Meteorological Service Singapore
Centre for Climate Research Singapore

The Critical Role Of Supercomputing in Weather and Climate Science

Prof Dale Barker

Director, CCRS

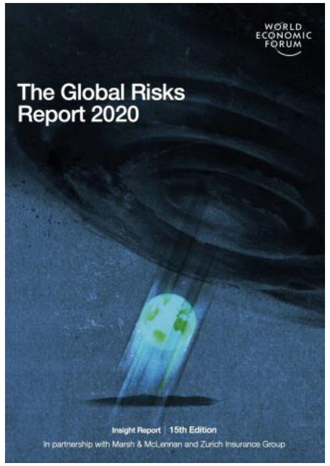
NSCC Webinar

1 October 2020

Overview

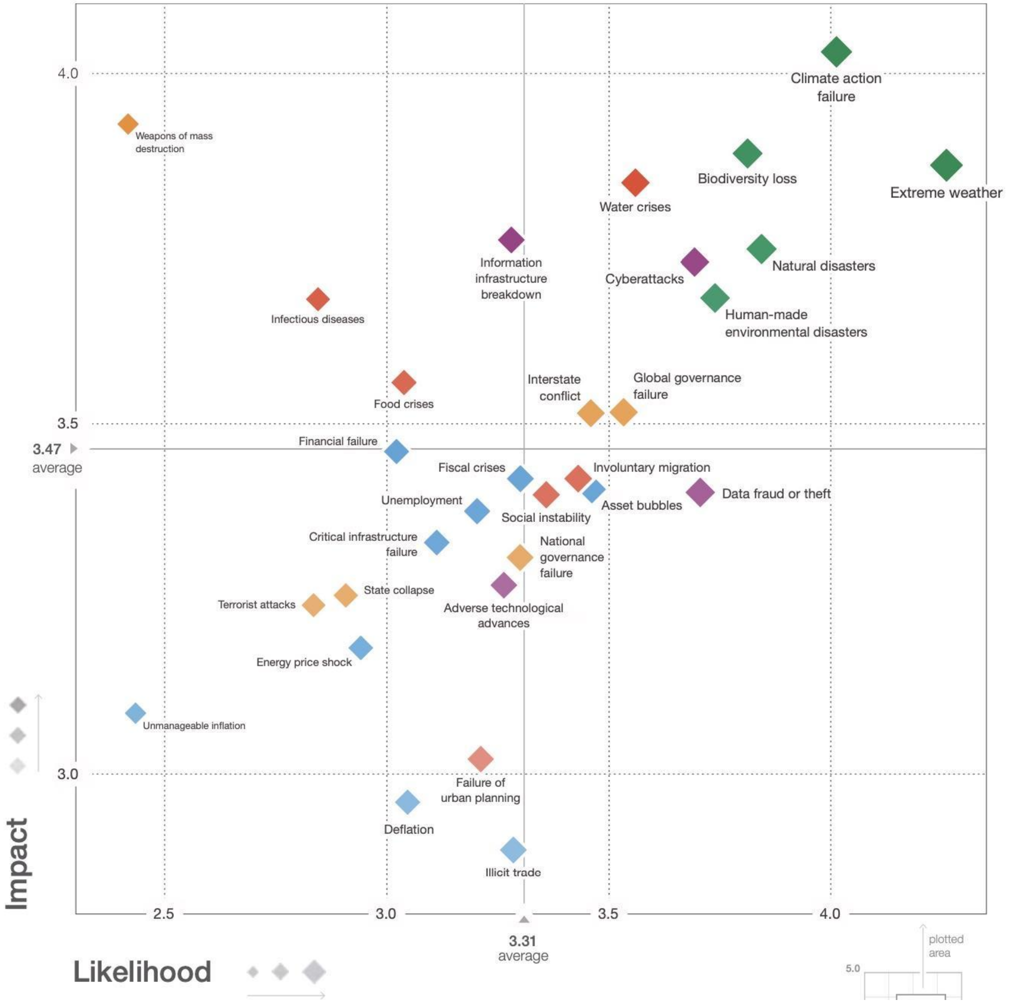
- The Climate Challenge
- Brief History of Supercomputing in Weather/Climate Science
- Climate System Complexity
- CCRS and Supercomputing
- Future Challenges

The Climate Challenge

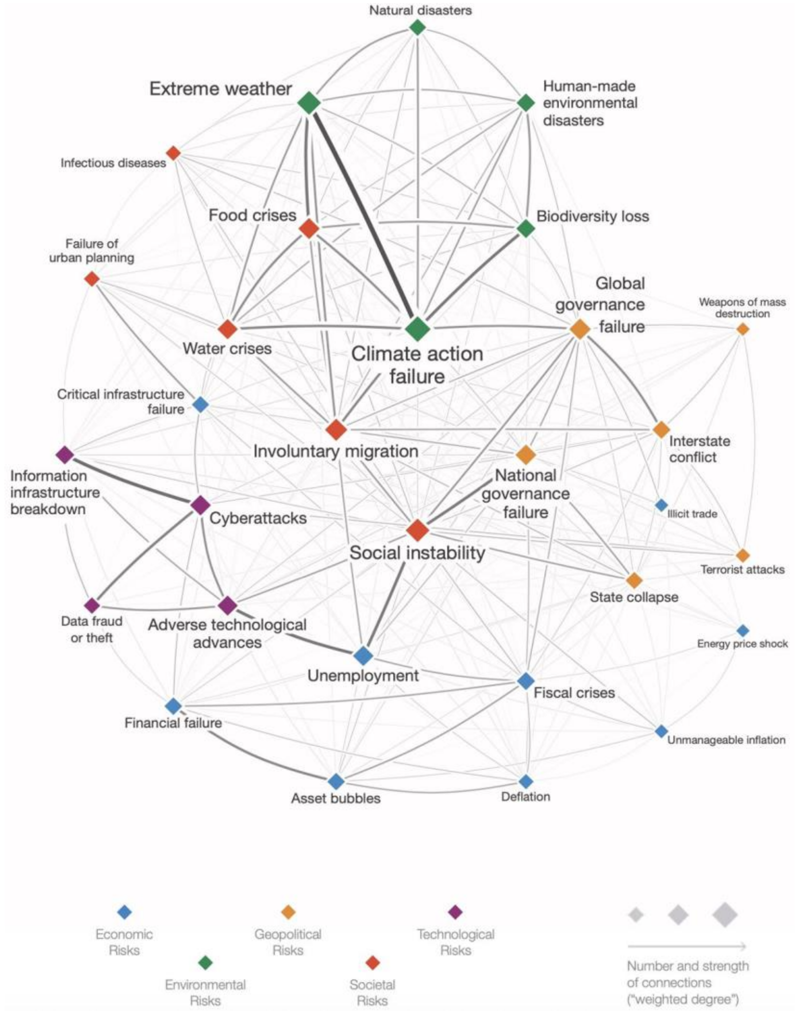


World Economic Forum - Global Risks

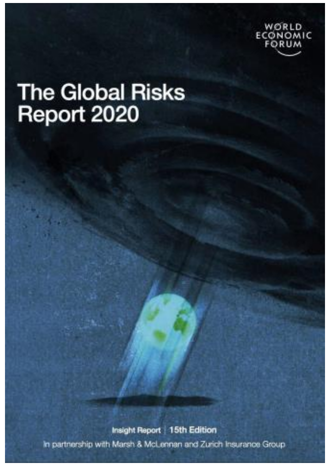
Top Risks 2020



Global Risk Interconnection



http://www3.weforum.org/docs/WEF_Global_Risk_Report_2020.pdf



World Economic Forum - Evolving Top Risks

Figure I: The Evolving Risks Landscape, 2007–2020

Top 5 Global Risks in Terms of Likelihood

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1st	Infrastructure breakdown	Blow up in asset prices	Asset price collapse	Asset price collapse	Storms and cyclones	Income disparity	Income disparity	Income disparity	Interstate conflict	Involuntary migration	Extreme weather	Extreme weather	Extreme weather	Extreme weather
2nd	Chronic diseases	Middle East instability	China economic slowdown	China economic slowdown	Flooding	Fiscal imbalances	Fiscal imbalances	Extreme weather	Extreme weather	Extreme weather	Involuntary migration	Natural disasters	Climate action failure	Climate action failure
3rd	Oil price shock	Failed and failing states	Chronic diseases	Chronic disease	Corruption	Greenhouse gas emissions	Greenhouse gas emissions	Unemployment	Failure of national governance	Climate action failure	Natural disasters	Cyberattacks	Natural disasters	Natural disasters
4th	China hard landing	Oil price shock	Global governance gaps	Fiscal crises	Biodiversity loss	Cyberattacks	Water crises	Climate action failure	State collapse or crisis	Interstate conflict	Terrorist attacks	Data fraud or theft	Data fraud or theft	Biodiversity loss
5th	Blow up in asset prices	Chronic diseases	Deglobalization (emerging)	Global governance gaps	Climate change	Water crises	Population ageing	Cyberattacks	Unemployment	Natural catastrophes	Data fraud or theft	Climate action failure	Cyberattacks	Human-made environmental disasters

Top 5 Global Risks in Terms of Impact

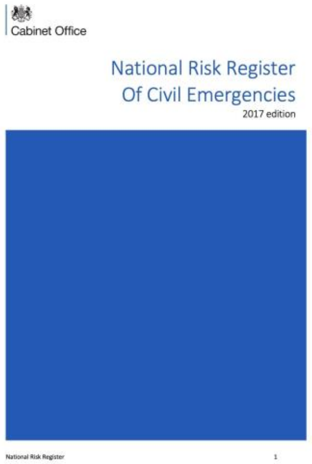
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1st	Blow up in asset prices	Blow up in asset prices	Asset price collapse	Asset price collapse	Fiscal crises	Financial failure	Financial failure	Fiscal crises	Water crises	Climate action failure	Weapons of mass destruction	Weapons of mass destruction	Weapons of mass destruction	Climate action failure
2nd	Deglobalization	Deglobalization (developed)	Deglobalization (developed)	Deglobalization (developed)	Climate change	Water crises	Water crises	Climate action failure	Infectious diseases	Weapons of mass destruction	Extreme weather	Extreme weather	Climate action failure	Weapons of mass destruction
3rd	Interstate and civil wars	China hard landing	Oil and gas price spike	Oil price spikes	Geopolitical conflict	Food crises	Fiscal imbalances	Water crises	Weapons of mass destruction	Water crises	Water crises	Natural disasters	Extreme weather	Biodiversity loss
4th	Pandemics	Oil price shock	Chronic diseases	Chronic disease	Asset price collapse	Fiscal imbalances	Weapons of mass destruction	Unemployment	Interstate conflict	Involuntary migration	Natural disasters	Climate action failure	Water crises	Extreme weather
5th	Oil price shock	Pandemics	Fiscal crises	Fiscal crises	Energy price volatility	Energy price volatility	Climate action failure	Infrastructure breakdown	Climate action failure	Energy price shock	Climate action failure	Water crises	Natural disasters	Water crises

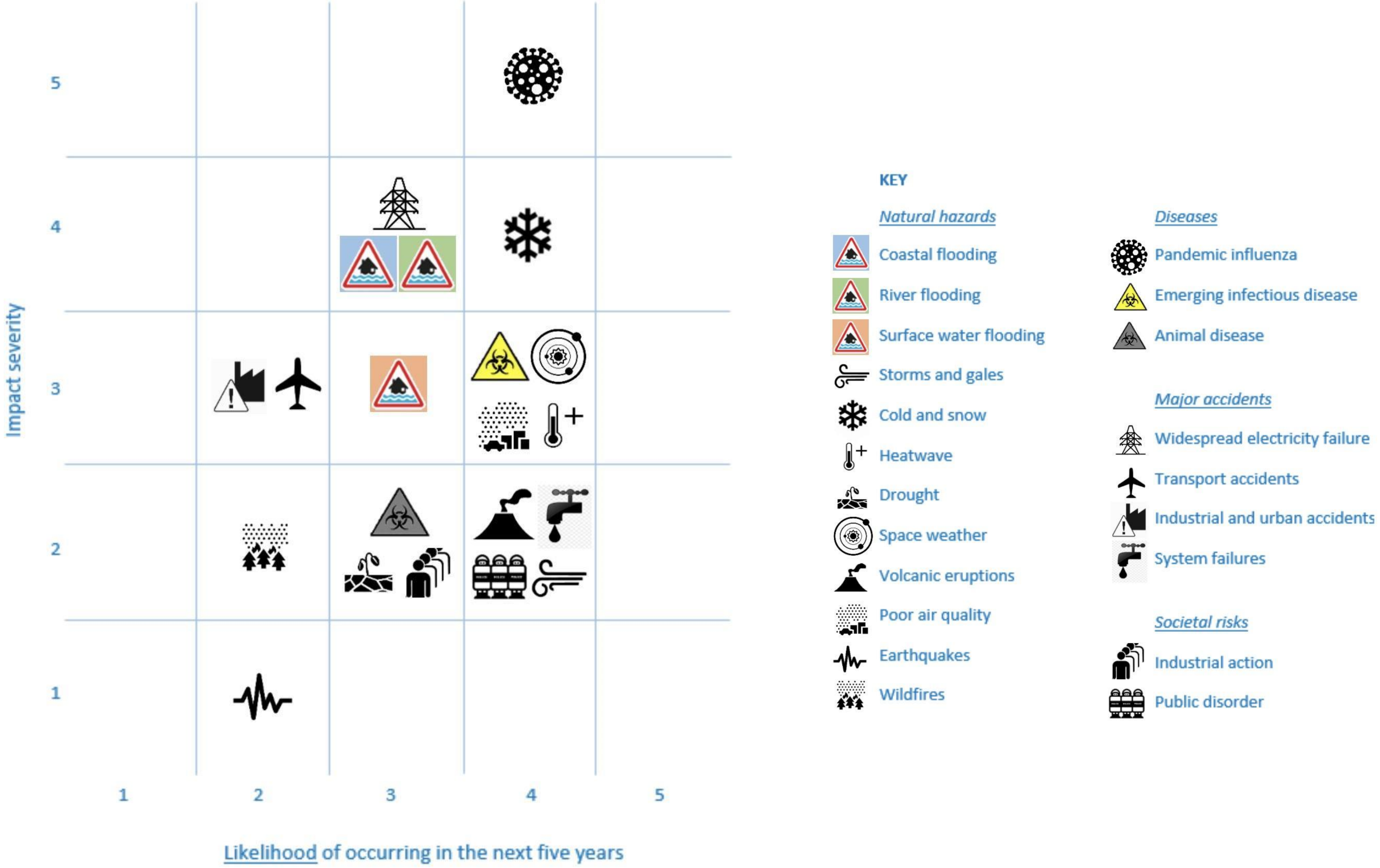
Economic Environmental Geopolitical Societal Technological

