Exploring High Performance Computing in Numerical Weather Prediction and Climate Modeling

By: Krish Patel

Introduction

- **Transforming Meteorology**
  - HPC has revolutionized weather and climate prediction.
  - Enables processing of vast atmospheric data for real-time weather prediction.
  - Can model long term climate effects for policy planning and climate change adaptation.
- **Faces Challenges**
  - Requires consistent Software Investment.
  - Requires low latency handling of large quantities of daily produced data.
  - Produces a large carbon footprint and has a consistently large energy requirement.
- **Critical Infrastructure**
  - Modern meteorology depends on supercomputing capabilities.
  - Supports operational forecasting and climate research worldwide.
  - Can impact public safety, economic decisions, and policy planning.

Early Beginnings

The Idea of forecasting weather dates to 1904 when Vilhelm Bjerknes suggested it was possible to forecast the weather by solving differential equations.

Attempted by Lewis Fry Richardson during WW1 when he spent 6 weeks computing by hand the change in pressure at a single point over a six-hour period.

Richardson foresaw a “forecast factory” where 64,000 humans each responsible for a small section of the world would forecast the weather.

Computer Era

1948 - John Von Neumann assembles a group of theoretical meteorologists headed by Jule Charney to create a model of the atmosphere.

1950 – First one-day weather prediction was made on ENIAC proving to the meteorological community that numerical weather prediction was feasible.

1954 – Real time numerical weather predictions is under serious consideration, and as such the JNWPU (Join Numerical Weather Prediction Unit) is created.

1955 - The JNWPU by using the IBM 701 can make numerical weather predictions twice a day, however they still lagged behind weather predictions being made manually.

