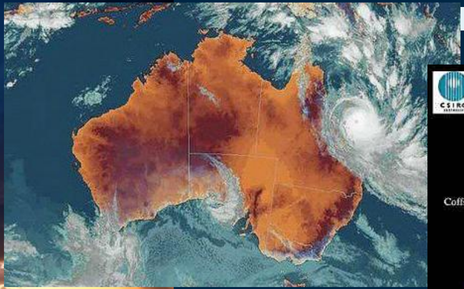
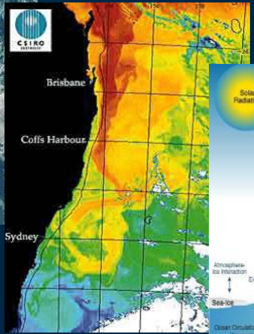
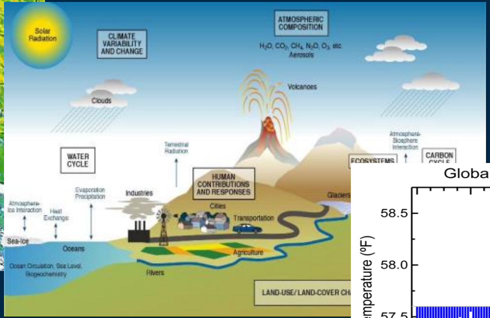
Toward Seamless Weather and Climate Earth-system Prediction and Insight

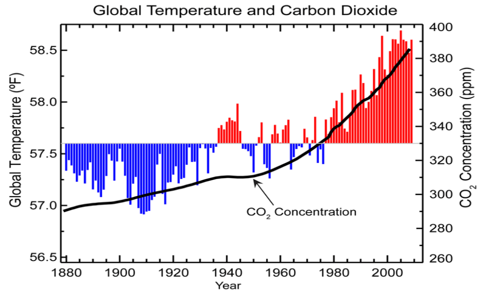
Gilbert Brunet

Chief Scientist, Bureau of Meteorology









Acknowledgements: contributions of many Environment and Climate Change Canada, UK Met Office, Bureau of Meteorology and ECMWF weather and climate science colleagues.

The 19th century: Canada and Australia long tradition of meteorological observations.



- Charles Smallwood made recording weather and rainfall every six hours each day in Laval (1833) and McGill University started in Montreal (1863);
- Sir James Clark Ross (Hobart, 1840) and Sir Charles Todd (Adelaide, 1855) started meteorological observations in Australia.
- Admiral Robert Fitzroy, Captain of the HMS Beagle, founded the meteorological service (UK Met Office) in 1854 (telegraph, the first public forecast appeared in The Times on 1 August 1861 …).

HMS Beagle

The 20th century: Numerical Weather Prediction (NWP)

- Numerical weather prediction model are based on the physical laws of fluid,

Horizontal Momentum

$$\frac{d\mathbf{V}^H}{dt} + \frac{1}{\rho}\nabla p + f\mathbf{k}\times\mathbf{V}^H = \mathbf{F}^H$$

Vertical Momentum

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

Continuity

$$\frac{d\ln\rho}{dt} + \nabla.\mathbf{V} = 0$$

Thermodynamic

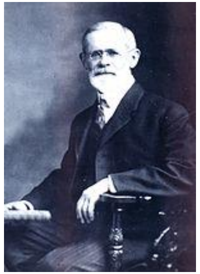
$$\frac{d\theta}{dt} = F^\theta$$

Moisture

$$\frac{dq}{dt} = F^q$$

State

$$p = \rho RT \quad where \quad \theta = T\left(\frac{p_r}{p}\right)^k.$$



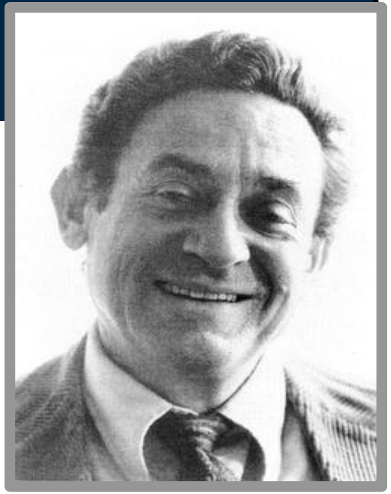
C. Abbe (1901)

V. Bjerknes (1904)

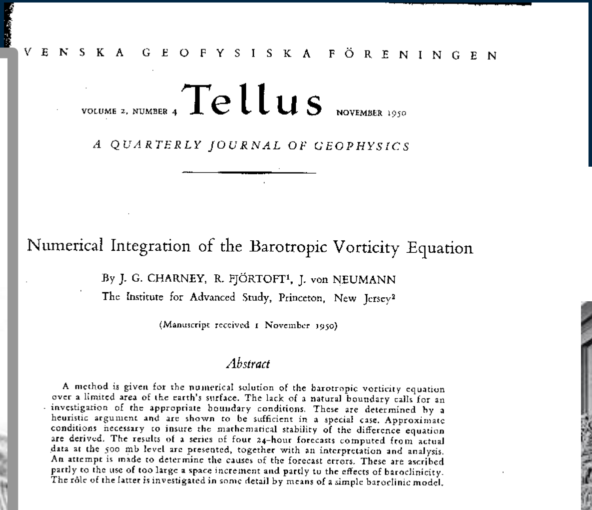
The 20’s: L.F. Richardson

Weather prediction equations can be discretized and solved with sophisticated mathematical algorithms and calculation techniques (L.F. Richardson, 1922)

The 50's



Jule Gregory Charney (1917-81)



VENSKA GEOFYSISKA FÖRENINGEN

VOLUME 2, NUMBER 4 **Tellus** NOVEMBER 1950

A QUARTERLY JOURNAL OF GEOPHYSICS

Numerical Integration of the Barotropic Vorticity Equation

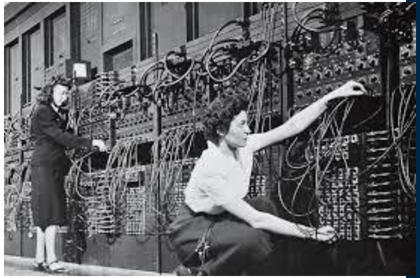
By J. G. CHARNEY, R. FJÖRTOFT[1], J. von NEUMANN
The Institute for Advanced Study, Princeton, New Jersey[2]

(Manuscript received 1 November 1950)

Abstract

A method is given for the numerical solution of the barotropic vorticity equation over a limited area of the earth's surface. The lack of a natural boundary calls for an investigation of the appropriate boundary conditions. These are determined by a heuristic argument and are shown to be sufficient in a special case. Approximate conditions necessary to insure the mathematical stability of the difference equation are derived. The results of a series of four 24-hour forecasts computed from actual data at the 500 mb level are presented, together with an interpretation and analysis. An attempt is made to determine the causes of the forecast errors. These are ascribed partly to the use of too large a space increment and partly to the effects of baroclinicity. The rôle of the latter is investigated in some detail by means of a simple baroclinic model.

Trevor Pearcey (1919-98) with CSIRAC



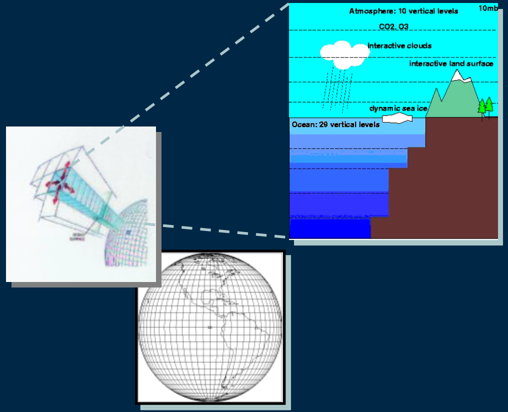
- Von Neumann, pionnier of modern computers, and the American meteorologist Charney were the first to do a Numerical Weather Prediction (NWP) forecast with the ENIAC (1950); and,
- Charney's thinking on weather and climate prediction was visionary (GARP, 1969; Carbon dioxide and climate, 1979).

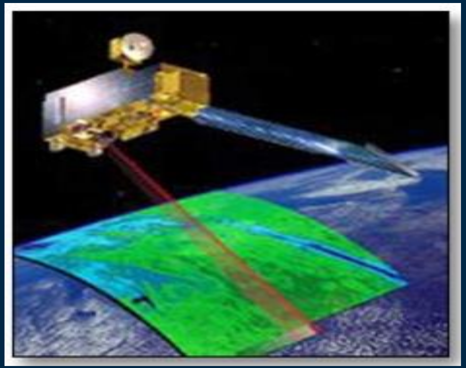
The 60’s

André Robert
(1929-93)

- The first successful integrations of a global model were performed in Montreal by the Canadian André Robert (1969);
- Bureau of Meteorology collaborator: Bill Bourke;
- The ancestor of all existing global weather and climate computer models;

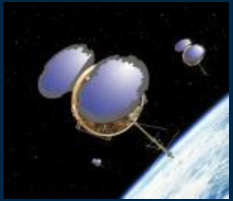
- Unprecedented space and surface based observation systems were put in operation.