Source: World Economic Forum 2007-2020, *Global Risks Reports*.
Note: Global risks may not be strictly comparable across years, as definitions and the set of global risks have evolved with new issues emerging on the 10-year horizon. For example, cyberattacks, income disparity and unemployment entered the set of global risks in 2012. Some global risks have been reclassified: water crises and income disparity were recategorized as societal risks in the 2015 and 2014 *Global Risks Reports*, respectively.

http://www3.weforum.org/docs/WEF_Global_Risk_Report_2020.pdf

UK National Risk Register (2017)

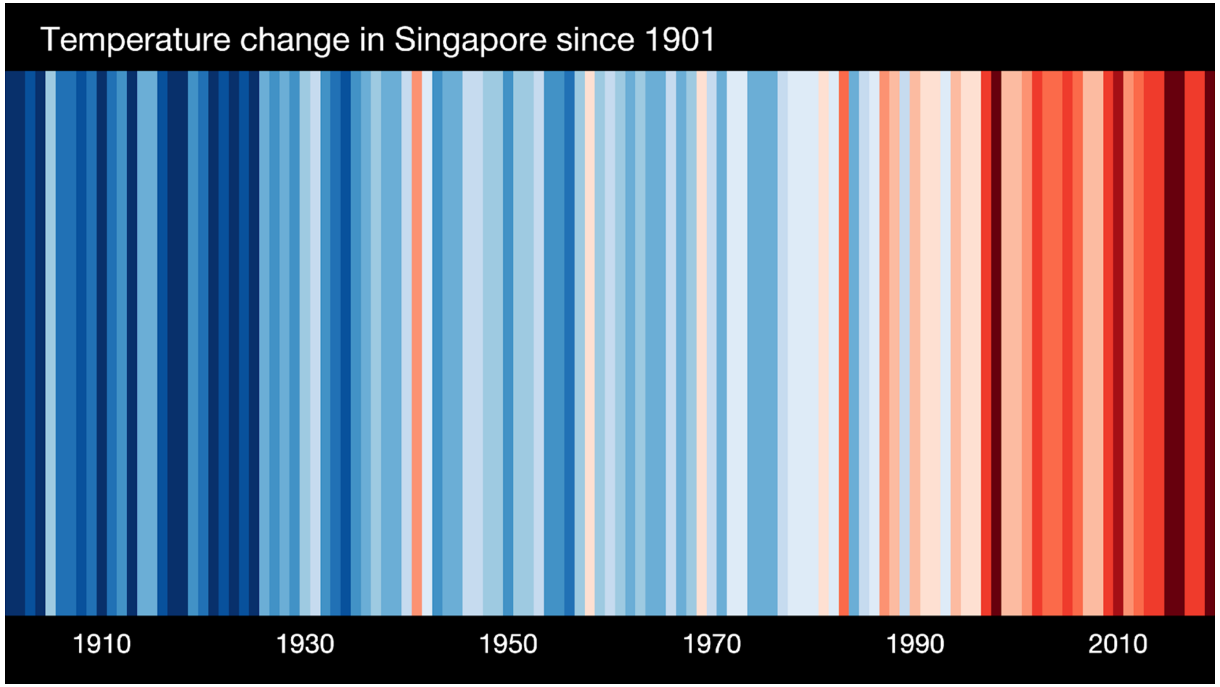




https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/644968/UK_National_Risk_Register_2017.pdf

The Climate Challenge For Singapore

"Warming Stripes" for Singapore

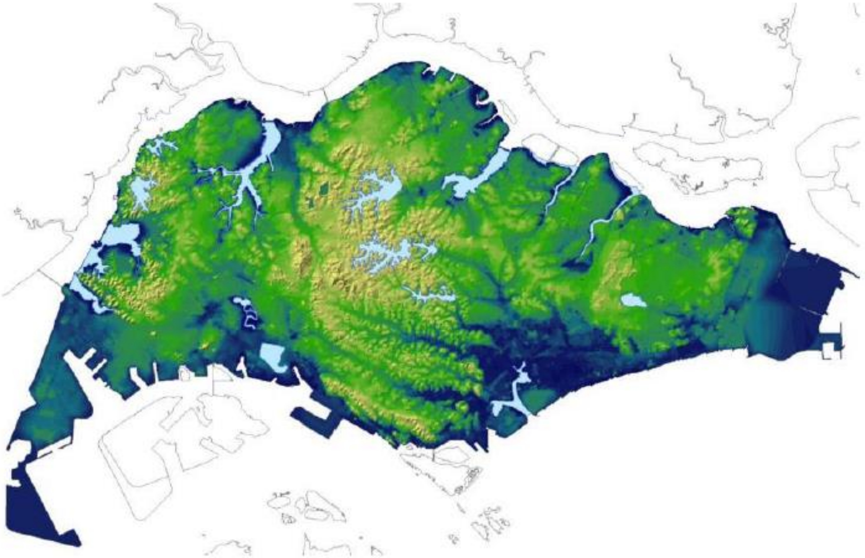


Source: Ed Hawkins

Singapore's vulnerability

- Surrounded by the sea with tidal range of about 3m
- Low-lying – Over 30% of Singapore's land area is < 5m, with some < 2 m from mean sea level [1]
- Singapore is already at risk today

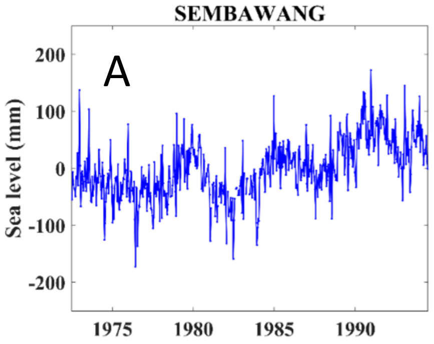
Mean sea level determined at a tidal gauge located at Victoria Dock (1935 – 1937)

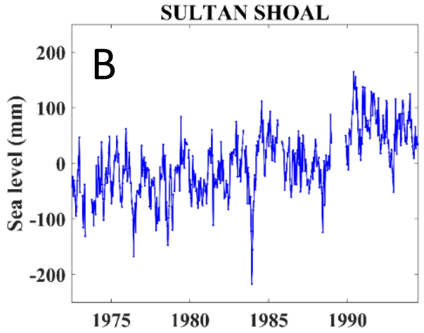


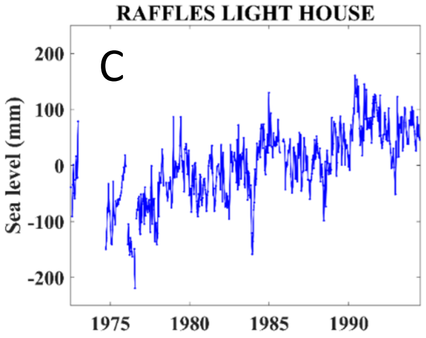
Source: PUB

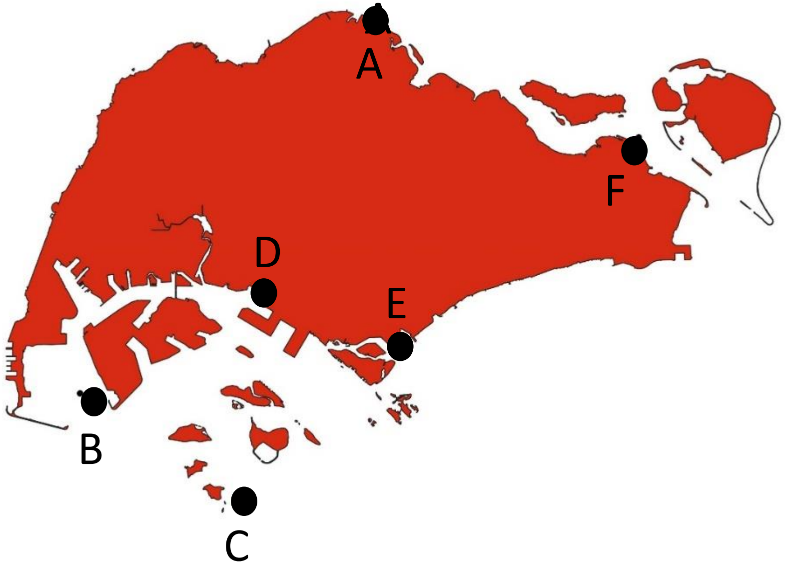
Climate Change Is Already A Challenge For Singapore…

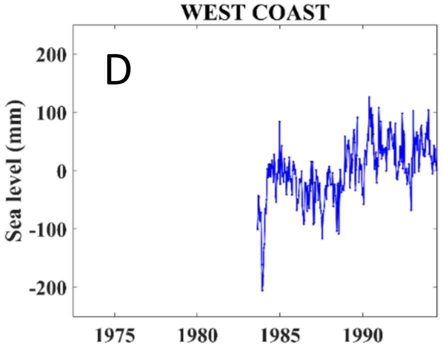
Observed SLR in Singapore and Global

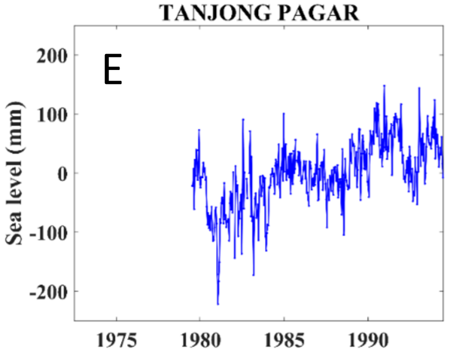


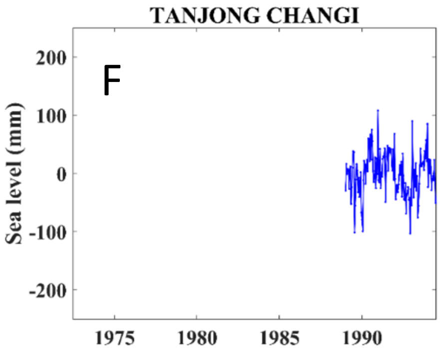




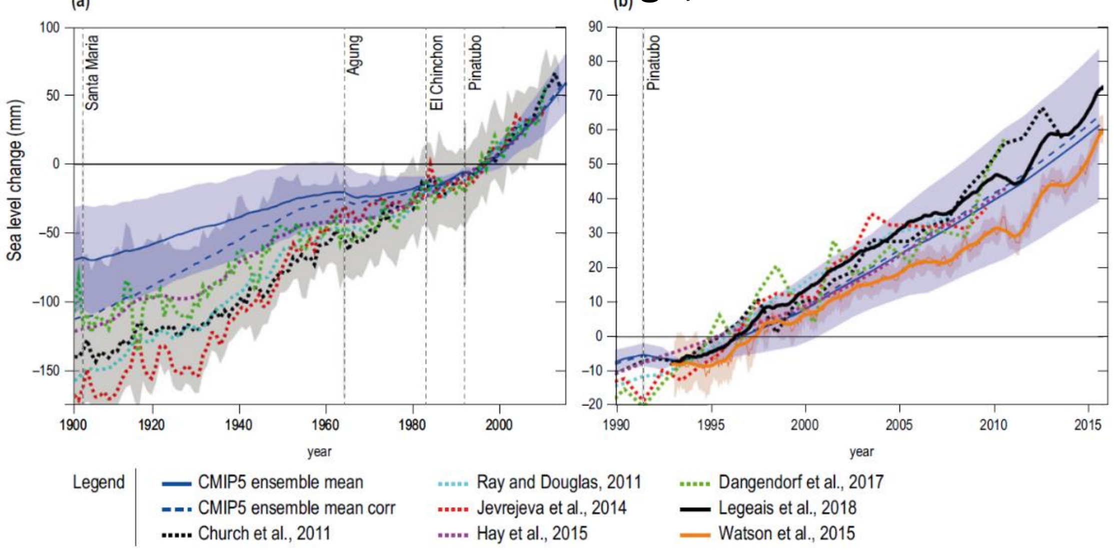








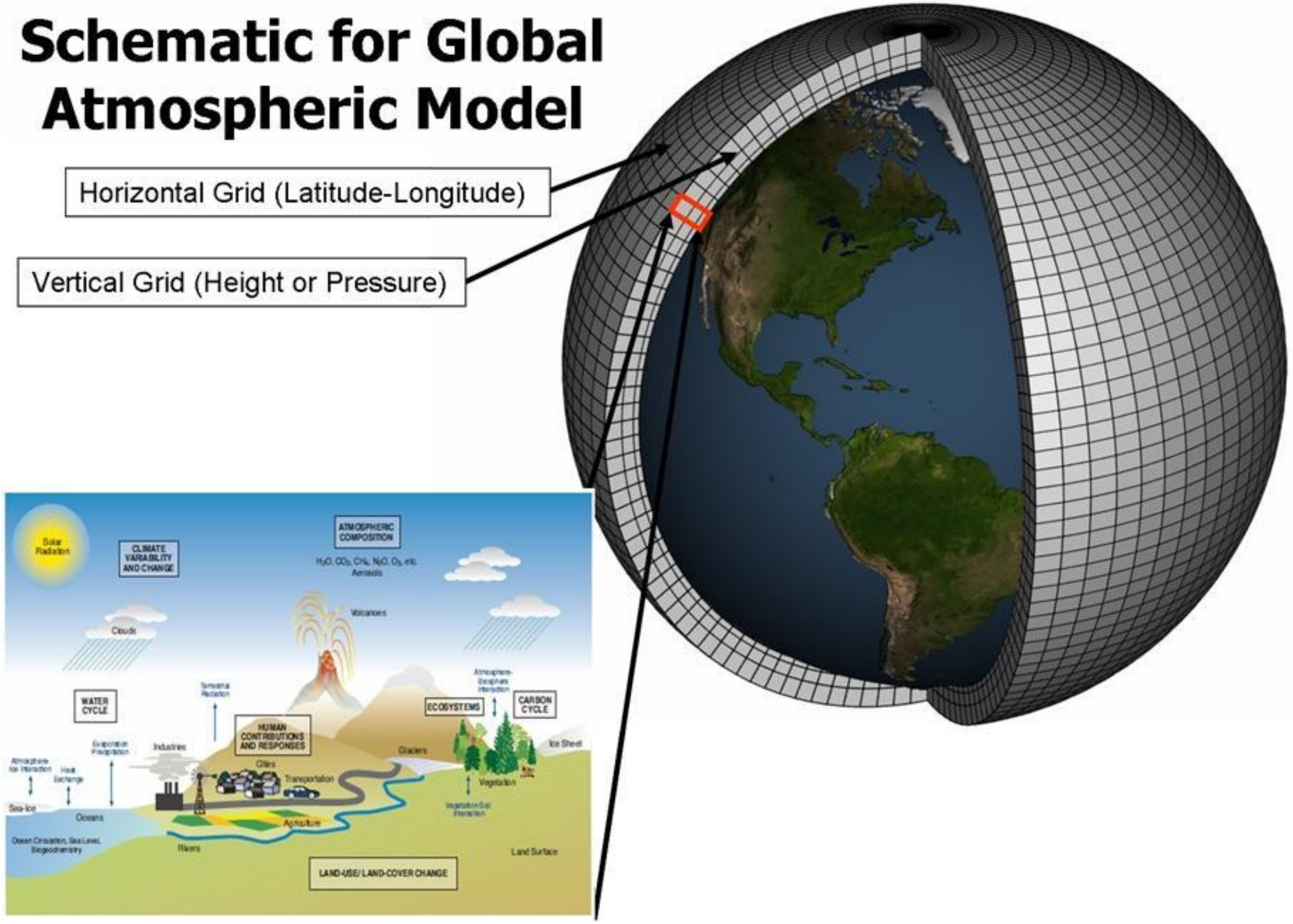
Global mean sea level change, 1900 and 1993