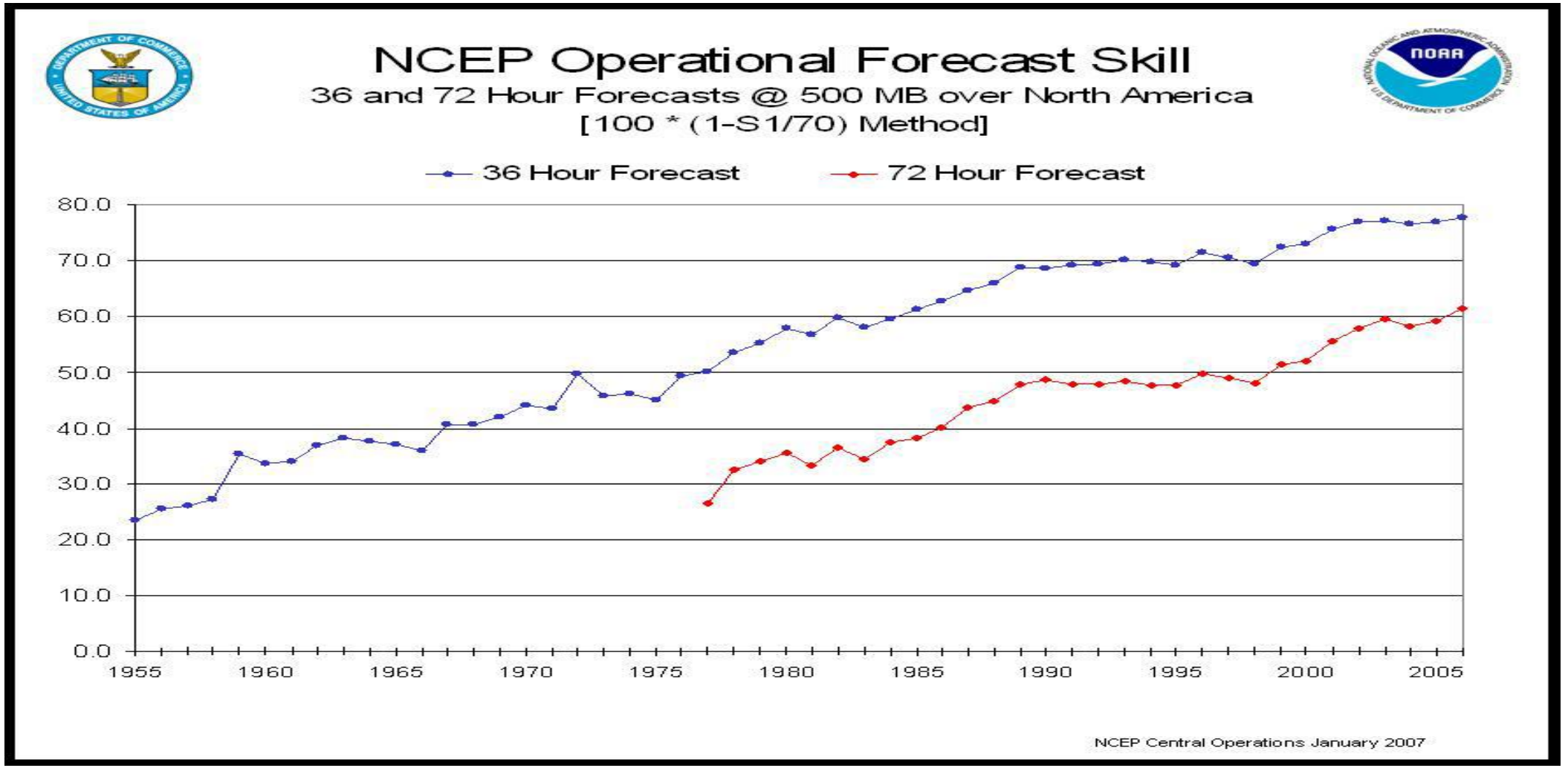
Supercomputing Era

1975 – ECMWF(European Centre for Medium-Range Weather Forecasts) is established utilizing the CRAY series of supercomputers for weather prediction.

2002 - Japan's Earth Simulator (35.9 teraflops) revolutionizes climate modeling and studies effects of global warming.

Present – E3SM running on Frontier an Exascale supercomputer pushes the boundaries of weather prediction models with the most detailed predictions to date!

Improvement of Models Visualized



Graph 1: An example of the improvements of 36hr and 72hr forecasts. The 72hr forecasts of 2007 are just as accurate as the 36hr forecasts of 1985 showcasing a large improvement with the advancements of HPC.

Numerical Weather Prediction

- Using HPC we run millions of mathematical equations to determine weather patterns over a certain area.
- Global Models although less accurate can provide a prediction for large areas of space (10-25km).
- Regional Models require more compute but can provide weather predictions for smaller areas with more detail. Which is much more useful for determining weather events such as thunderstorms which happen over smaller areas (1-3km).

Evolution of HPC throughout the Years

- Great improvement in resolution over the past few decades going from 500 Flops with a resolution of 700km to current E3SM model running on Frontier being able operate at Exaflop speeds and generating climate simulations accurate to 3km!

YEAR	HPC SYSTEM (SPEED)	CAPABILITY (SIZE OF AREA)
1950	ENIAC (500 Flops)	700km Resolution (First 1 day weather forecast)
1979	CRAY 1 (160 MFlops)	200km Resolution (First to add vector processing)
2002	Earth Simulator (35 TFlops)	15km Resolution
2023	Atos (250 PFlops)	9km Resolution (Used ensemble learning for more accurate results)
2023	E3SM(Model on Frontier) (10 ^ 18 Flops)	3km Resolution (Current most accurate model)

- Table 1: Showcases HPC systems with their respective flops and the resolution of the weather forecasts generated.

Numerical Weather Prediction cont.

Global models such as the U.S. GFS (Global Forecast System) and the European IFS (Integrated Forecasting System) can produce forecasts of 10-15 days and are run 2-4 times a day.

Some global models such as the ECMWF's Ensemble model use Ensemble learning to run the same model with different starting conditions to find which weather conditions are more likely to occur.

Weather Forecast Model

- Shows how HPC models the weather in certain regions in this case with a spacing of 10-20km.
- The model extends the grids outwards using HPC to calculate not only the grids at surface level but every 10-20km into the air as well.

