Advancing Weather and Climate Forecasting for Our Changing World

Gilbert Brunet

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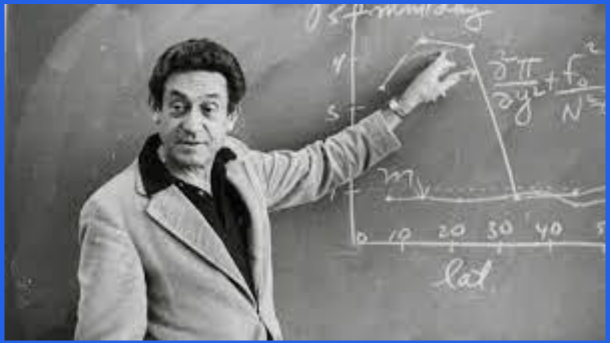
Member of Scientific Advisory Panel, World Meteorological Organization (WMO).

ECMWF at 50 (1975-2025)

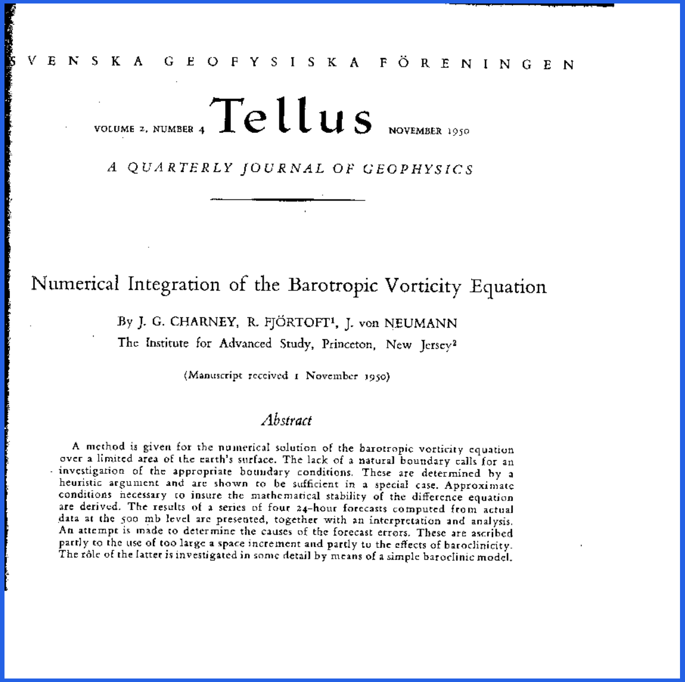
Annual Seminar 2025, 7-11 April 2025, Bonn.

Acknowledgements: Peter Bauer and Catherine de Burgh-Day

50th Anniversary of Numerical Weather Prediction, Commemorative Symposium in Potsdam, March 2000



Jule Gregory Charney
(1917-81)



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A QUARTERLY JOURNAL OF GEOPHYSICS

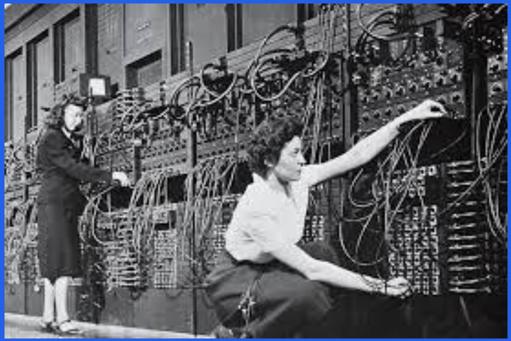
Numerical Integration of the Barotropic Vorticity Equation

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.



- 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).

World Meteorological Organisation (WMO) Strategic Plan 2024-27

LONG-TERM GOAL 1. BETTER SERVE SOCIETAL NEEDS
Delivering, authoritative, accessible, user-oriented and fit-for-purpose information and services

LONG-TERM GOAL 2. ENHANCE EARTH SYSTEM OBSERVATIONS AND PREDICTIONS
Strengthening the technical foundation for the future

LONG-TERM GOAL 3. ADVANCE TARGETED RESEARCH
Leveraging leadership in science to improve understanding of the Earth system for enhanced services

LONG-TERM GOAL 4. CLOSE THE CAPACITY GAP
Enhancing service delivery capacity of developing countries to ensure availability of essential information and services needed by governments, economic sectors and citizens

World Meteorological Organisation (WMO)

3 Programmes to deliver its science strategy

WWRP
WORLD WEATHER
RESEARCH PROGRAMME

WCRP
World Climate
Research Programme

GLOBAL
ATMOSPHERE
WATCH

WMO Science Advisory Panel (SAP): Science and Technology Vision Paper

- The SAP, in collaboration with other constituent bodies of the WMO, has developed the SAP Science and Technology Vision Paper.

- This paper explores potential future demands, disruptors, and opportunities for current weather, climate, water, and environment-related services.

WMO-NO. 1263

Contributors

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WMO-NO. 1263

Advancing Weather and Climate Forecasting for our Changing World

Brunet et al., Bulletin of the American Meteorological Society, 2023.

