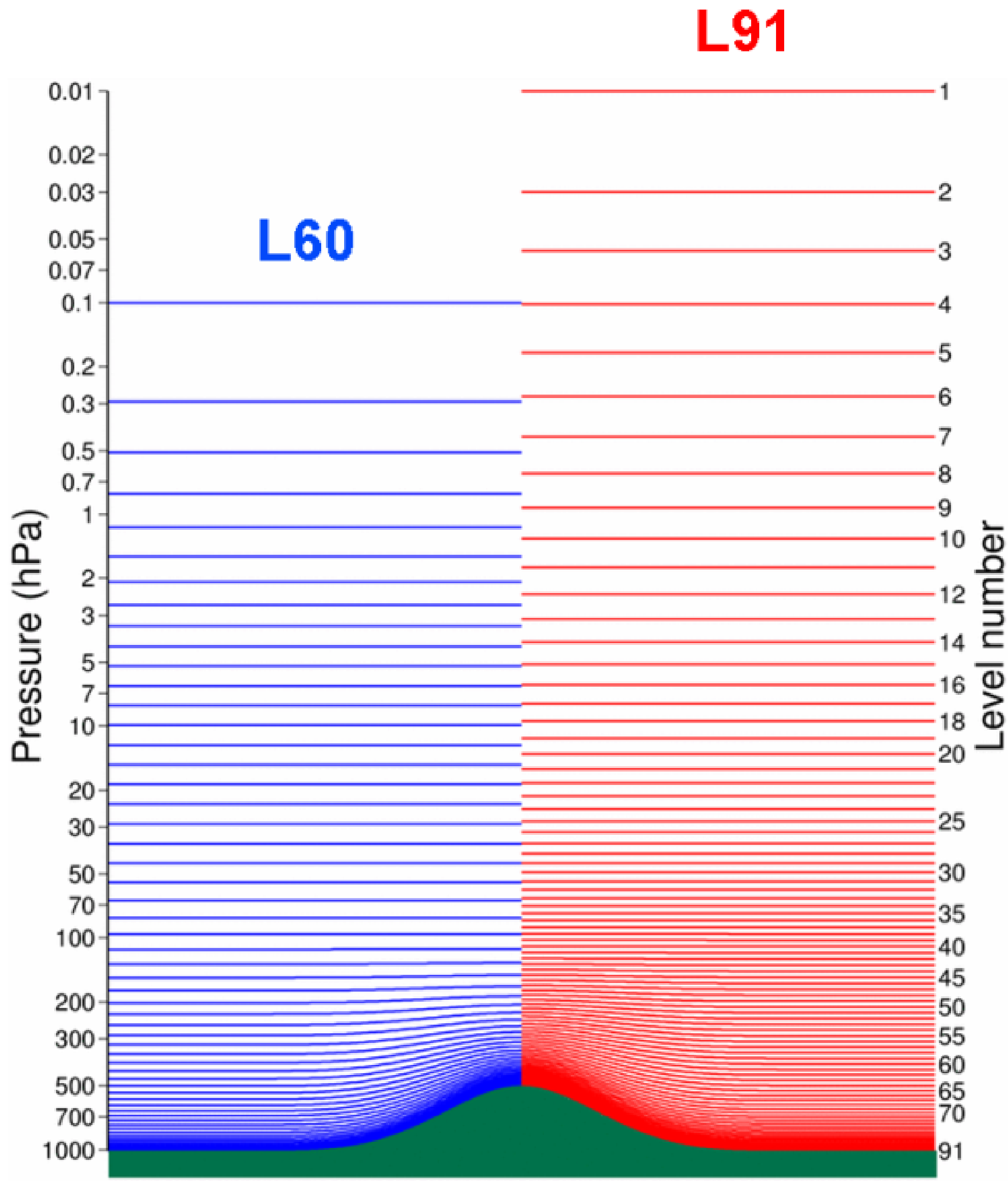


Discretisation

Vertical levels of two version of the ECMWF global model over an idealised mountain

Levels follow orography near the surface and become constant-pressure surfaces aloft

Many small-scale processes cannot be resolved and have to be parametrised

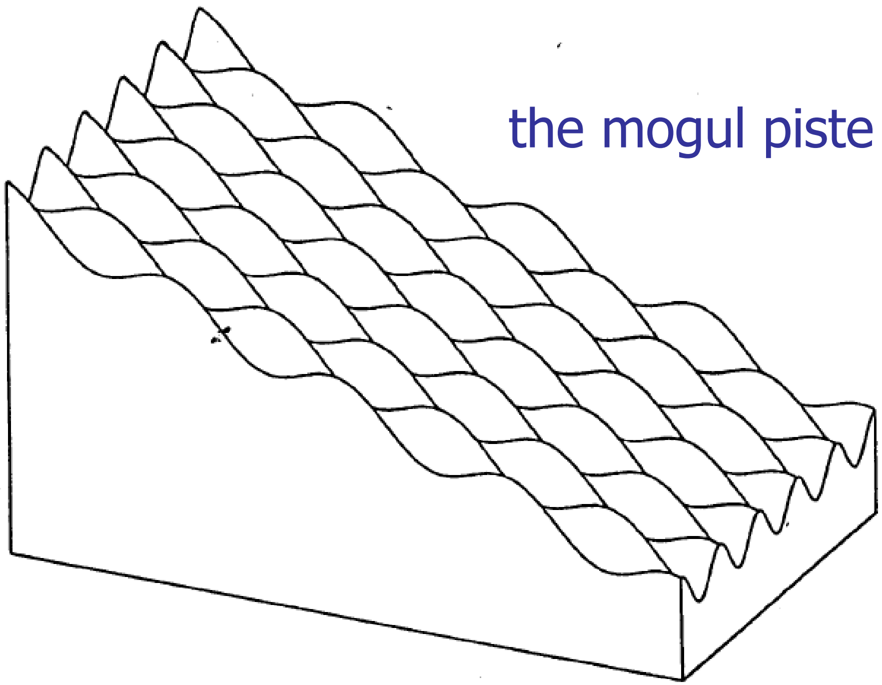


The idea of ensemble predictions

- The atmosphere is a chaotic system, too
  $\rightarrow$ weather forecasts are sensitive to initial conditions
- Uncertainties in initial conditions can lead to large prediction errors after only few days, even if we had a perfect model.
- Idea: Estimate uncertainties through computing an ensemble of predictions with slightly different initial conditions.
- Spread allows inferring the robustness of the forecast.
- Different evolutions reveal possible scenarios
  $\rightarrow$ important for extreme weather

Limited predictability for chaotic systems

In a chaotic system, small differences in initial conditions ultimately will lead to large differences in the final result, even though system is deterministic



the mogul piste

From Lorenz, *The essence of chaos*.