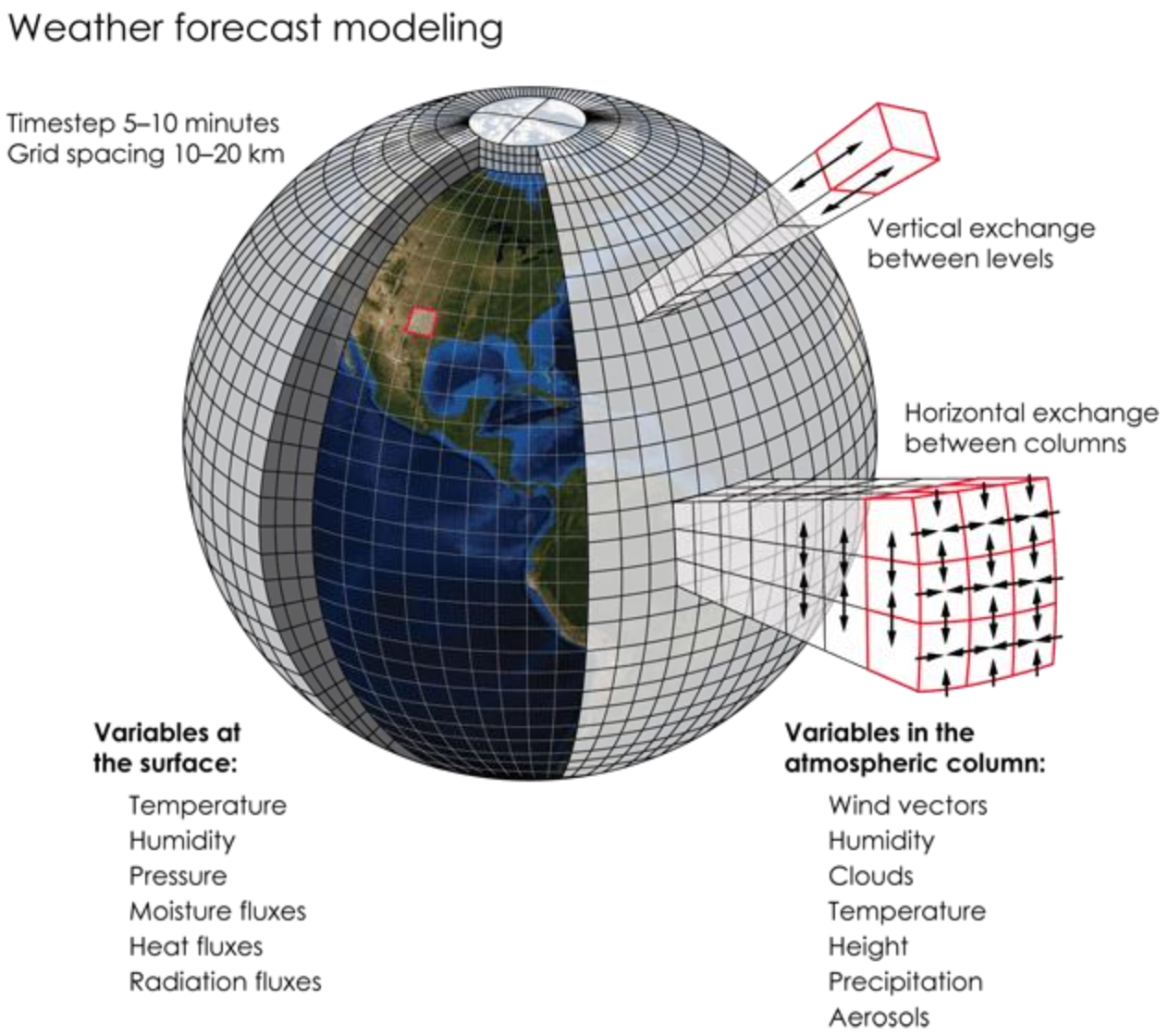