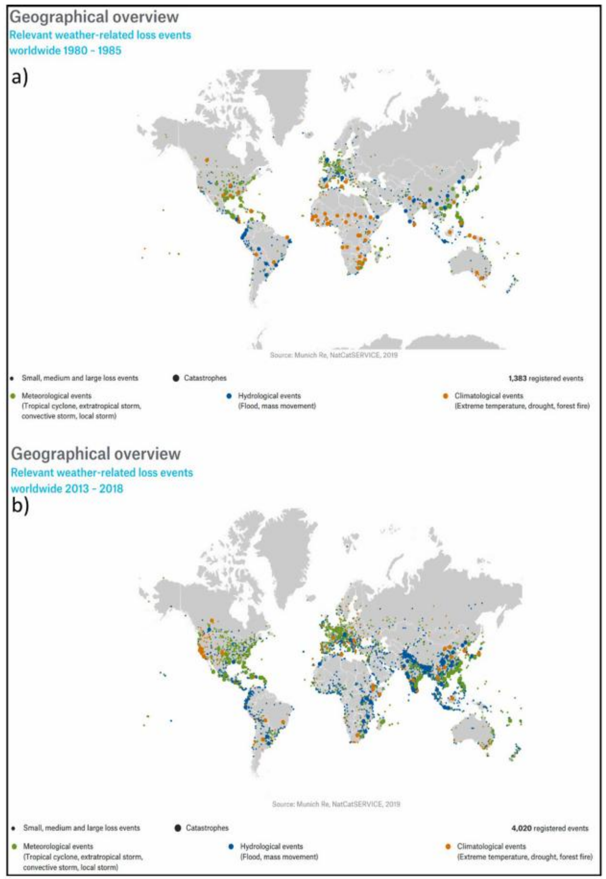
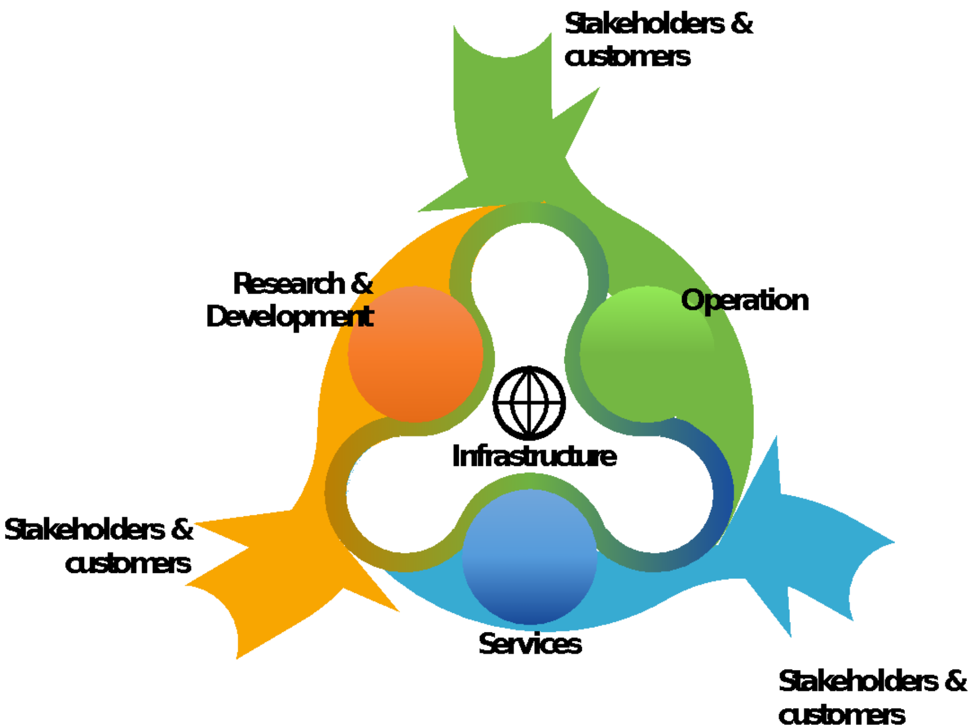


Fig. 1. Major weather- and climate-related loss events from the Munich Re, NatCatService, 2019 database plotted utilizing their online data access tools. For the periods (a) 1980–85 and (b) 2013–18. From keynote presentation by D. Parsons at InterMet Asia 2019.

The innovation/value cycle of weather and climate services: the Public Private Engagement (PPE) challenge.

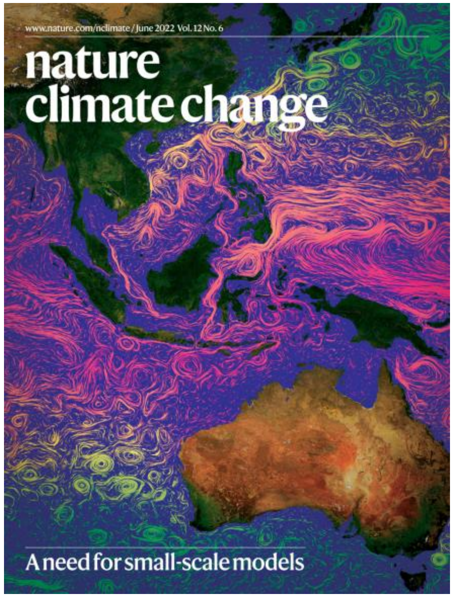


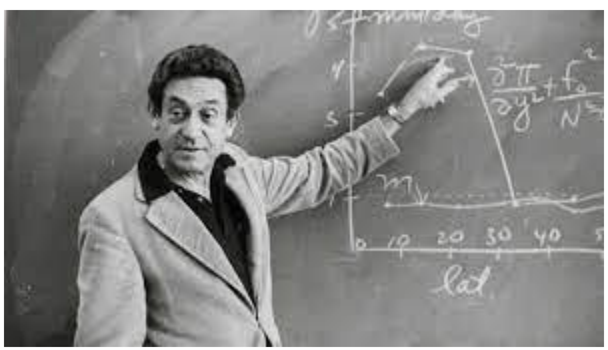
The PPE will play an important and different role for each of these components.

Eight Recommendations

#	Recommendation
1	Major International Climate Research and Development Effort in the Exploitation of Global kilometer (k-Scale) Computing and Earth System Observations
2	Bridge the Gap Between Developing Global Science and Delivering Local Impact
3	Develop a Digital Strategy
4	Accelerate the Development of Attribution Science
5	Development of Quality Assurance Strategy for Weather, Climate and Water-Related Services
6	Work Across Agencies to Enable Closer Integration of Geophysical and Social Sciences to Support Better Understanding of the Impacts of Weather, Climate and Water Events
7	Develop Education and Training Strategies to Broaden Expertise Beyond Traditional Disciplines
8	WMO, Together with NMHSs, Provide Leadership in the Move Towards Net-Zero

Recommendation 1: think big and model small





Ambitious partnership needed for reliable climate prediction

Current global climate models struggle to represent precipitation and related extreme events, with serious implications for the physical evidence base to support climate actions. A leap to kilometre-scale models could overcome this shortcoming but requires collaboration on an unprecedented scale.