Source: Annual Climate Assessment Report (ACAR) 2019

Brief History of Supercomputing in Weather/Climate Science

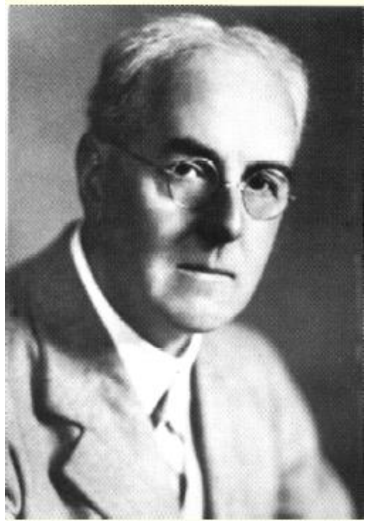
Climate And Numerical Weather Prediction (NWP) Models



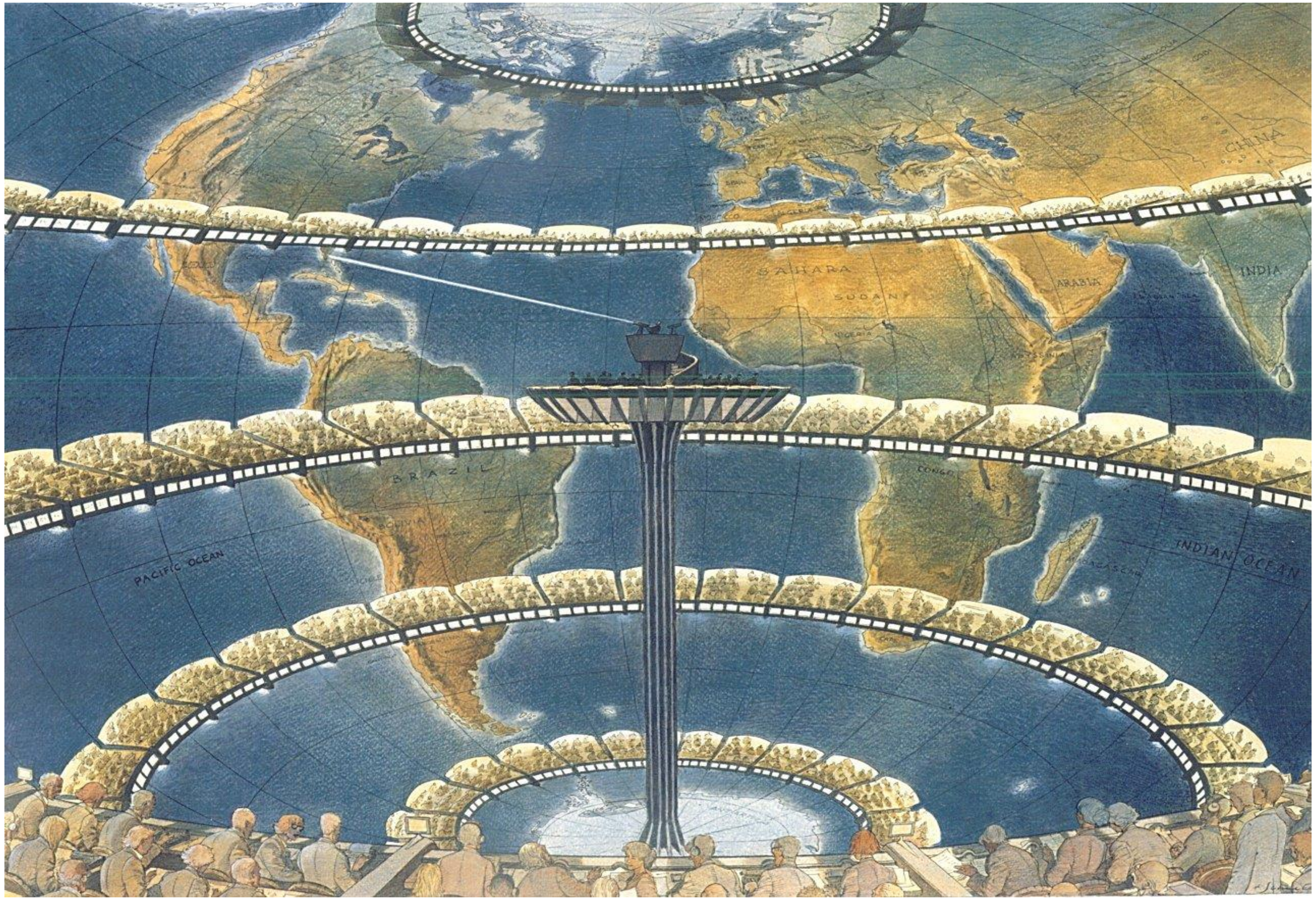
Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To "run" a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points. (https://en.wikipedia.org/wiki/Climate_model)

Weather models use systems of differential equations based on the laws of physics, which are in detail fluid motion, thermodynamics, radiative transfer, and chemistry, and use a coordinate system which divides the planet into a 3D grid. Winds, heat transfer, solar radiation, relative humidity, phase changes of water and surface hydrology are calculated within each grid cell, and the interactions with neighboring cells are used to calculate atmospheric properties in the future (https://en.wikipedia.org/wiki/Numerical_weather_prediction)

1920’s Vision Of Numerical Weather Prediction (NWP)



L. F. Richardson 1881 - 1953

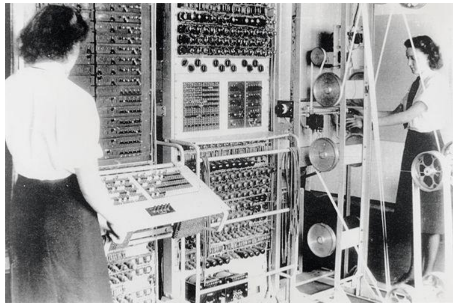


Royal Albert Hall, London

Weather Prediction By Numerical Processes : L. F. Richardson, 1922

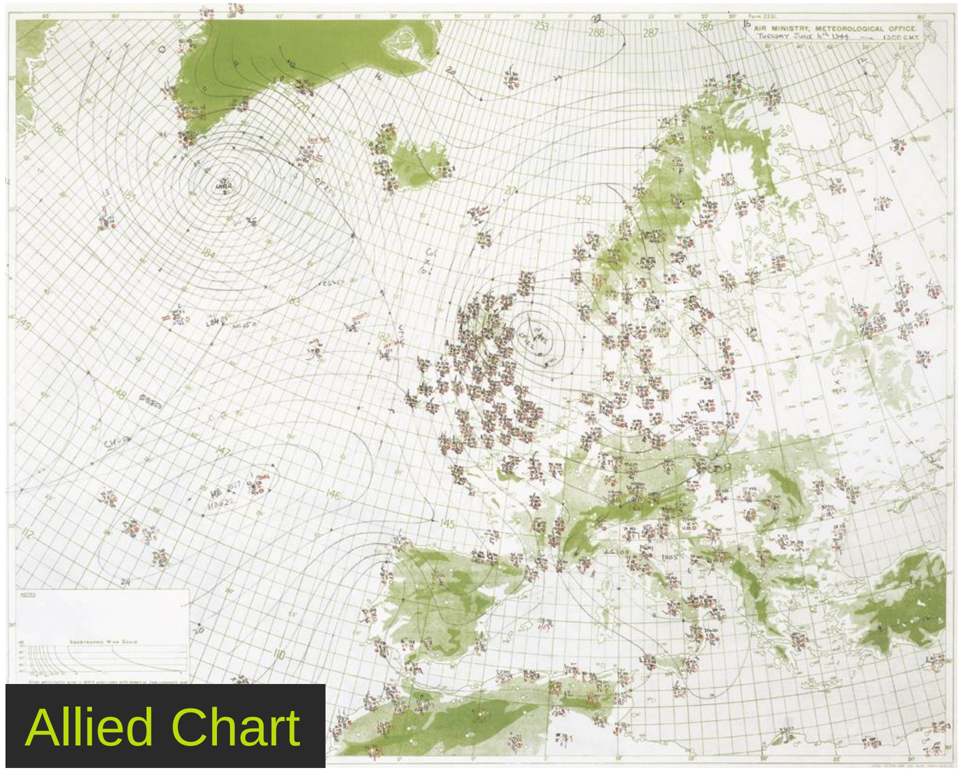
7 June 1944 - The Most Important Forecast in History?