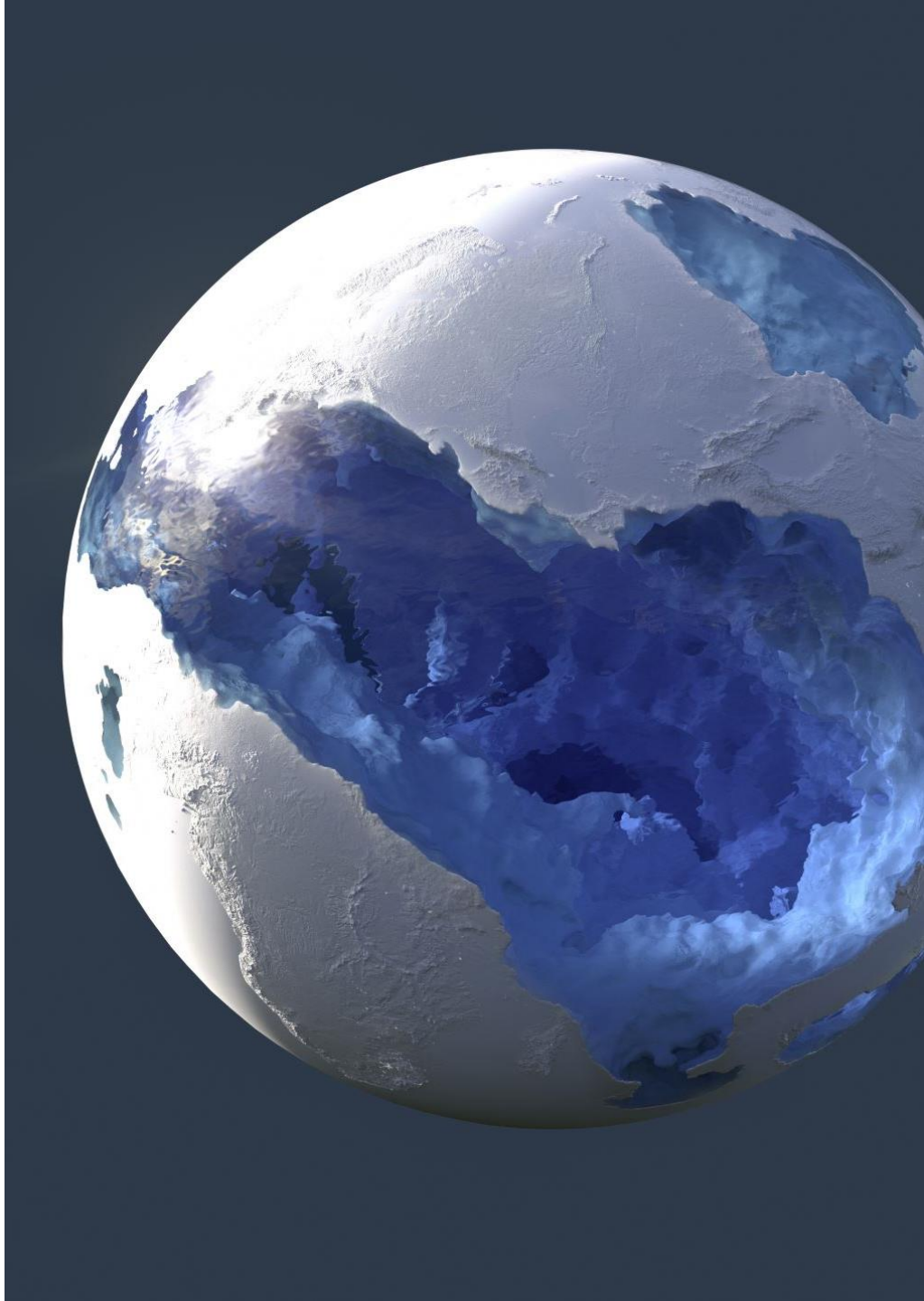