Julia Slingo, Paul Bates, Peter Bauer, Stephen Belcher, Tim Palmer, Graeme Stephens, Bjorn Stevens, Thomas Stocker and Georg Teutsch

Water is Earth's life blood and fundamental to our future. Hydro-meteorological extremes (storms, floods and droughts) are among the costliest impacts of climate change, and changes in the seasonality and natural variability of precipitation can have profound effects on many living systems, in turn threatening our food security, water security, health and infrastructure investments. Yet the current generation of global climate models struggles to represent precipitation and related extreme events, especially on local and regional scales[1,2]. The model precipitation biases are substantial in both space and time, and in the tropics they overwhelm the projected signal of climate change[3]. Despite decades of enormous efforts by the community, these biases have remained stubbornly intractable[1,2] (Box 1). Consequently, future scenarios of precipitation remain very uncertain in the IPCC assessments so far[4]. As water is an essential resource for humans

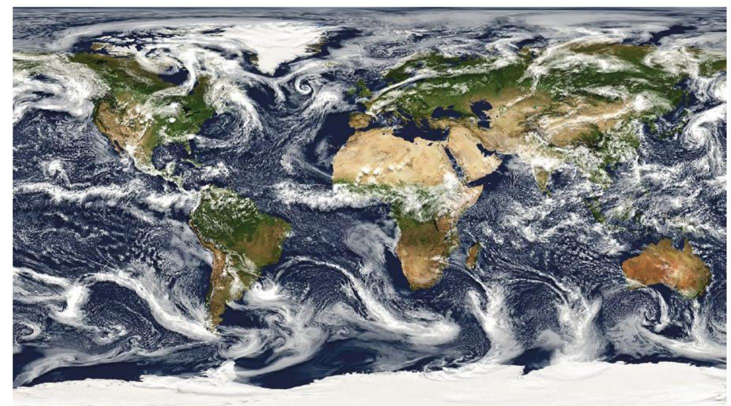


Fig. 1 | The realism of k-scale global climate modelling. Snapshot of clouds from a simulation with a global k-scale climate model, showing the detailed structures of tropical clouds, mid-latitude storms and evidence of MCSs across West Africa and the US Great Plains[13]. Base map provided by NASA's Earth Observatory.

Charney's thinking on weather and climate prediction was visionary (GARP, 1969; Carbon dioxide and climate, 1979).

The need for km-scale resolution

Nobody questions the benefits of high spatial resolution* for achieving more reliable forecasts at local scale — which is why we maintain limited area systems …

… does resolving small scales matter for large (and global) scales?

“The single most important development in NWP in the coming years will be the implementation of global ensemble prediction systems with grid-point spacing (or spectral equivalent) of 1-3km, where some of the key atmosphere/ocean processes (deep convection, orographic gravity wave drag and ocean mesoscale eddies) are represented by the laws of physics:

1. *Extreme events are often associated with coherent nonlinear organised or self- aggregated structures, such as associated with mesoscale convection […], or with persistent quasi-stationary anticyclones […]. There is ample evidence that high-resolution models capture better the scale interactions that are crucial for maintaining these types of extreme events.*
2. *[…] we are unable to assimilate the crucial information in our observational network due to inadequate model resolution […] there is no shortage of observations of such convective systems.*
3. *[…] important is that it will help reduce the systematic errors in model which, as mentioned, are typically of the same magnitude as the signals such models attempt to predict.”*

Palmer 2020, https://arxiv.org/pdf/2007.04830]

nature climate change

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Editorial | Published: 16 June 2022

Think big and model small

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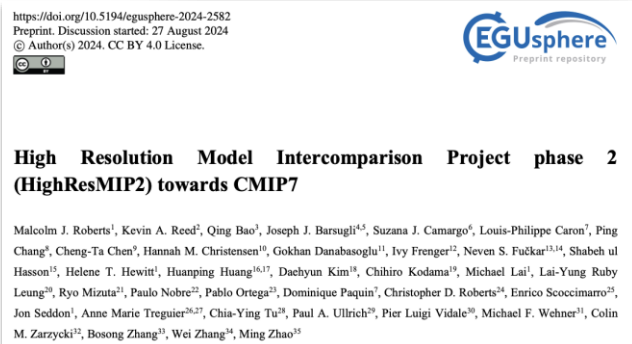


https://doi.org/10.5194/egusphere-2024-2582
Preprint. Discussion started: 27 August 2024

EGUsphere Preprint repository

High Resolution Model Intercomparison Project phase 2 (HighResMIP2) towards CMIP7

Malcolm J. Roberts[1], Kevin A. Reed[2], Qing Bao[3], Joseph J. Barsugli[4,5], Suzana J. Camargo[6], Louis-Philippe Caron[7], Ping Chang[8], Cheng-Ta Chen[9], Hannah M. Christensen[10], Gokhan Danabasoglu[11], Ivy Frenger[12], Neven S. Fučkar[13,14], Shabeh ul Hasson[15], Helene T. Hewitt[1], Huanping Huang[16,17], Daehyun Kim[18], Chihiro Kodama[19], Michael Lai[1], Lai-Yung Ruby Leung[20], Ryo Mizuta[21], Paulo Nobre[22], Pablo Ortega[23], Dominique Paquin[7], Christopher D. Roberts[24], Enrico Scoccimarro[25], Jon Seddon[1], Anne Marie Treguier[26,27], Chia-Ying Tu[28], Paul A. Ullrich[29], Pier Luigi Vidale[30], Michael F. Wehner[31], Colin M. Zarzycki[32], Bosong Zhang[33], Wei Zhang[34], Ming Zhao[35]

*acknowledging that resolved process scale is 4-8Δx, i.e. true km-scale requires hm-scale simulations

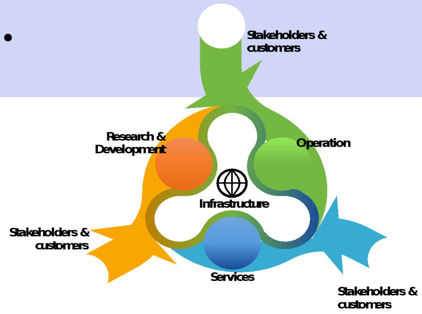
Acknowledgement: Peter Bauer

Key Messages and Recommendations

Towards an improved forecasting system: global, regional and local approaches

- International cooperation at State level will continue to be a main factor. WMO should increase significantly its effort in international R&D coordination and promotion.

- At the national level, Met and Hydro Services need to engage more in community-based modelling and data initiatives, and R&D consortia. The importance of working closely with users and the opportunities for Public Private Engagement (PPE) should be recognized and promoted.



Key Messages and Recommendations

Towards an improved forecasting system: global, regional and local approaches

- Governments need to sustain and ideally accelerate public investments in global observing system and supercomputing capability which are fundamental for the PPE.

- WMO should continue to be the backbone of capacity building and to provide numerical forecast for various global and regional service providers (e.g., GPDFS).