Meteorological observing systems used by National Meteorological and Hydrological Services

Geostationary Satellites



Micro satellites GPS-RO

Polar-orbiting Satellites

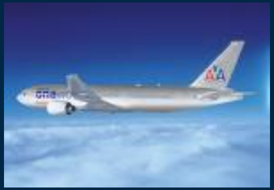
Radar Network

Wind profilers

Surface stations

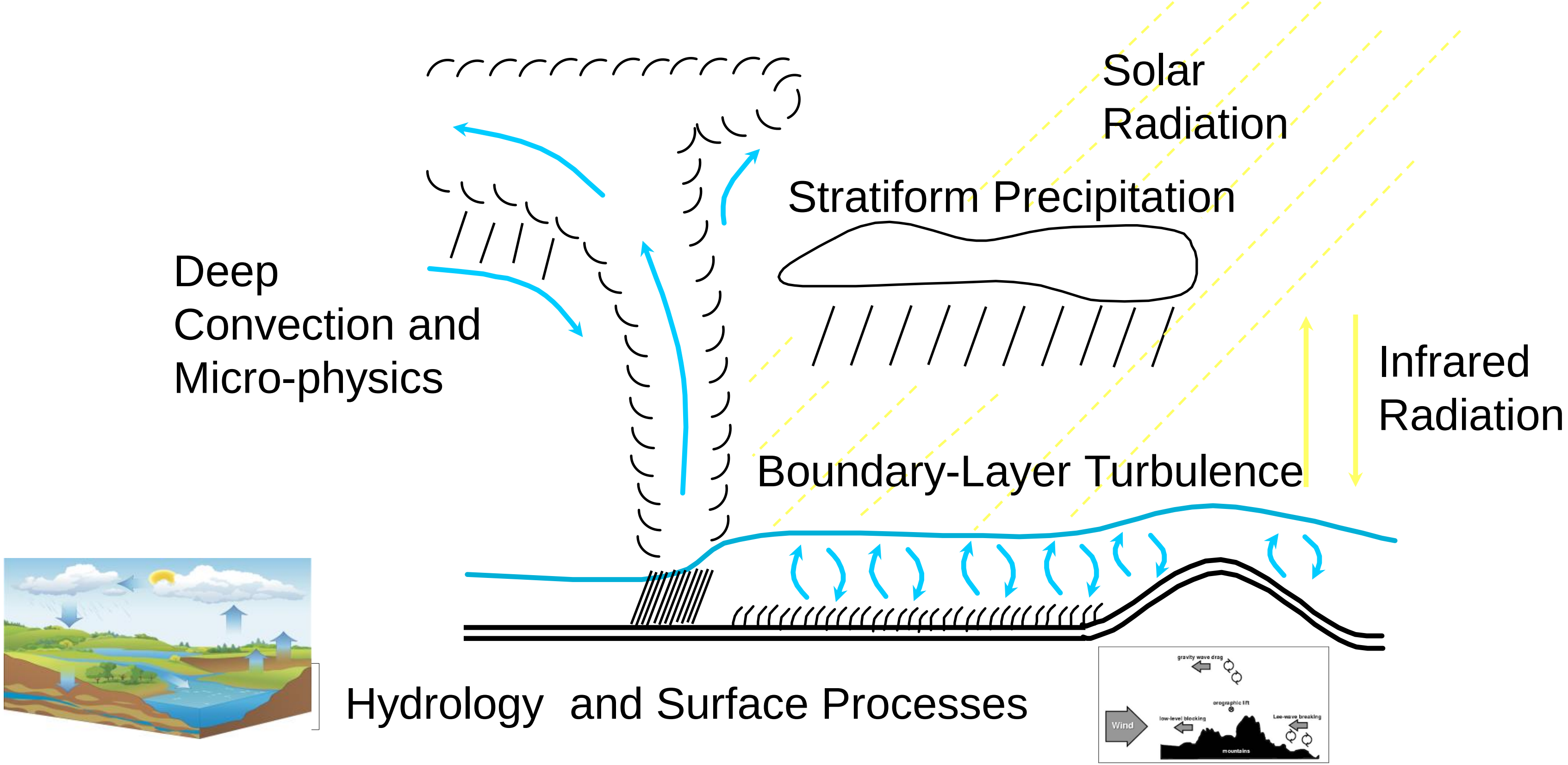
Upper-air sites

Buoys and ships



Aircraft

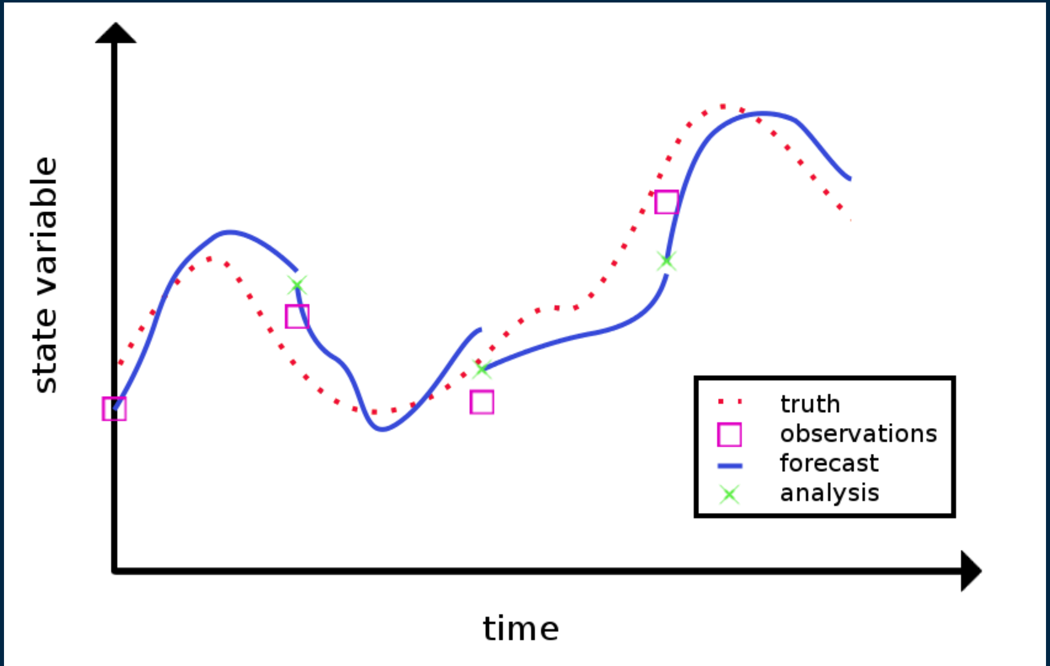
A prediction model grand challenge: representation of the sub-grid scale dynamical and physical processes



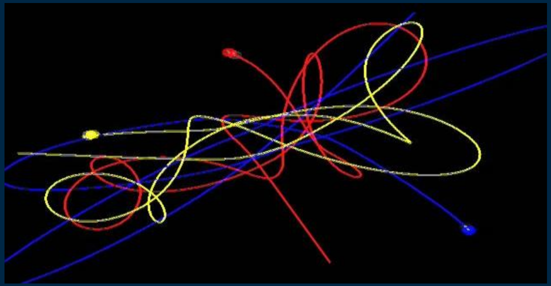
The Data Assimilation grand challenge: combining observations with global model forecasts

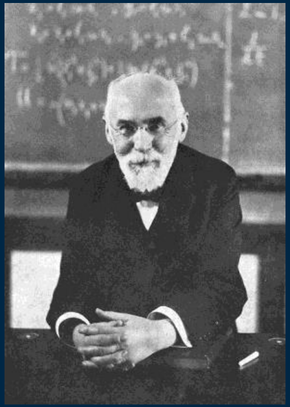
- Over 800M ingested and 70M processed observations per day at ECMWF.

- The information content of analyses due to observations is around 10%, the rest come from past observations propagated by the global numerical prediction model



Chaos: an old problem





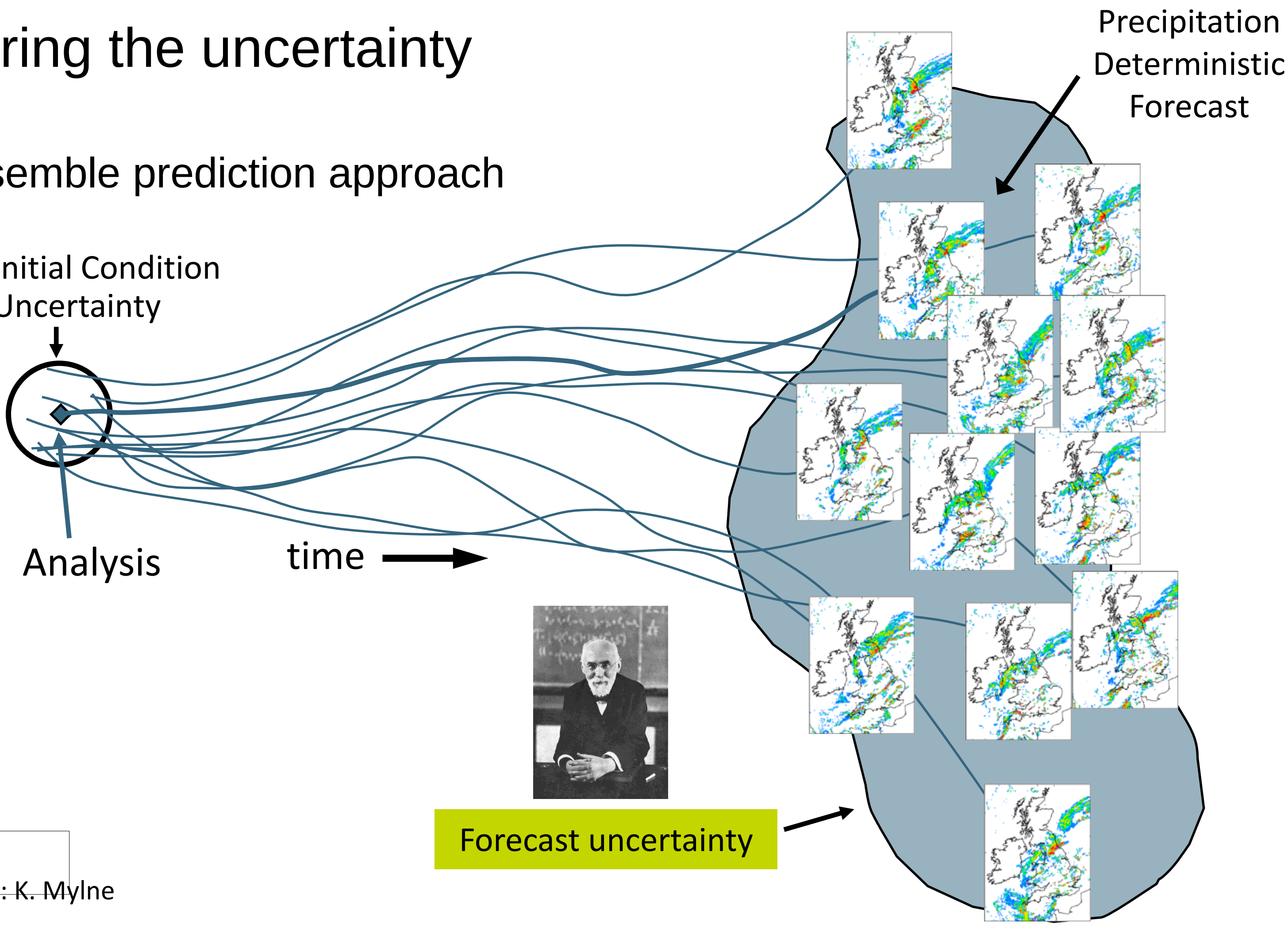
Henri Poincaré (1854-1912)

