Weather Forecasting for Data Scientists

COMP 5360/Math 4100
14 April 2020

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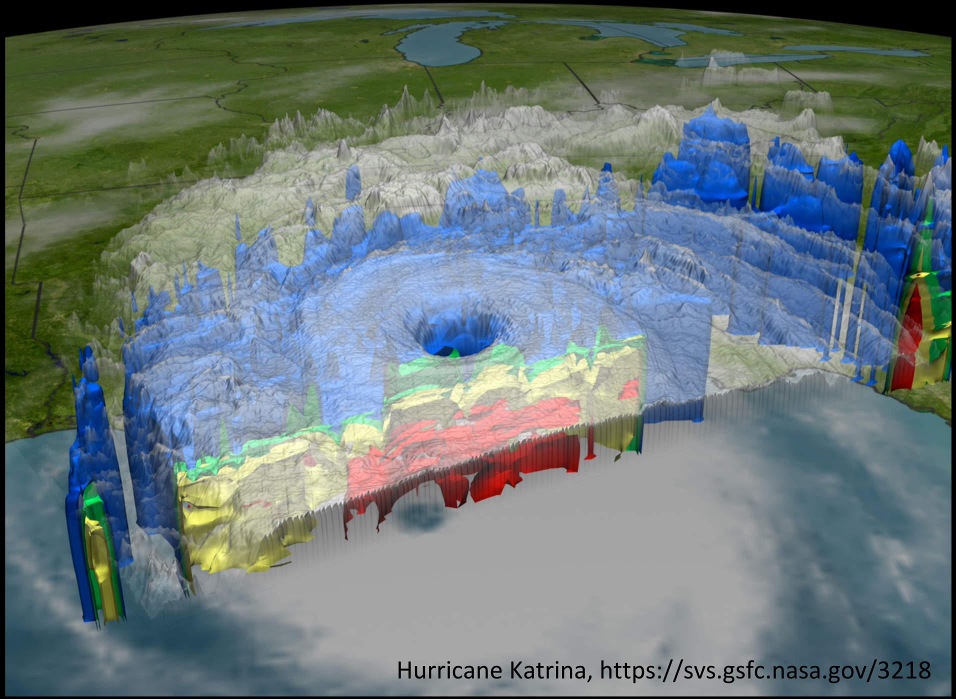
@ProfessorPowder



Hurricane Katrina, https://svs.gsfc.nasa.gov/3218

Personal Introduction

- Native of upstate NY
- Avid skier (Touring, Nordic, Alpine)
- UU Prof since 1995
- Mountain weather, winter storms, numerical modeling and weather forecasting
- Not a data scientist, but…

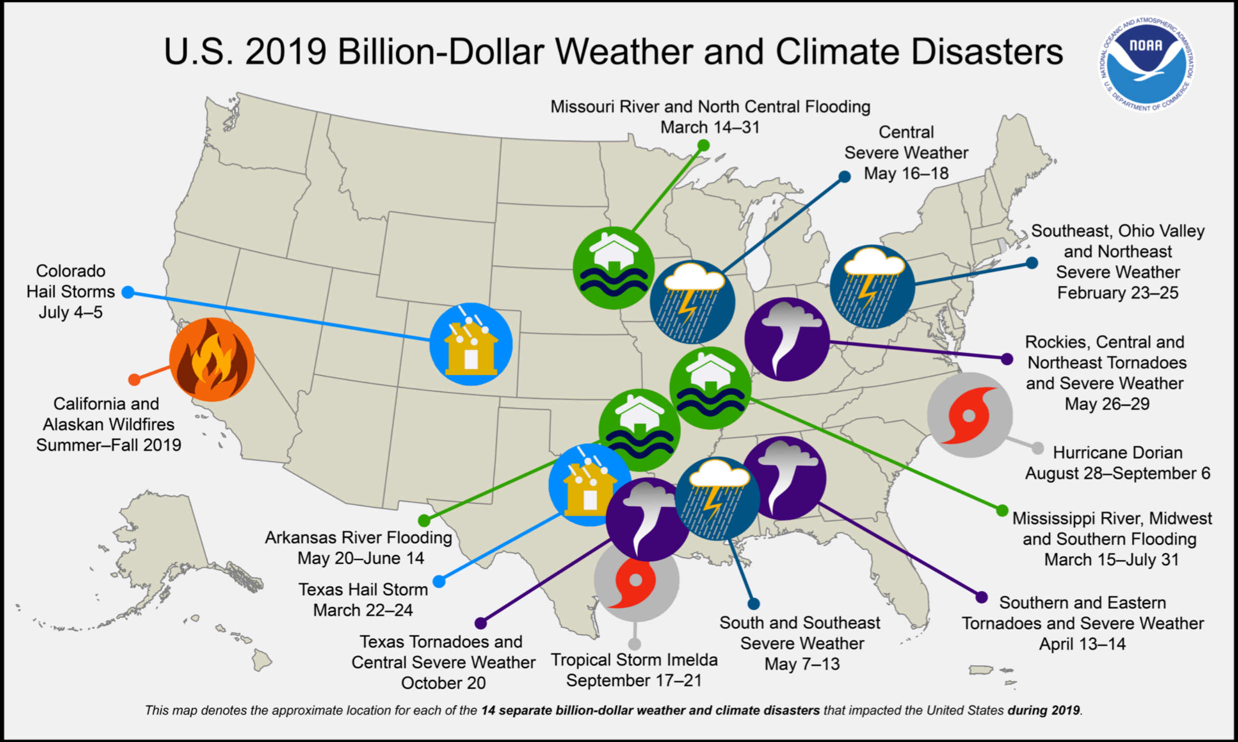
Why Weather Forecasting Matters

- 2010–2019 in the US
  - 119 weather disasters with damages/costs ≥ \$1 billion
  - Total damage from these events: \$802 billion
  - Lives lost: 522

2018 Woolsey fire (Wally Skalij/Los Angeles Times

https://www.ncdc.noaa.gov/billions/

Why Weather Forecasting Matters



2019 Billion-Dollar Disasters

Floods (3): \$20.0B
Severe Storms (8): \$13.9B
Tropical Cyclones (2): \$ 6.6B
Wildfire (1): \$4.5B
Total: \$45B

https://www.ncdc.noaa.gov/billions/

Why Weather Forecasting Matters

- 24% of US weather-related vehicle crashes occur on snowy, slushy, or icy pavement, leading to
  - 1,300 fatalites/yr
  - 116,800 injuries per year
- State and local agencies spend more than $2.3 billion on snow and ice control

Info Source: http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm
Photo: https://www.answerfinancial.com/insurance-center/winter-driving-tips/?a=insurance-quote

Why Weather Forecasting Matters

“Weather directly and indirectly affects production and consumption decision making in every economic sector of the United States at all temporal and spatial scales”

“U.S. economic output varies by up to \$485 billion yr^{-1}…owing to weather variability”

– Lazo et al. (2011)

Photo: https://www.clnsmedia.com/3-myths-money/

Why Weather Forecasting Matters

Energy Sector

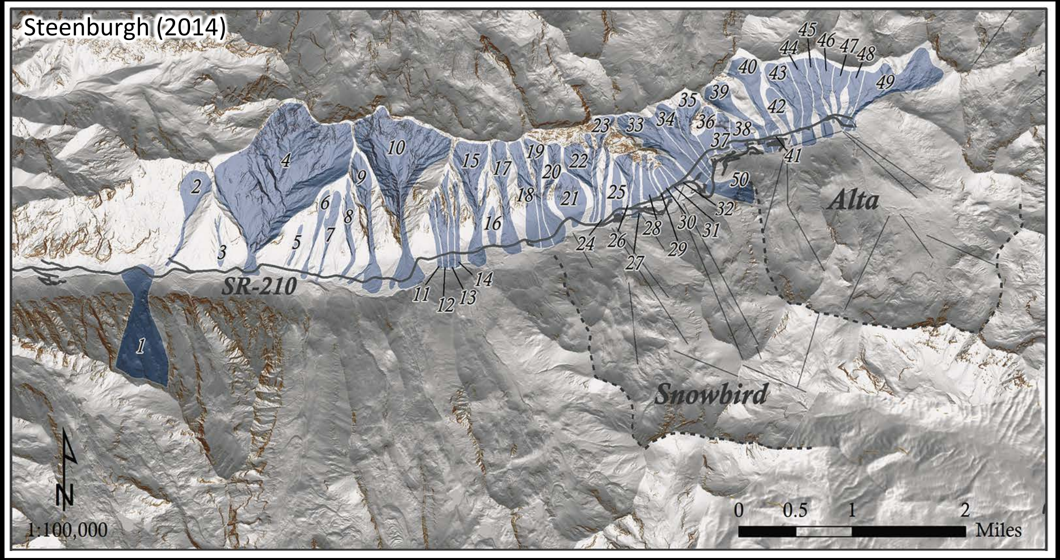
Photo: https://www.clnsmedia.com/3-myths-money/