'Enigma' Machine

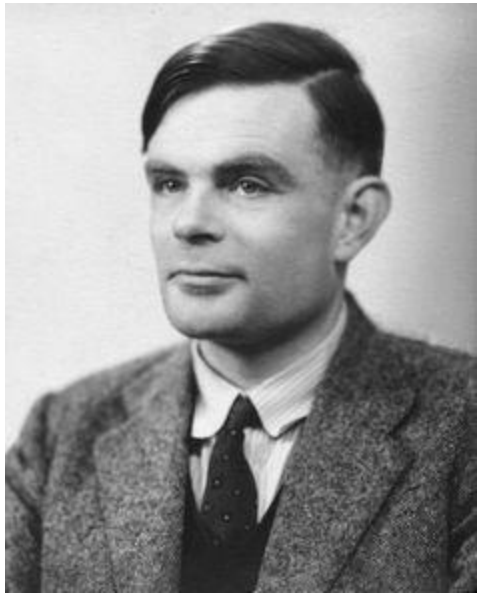


'Colossus' Computer

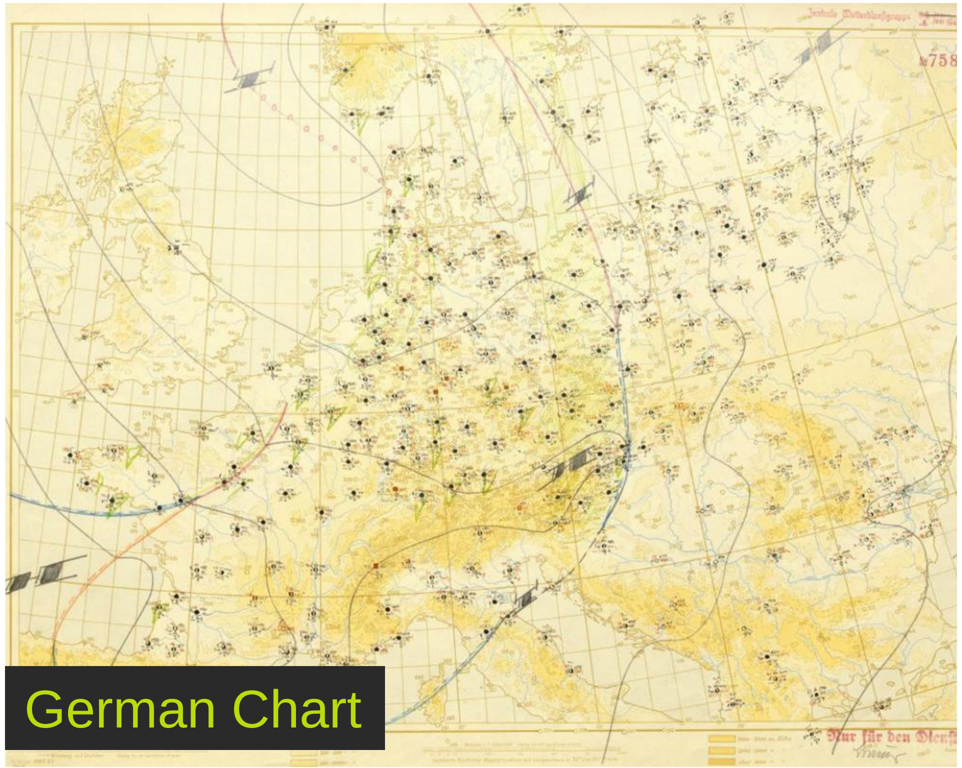
D-Day Landings



Allied Chart



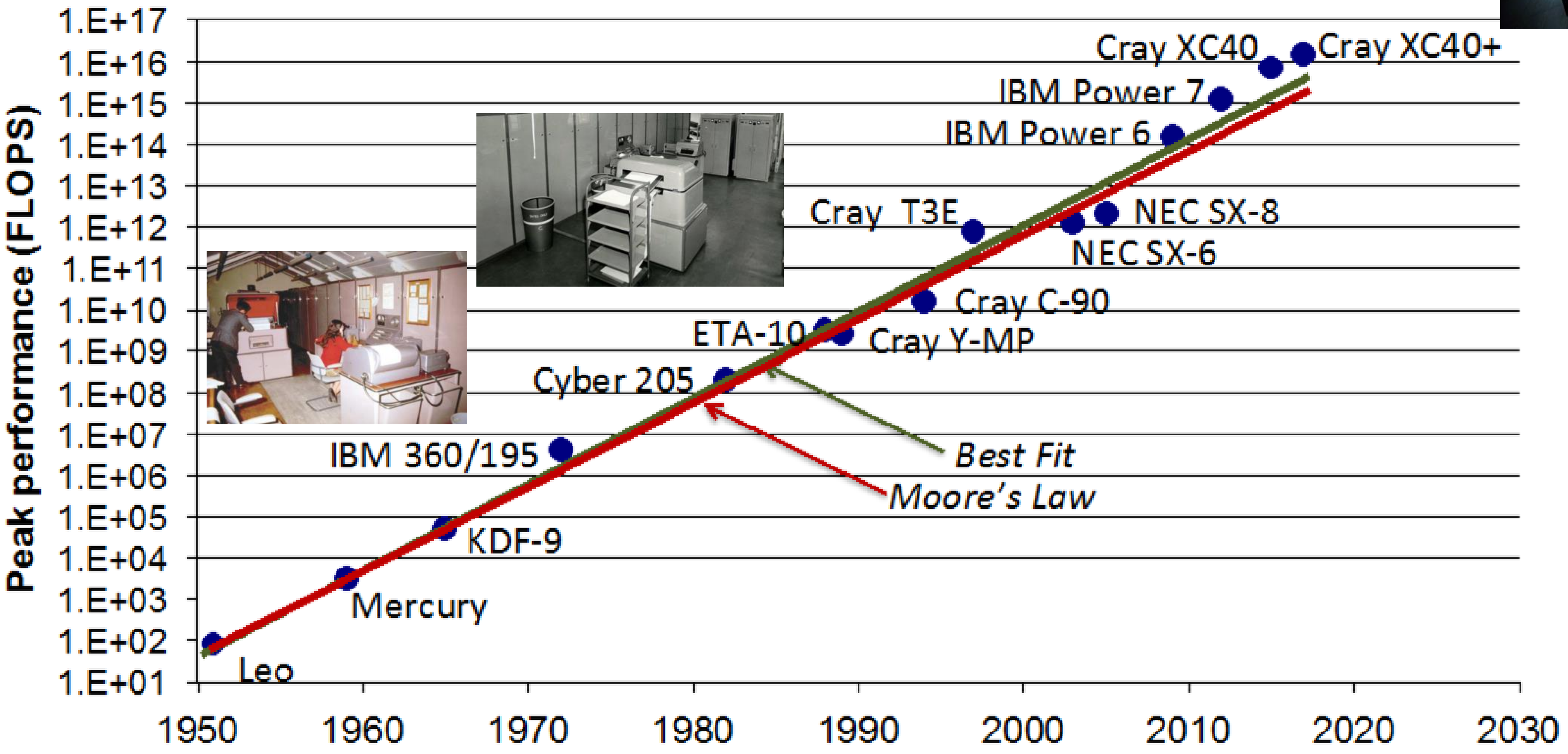
The Alan Turing Institute



German Chart

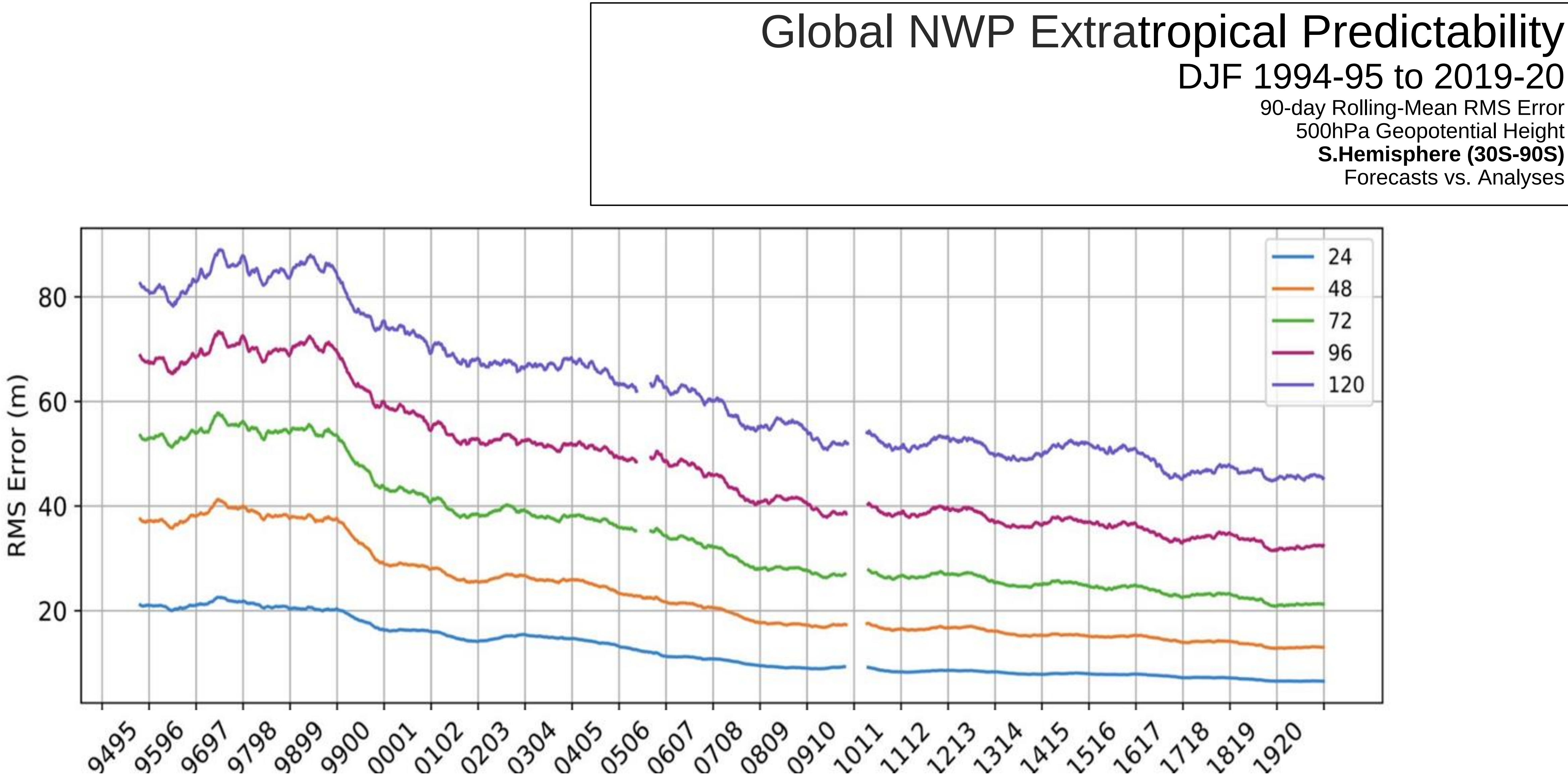
Met Office

~70 Years of Met Office Computers



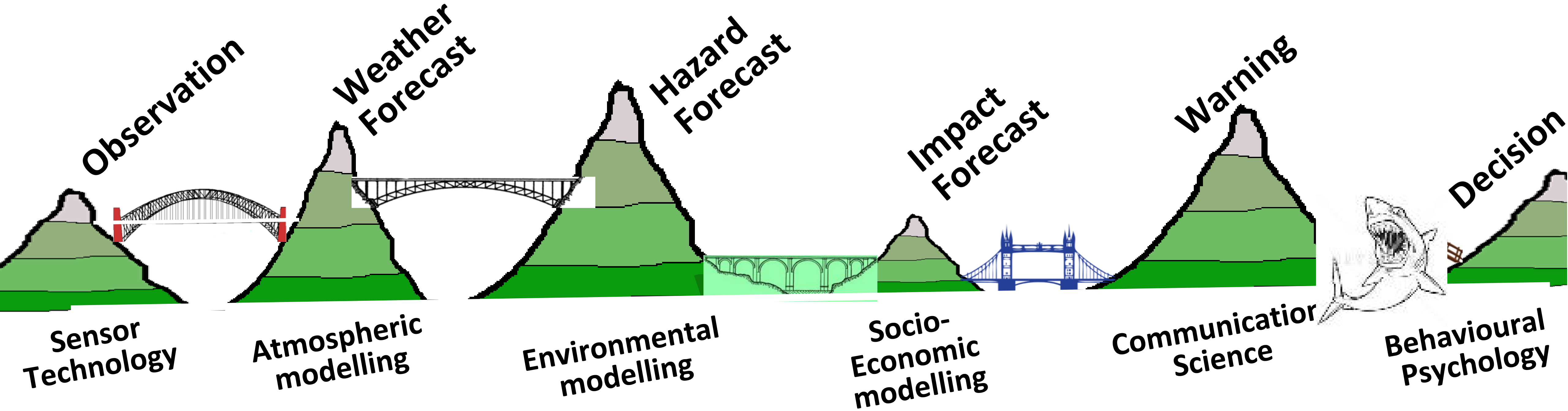
- Moore's Law: 18 month doubling time; Order of magnitude increase in power every decade
- 2015 Business Case Built on Projected 22:1 return on investment due to improved weather/climate services.

Global NWP Skill Improvements



'1 Day Decade Improvement In Global NWP Skill'

Weather/Climate Impacts: The Five Valleys Of Death



- Mountains represent expertise. Bridges represent communication. Value is lost in each valley.
- WMO HIWeather aims to address weak points in the chain so as to optimise the value of the warning to the decision maker

Prof. Brian Golding, Co-Chair WMO HIW Project

https://public.wmo.int/en/resources/bulletin/hiweather-10-year-research-project

Example Benefits Of Investment in HPC For Weather/Climate

- In 2014, UKG approved £97M for new HPC at Met Office HQ, Exeter.
- Business case: Set out socio-ecocomic benefits (SEBs) for different HPC investment options.
- Approach (Cambridge Uni): PAGE09 (Hope 2011).
- Option chosen has a 5-year benefit-cost ratio of 22:1.
- Conservative estimate: limited number of 6 weather/climate case studies:

HPC Estimates	Civil aviation (£m)	Renewable energy (£m)	Food supply (£m)	Flooding (£m)	Winter travel disruption (£m)	Climate change (£m)
	295	526	104	242	75	933


Science & Environment

Met Office forecasters set for 'billion pound' supercomputer

By David Shukman
Science editor

17 February 2020

Share

Storm Ciara and Storm Dennis have both caused widespread wind and flooding damage

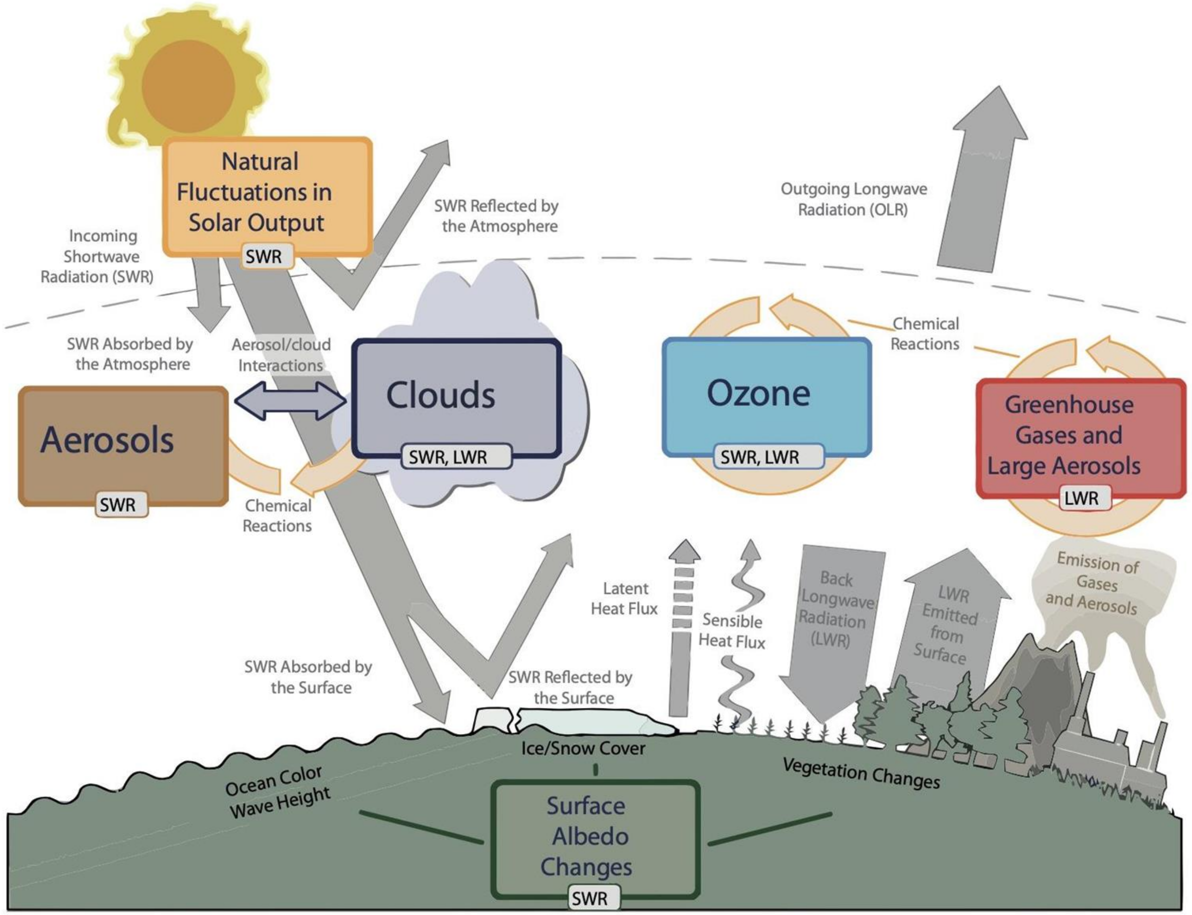
https://londoneconomics.co.uk/blog/publication/met-office-general-review-march-2016/