"A small error in the former will produce an enormous error in the latter...The meteorologists see very well that the equilibrium is unstable, that a cyclone will be formed somewhere, but exactly where they are not in a position to say; a tenth of a degree more or less at any given point, and the cyclone will burst here and not there, and extend its ravages over districts it would otherwise have spared."

Science and Method, 1908, Henri Poincaré

Capturing the uncertainty

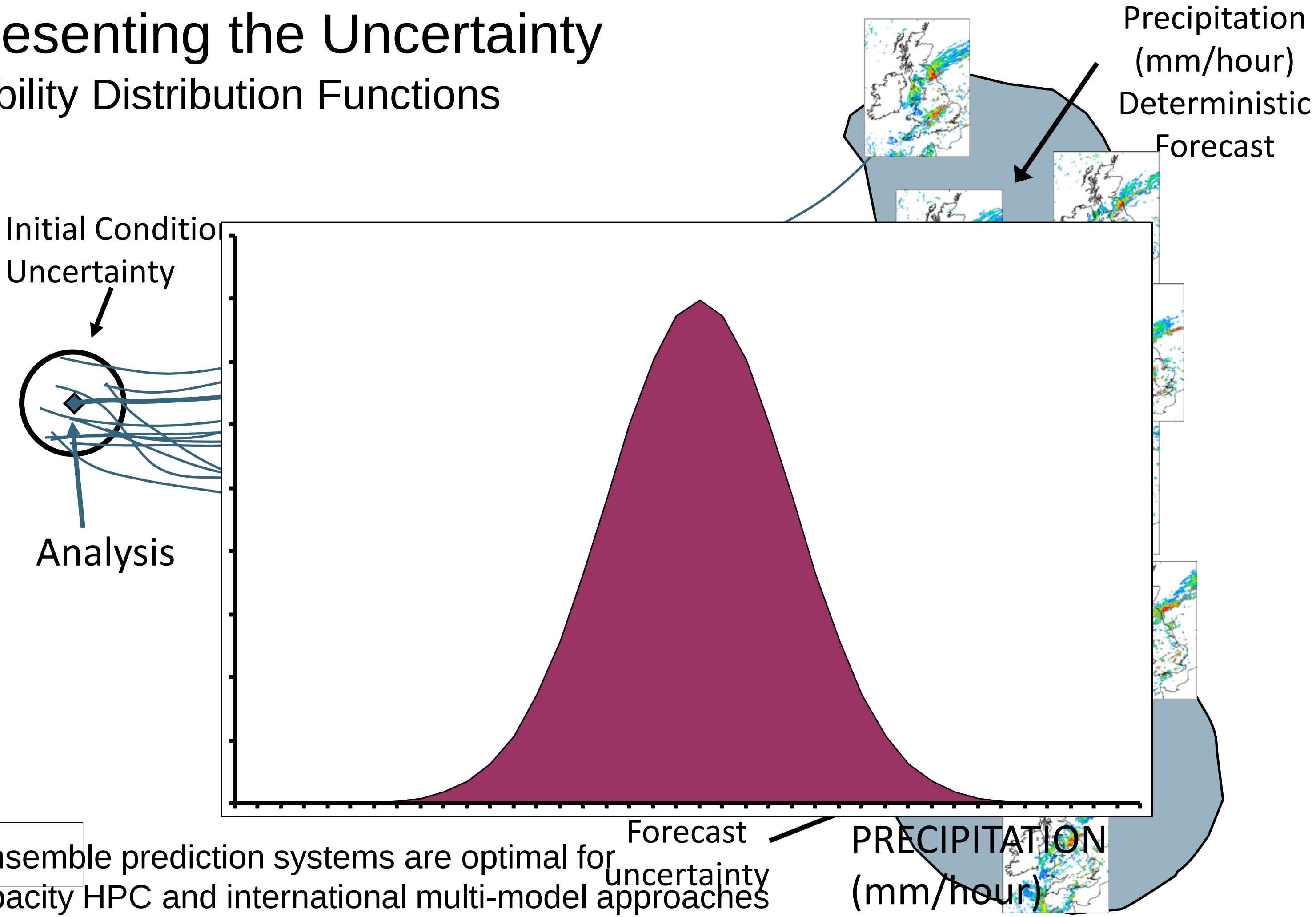
The ensemble prediction approach



Acknowledgement: K. Mylne

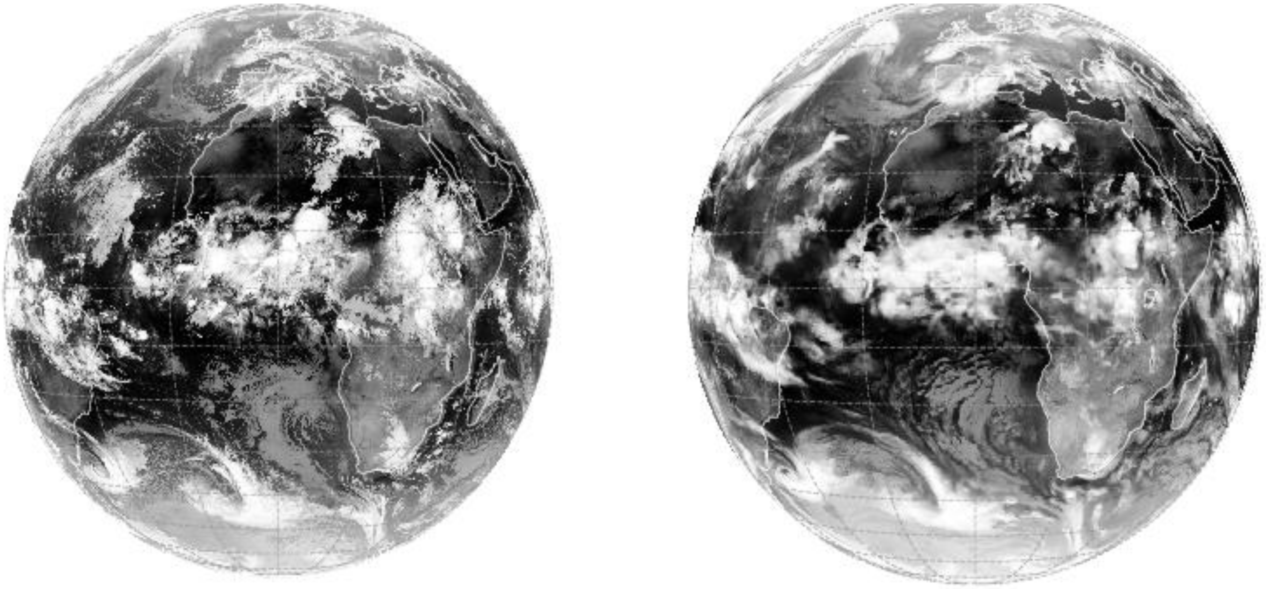
Representing the Uncertainty

Probability Distribution Functions



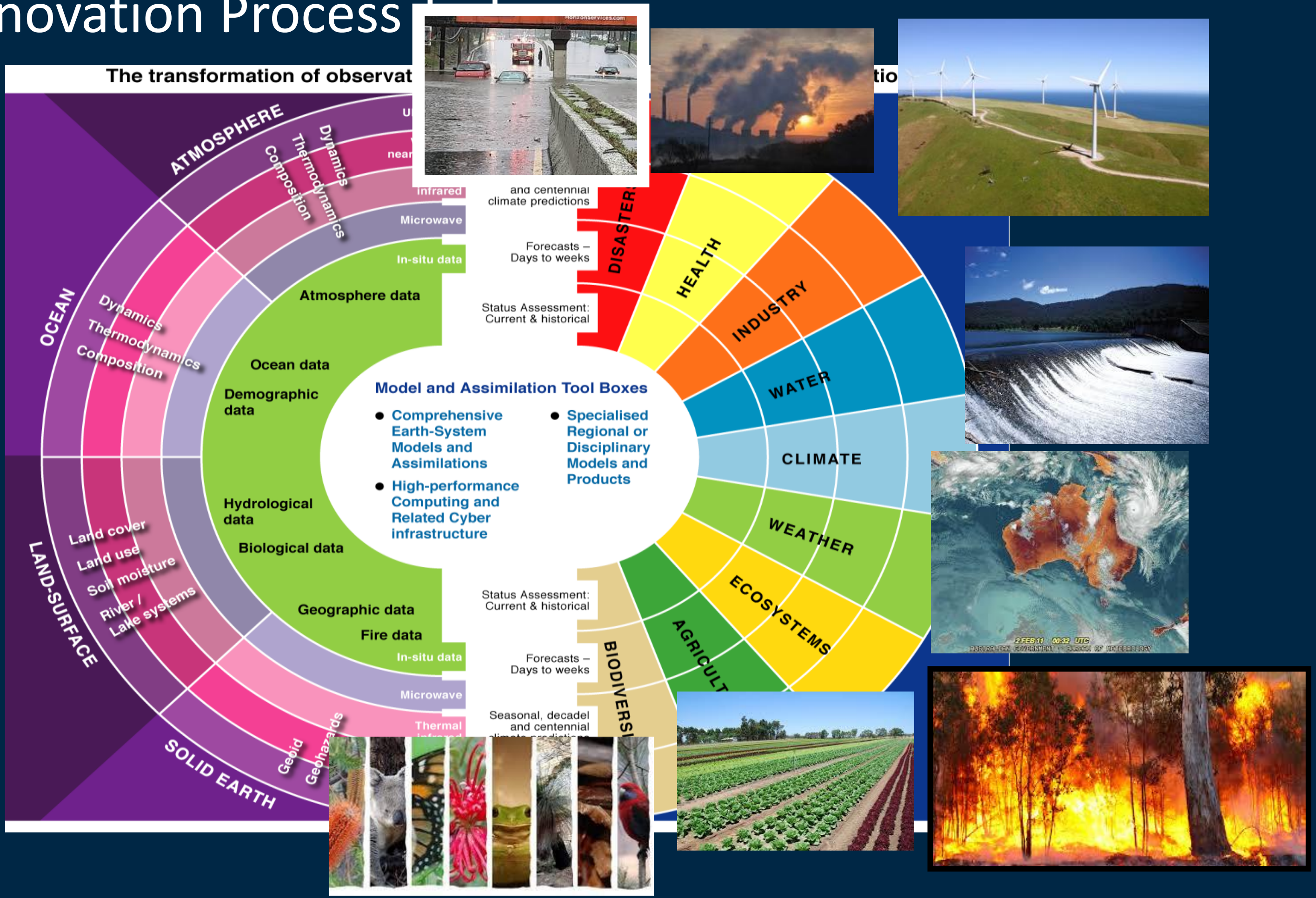
Note: ensemble prediction systems are optimal for high capacity HPC and international multi-model approaches