Global Data-Processing Forecast System Centres

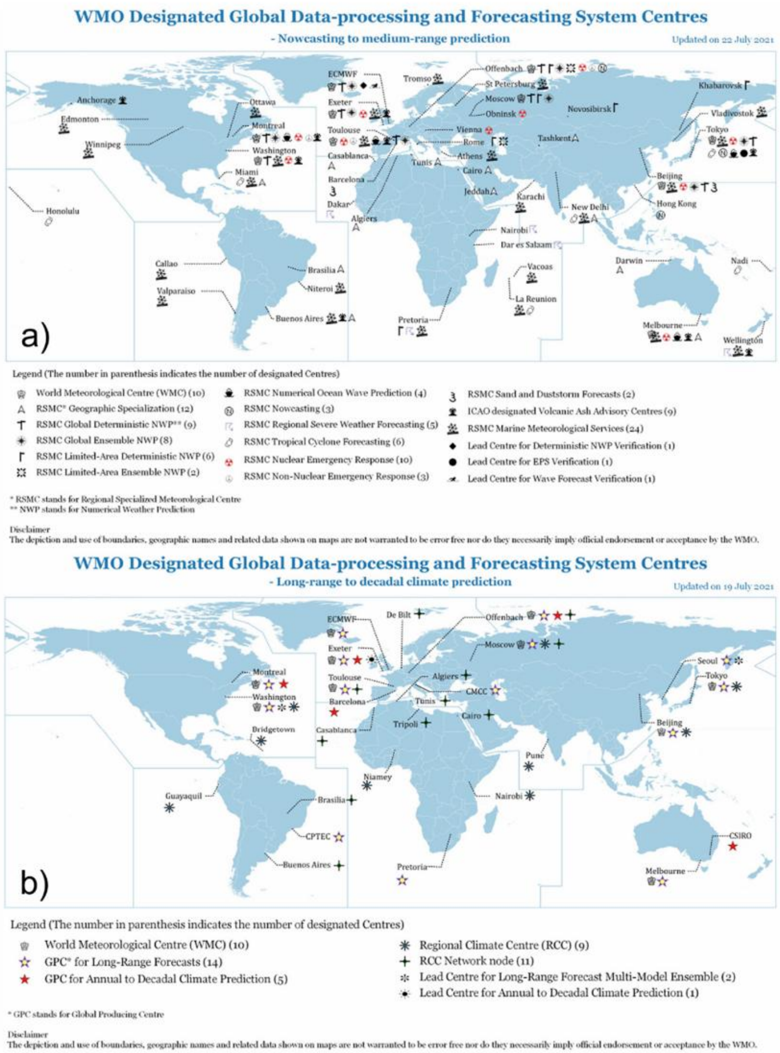


Fig. 3. WMO-designated (a) GDPFS centers for nowcasting and weather forecasting (up to 30 days) and (b) long-range and climate forecasting (over 30 days) (WMO 2019a,b,c).

Key Messages and Recommendations

Towards an improved forecasting system: global, regional and local approaches

- Implementing numerical prediction systems with post-processing, production and visualization on the cloud may offer a unique advantage for Met and Hydro Services, especially in developing countries and make more effective PPE.
- WMO with PPE could come to an agreed methodology for validation of quality, and recognition and attribution of various providers of weather and climate forecasts.

Key Messages and Recommendations

Towards an improved forecasting system: global, regional and local approaches

- Investments in observational networks will need to be coordinated with those for numerical forecast systems development, considering the cost/benefits impact of observations on forecast skill and reanalyses.
- The development/improvement of climate models needs to be in line with the strategy for weather prediction. A unified single model system across a range of timescales (nowcasting to centennial) and spatial scales (convective scale to climate system Earth modelling) is possible and desirable.

Key Messages and Recommendations

Progressing together with developing countries

- Massive investments through various development assistance projects have often provided disappointing results. The failures are often due to the lack of attention to the needs of Met and Hydro Services and planning for sustainable operations.

- A way forward could be building national sustainable expertise and computation infrastructure for accessing and utilizing on the cloud available high resolution global ensemble forecasts.

Key Messages and Recommendations

Progressing together with developing countries

- A federated model like ECMWF may need to be replicated to a certain extent to other regions, which will allow consolidation of human resources and expertise, and optimization of running costs. Such a regional approach will need strong political support for home-based regional institutions and scientists.

- Numerical forecast systems science needs insights from developing countries scientists. This can be achieved with an increase WMO support to international R&D coordination, participation and training.

The elephant in the room

Current financial uncertainty in international development programs could greatly affect the execution of these recommendations.

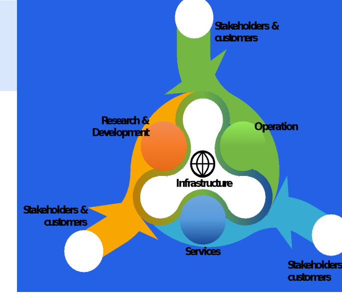
- “As an example, WMO has recently established the Systematic Observations Financing Facility (SOFF) to provide financial and technical support for the implementation and sustained operation of Global Basic Observing Network (GBON) for low-income countries.”

- “Increasing partnerships between academic institutions and those working on development activities relevant to the Numerical Earth-system and Weather-to-climate Prediction (NEWP) enterprise are likely to be beneficial (e.g., WMO, World Bank, U.S. Agency for International Development).”

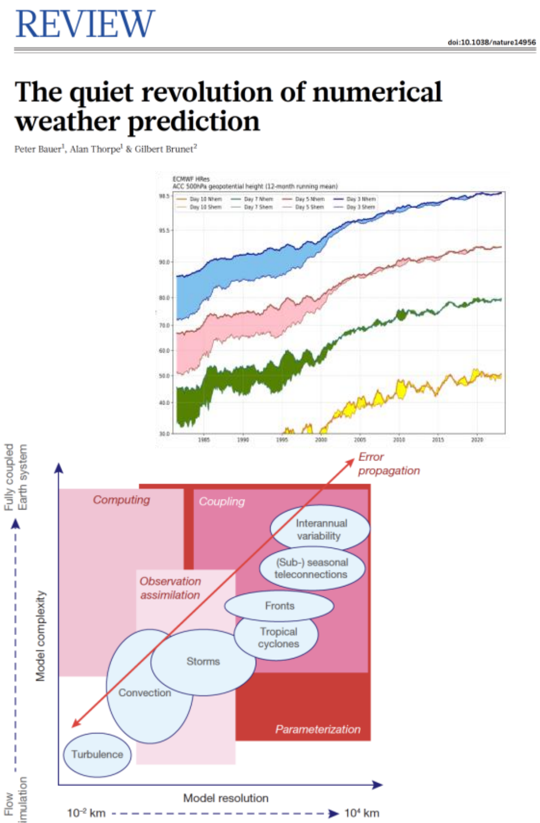
- “An excellent model to build on is three International Desks (i.e., African, South American, and Tropical) at NOAA’s National Centers for Environmental Prediction. This program hosts ~20 visitors each year with its in-residence training program and also includes on-site training via workshops, and follow-up training through distance learning.”