https://www.bbc.com/news/science-environment-51504002

Climate System Complexity

The Complexity Of The Climate System

Physical Drivers Of Climate Change



Increasing Complexity of Climate Models

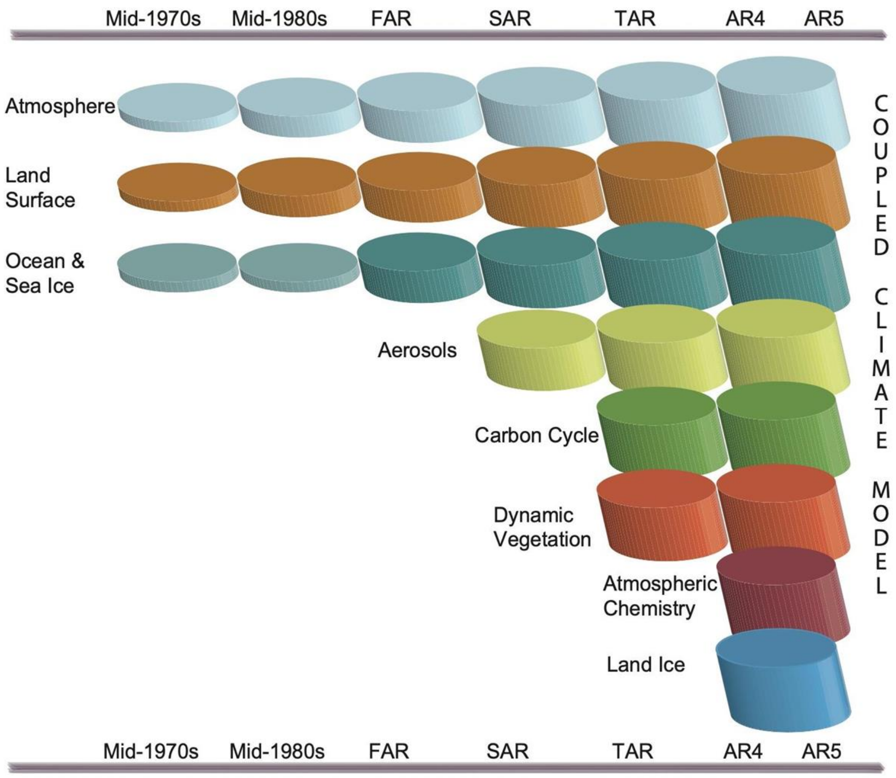
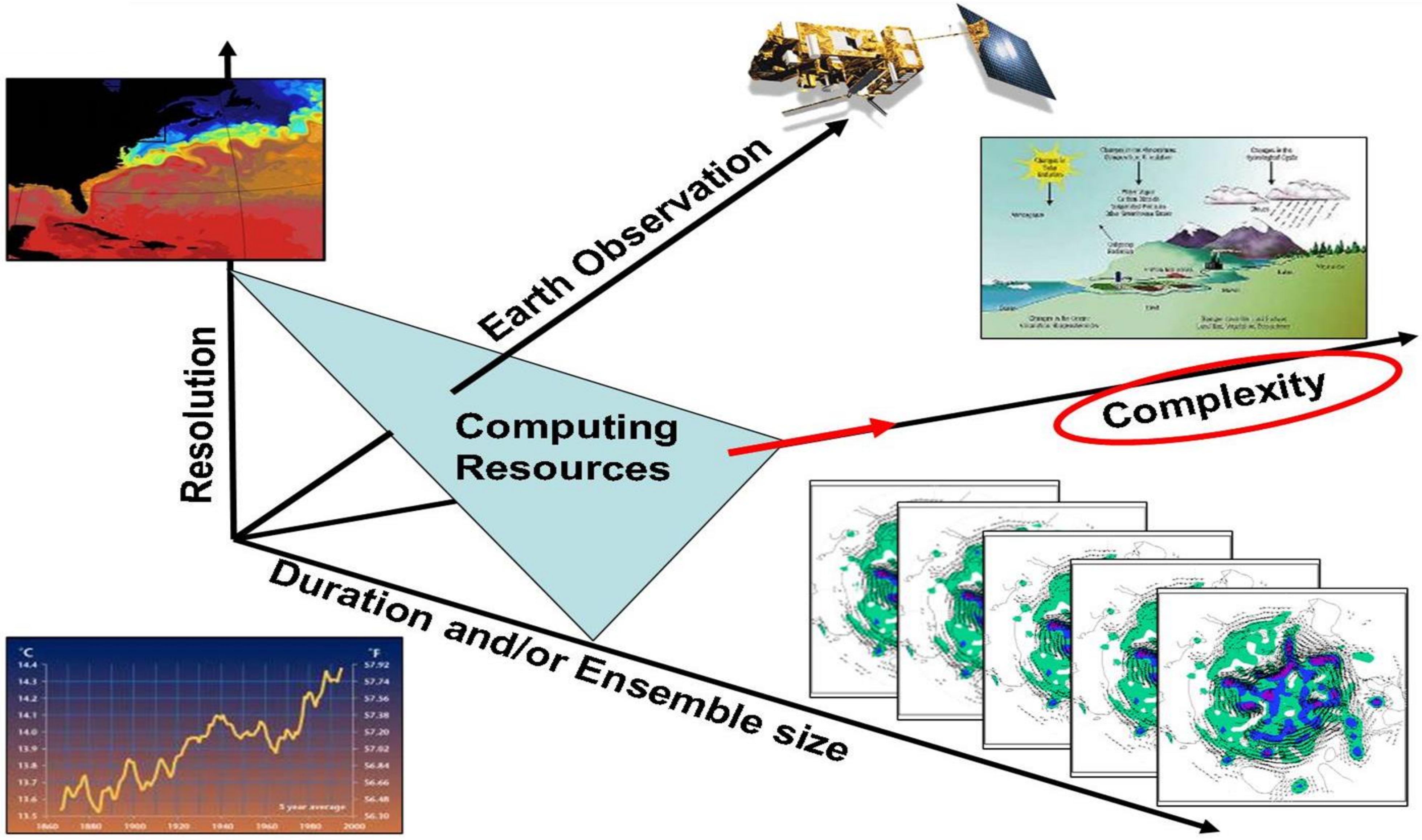


Figure 1.13 | The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resolution and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independent experiments can be considered as standard.

IPCC AR5, WG1 Report, 2013

https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

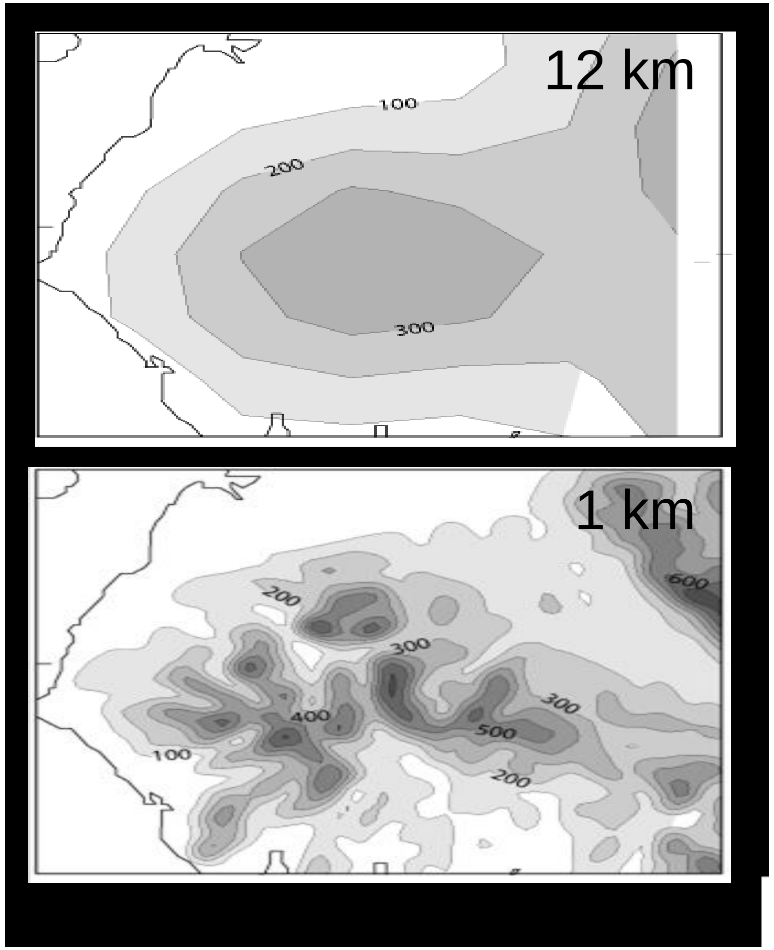
Multi-Dimensional Climate/Weather Model Complexity



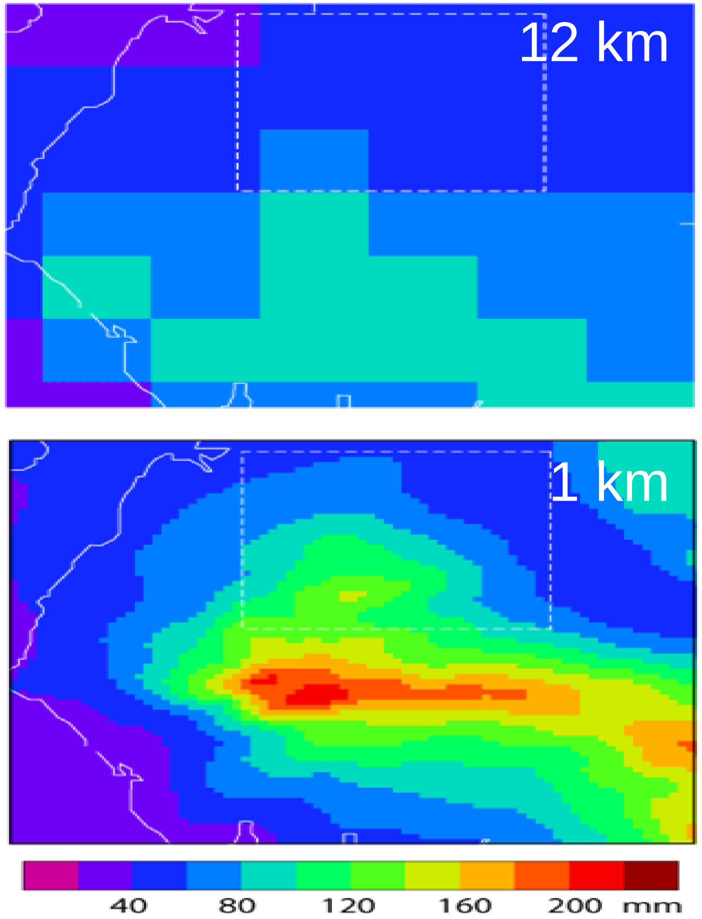
The Value Of High-Resolution

Storm Desmond (4 – 6 Dec 2015)

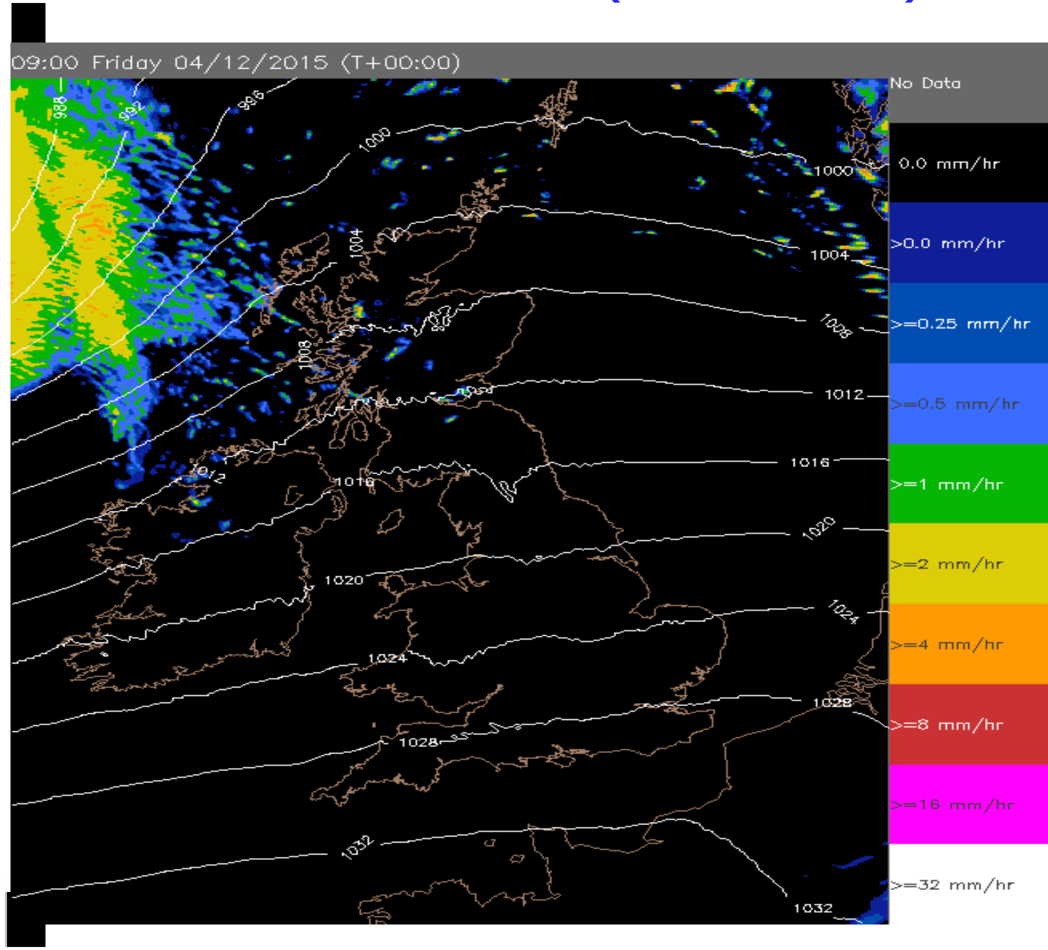
Topography



Rainfall



1.5km Forecast (09Z 4/12)

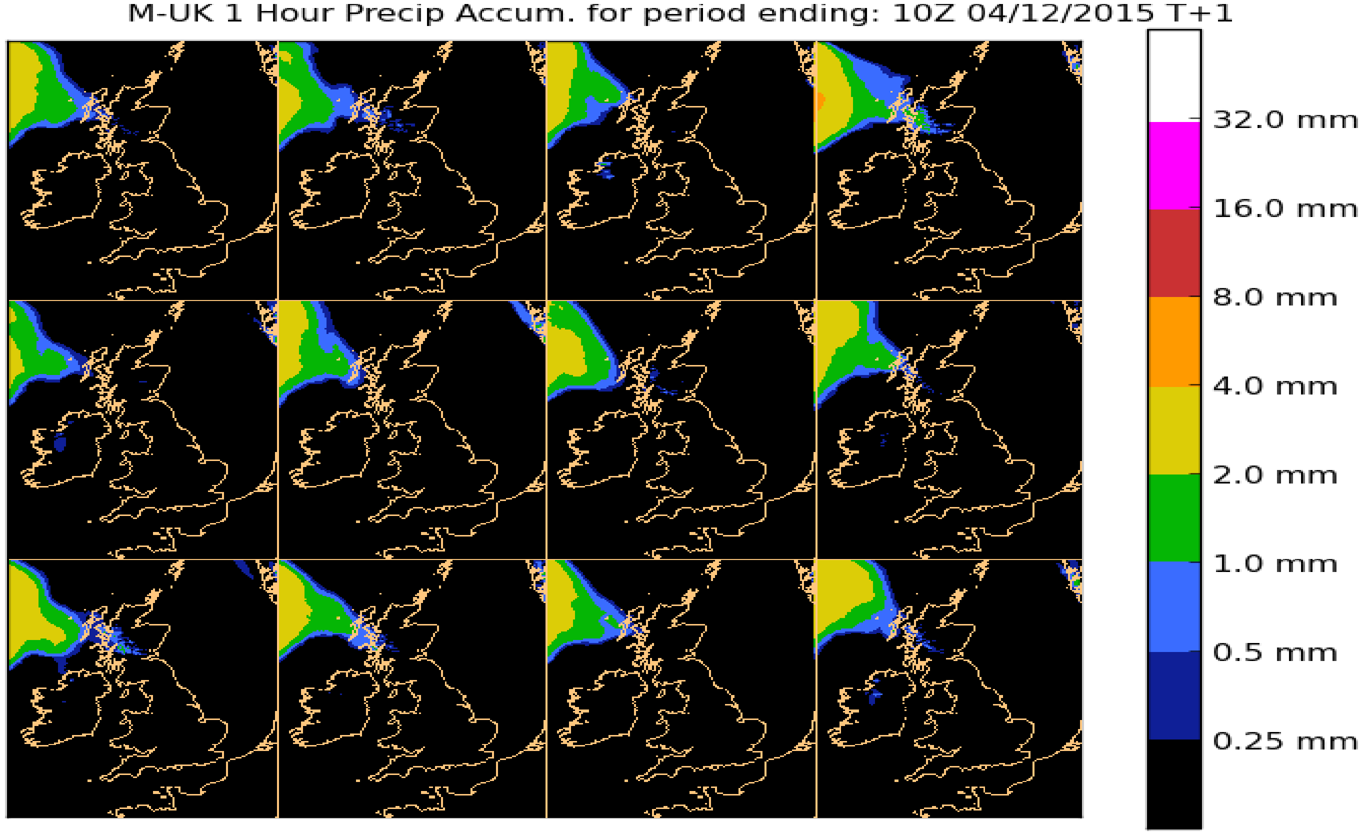


UK model rainfall accumulations up to 250mm; global all < 100mm.