Weather Prediction (horizontal resolution~15 km)
compared with Satellite Observations
ECMWF predictions and Meteosat observations
(Martin Miller, ECMWF)



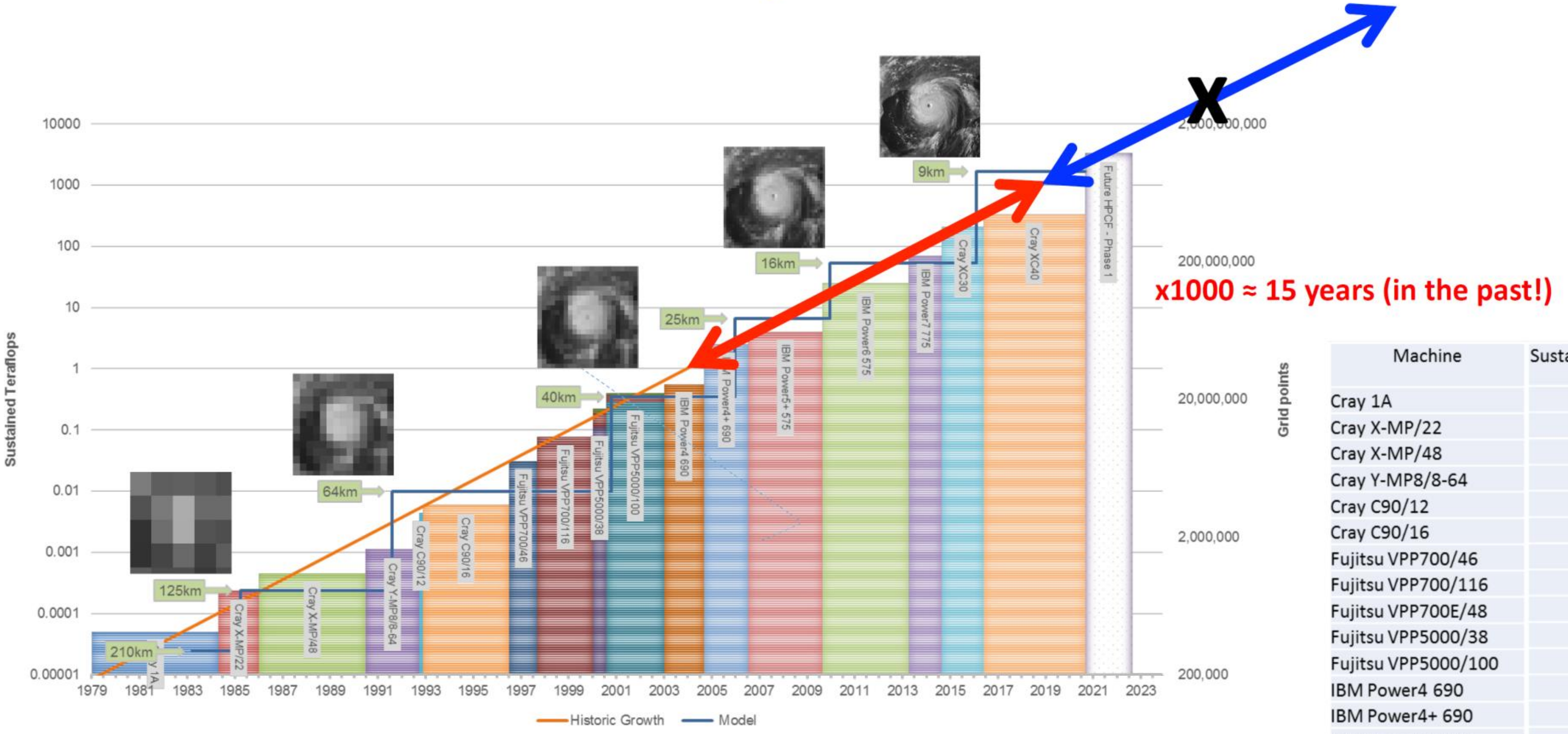
The Forecast Innovation Process T

- Monitoring
- Research
- Development
- Operation
- Service



The Way Forward

HPC history at ECMWF

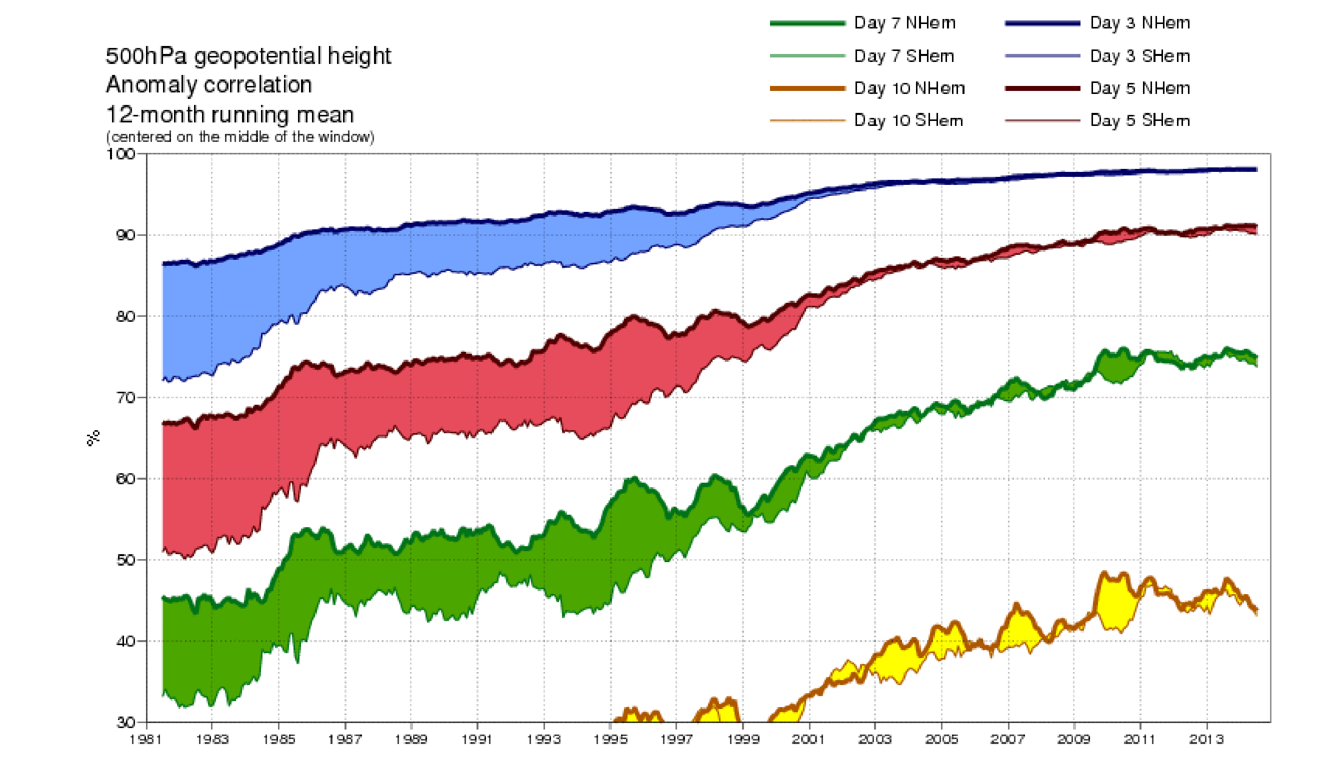


Machine	Sustained/Peak %
Cray 1A	31%
Cray X-MP/22	50%
Cray X-MP/48	48%
Cray Y-MP8/8-64	42%
Cray C90/12	39%
Cray C90/16	39%
Fujitsu VPP700/46	31%
Fujitsu VPP700/116	30%
Fujitsu VPP700E/48	31%
Fujitsu VPP5000/38	30%
Fujitsu VPP5000/100	30%
IBM Power4 690	6%
IBM Power4+ 690	8%
IBM Power5+ 575	11%
IBM Power6 575	8%
IBM Power7 775	5%
Cray XC30	6%
Cray XC40	4%