Why Weather Forecasting Matters

Air Quality

Ski Quality

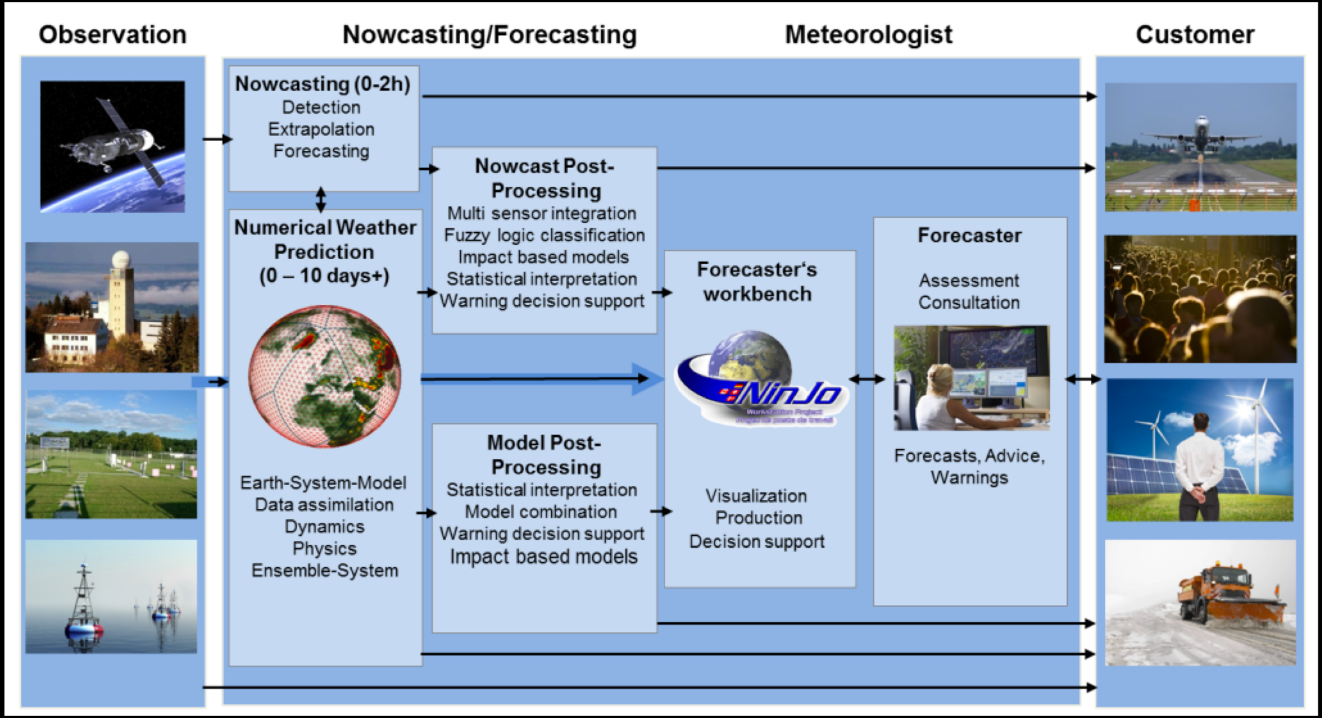
Why Weather Forecasting Matters



"The estimated revenue loss for ski resorts in upper LCC during the closure of SR-210 for avalanche hazard is \$1.4million day^{-1} [\$2.3 million day^{-1} in 2013 dollars (Blattenberger and Fowles 1995)]"

– Campbell and Steenburgh (2014)

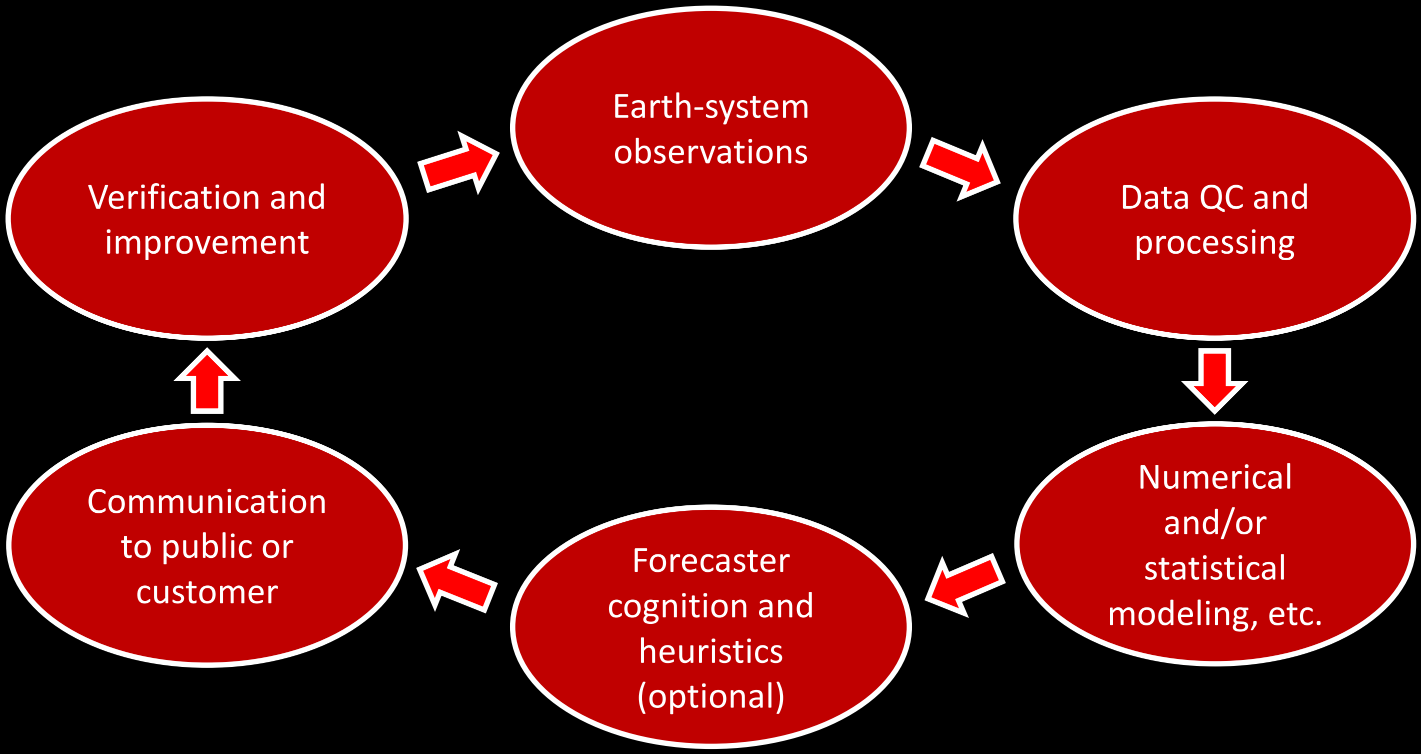
The Forecast Process



Data science contributes/can contribute in every component

https://www.dwd.de/EN/research/weatherforecasting/weatherforecasting_node.html

The Forecast Process (like a DS lifecyle)



*This is an oversimplification ☺

Nowcasting vs. Forecasting

- Nowcasting
  - Very-short (< 2 h) or short-range (< 6 h) forecasting
  - Based strongly on observation and extrapolation
  - Modern ML techniques playing an increasing role
    - E.g., radar nowcasting using deep learning

- Forecasting
  - Predictions > 6 h
  - Based strongly on numerical weather prediction models combined with statistical approaches
  - Modern ML techniques playing an increasing role

Nowcasting

Historical Radar Nowcasting

Geosci. Model Dev., 12, 1387–1402, 2019
https://doi.org/10.5194/gmd-12-1387-2019

Geoscientific Model Development
Open Access

Optical flow models as an open benchmark for radar-based precipitation nowcasting (rainymotion v0.1)

Georgy Ayzel[1], **Maik Heistermann**[1], **and Tanja Winterrath**[2]

[1]Institute for Environmental Sciences and Geography, University of Potsdam, Potsdam, Germany
[2]Department of Hydrometeorology, Deutscher Wetterdienst, Offenbach, Germany

Correspondence: Georgy Ayzel (ayzel@uni-potsdam.de)

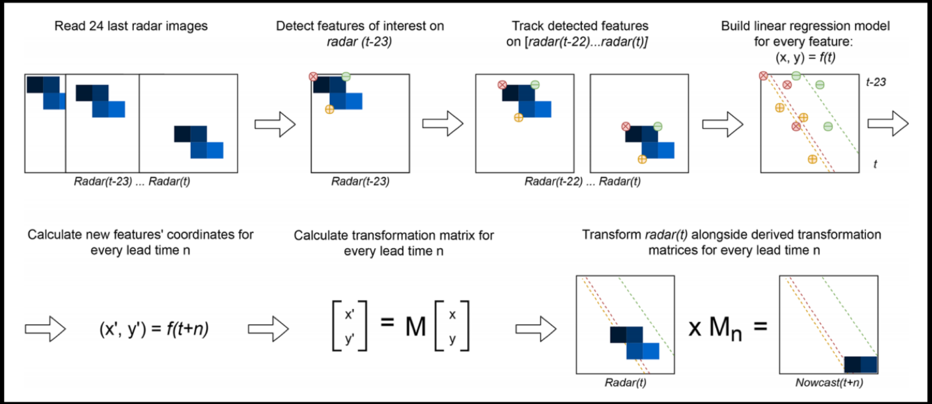
Received: 6 July 2018 – Discussion started: 10 September 2018
Revised: 21 March 2019 – Accepted: 21 March 2019 – Published: 9 April 2019