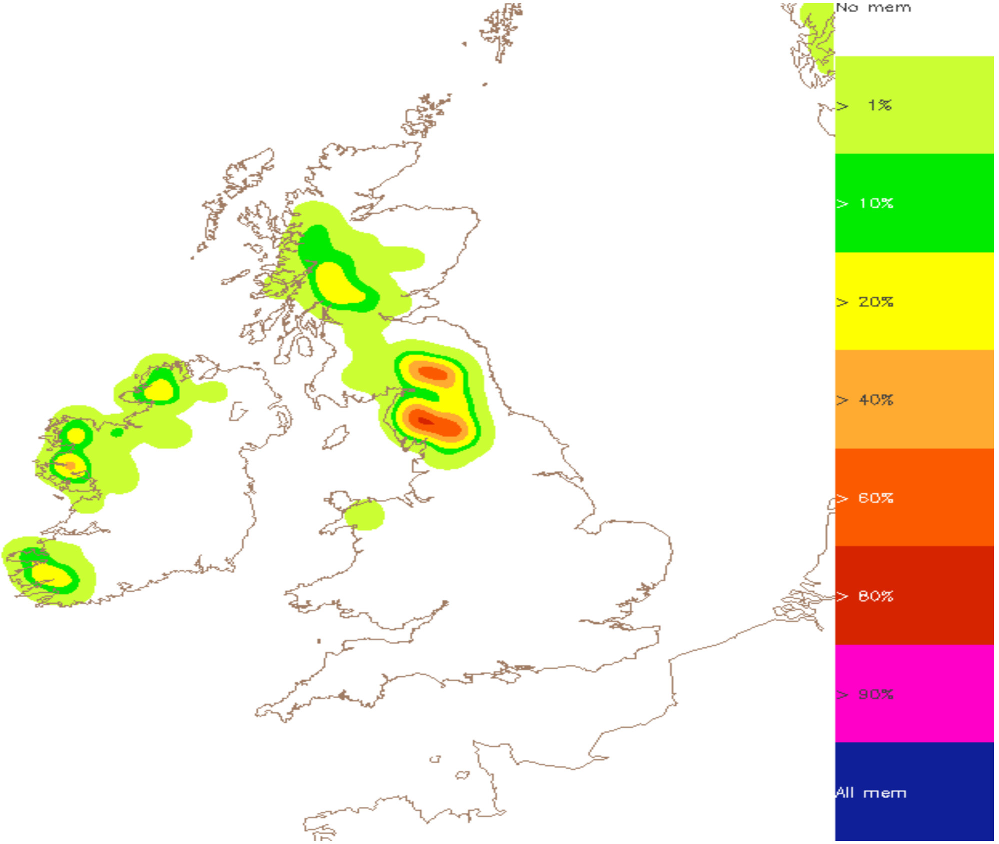
The Value Of Probabilistic Forecasting

Storm Desmond (4 – 6 Dec 2015)

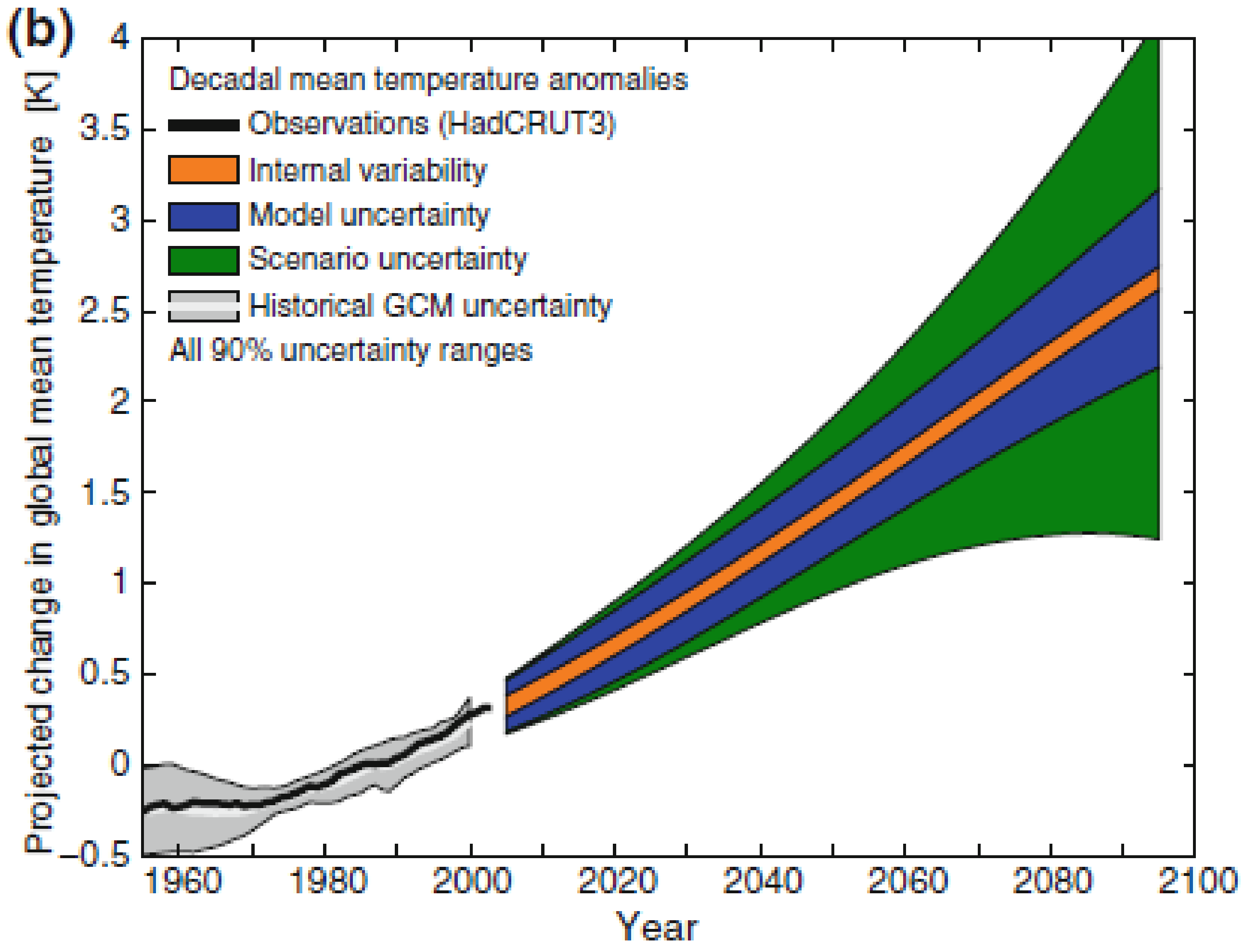
12 member 2.2km ‘Ensemble’



Probability 24hr rain > 100mm.
(2100 4 Dec - 2100 5th Dec)



Uncertainty In Climate Projections



The uncertainty of future climate change as simulated by CMIP5/6 models is mainly driven by three sources:

(1)scenario uncertainty;

(1)model uncertainty;

(1)internal variability

CCRS And Supercomputing

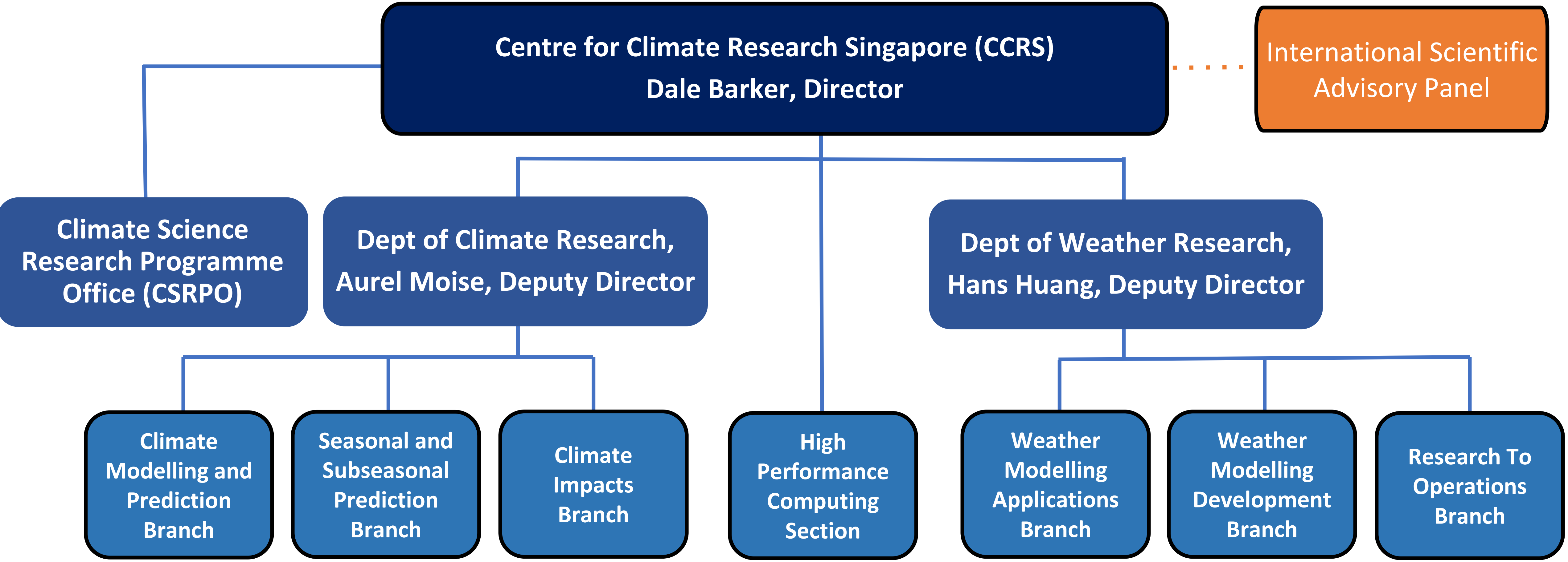
CCRS Mission and Vision

- 2013: CCRS established under MSS

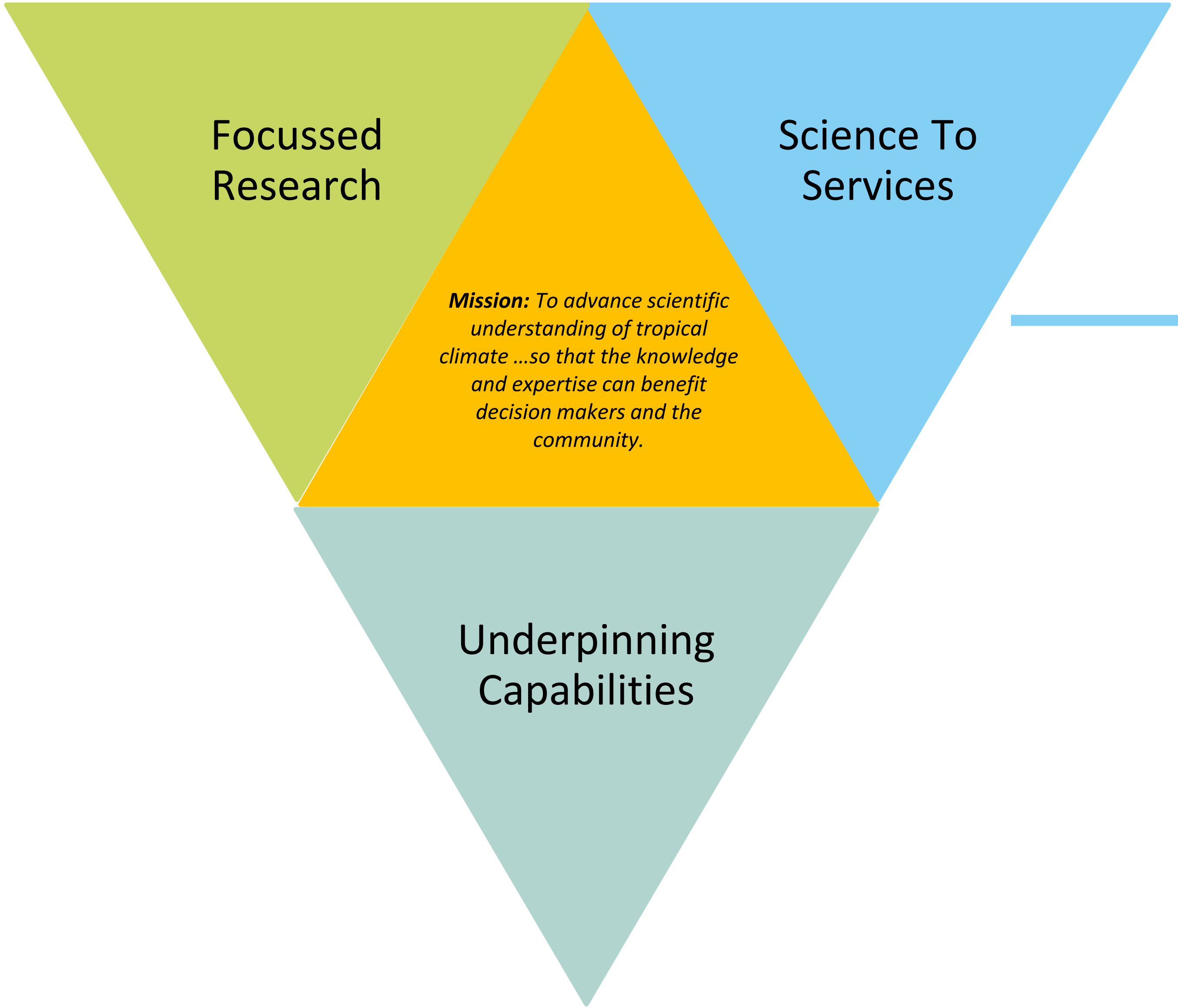
- **Mission:** To advance scientific understanding of tropical climate variability and change and its associated weather systems affecting Singapore and the wider Southeast Asia region, so that the knowledge and expertise can benefit decision makers and the community.