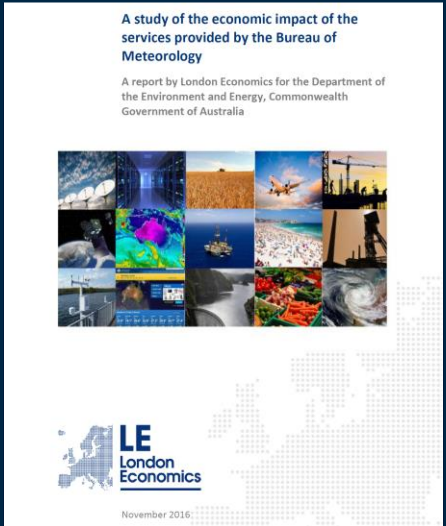
ECMWF

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Acknowledgement: P. Bauer

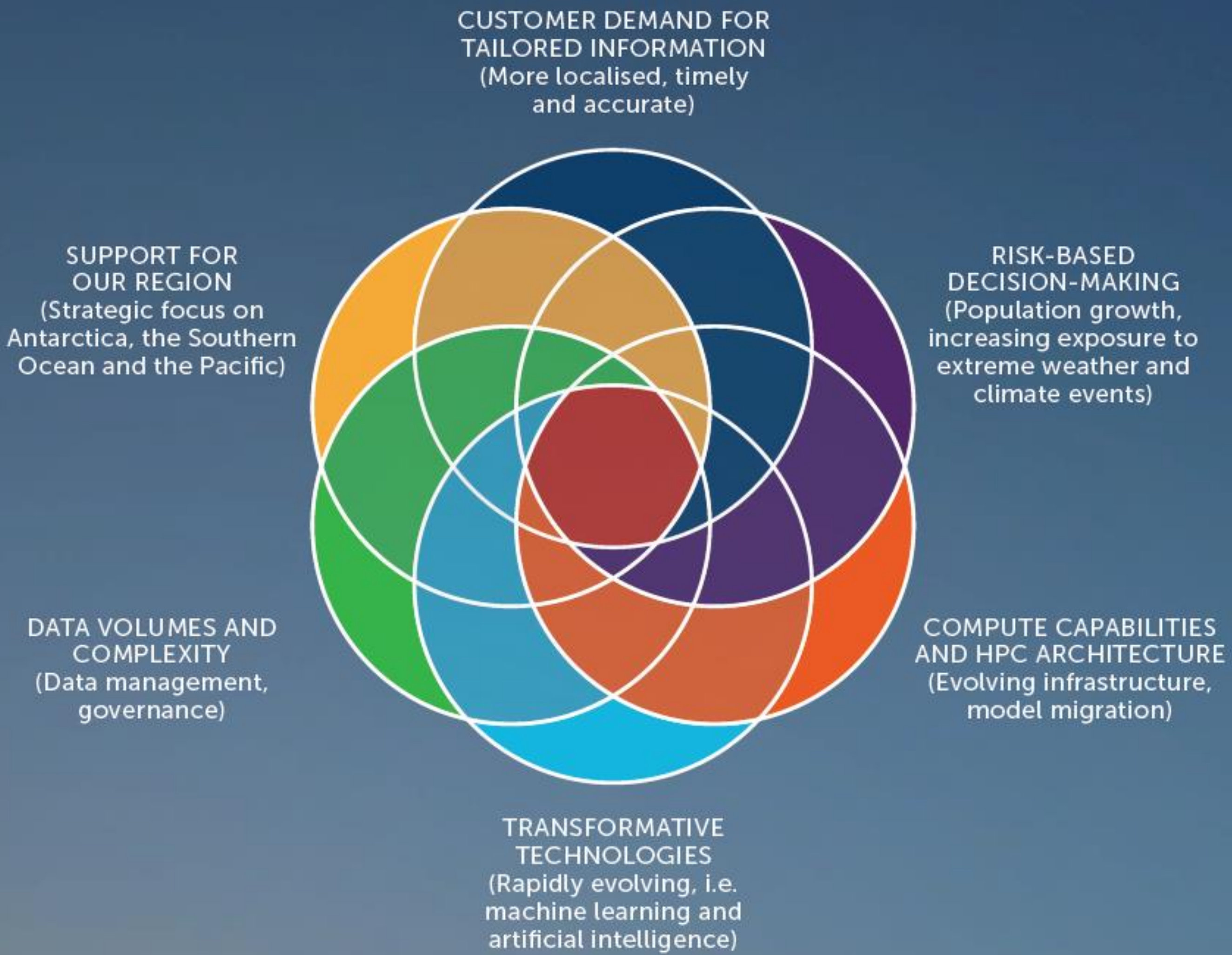


The quiet revolution of Numerical Weather Prediction
Bauer, Thorpe and Brunet (Nature, 2015)



"for every dollar spent on delivering Bureau services, these services return a benefit of $11.60 to the Australian economy."

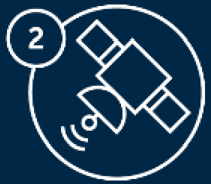
Key drivers influencing BoM R&D efforts over the next decade



BoM R&D 2020-30 Plan:The four R&D objectives, day after day

Day 1: Customised impact-based forecasts and warnings when and where it counts

- More localised, timely and better information for cities and regional areas



Day 2: Reliable and trusted forecasts

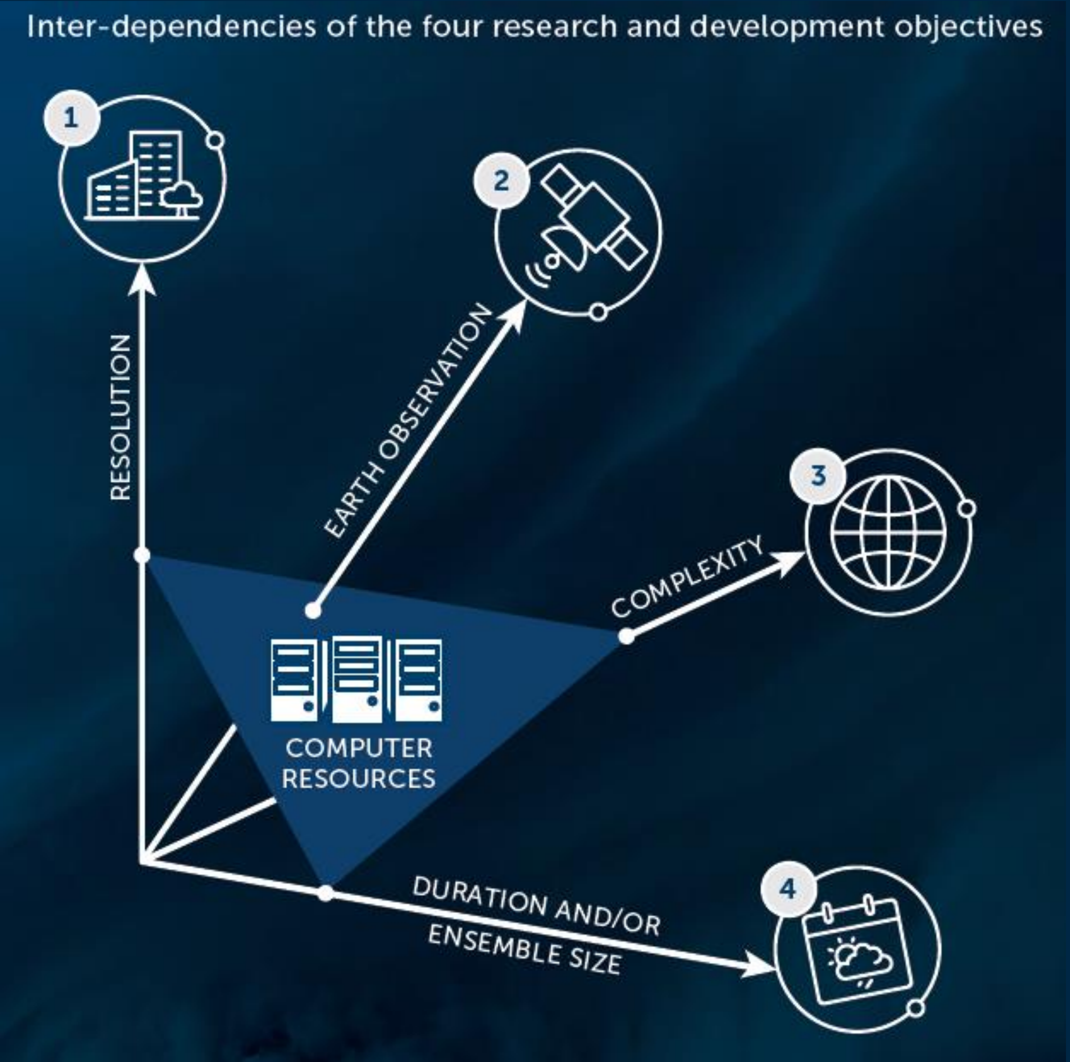
- Enhanced assimilation of observations for more accurate predictions

Day 3: An Earth system prediction capability

- Fully integrated atmosphere, ocean, sea-ice and hydrology models

Day 4: Seamless weather and climate insights

Historical observations and predictions, from minutes to decades



Operating in a 'system of systems'

- Together enabling improvements in numerical prediction accuracy and precision and downstream products
- Reliant on HPC availability and optimal utilisation

Day 1: Customised impact-based forecasts and warnings when and where it counts

More localised, timely and better information for cities and regional areas

Customised impact-based forecasts and warnings when and where it counts

Products and services targeted to customer needs

- Social science-based impact warnings framework
- Impact-based decision support

Data and processes to support impact-based products and services

- Streamlining routine and high impact forecasts and warnings
- Comprehensive verification

High resolution rapid update inputs for streamlined forecasting

- Post-processing of numerical guidance
- High resolution numerical prediction models over regional and urban domains

Observing and understanding high impact weather

- Integration of observations
- Research for better understanding

Numerical Earth-system and Weather-to-Climate Prediction (NEWP) for the 2015 Pan Am Games, TORONTO: from urban to regional scales.