Lagrangian framework

Tracking and extrapolation

Optical Flow

Motion patterns inferred from series of images



Global Optical Flow (Ayzel et al. 2019)

New Approach: Deep Neural Network

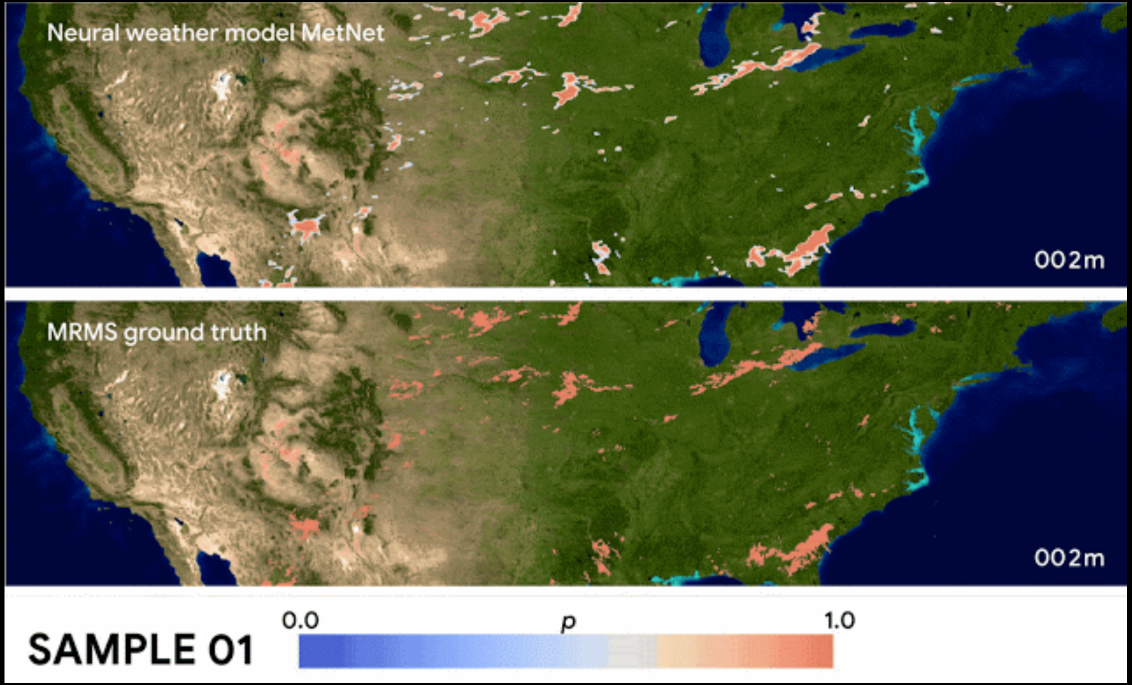
Google AI Blog

The latest news from Google AI

A Neural Weather Model for Eight-Hour Precipitation Forecasting

Wednesday, March 25, 2020

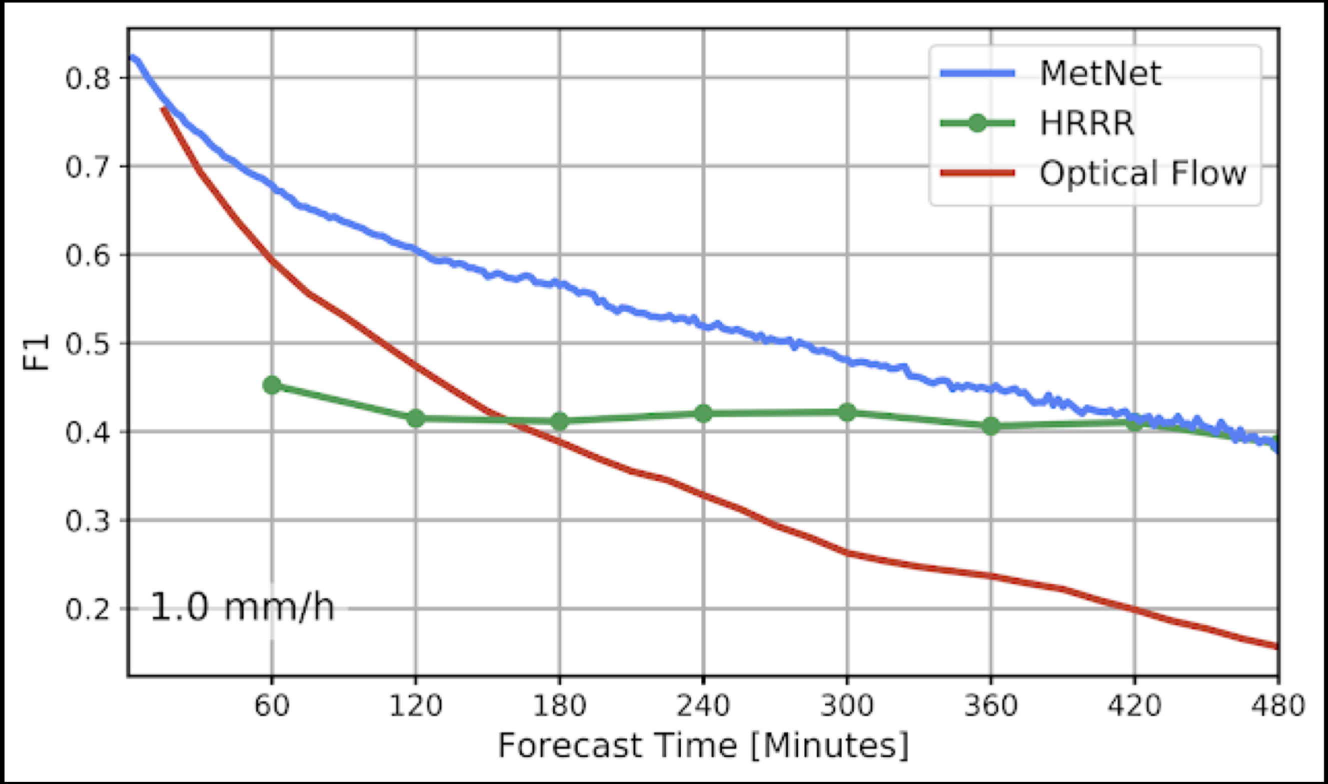
Posted by Nal Kalchbrenner and Casper Sønderby, Research Scientists, Google Research, Amsterdam



https://ai.googleblog.com/2020/03/a-neural-weather-model-for-eight-hour.html

Performance

Better

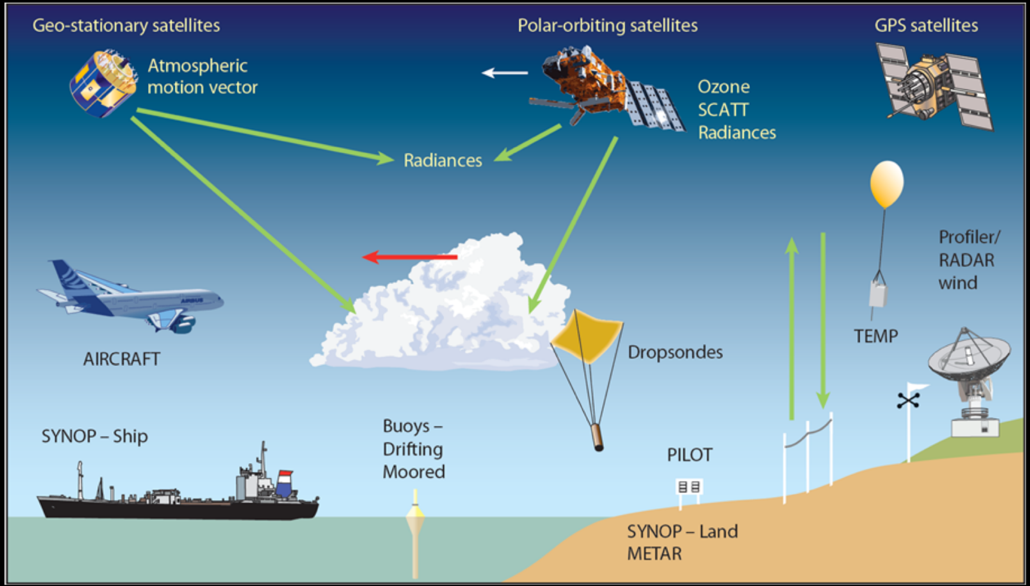


https://ai.googleblog.com/2020/03/a-neural-weather-model-for-eight-hour.html

Forecasting

Observations

Weather forecasting is an initial value problem



ECMWF processes and uses 40 million weather observations daily, most from satellite

https://www.ecmwf.int/en/research/data-assimilation/observations

Data Assimilation

Process of determining the best estimate of the initial state of the atmosphere, ocean, and land using prior forecasts and observations