Advancing Weather and Climate Forecasting for our Changing World, Brunet et al. (BAMS, 2023)

Potential major breakthroughs from ML: accelerating the implementation of some of these recommendations



The quiet revolution
1980 - today

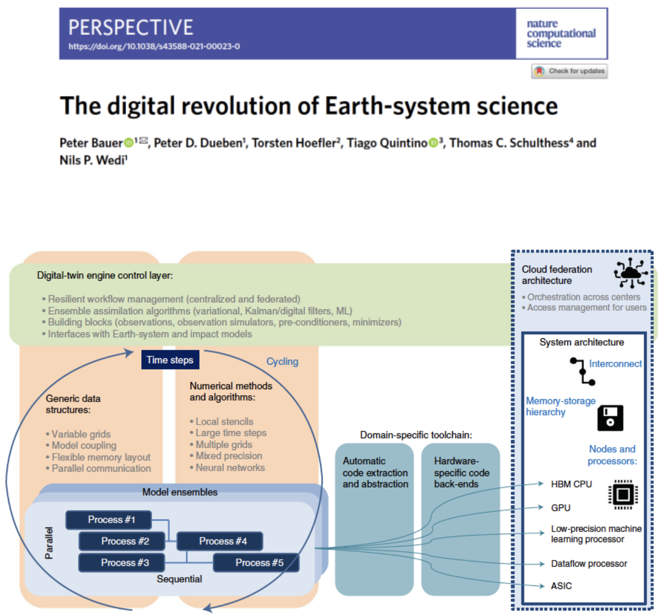

REVIEW

doi:10.1038/nature14956

The quiet revolution of numerical weather prediction

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

The digital revolution
2015 - today


PERSPECTIVE

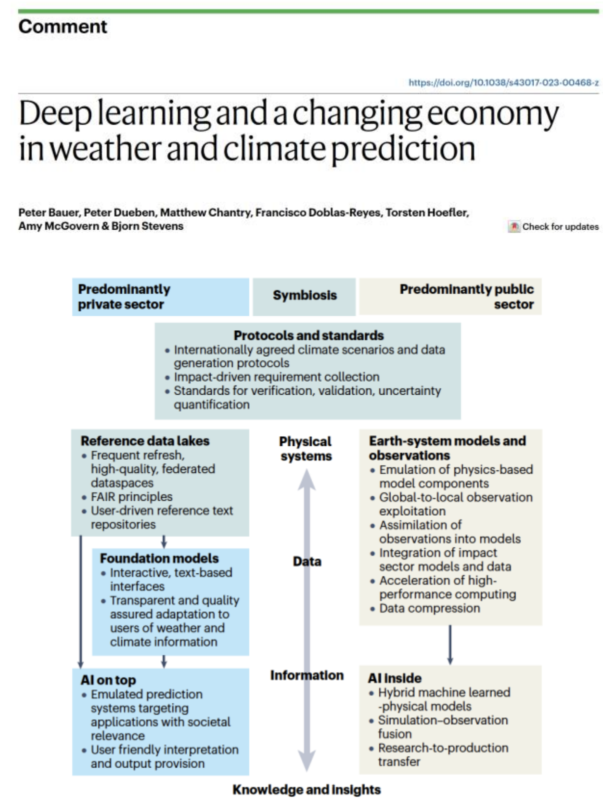
https://doi.org/10.1038/s43588-021-00023-0

nature computational science

The digital revolution of Earth-system science

Peter Bauer[1], Peter D. Dueben[1], Torsten Hoefler[2], Tiago Quintino[3], Thomas C. Schulthess[4] and Nils P. Wedi[1]

The AI revolution
2020 - today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https://doi.org/10.1038/s43017-023-00468-z

Deep learning and a changing economy in weather and climate prediction

Peter Bauer, Peter Dueben, Matthew Chantry, Francisco Doblas-Reyes, Torsten Hoefler, Amy McGovern & Bjorn Stevens

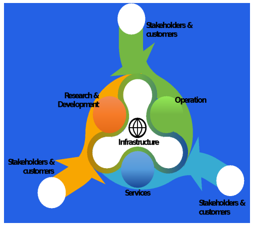
Acknowledgements: Peter Bauer

Potential major breakthroughs from ML: a few examples

Implementing machine learning will drive substantial advancements across the entire spectrum of numerical forecast services, from research and development to end-user delivery, in the next decade.

- Current and future research topics and potential advantages of utilizing ML include the following:
  - Training subgrid parameterizations on data provided by higher-resolution models like large-eddy simulation models
  - Advance post-processing of numerical variables by allowing incorporation of nonlinear correlations
  - Advance nowcasting and improve rainfall estimation by applying ML to radar observations
  - Application of large language models (LLMs) to deliver guidance on responding to high-impact weather events
  - Explore whether ML is a computationally efficient tool to replace the NEWP forecast approach

The good news, and a few ‘but’



- The NWP community is already empowering itself to stay ahead of ML-methodology game (but: some waste of resources b/c everybody wants to play)
- Technology companies have been very innovative and supportive (& saved us years of R&D) (but: they may stop sharing and patent everything)
- Countries & European Commission are investing massive amounts of money in HPC and AI (but: they mostly do it for commercial & sovereignty reasons)
- Existing programmes are already developing & testing solutions with NWP representatives, e.g. Destination Earth
  (but: funding is temporary and EC focus may change)
- Climate community can benefit from very similar infrastructure solutions (e.g., EVE) (but: needs international commitment to ‘operationalise’*)
- Low income countries can easily piggy-back on ML suites (own needs/data/schedules) (but: of course the bar is WAY lower than to run NEWP systems, but still not sufficient infrastructure (GPUs, storage and network), lack of expertise and sparse observations and data.

*[Jakob et al. 2023, NCC; Stephens 2024, AGU Adv.]

Empirical Normal Mode for ML/AI prediction

- Collaboration with with Craig Bishop, Catherine de Burgh-Day, Michal Novomestsky and Ashyk Raman Kan

“In our mind pre-existed the latent idea of a certain number of groups – those whose theory Lie has developed.”

Henri Poincare (1913)
Experience and Geometry

Statistical Prediction

- Dynamical system

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{Ax} + \eta, \text{ where } \langle \eta \boldsymbol{x}^T \rangle = \mathbf{0}, \langle \eta \eta^T \rangle = \widetilde{\boldsymbol{Q}}, \langle \eta \rangle = \mathbf{0}$$

where η is stochastic, and ⟨ ⟩ is the expectation operator.