Environment Canada

- Meteorological Research Division
- Air Quality Research Division
- Meteorological Service of Canada

Environment Canada Science Project for the 2015 Pan Am Games

The Pan American Games are **the world's third largest international multi-sport Games**

Demonstration of seamless atmospheric and environmental forecasting

Enhanced local forecasts:
Weather, air quality, hydrology and lakes

Observational networks:
surface observations, mobile platforms, air quality, lightning

Numerical Modeling for Pan Am: Objectives

Improve forecasts related to:

Extreme heat

Intense precipitation

Strong winds

Lake breezes

Air quality events

Lake conditions

The City of Toronto

Numerical Modeling for Pan Am: Resolution

Improve forecasts related to:

Extreme heat

Intense precipitation

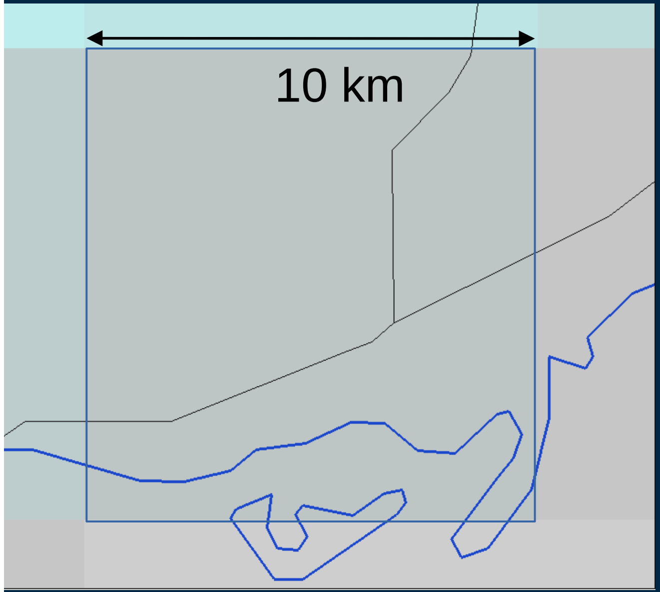
Strong winds

Lake breezes

Air quality events

Lake conditions

The City of Toronto



Current Operational BoM Global Model ~10 km

Numerical Modeling for Pan Am: Resolution

Improve forecasts related to:

Extreme heat

Intense precipitation

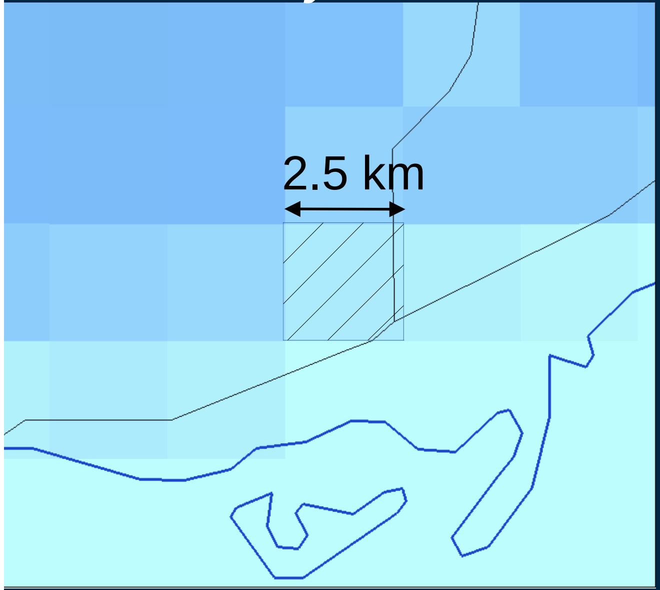
Strong winds

Lake breezes

Air quality events

Lake conditions

The City of Toronto



BoM regional model – 1.5 km

Numerical Modeling for Pan Am: Resolution

Improve forecasts related to:

Extreme heat

Intense precipitation

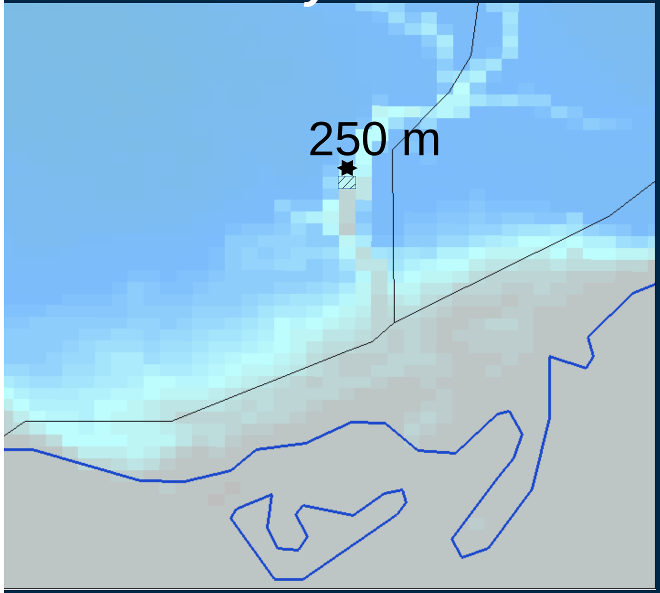
Strong winds

Lake breezes

Air quality events

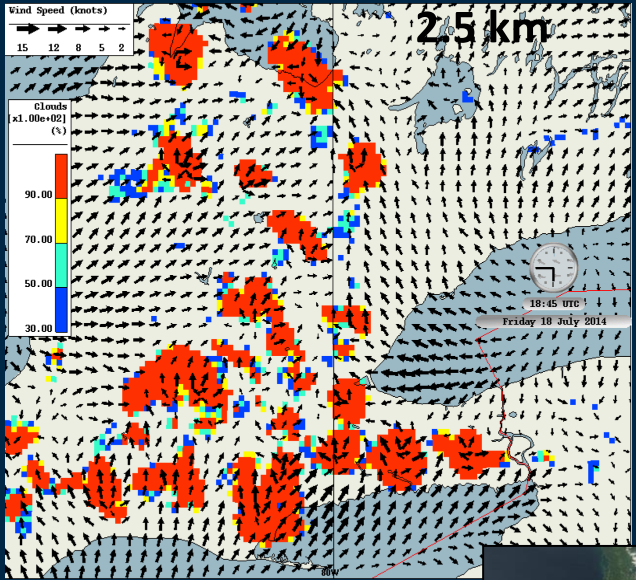
Lake conditions

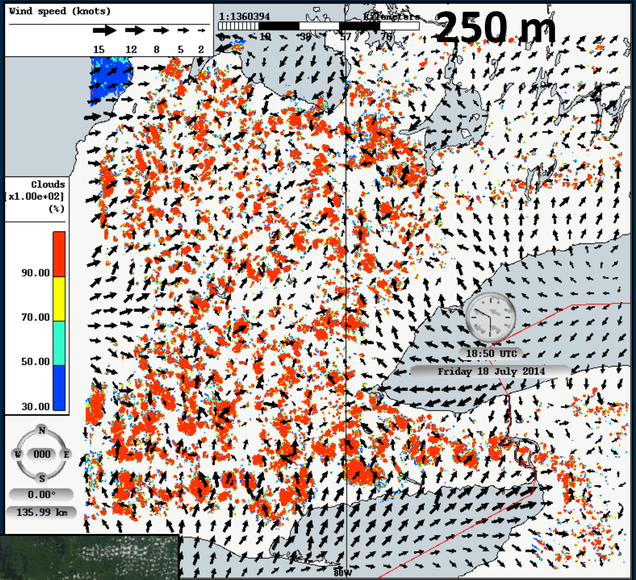
The City of Toronto



BoM experimental sub-km model – *0.1km to 0.4 km*

Example of Daytime Convective Activity





Cloud coverage and near-surface winds Valid at 1850 UTC 18 July 2014

MODIS (Aqua satellite)

How to accelerate forecast advances in regional/urban areas?

- **For water management**, including the need for long-term infrastructure investment to address expanding potable water shortages;

- **To deal with more frequent and more severe floodings** in high-risk coastal plains and river valleys densely populated areas;

- **For even higher resolution (sub-km) models with integration of local geography and observations**, that would allow producing sector-specific forecast products, for instance, in support of energy management or public healthcare in highly populated urban regions;

- **Weather and climate observing data in the future should be interoperable** with those of socio-economic data, biophysical and other data ideally in the cloud where more and more users and customers are.

Acceleration will certainly go through enhanced Public Private Engagement (PPE)

Reliable and trusted forecasts

Enhanced assimilation of observations for more accurate predictions

Reliable and trusted forecasts

More and better used observations

- More timely and specific information
- Improved numerical predictions
- Support for verification

More effective observation network

- Integrated satellite, radar, in situ, 3rd party, …
- Additional quality monitoring
- Optimized observing network

Improving our science

- Improved process understanding
- Advances in observations & Data Assimilation

Improvement of skill: what are the main contributors? Observations vs Data Assimilation and Numerical Prediction Model (Dee et al., BAMS, 2014)

- In the last 30 years, improvements in the global observing system contribute to 10% in the global forecast skill gain.