Based on ABCs

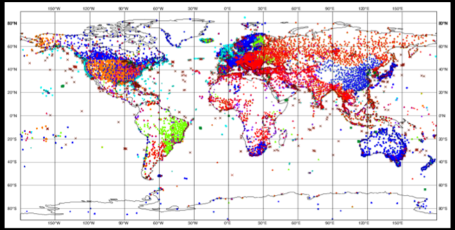
Analysis = Background + Correction

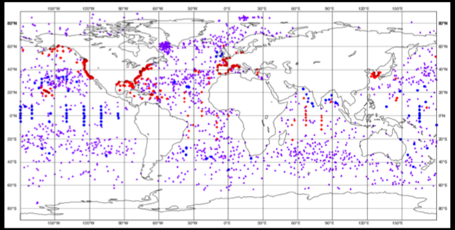
Initial State

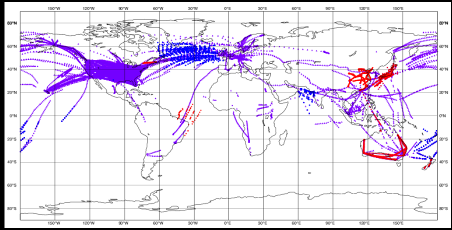
Prior Forecast

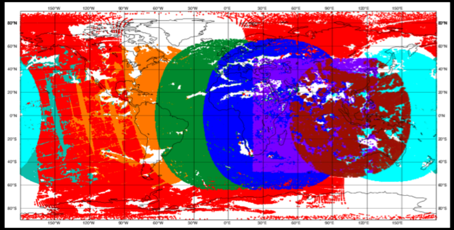
Adjustments Based On Observations

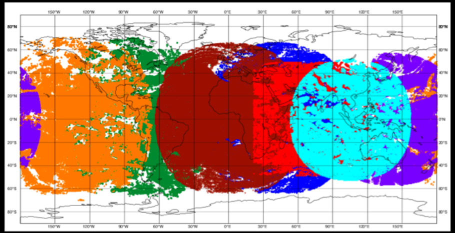
What Goes into a Weather Model?

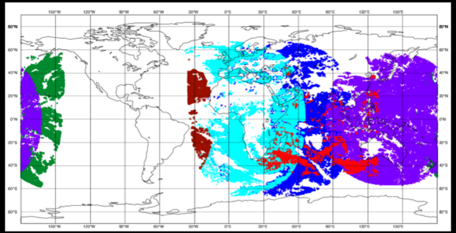

122,111 Surface Obs

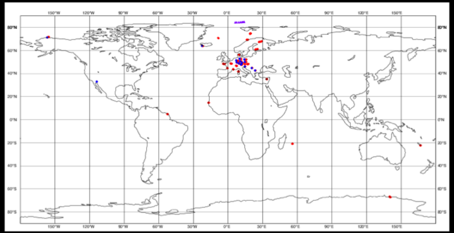

2,201 Buoy Obs

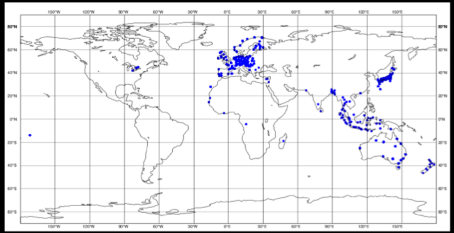

79,263 Aircraft Obs

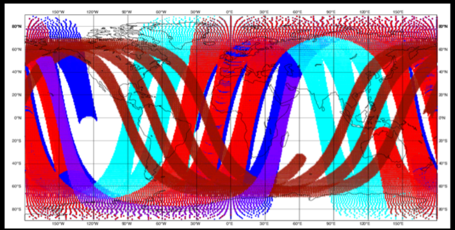

1,314,580 IR Wind Obs

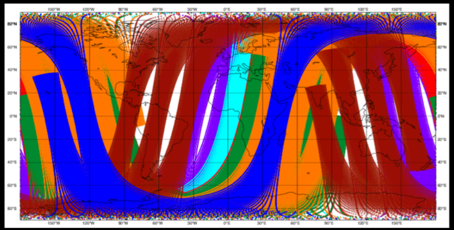

932,486 WV Wind Obs

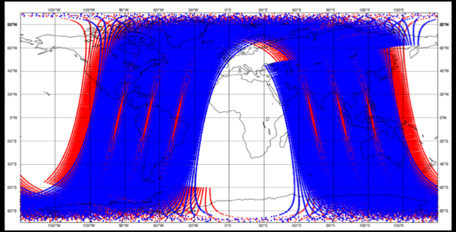

391,771 VIS Wind Obs

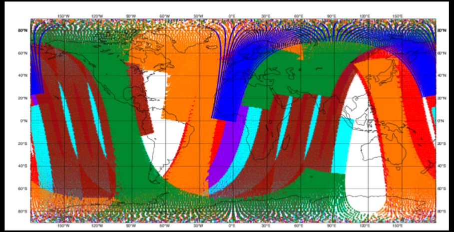

53 Weather Balloon Obs


3,069 PILOT Obs


155,294 Microwave Obs

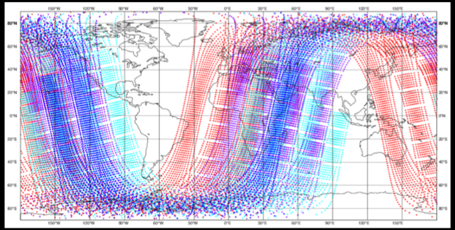

604,163 AMSU-A Obs

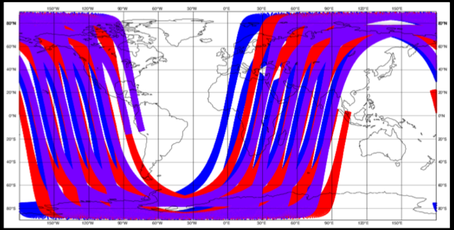

163,819 ATMS Obs

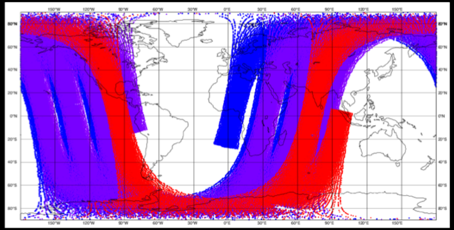

278,775 ATMS Obs

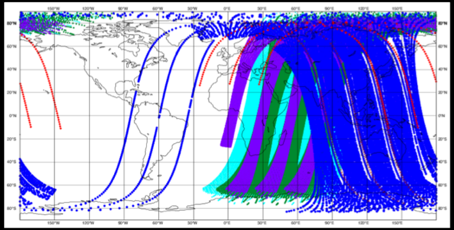
https://www.ecmwf.int/en/forecasts/charts/monitoring/dcover?facets=undefined&time=2020040306,0,2020040306&obs=synop-ship&Flag=all, 0600 UTC 3 Apr 2020 IFS Forecast

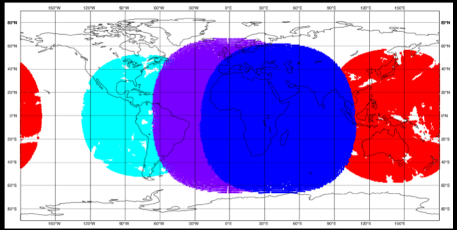
What Goes into a Weather Model?