Figure 2: An image showing what forecast modeling does and how what parameters it uses. Current forecast models are pushing the limits of HPC to produce forecasts at smaller and smaller Grid spacings. (In the image above, we have spacings of 15-20km visualized, but the best of today can reach spacings as low as 3km!) Credit: K. Cantner, AGI.

Climate Simulation/Earth System Modeling

- Uses HPC to simulate the climate over long periods of times (years, decades, centuries).
- Takes in various considerations outside the scope of weather prediction such as human influence of greenhouse gases.
- The Department of Energy's E3SM can simulate the Earths climate factoring in data as complex as human influence to the scale of 3km while running on Frontier a supercomputer operating at 10 ^ 18 flops (Exaflop).



ICON Climate Simulation EU H2020

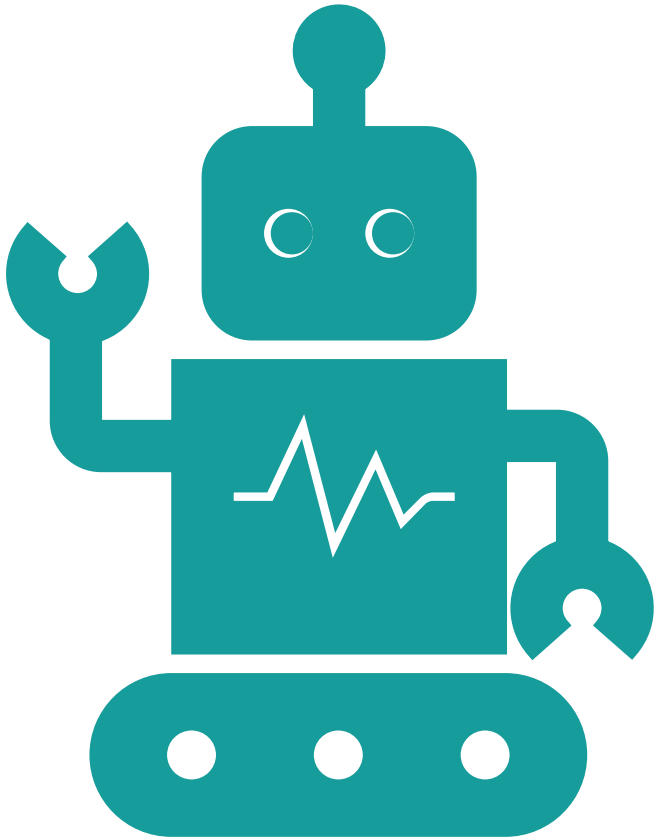
Video: This simulation performed with the ICON weather and climate model in the EU H2020 project nextGEMS covers a 5 year period starting in January 2020. The model consists of atmosphere and ocean components, both running on the same 5 km resolution grid.

Software Investment

- Software Investment
  - New systems will need to focus on designing, developing, and deploying new software for their models.
  - Requires research into areas such as libraries, compilers, operating systems, job schedulers.
  - Requires billions of dollars in funding and Years of research with every new model.