- Today's backbone observing system needs to be maintained with sufficient redundancy to fill potential gaps in case of individual mission failure. But the global observation network shows already great resilience and coverage, so how much is 'good enough'?

- With the phenomenal impact of the increase in satellite observations for numerical prediction, in-situ observations will always be needed to anchor them; but what are the optimal investments in such in-situ observations to satisfy all user requirements is still an open question.

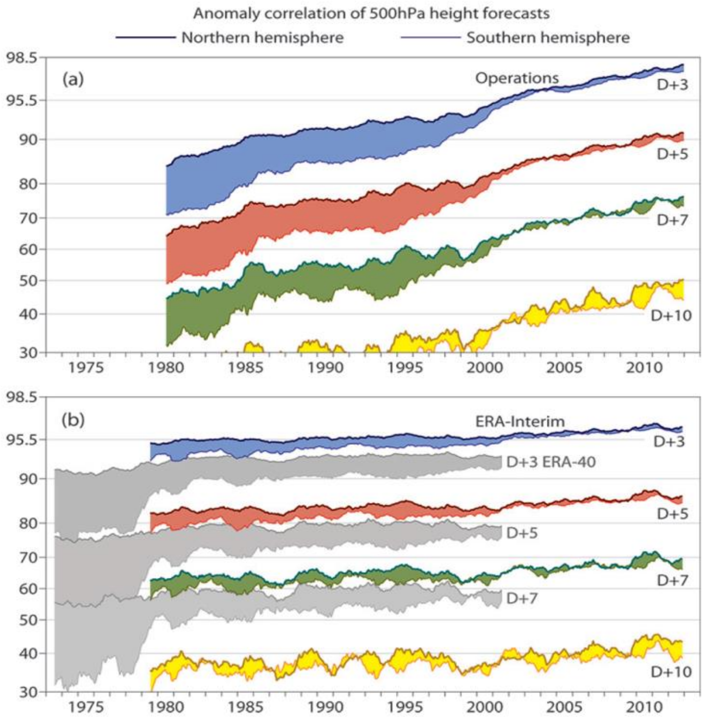
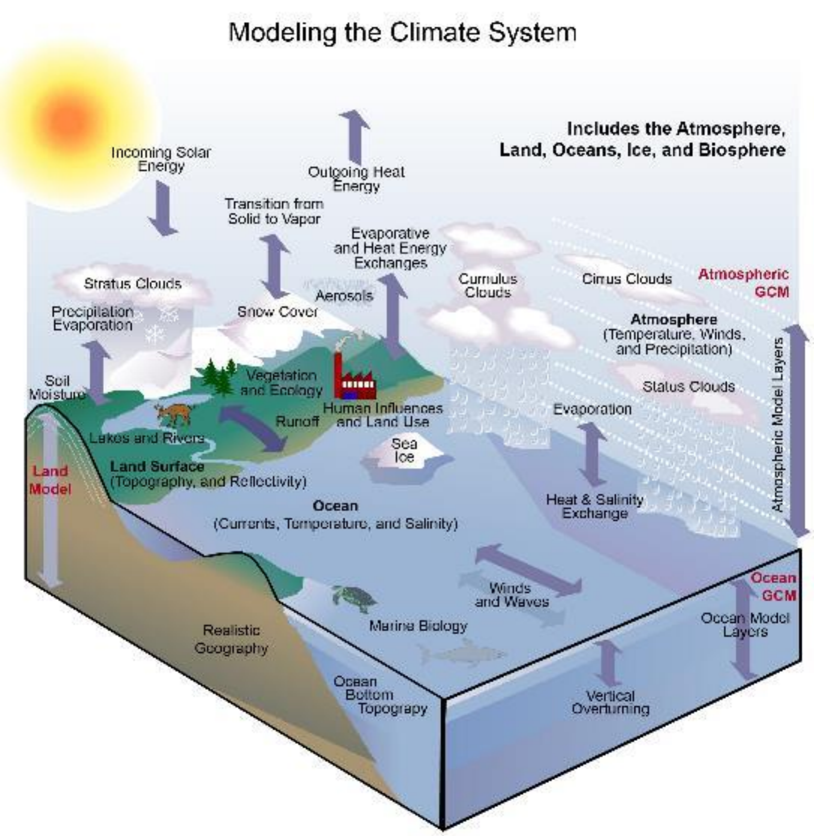


FIG. 1. Twelve-month running mean anomaly correlations (%) of 3-, 5-, 7- and 10-day 1200 UTC forecasts of 500-hPa height for the extratropical Northern and Southern Hemispheres from (a) ECMWF operations from Jan 1980 to May 2013 and (b) ERA-Interim from Jan 1979 to Apr 2013 and ERA-40 from Jan 1973 to Dec 2001. The shading shows the difference in scores between the two hemispheres at the forecast ranges indicated.

An Earth system numerical prediction capability

Fully integrated atmosphere, ocean, sea-ice and hydrology models

An Earth system numerical prediction capability



Supporting the full range of user needs

- Multi-hazard information
- Certainty & scenarios
- All environmental realms

Fully integrated information

- Consistency of information
- Coupling where warranted

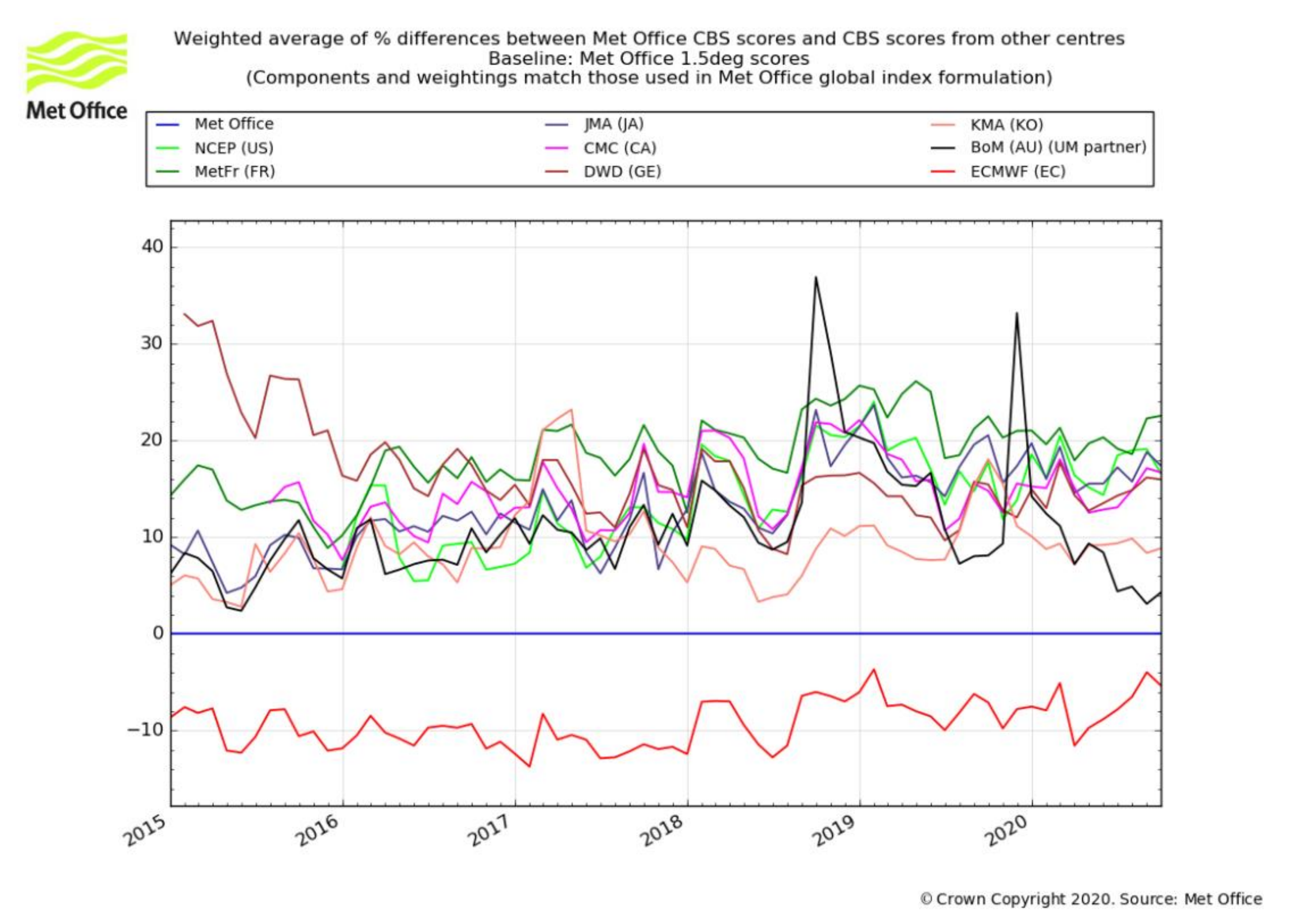
World class modeling systems

- Very high resolution
- Continuous improvement

Cost effective

- HPC use and software management
- Transition to operations
- Development

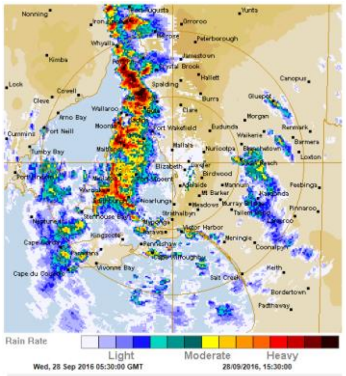
Ranking of global weather prediction centers