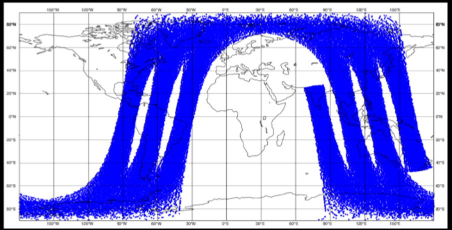

27,627 HIRS Obs

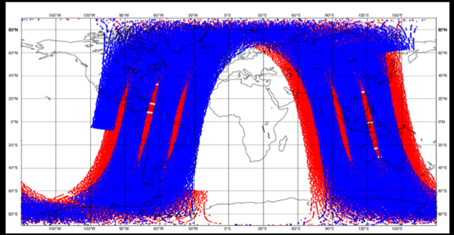

768,711 Scatterometer Obs

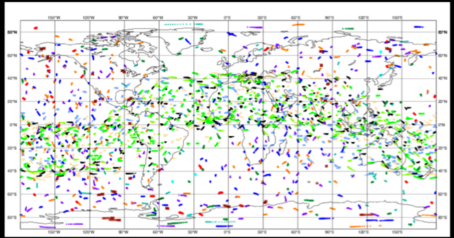

180,328 IASI Obs

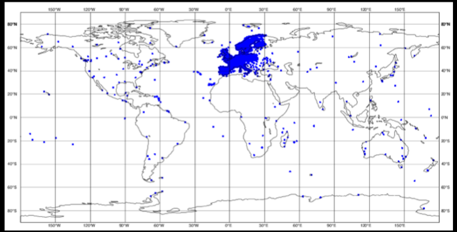

92,744 RESAT Obs

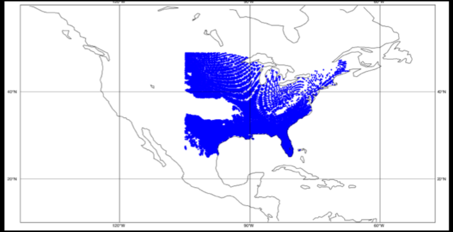

1,354,204 GEOS Radiance Obs

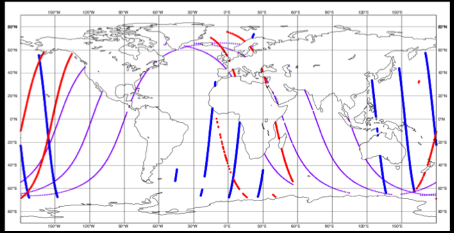

71,305 AIRS Obs

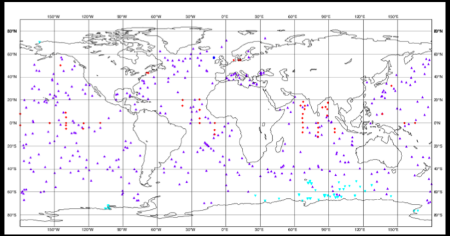

153,330 CRIS Obs


43,353 GPSRO Obs


150,816 Ground-Based GPS Obs

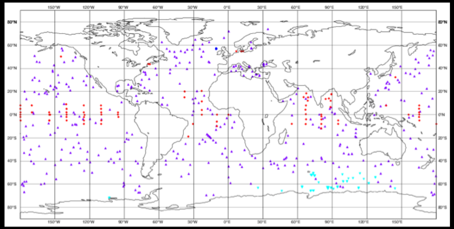

14,442 NEXRAD Precip Obs


2,507 Wave Height Obs

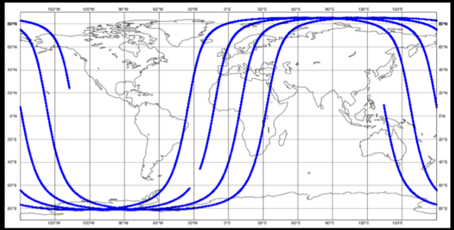

562 Salinity Obs

https://www.ecmwf.int/en/forecasts/charts/monitoring/dcover?facets=undefined&time=2020040306,0,2020040306&obs=synop-ship&Flag=all, 0600 UTC 3 Apr 2020 IFS Forecast

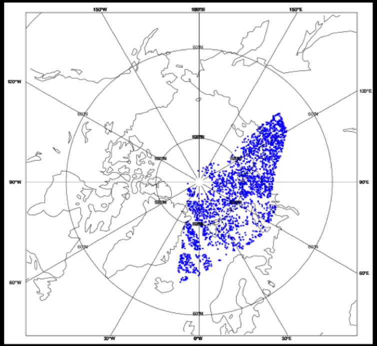
What Goes into a Weather Model?



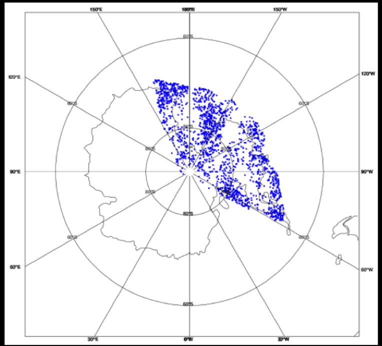
552 Potential Temperature Obs



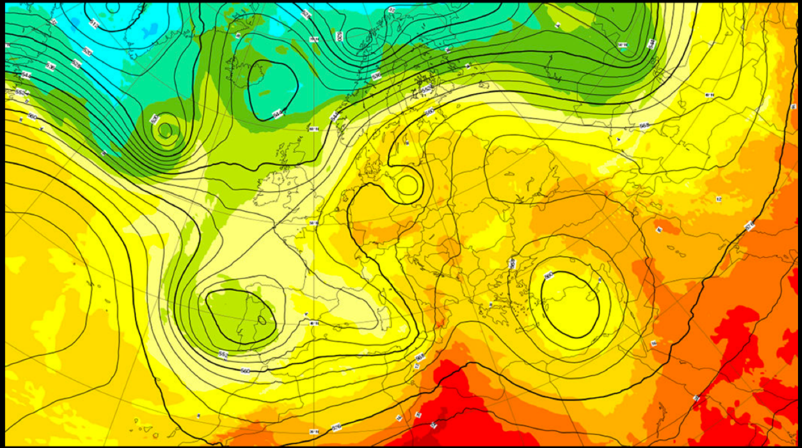
311,294 AEOLUS Obs



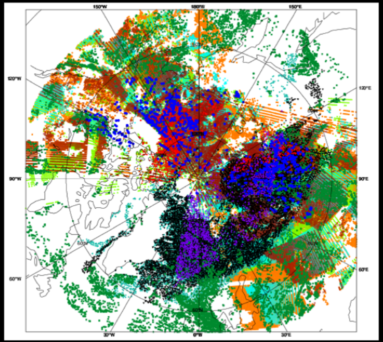
2,218 NH WV Polar Obs



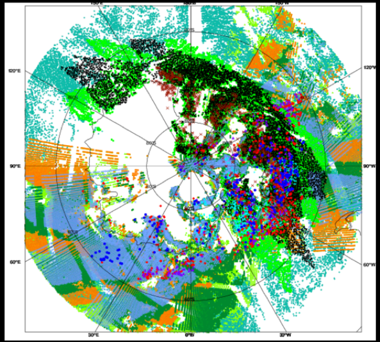
1,653 SH WV Polar Obs



Prior Short-Range (12-hour) Forecast



166,204 NH IR Polar Obs



183,499 SH IR Polar Obs

https://www.ecmwf.int/en/forecasts/charts/monitoring/dcover?facets=undefined&time=2020040306,0,2020040306&obs=synop-ship&Flag=all, 0600 UTC 3 Apr 2020 IFS Forecast

How It's Done: 4DVAR

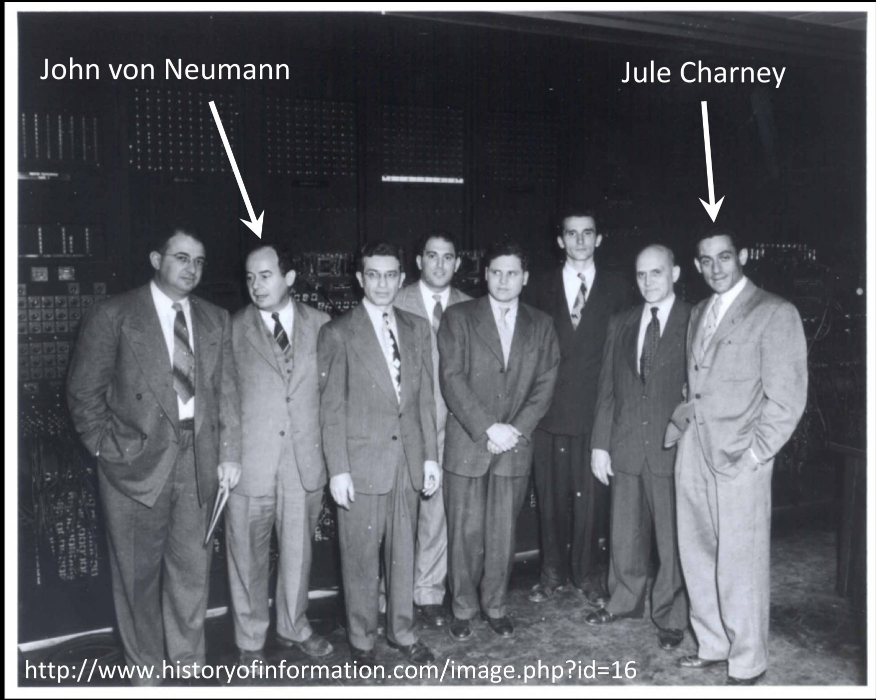
https://www.ecmwf.int/en/about/media-centre/news/2017/20-years-4d-var-better-forecasts-through-better-use-observations

Numerical Weather Prediction (NWP)