- The linear prediction is provided by

$$\boldsymbol{x} = \boldsymbol{e}^{\boldsymbol{A}\boldsymbol{t}} \boldsymbol{x}_{\mathbf{0}}$$

where A = $\langle \frac{d\boldsymbol{x}}{dt} \boldsymbol{x}^{\boldsymbol{T}} \rangle \langle \boldsymbol{x}\boldsymbol{x}^{\boldsymbol{T}} \rangle^{-1}$ is the propagator.

The challenge: dimension reduction

A = $\langle \frac{dx}{dt} \boldsymbol{x}^{\boldsymbol{T}} \rangle \langle \boldsymbol{x}\boldsymbol{x}^{\boldsymbol{T}} \rangle^{-1}$

- Dimension reduction using Empirical Orthogonal Function (EOF) truncation of order N for a given explained variance.

- In EOF space, A is N x N matrix, so the model has N^2 parameters to estimate.

- Prediction errors are closely link to the number of estimated parameters (e.g. Akaike information criterion)

- How sparse/dense is the propagator A?

The challenge: dimension reduction

- If the dynamical system is Hamiltonian, we can demontrate that Empirical Normal Mode (ENM) truncation will be a good dimension reduction technique and diagonalise the propagator A at the same time.

  References: Brunet (1994, JAS) and Brunet and Methven (2018, Editors Robertson and Vitart, Elsevier.)

- Hence reducing the model propagator to N estimated parameters compared to the N^2 for a standard EOF truncation.

- Empirical normal modes versus empirical orthogonal functions for S2S statistical prediction (Brunet and Vautard, JAS, 1996)

ENM vs EOF: barotropic numerical experiments with realistic subseasonal variability.

T= 6 weeks

T= 1 week

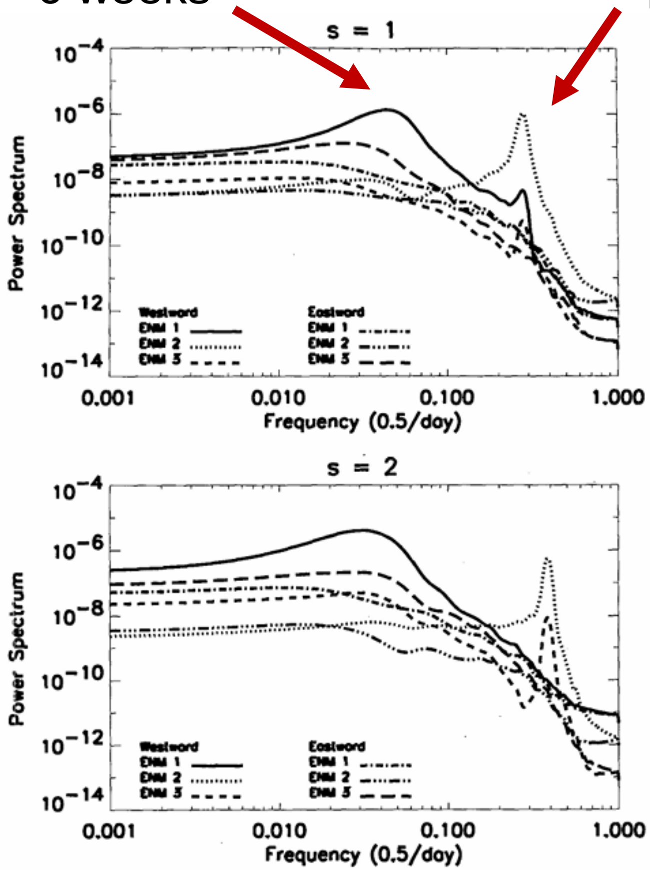


FIG. 3. The power spectrum of the principal component for each Fourier contribution and for the mean basic state ENM in the small amplitude experiments (h = 0.01) for (a) s = 1, s = 2 and (b) s = 3, s = 4. It shows the westward and eastward phasespeed contribution for the first three ENMs. The frequency unit is 0.5 day^{-1} and we are using logarithmic axes.

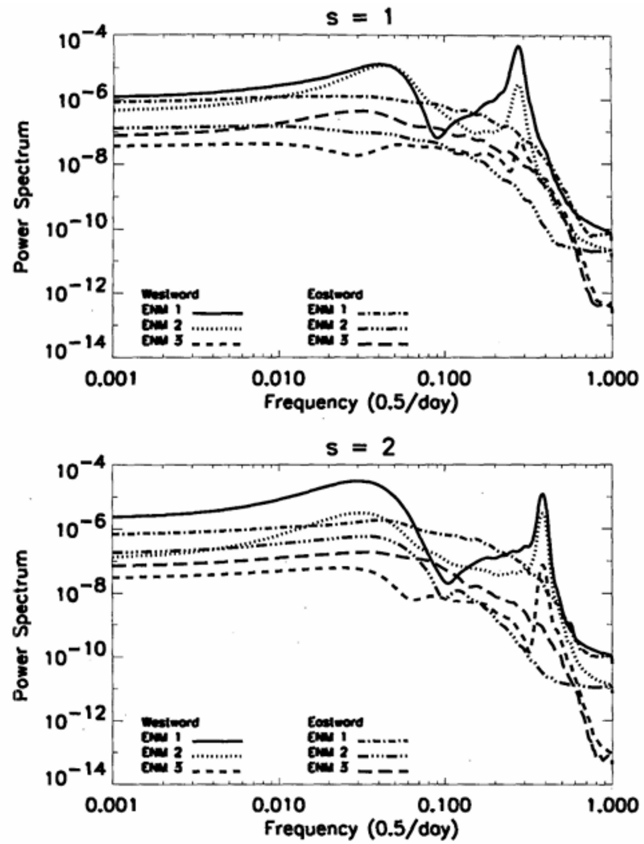


FIG. 7. The same as Fig. 3 but with the standard EOF analysis.

ENM

EOF

Zonal wave 1 and 2 power spectrum

ENM vs EOF: barotropic numerical experiments with realistic subseasonal variability.