- **Vision:** To be a world leading centre in tropical climate and weather research focusing on the Southeast Asia region.

CCRS Structure



CCRS Strategy



Civil Aviation

Government Agencies (e.g. Water, Defence)

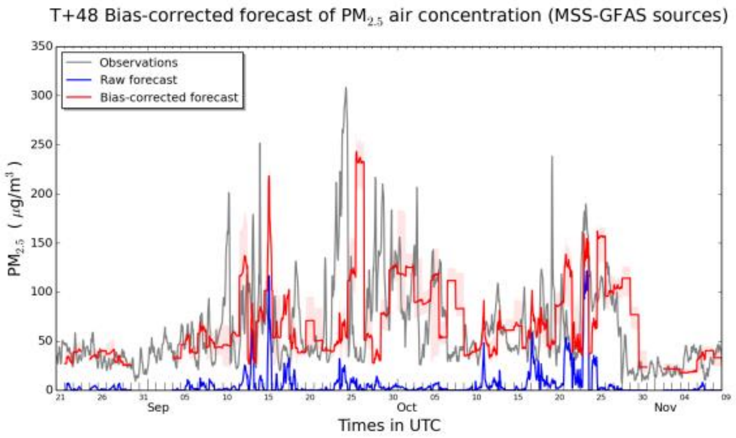
Public

Businesses (e.g. shipping, insurance, construction)

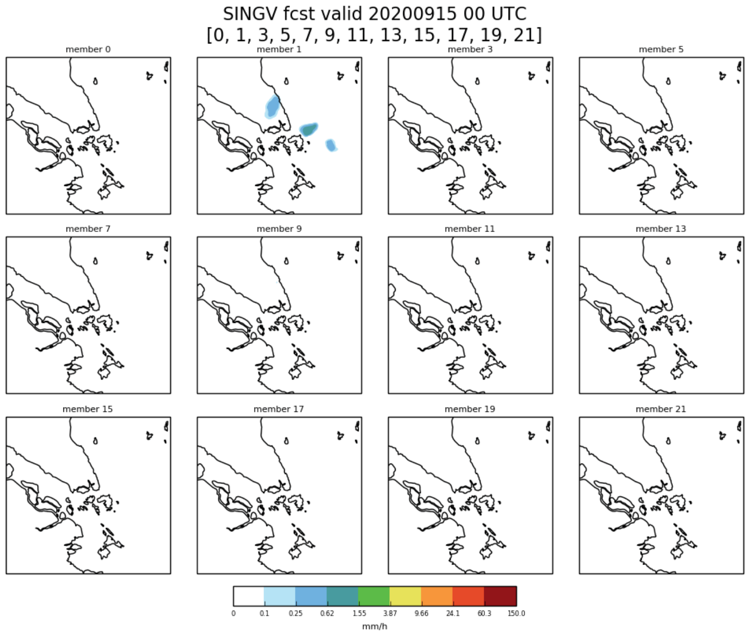
ASMC
ASEAN SPECIALISED METEOROLOGICAL CENTRE

Regional Entities

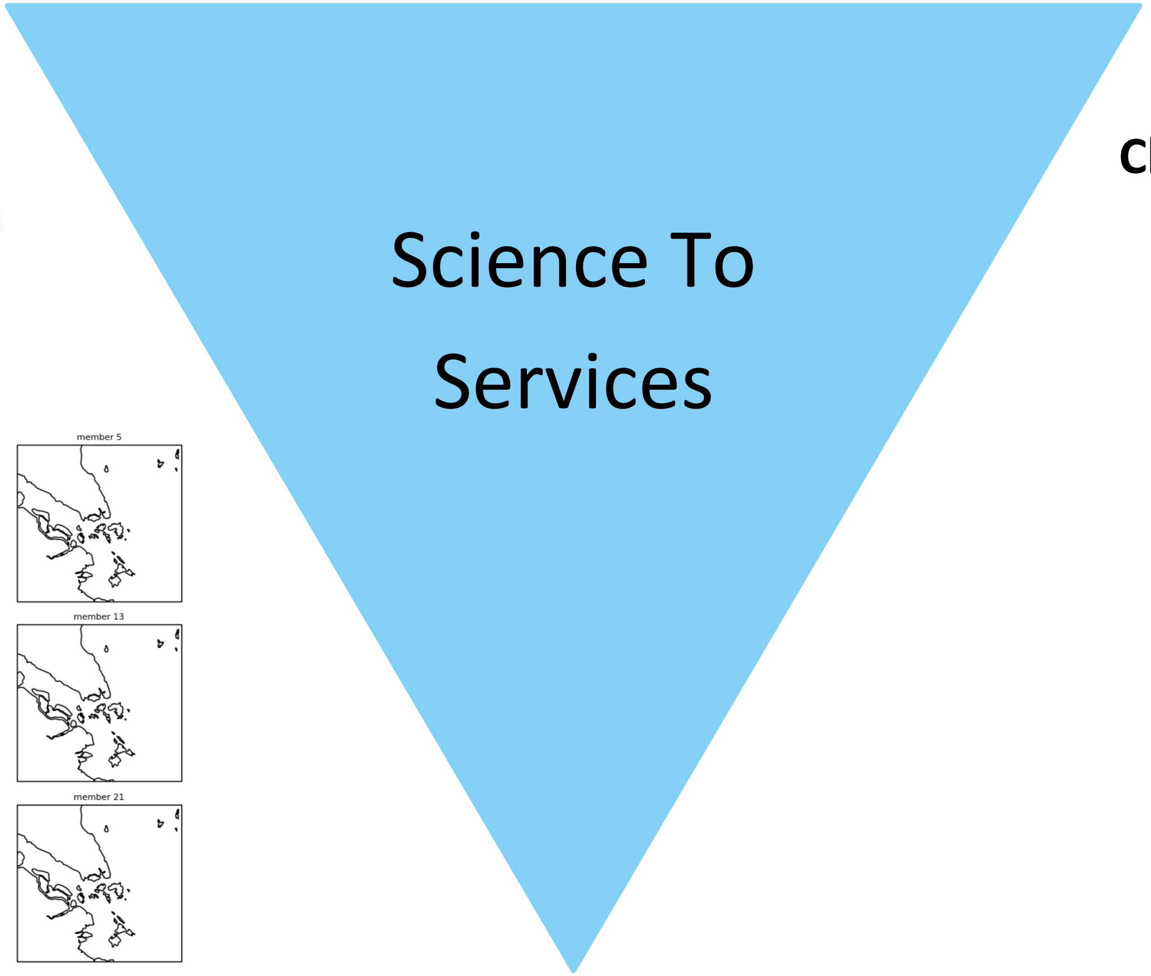
CCRS Strategy



Haze / Air Quality Prediction



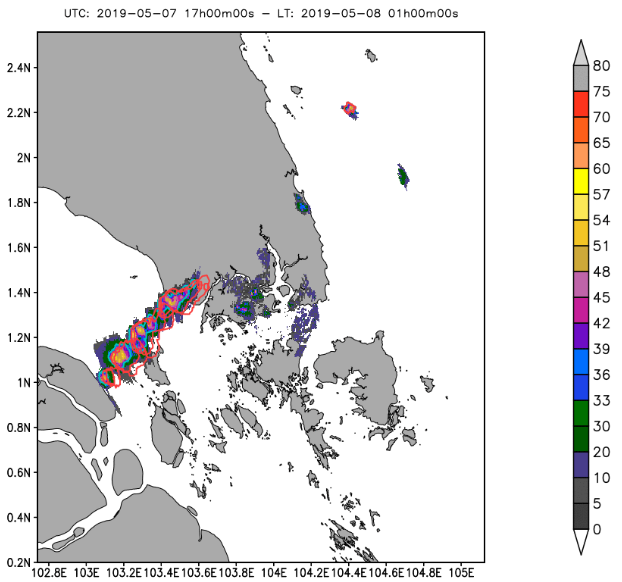
Operational 'SINGV' Weather Forecasting



Climate Change Policy Advice

Climate Impacts Modelling

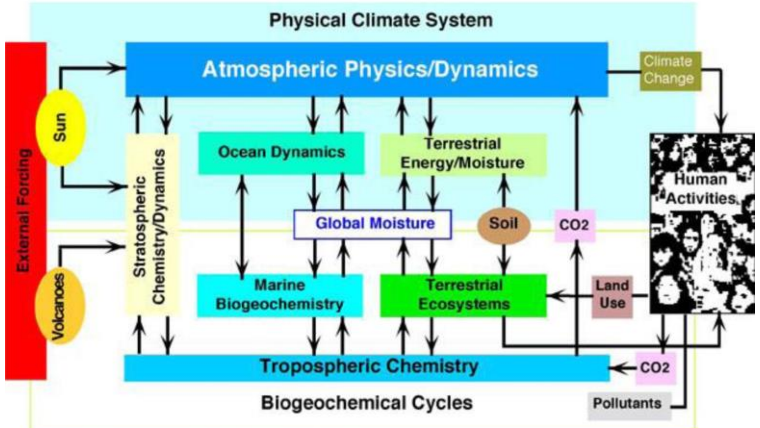
CCRS Strategy



Observations

Underpinning Capabilities

Supercomputing



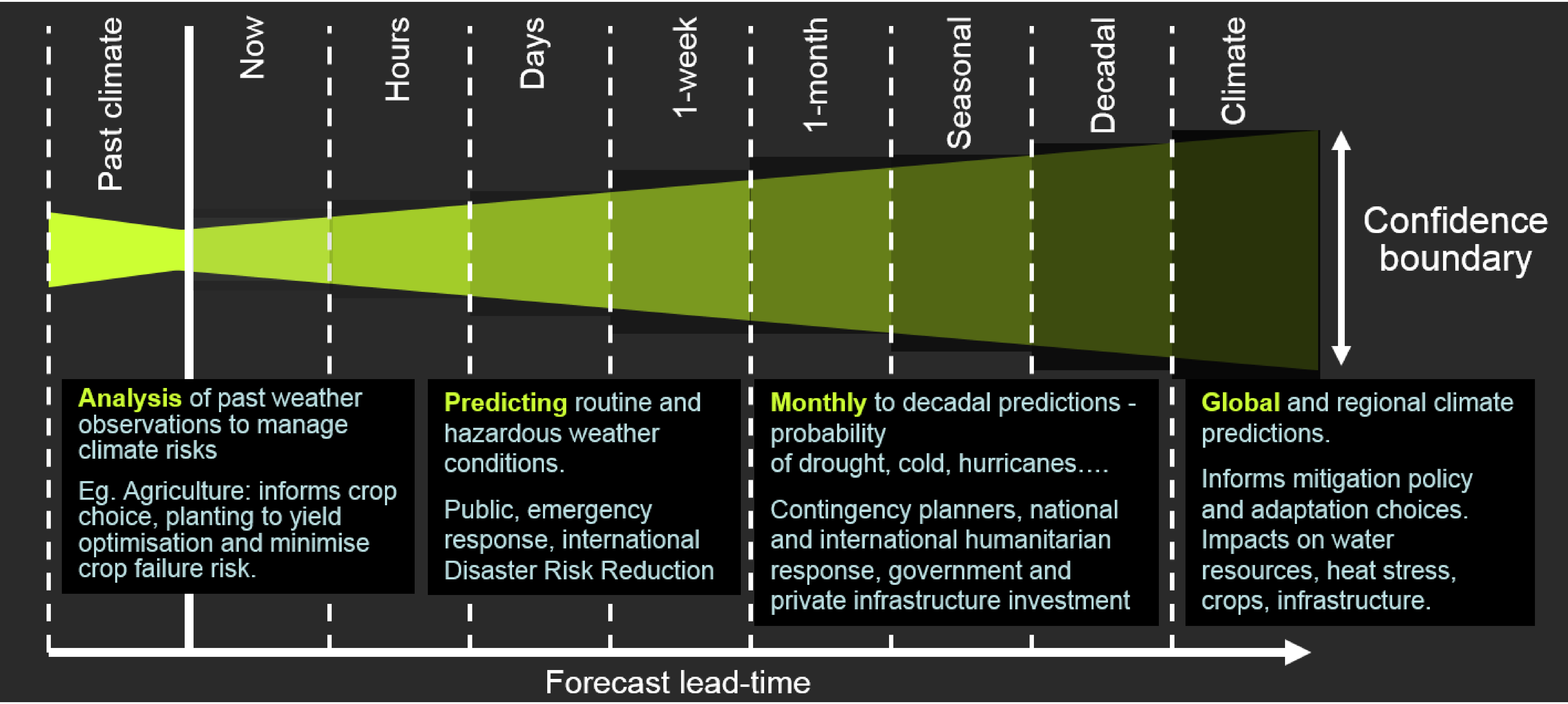
(from Earth System Science: An Overview, NASA, 1988)

Weather/Climate Modelling System

NUS, Nanyang Technological University, WMO, ASEAN, ASMC, SMU, MPA Singapore, University of Reading, SLA Singapore Land Authority, Urban Redevelopment Authority, NCAR, National Environment Agency, PUB, Singapore Food Agency, Deltares, Australian Government Bureau of Meteorology, Met Office, NSCC National Supercomputing Centre Singapore