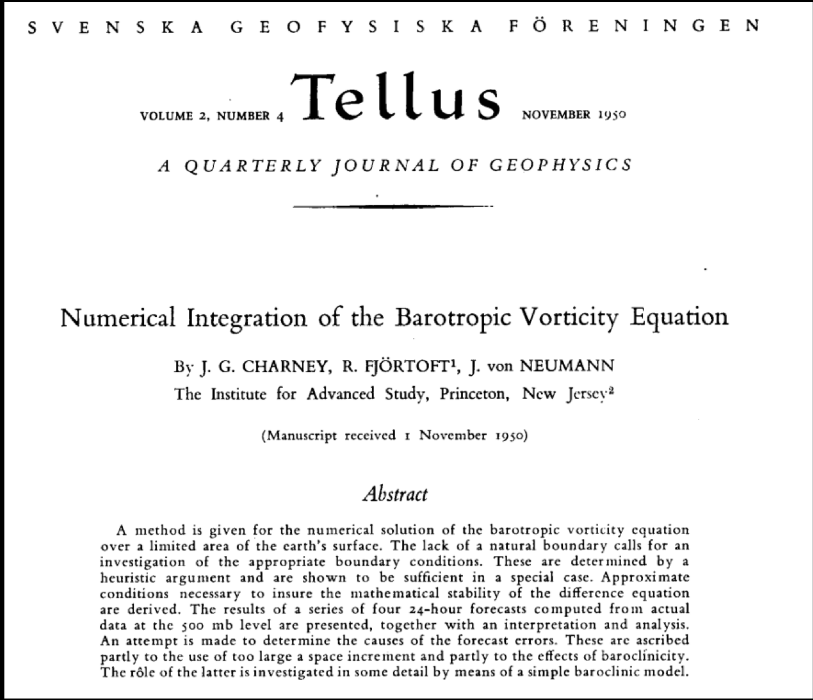
- The use of mathematical models of the atmosphere, oceans, land-surface, and other Earth-system components to predict the weather (Wikipedia 2012)

- Historically has been used to describe all activities involving the use of mathematical models to simulate atmospheric models, including research and other non-forecast applications (Warner 2011)

NWP History



ENIAC group in 1950


SVENSKA 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.

24 hours to produce a 24-hour forecast!

http://celebrating200years.noaa.gov/foundations/numerical_wx_pred/welcome.html, Wikipedia

Current Horsepower

54	ECMWF United Kingdom	Cray XC40, Xeon E5-2695v4 18C 2.1GHz, Aries interconnect Cray/HPE	126,468	3,944.7	4,249.3	1,897
55	ECMWF United Kingdom	Cray XC40, Xeon E5-2695v4 18C 2.1GHz, Aries interconnect Cray/HPE	126,468	3,944.7	4,249.3	1,897

ECMWF

Operational in June 2016

Two identical Cray XC40 Clusters

Each with…
Stripped-down Linux OS for
"extreme scalability"
126,468 compute cores
10 petabytes storage
350 gigabyte/s I/O
4,249.3 Rpeak Tflop/s

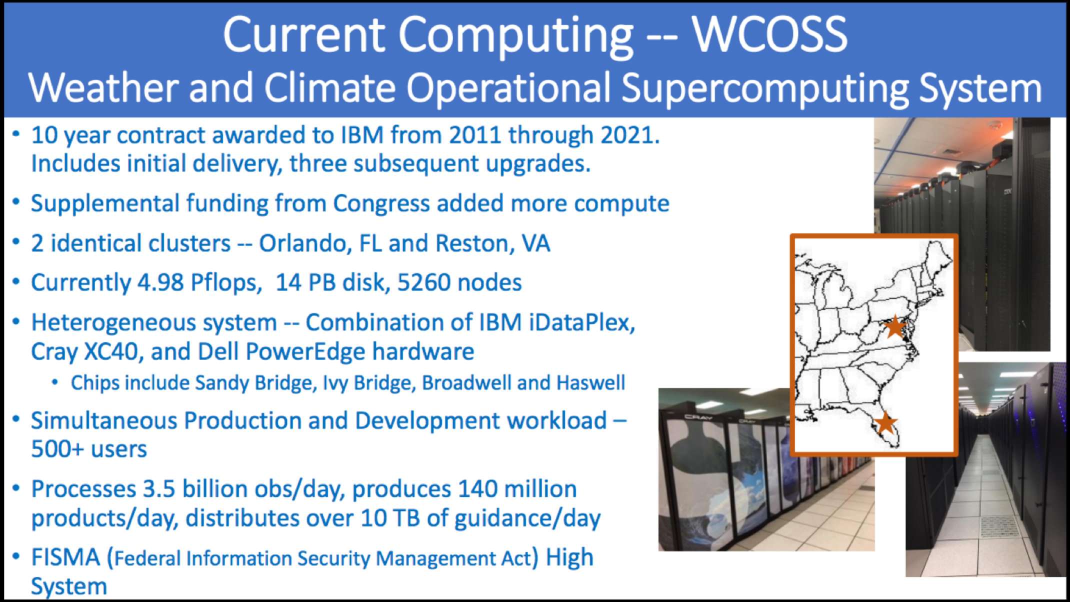
54 and 55th fastest in world in Nov 2019

https://www.ecmwf.int/en/computing/our-facilities/supercomputer, top500.org

Current Horsepower

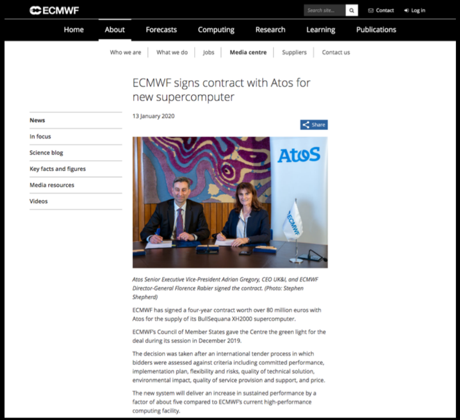
United States

National Centers for Environmental Prediction (NCEP)



https://www.ecmwf.int/sites/default/files/elibrary/2018/18607-supercomputing-us-national-weather-service.pdf (talk by Rebecca Cosgrove, 2018)

Future Horsepower


ECMWF

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ECMWF signs contract with Atos for new supercomputer

13 January 2020

Atos Senior Executive Vice-President Adrian Gregory, CEO UK&I, and ECMWF Director-General Florence Rabier signed the contract. (Photo: Stephen Shepherd)

ECMWF has signed a four-year contract worth over 80 million euros with Atos for the supply of its BullSequana XH2000 supercomputer.

ECMWF's Council of Member States gave the Centre the green light for the deal during its session in December 2019.

The decision was taken after an international tender process in which bidders were assessed against criteria including committed performance, implementation plan, flexibility and risks, quality of technical solution, environmental impact, quality of service provision and support, and price.

The new system will deliver an increase in sustained performance by a factor of about five compared to ECMWF's current high-performance computing facility.

ECMWF 13 January 2020

Contract signed with ATOS for new computer that will increase performance 5 fold

NOAA 20 February 2020

Contract signed with ATOS for new computer that will increase performance 3 fold


National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Search NOAA sites

Home / News & Features

U.S. to triple operational weather and climate supercomputing capacity

Computing upgrade paves way for planned model improvements

Weather | modeling forecasting supercomputing/IT

February 20, 2020 — The United States is reclaiming a global top spot in high-performance computing to support weather and climate forecasts. NOAA, part of the Department of Commerce, today announced a significant upgrade to computing capacity, storage space, and interconnect speed of its Weather and Climate Operational Supercomputing System. This upgrade keeps the agency's supercomputing capacity on par with other leading weather forecast centers around the world.

https://www.ecmwf.int/en/about/media-centre/news/2020/ecmwf-signs-contract-atos-new-supercomputer
https://www.noaa.gov/media-release/us-to-triple-operational-weather-and-climate-supercomputing-capacity

Components of an NWP System

- Governing system of equations (i.e., “dynamics”)
  - Conservation of mass, momentum, energy
  - Equation of state
  - Conservation of water
    - E.g., vapor, cloud water, cloud ice, precipitation
  - Solution involving Reynolds averaging, numerical approximation, and discretization

Warner (2011)

Components of an NWP system

- Parameterizations for processes that cannot be directly simulated (i.e., “physics”)
  - Cloud microphysics
  - Convection (grid spacings > ~4 km)
  - Turbulence
  - Radiation (solar & terrestrial)
  - Land surface

Warner (2011)

Components of an NWP system

- Coupling with oceanic, cryospheric, hydrologic or other mathematical models of Earth-system components

- Data assimilation
  - Creation of initial conditions
  - Can be continuous or intermittent