ENM (thick lines) and EOF (dashed lines) truncations

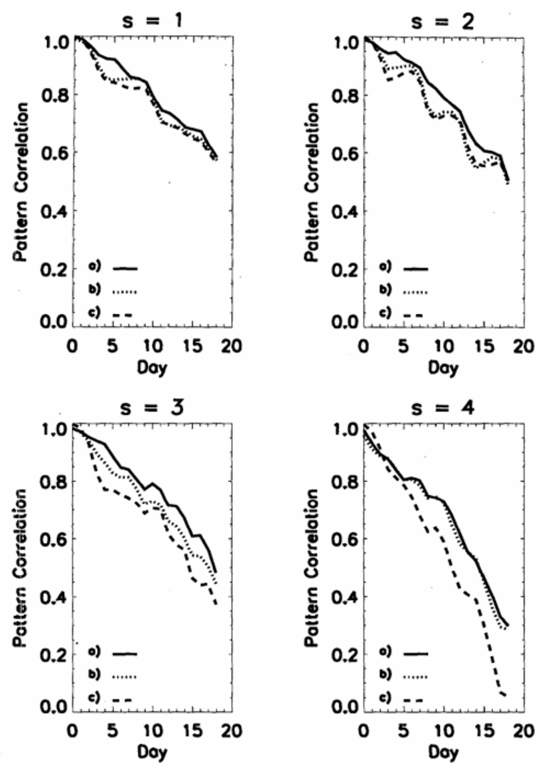


FIG. 8. The Fourier components pattern correlation versus time for the height disturbance. We show the prediction experiment with the mean basic state (a) ENMs (thick line), (b) with the solid rotation basic state ENMs (dotted lines), and (c) and the standard EOF analysis (dashed lines) for (s = 1, 2, 3, and 4) and the small amplitude experiments (h = 0.01). The data has been projected on the first 8 ENMs. Note that we are showing the geometrical mean of the cos(s λ) and sin(s λ) pattern correlations.

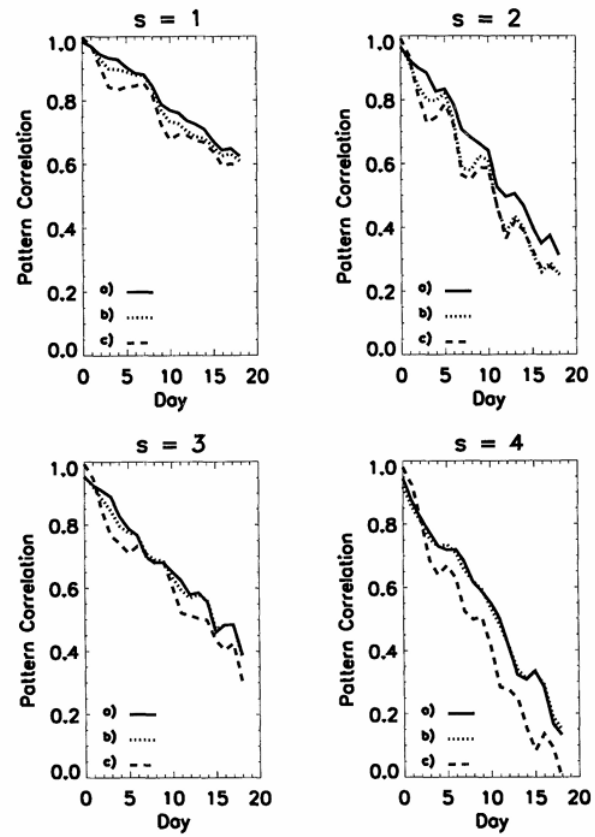


FIG. 9. The same as Fig. 8 but for the large amplitude case (h = 0.16).

Linear

Nonlinear

Forecast skill: pattern correlation

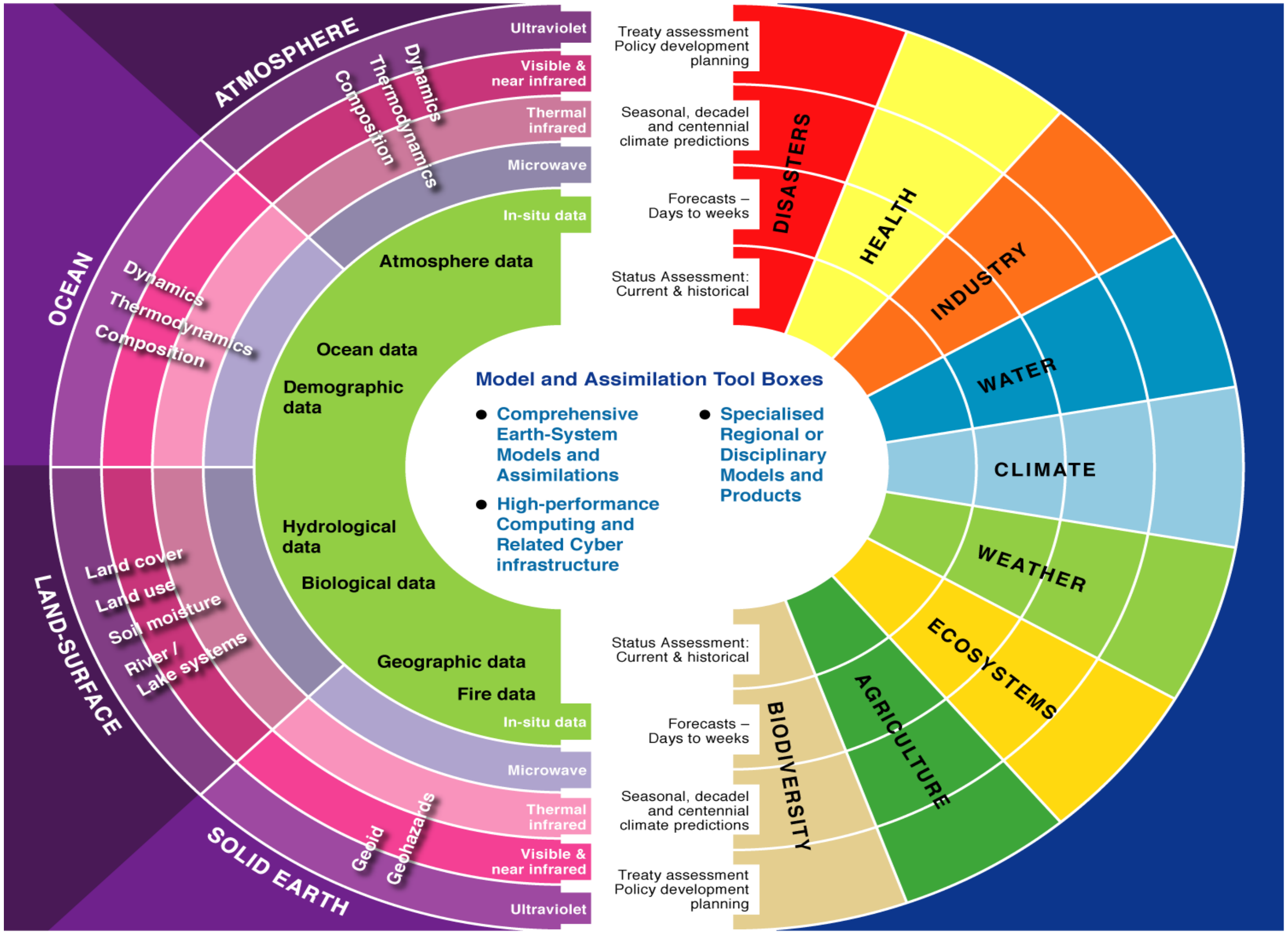
A proposition: Empirical Normal Mode for ML/AI prediction