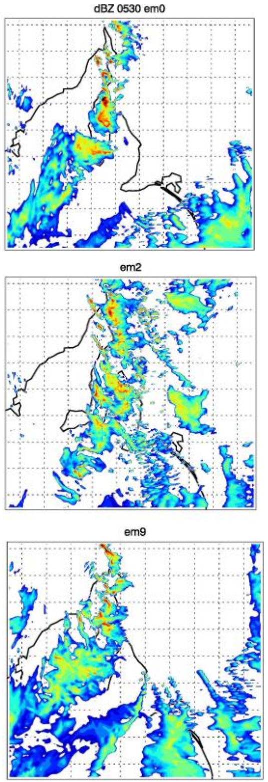
SA severe thunderstorm and tornado outbreak September 2016

Observed and simulated radar rain rate

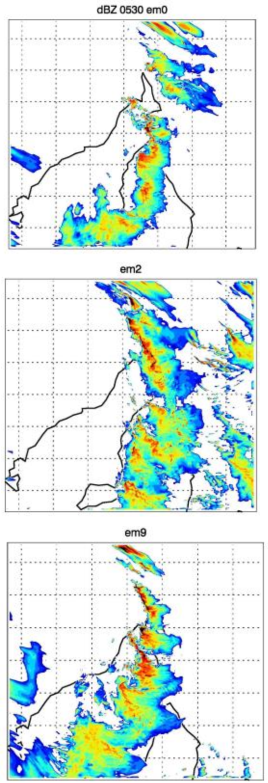
- Charmaine Franklin (Bureau of Meteorology)
- 400m better resolves convection and has more realistic storm structure



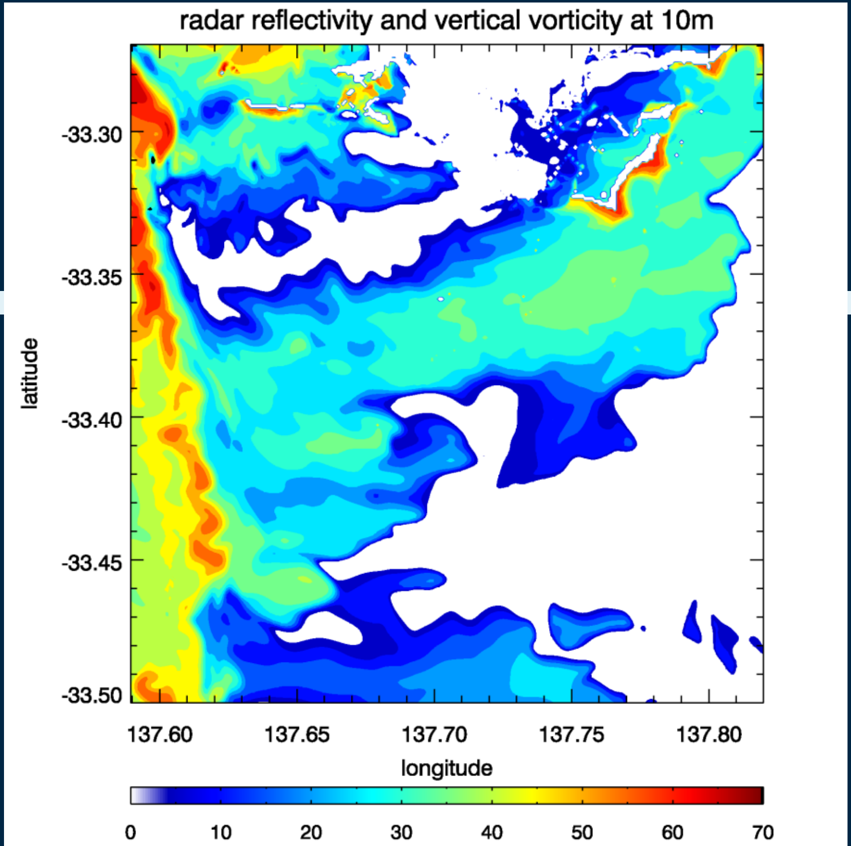
1.5 km



400 m



Zoomed in 100m simulation showing tornado-like vortices



Seamless weather and climate insights

Historical observations and predictions, from minutes to decades

Seamless weather and climate insights

Seamless climate products

- Across time, space and severity
- Including national water information

Climate risk services to meet sector needs

- Underpinned by climate predictions, forecasts, event attribution, projections and observations

Understanding of exposure and vulnerability to high impact weather and climate

- Predicting the socioeconomic impact

Co-designing climate impact assessments and climate services

- Better aligned to user needs
- Enabling enhance response and adaptation

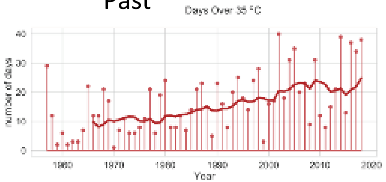
Increased knowledge of past and future climate variability and change

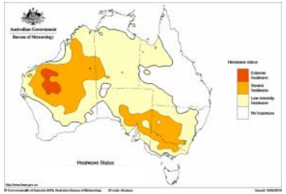
Improving our record of past climate

- Including through reanalyses

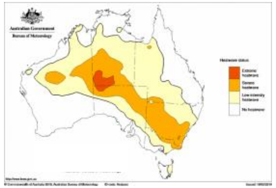
Seamless climate products across time, space, field and severity

Past



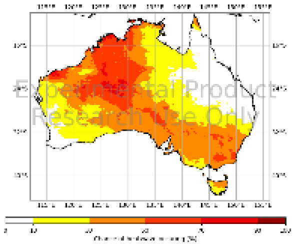


Recent heatwave observations

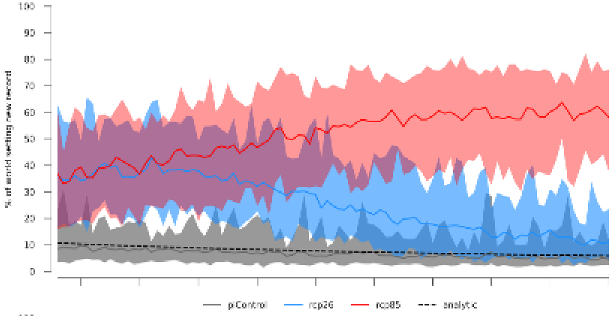


Heatwave forecast for the next few days

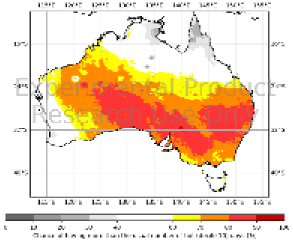
Forecast for the upcoming weeks: chance of a heatwave



Projected change in rate we will experience high temperatures in the future



Forecast for the upcoming season: chance of more hot days than usual

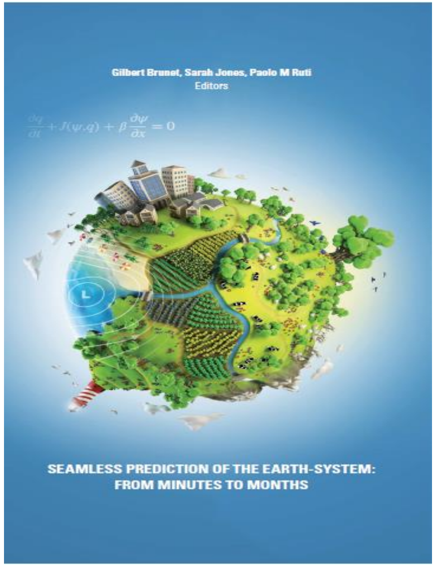


Historical Context | Operational | Tactical | Strategic

The way forward

- *Seamless Prediction of the Earth System: from minutes to months*
  Editors: (Brunet, Jones and Ruti)

  - ❑ Provide a reference of current state and future challenges of NWP Science in 25 chapters.
  - ❑ It is freely available on the World Meteorological Organization (WMO) website in English, French and Spanish.



- *The quiet revolution of numerical weather prediction*

  Bauer, Thorpe and Brunet
  (Nature, September 3, 2015)

Thank you very much! Q&As

A Personal Short List of Numerical Prediction Tipping Points

- Met Office weather forecast services using telegraphs established by FitzRoy 1861
- Toward global meteorological observatories and international data sharing with the foundation of the International Meteorolo gical Organization in Vienna 1873
- The birth of Numerical Weather Prediction with the works of Abbe (1901), Bjerknes (1904) and Richardson (1922)
- First computer NWP forecast on the ENIAC by Charney, Fjörtoft et von Neumann 1950
- Satellite based meteorological observations and telecommunications at the forefront of mankind technological innovations sin ce the launch of the first weather satellite TIROS-1 1960
- World Weather Watch (WWW) with its three main components (GOS, GTS, GDPS) established 1962
- Atmospheric predictability theory paved the way to numerical ensemble prediction in the 1980-90's initiated by Lorenz semin al work on chaos 1963
- Launched of the Global Atmospheric Research Program (GARP) lead by Charney 1969
- Global NWP innovations since the first global NWP simulation by Robert 1969
- Emergence of global atmosphere-ocean circulation models for climate research and forecasting 70-90's
- Federating global NWP R&D effort in Europe with the foundation of the ECMWF 1975
- Groundbreaking numerical prediction advances in the use of multiple sources of Earth system observations with the introducti on at ECMWF of four-dimension data assimilation 1997
- Earth Simulator, Japan: landmark supercomputer investment for climate, weather and geophysical research 2002
- A great step forward for weather and climate Earth-system forecast with 3000 ARGO oceanic floats in global operation 2007

Thank you very much!

Q&As

More at the BoM Annual R&D workshop

- 23-26 November
- Day 1, 2, 3 and 4 aligned with the four R&D objectives.