- Lateral boundary conditions
  - Limited area models

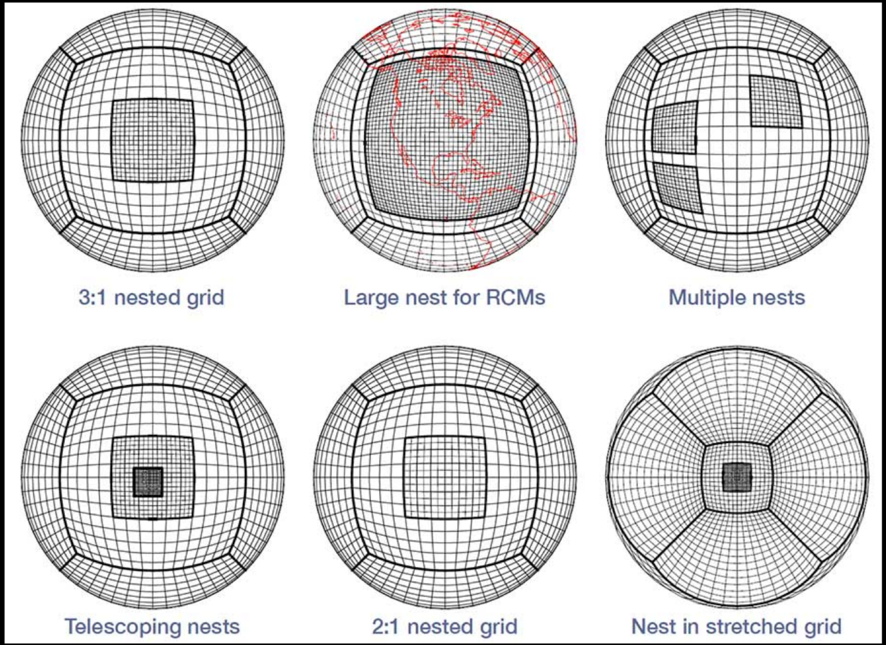
Warner (2011)

Numerical Frameworks

- Finite difference
  - E.g., rectangular, triangular, lat-lon, icosahedral
- Spectral
- Finite element
- Finite volume

US Unified Forecast System

Based on the FV3 Finite-Volume, Cubed Sphere Dynamical Core



https://www.gfdl.noaa.gov/fv3/

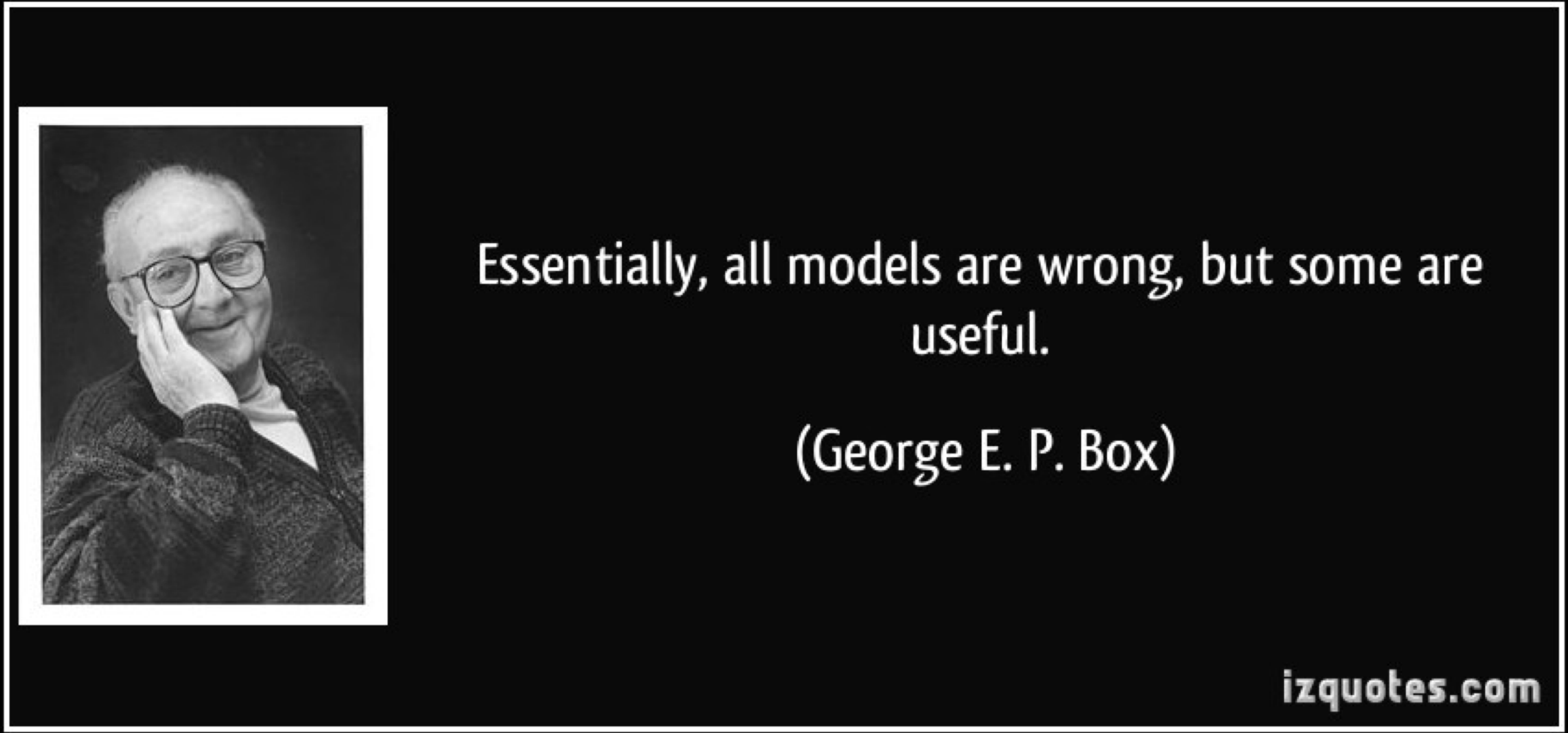
Hindcast of 2008 Hurricane Season

13-km grid spacing (current operational spacing)

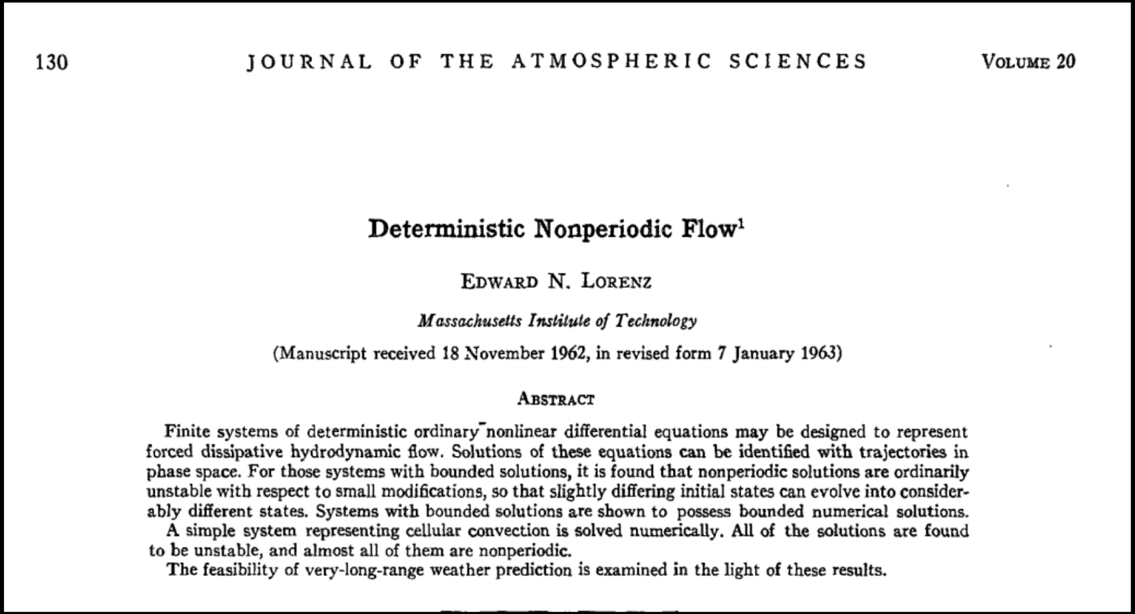
Research Simulation: EF5 Tornado

Simulation by Leigh Orf, University of Wisconsin–Madison/CIMSS

However…


Essentially, all models are wrong, but some are useful.
(George E. P. Box)
izquotes.com

However…



130 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 20

Deterministic Nonperiodic Flow[1]

EDWARD N. LORENZ

Massachusetts Institute of Technology

(Manuscript received 18 November 1962, in revised form 7 January 1963)

ABSTRACT

Finite systems of deterministic ordinary nonlinear differential equations may be designed to represent forced dissipative hydrodynamic flow. Solutions of these equations can be identified with trajectories in phase space. For those systems with bounded solutions, it is found that nonperiodic solutions are ordinarily unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states. Systems with bounded solutions are shown to possess bounded numerical solutions.

A simple system representing cellular convection is solved numerically. All of the solutions are found to be unstable, and almost all of them are nonperiodic.

The feasibility of very-long-range weather prediction is examined in the light of these results.

"Slightly differing initial states can evolve into considerably different solutions"

- Lorenz (1963), "Father of Chaos Theory"

Sources of Error

- Initial condition uncertainty
  - Atmosphere, land surface, sea surface...
- Model uncertainty and approximations
  - Physical parameterizations
  - Numerics, discretization, etc.