- Neural networks have the capability to emulate nonlinear physical systems with high precision.
- However, these networks can yield physically inconsistent results when they violate basic constraints like conversation laws.
- Prediction requirements:
  - Dimension of the training dataset >>> dimension of the dynamical system (including the propagator)
  - Should be dynamically consistent hence satisfy basic physic laws as much possible (e.g., conservation laws)
- These requirements can be achieved by projecting the data on low dimension and dynamically consistent ENM canonical basis (i.e. diagonalise the linear propagator operator).
- Revisiting “Empirical normal modes versus empirical orthogonal functions for S2S statistical prediction (Brunet and Vautard, JAS, 1996)” with Craig Bishop, Catherine de Burgh-Day, Michal Novomestsky and Ashyk Raman Kan

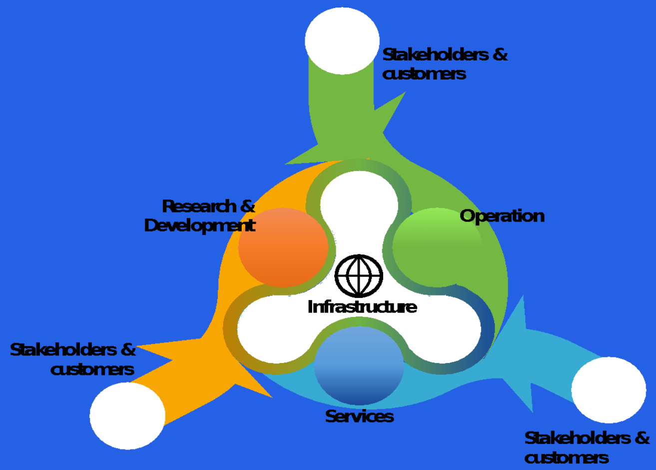
So much progress in the last 50 years!

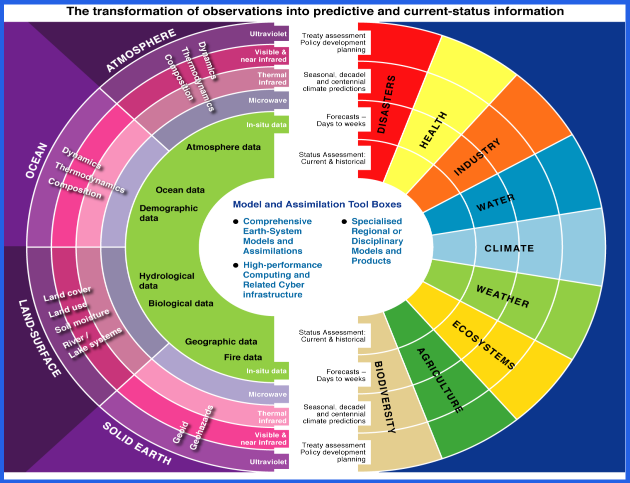
- Monitoring
- Research
- Development
- Operation
- Service

The transformation of observations into predictive and current-status information



Dr. Anthony (Tony) Hollingsworth: 1943 - 2007





Thank you
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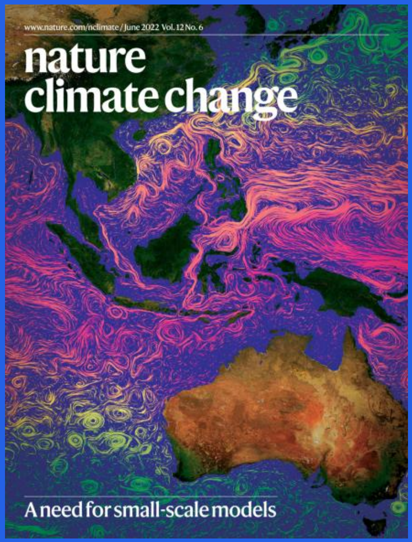

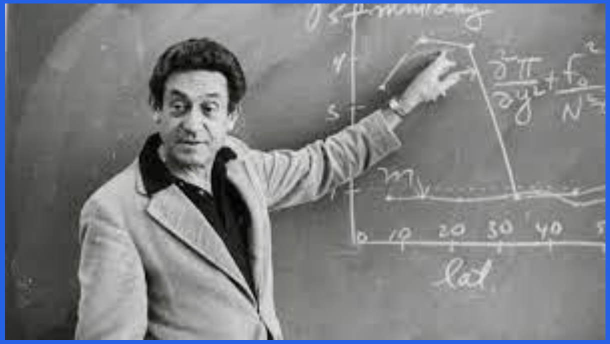

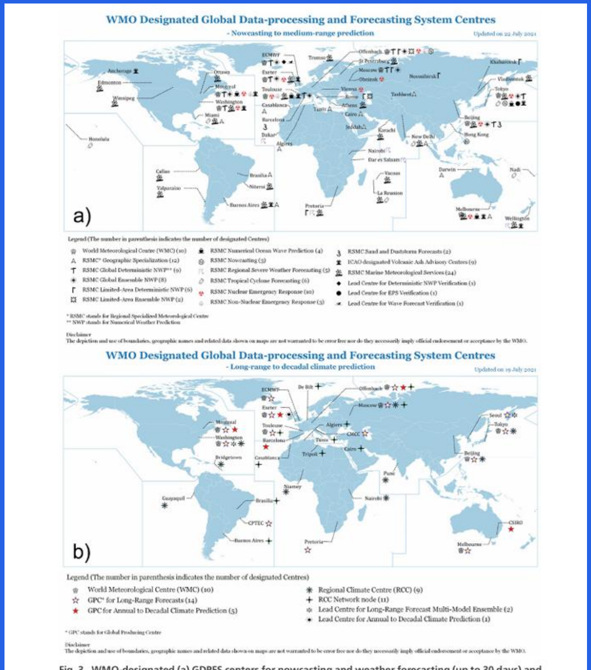

Fig. 3. WMO-designated (a) GDPFS centers for nowcasting and weather forecasting (up to 30 days) and (b) long-range and climate forecasting (over 30 days) (WMO 2019a,b,c).