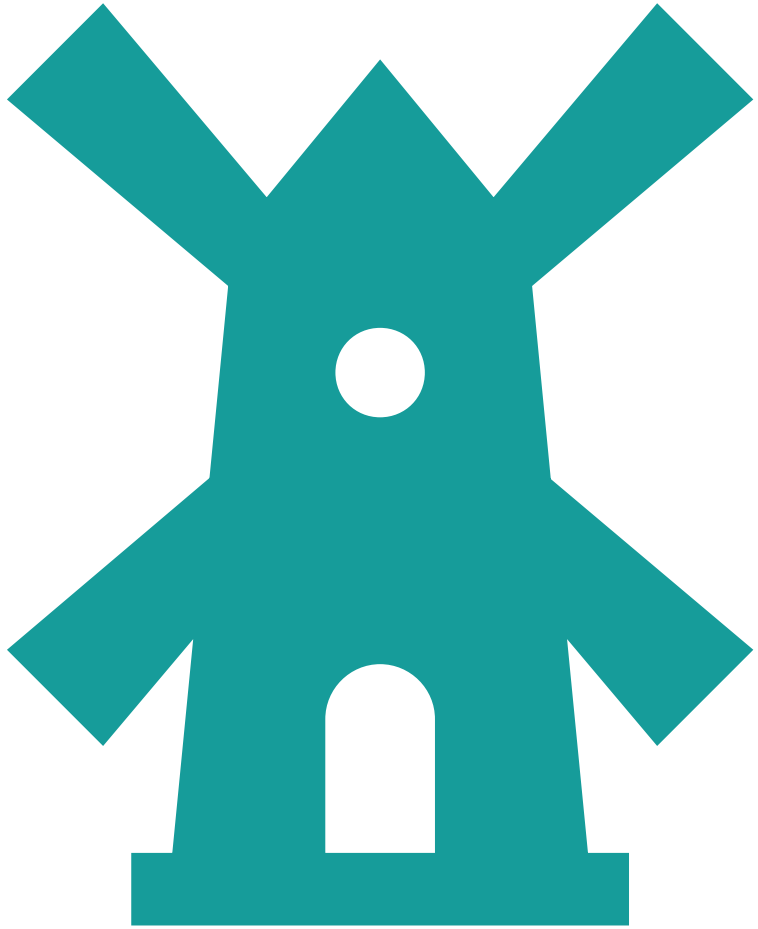
Data Handling

- High-resolution models generate petabytes of data.
- Machines face massive storage and transfer challenges requiring a need for low latency data access.
- Due to the unique operational requirements of being run multiple times per day every day amplifies this challenge.



Energy / Environmental Impact

- Running weather prediction models require large amounts of energy daily.
- 29MW supercomputer produces ~100,000 tons of carbon annually and this is only increasing.
- Research and funding will be required for more energy efficient systems.



Conclusion

- **HPC: The Foundation of Modern Meteorology**
  - Transformed weather prediction from theoretical concept to reality with HPC.
  - Enables increasingly accurate and timely forecasts at multiple scales.
  - Provides critical insights into climate variability and change.
- **Persistent Challenges**
  - Software Investment for new systems.
  - Managing growth in data volume with more complex models.
  - Addressing energy consumption and environmental impacts.
- **Societal Impact**
  - Better weather forecasts can save lives and resources.
  - Enhanced climate projections inform critical long-term planning.
  - HPC investments in meteorology deliver substantial public benefits.

Sources

- National Oceanic and Atmospheric Administration. (2006, December 12). *The history of Numerical Weather Prediction*. NOAA 200th Foundations: Weather, Ocean, and Climate Prediction. https://celebrating200years.noaa.gov/foundations/numerical_wx_pred/welcome.html#:~:text=The%20first%20one,numerical%20weather%20prediction%20was%20feasible
- Meteomatics. (2024). *What is numerical weather prediction?*. meteomatics. https://www.meteomatics.com/en/weather-model-europe/what-is-numerical-weather-prediction/
- National Oceanic and Atmospheric Administration. (2021). *Global Forecast System*. GFS. https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php
- Met Office. (n.d.). *What is an ensemble forecast?* https://www.metoffice.gov.uk/research/weather/ensemble-forecasting/what-is-an-ensemble-forecast
- ECMWF. (2023, July 24). *ECMWF high-performance computing facility boosts forecasts and research*. https://www.ecmwf.int/en/about/media-centre/focus/2023/ecmwf-high-performance-computing-facility-boosts-forecasts-and#:~:text=ECMWF's%20medium,twice%20a%20week%20to%20daily
- Department of Energy. (n.d.). *Doe explains...Earth system and climate models*. Energy.gov. https://www.energy.gov/science/doe-explainsearth-system-and-climate-models
- Bader, D. C., & Taylor, M. A. (2023, April 6). *Revolutionizing earth system modeling through Exascale Computing • SC23*. SC23. https://sc23.supercomputing.org/2023/04/revolutionizing-earth-system-modeling-through-exascale-computing/#:~:text=more%20focused%20approach%20to%20studying,regional%20climate%20change%20impacts
- Govett, M., Bah, B., Bauer, P., Berod, D., Bouchet, V., Corti, S., Davis, C., Duan, Y., Graham, T., Honda, Y., Hines, A., Jean, M., Ishida, J., Lawrence, B., Li, J., Luterbacher, J., Muroi, C., Rowe, K., Schultz, M., … Williams, K. (2024). Exascale computing and Data Handling: Challenges and opportunities for weather and climate prediction. *Bulletin of the American Meteorological Society*, *105*(12). https://doi.org/10.1175/bams-d-23-0220.1
- https://www.youtube.com/watch?v=-l_N8nT9Bnc&t=11s