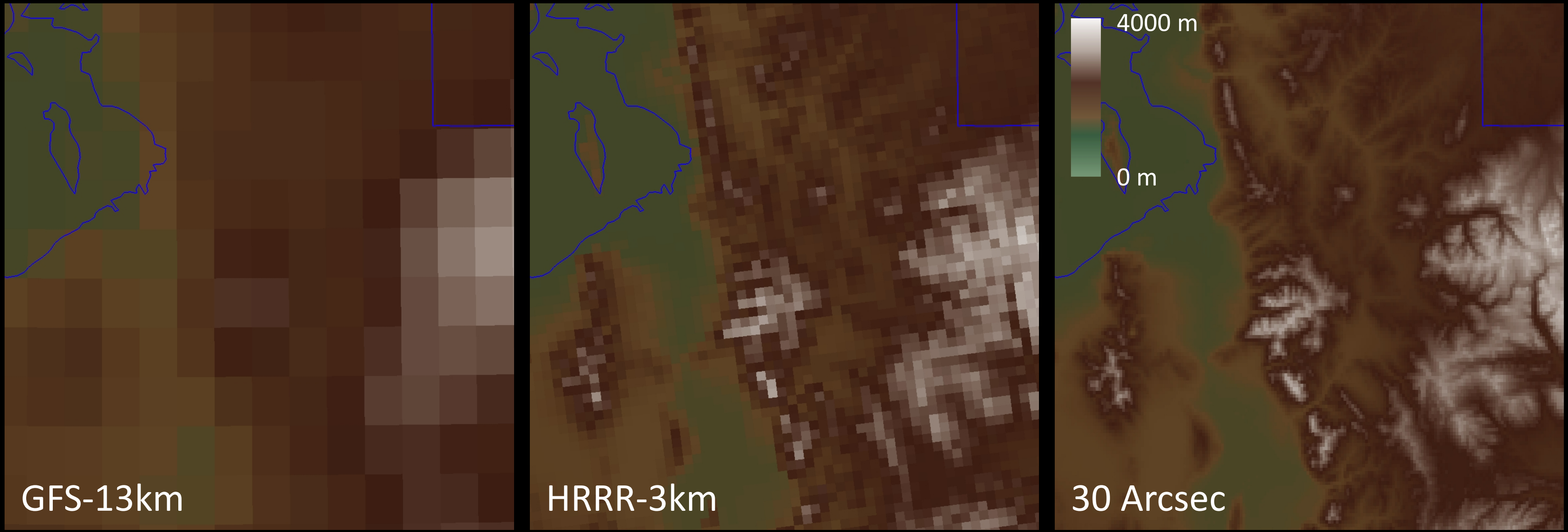
Ensemble Prediction

Enables calculation
of probabilities and
quantification
of uncertainty

However…

- There still are problems
  - Systematic errors and biases
  - Poorly represented phenomenon and processes

Example: Topographic Processes



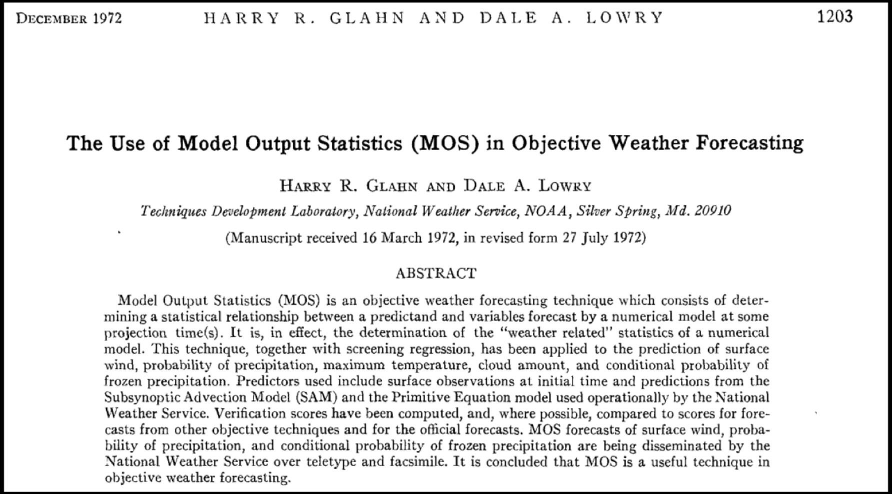
Example: Topographic Processes

Model Postprocessing

- Statistical and other techniques to improve NWP-derived forecasts

- Except at very-short lead times, a combination of NWP and statistical approaches typically outperforms NWP or statistical approaches alone
  - "Stochastic-Dynamic Prediction" (Epstein 1969)

Model Postprocessing



DECEMBER 1972 HARRY R. GLAHN AND DALE A. LOWRY 1203

The Use of Model Output Statistics (MOS) in Objective Weather Forecasting

HARRY R. GLAHN AND DALE A. LOWRY

Techniques Development Laboratory, National Weather Service, NOAA, Silver Spring, Md. 20910

(Manuscript received 16 March 1972, in revised form 27 July 1972)

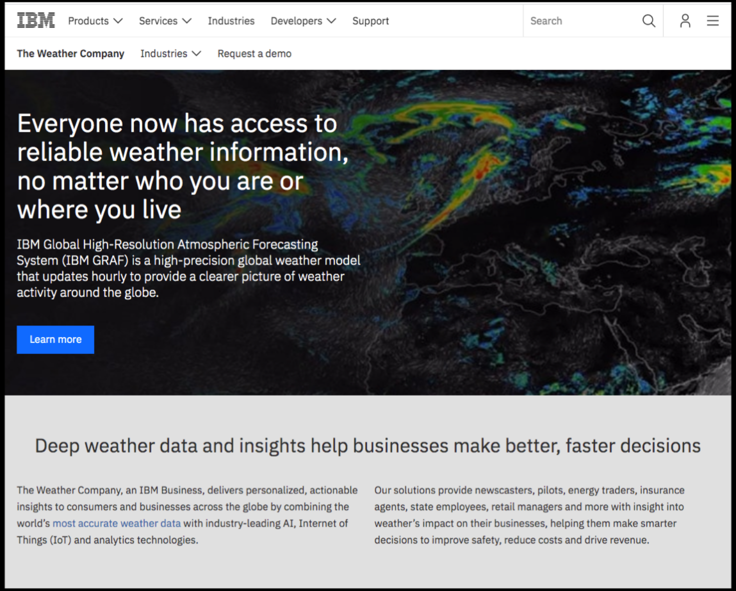
ABSTRACT

Model Output Statistics (MOS) is an objective weather forecasting technique which consists of determining a statistical relationship between a predictand and variables forecast by a numerical model at some projection time(s). It is, in effect, the determination of the "weather related" statistics of a numerical model. This technique, together with screening regression, has been applied to the prediction of surface wind, probability of precipitation, maximum temperature, cloud amount, and conditional probability of frozen precipitation. Predictors used include surface observations at initial time and predictions from the Subsynoptic Advection Model (SAM) and the Primitive Equation model used operationally by the National Weather Service. Verification scores have been computed, and, where possible, compared to scores for forecasts from other objective techniques and for the official forecasts. MOS forecasts of surface wind, probability of precipitation, and conditional probability of frozen precipitation are being disseminated by the National Weather Service over teletype and facsimile. It is concluded that MOS is a useful technique in objective weather forecasting.

<u>Old School (Glahn and Lowry 1972)</u>

Model Output Statistics (MOS)

Use of screening regression to improve NWP forecasts at specific locations



<u>IBM/The Weather Company 2020</u>

Combining weather data with "industry-leading AI"

Data Science and NWP at ECMWF

- Examples of use of ML at ECMWF
  - Bias correction of satellite observations
  - Learning model error within data assimilation
  - Emulation of model components to increase computational efficiency
  - Downscaling of model output
  - Monitoring IT infrastructure

ECMWF Archival System (Dec 2018)
225 Petabytes
250 Terabytes added daily

https://www.ecmwf.int/en/computing/our-facilities/data-handling-system
https://www.ecmwf.int/en/about/media-centre/news/2020/seminars-probe-potential-machine-learning-weather-prediction

Data Science and NWP at ECMWF

- ML seminars start 28 April
  - https://www.ecmwf.int/en/learning/workshops/machine-learning-seminar-series

<u>ECMWF Archival System (Dec 2018)</u>
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Summary

- Weather affects every sector of the economy
- Forecasting is a “big data science” — we need you
- It’s beneficial to society and there’s money to be made!

Sessions at 2020 AMS Meeting

- How Artificial Intelligence at Scale Will Link Weather and Climate Data to Society
- Applications of Machine Learning in Earth System Modeling
- Deep Learning Applications for Environmental Science
- AI Applied to Airborne or Spaceborne Earth Observation Datasets
- High-Impact Weather Prediction with AI
- AI and Climate: Impact and Opportunities
- AI Applications for the Detection of Earth Science Phenomena
- Transitioning Artificial Intelligence (AI) Prediction Systems to Operations
- AI in Radar Observations
- Tropical Cyclone Analysis and Prediction with Machine Learning
- Machine Learning for Subgrid Parameterization in Weather and Climate Models
- Machine Learning for Subseasonal to Seasonal Prediction
- Advances in the Use of Artificial Intelligence Techniques in Support of Aviation, Range, and Aerospace Meteorology
- AI for decision support