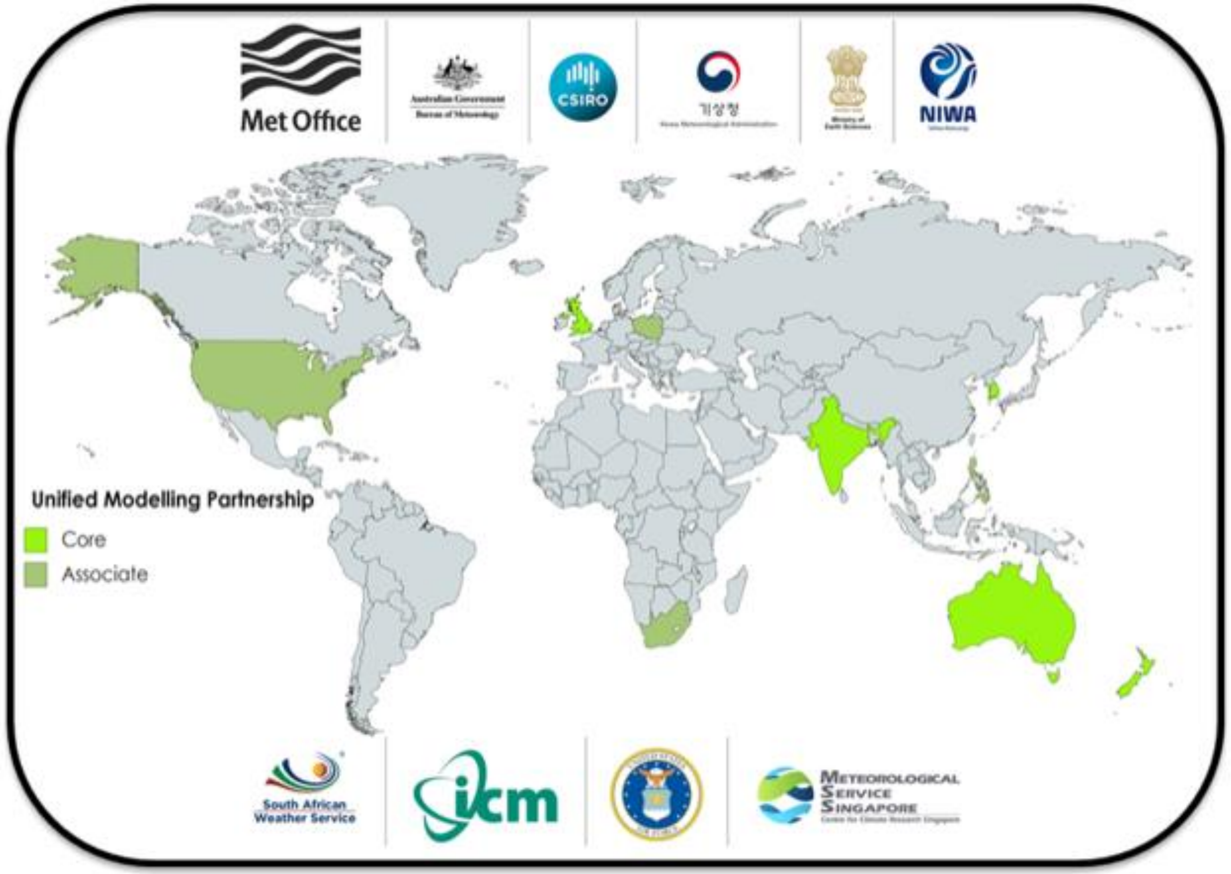
Expertise (in-house and partnerships)

Seamless Weather-Climate Prediction



The Unified Model Partnership

- MSS is an associate member of the ‘Unified Model’ Partnership:



- Members typically span entire R&D – Operations – End User: Ensures upstream climate/weather science remains focussed on service delivery

CCRS Supercomputing

- In-house HPC (Athena) for R&D and operational ‘SINGV’ weather forecasting system.

- CCRS building constraints: electric power + floor loading – cannot house next HPC.

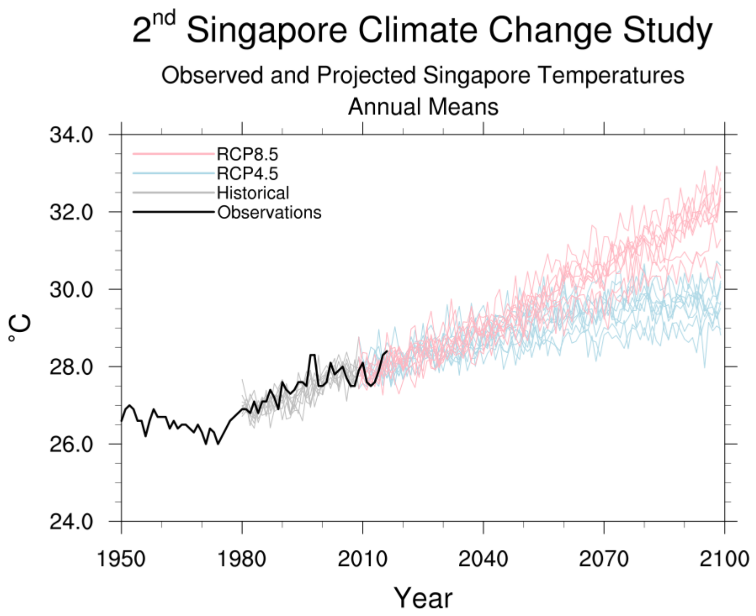
	2019 - 2021	2022+
Computing power	212TFlops	1.0PFLops
Storage	1PBytes	4.8PBytes

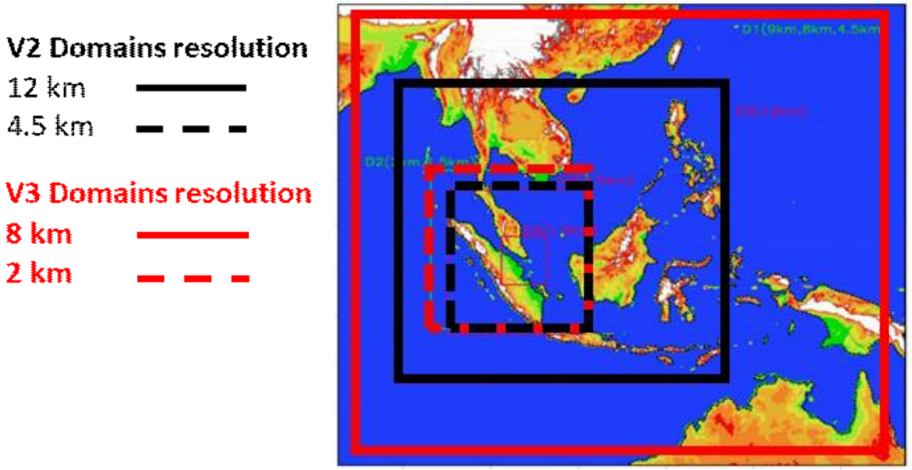
- NSCC ‘Koppen’ allocation for CCRS climate studies (e.g. V3 climate projections):

	Oct 2019 – Jan 2021	Feb 2021 (±Covid19 suspension)
Computing power	Koppen: 160TFlops	**20X** Koppen: ~3.2PFlops
Storage	1PBytes	3PBytes

Third National Climate Change Study – V3

- Conduct national assessment of the effect of climate change on Singapore and the surrounding region (2022).
- Based on the latest climate projections made available as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) coordinated by the World Climate Research Programme (WCRP) .
- Informed by stakeholder needs and feedback received after the Second National Assessment (V2) published in 2015.
- Use new science developed within SINGV – benefit of our seamless weather-climate modelling strategy.





Future Challenges

Big Weather-Climate Data

GCMs produce vast quantities of data, for example at the Met Office:

- Global models: 690 Gbytes per day
- Local models: 3200 Gbytes per day

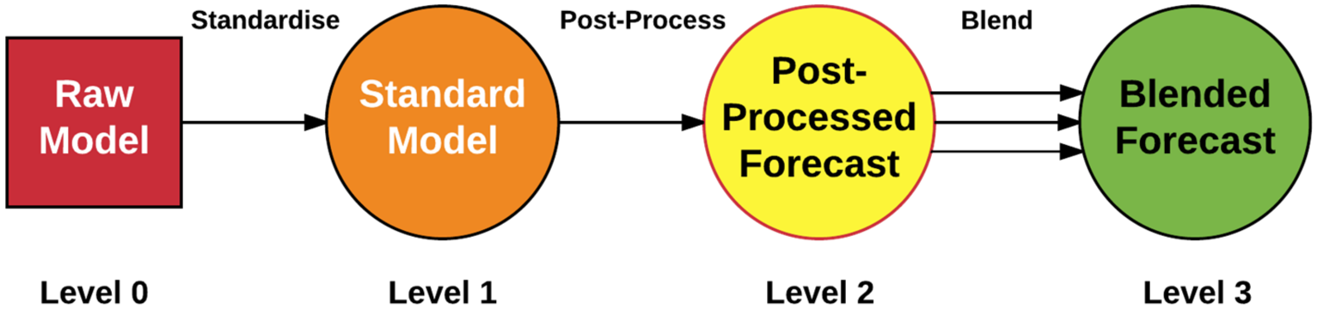
TOTAL: 3.9 Tbytes per day

Forecasts updated every hour or more

Huge computing investments in ensembles - probabilistic interpretation

How will users cope? Role for data science/AI

Need to decouple data, extract/condense info, make accessible e.g. cloud: '*bring application to data*' (not vice versa).



amazon web services Microsoft Azure DeepMind

Weather/Climate Supercomputers: The Next Generation

TOP 10 Sites for June 2020

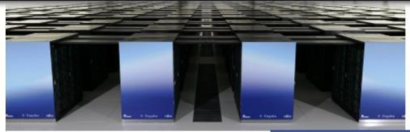
For more information about the sites and systems in the list, click on the links or view the complete list.

1-100 | 101-200 | 201-300 | 301-400 | 401-500

Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Supercomputer Fugaku** - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,299,072	415,530.0	513,854.7	28,335
2	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148,600.0	200,794.9	10,096
3	**Sierra** - IBM Power System AC922, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94,640.0	125,712.0	7,438
4	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway, NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371
5	**Tianhe-2A** - TH-IVB-FEP Cluster, Intel Xeon E5-2692v2 12C 2.2GHz, TH Express-2, Matrix-2000, NUDT National Super Computer Center in Guangzhou China	4,981,760	61,444.5	100,678.7	18,482

Fugaku
- Good for both ML and Big DA
(e.g, Global 3.5-km mesh 1024 samples)

K (or most other HPCs)
- Not suitable for ML
- Good for Big DA
(e.g., global 112-km mesh 10240 samples)



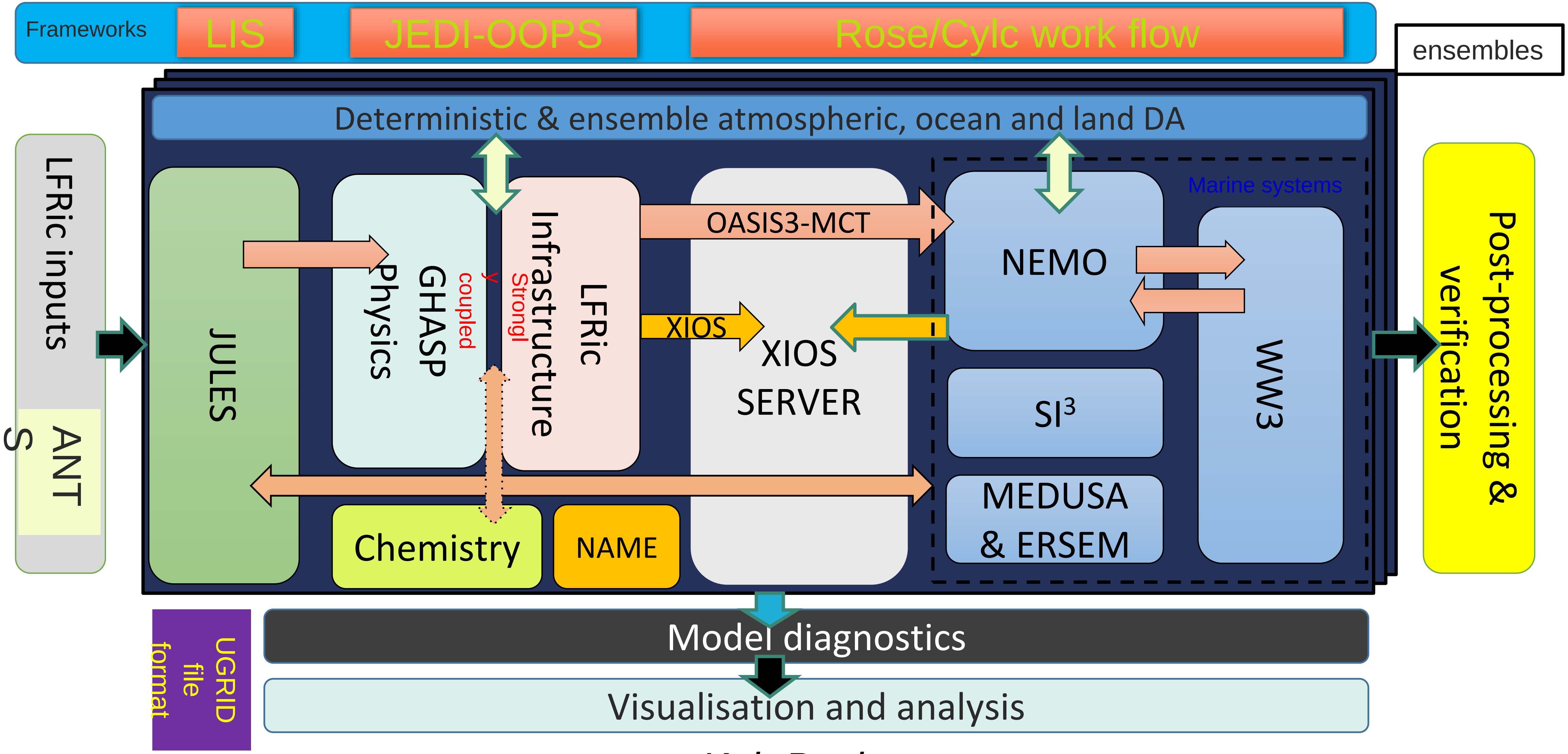
Fugaku : K = 100 : 1

Mesh size: 32x
(Grid points: 1024x)

Sample size: 0.1x

Takemasa Miyoshi, Riken Institute, Japan

UM (1990-2025) -> Next Generation Modelling System (NGMS)



Keir Bovis

Weather/Climate Supercomputers: How Green Can They Be?

- Climate science needs to be sustainable (practice what we preach).
- HPC carbon footprint can be large (MO Power 8MW -> 20000t CO_2/year).
- Need new technologies (greater power efficiency - Flops/Watt part of tendering process?)
- Renewable energy solution for some countries.
- Role for ‘the cloud’ here: globally distributed HPC for research, provides resilience as well reducing CO_2.

Green Top500 Supercomputer List (June 2020)

Rank	TOP500 Rank	System	Cores	Rmax (TFlop/s)	Power (kW)	Power Efficiency (GFlops/watts)
1	393	**MN-3** - MN-Core Server, Xeon 8260M 24C 2.4GHz, MN-Core, RoCEv2/MN-Core DirectConnect, Preferred Networks Preferred Networks Japan	2,080	1,621.1	77	21.108
2	7	**Selene** - DGX A100 SuperPOD, AMD EPYC 7742 64C 2.25GHz, NVIDIA A100, Mellanox HDR Infiniband, Nvidia NVIDIA Corporation United States	272,800	27,580.0	1,344	20.518

DMI’s Research Supercomputer (Iceland)

METEOROLOGICAL SERVICE SINGAPORE

Centre for Climate Research Singapore