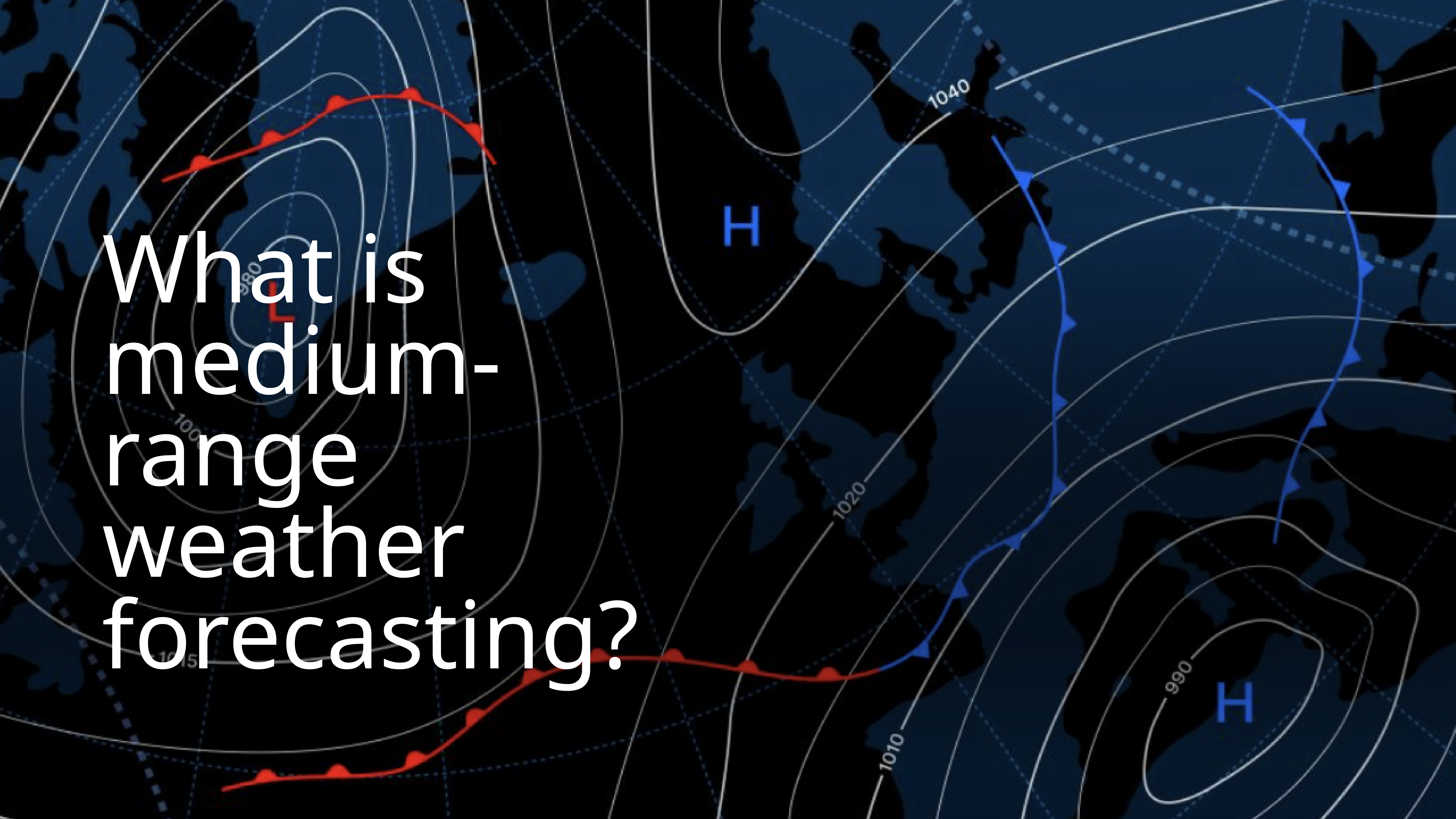
Learning skillful medium-range global weather forecasting

What is medium-range weather forecasting?



Medium-range forecasting covers 3 to 15 days ahead - this extended definition reflects modern capabilities.

It started becoming possible only in the 1960s with weather satellite

ECMWF was founded specifically for this challenge in 1975

This is the critical window for disaster planning and major decision

Why Is It So Difficult?

The Butterfly Effect:

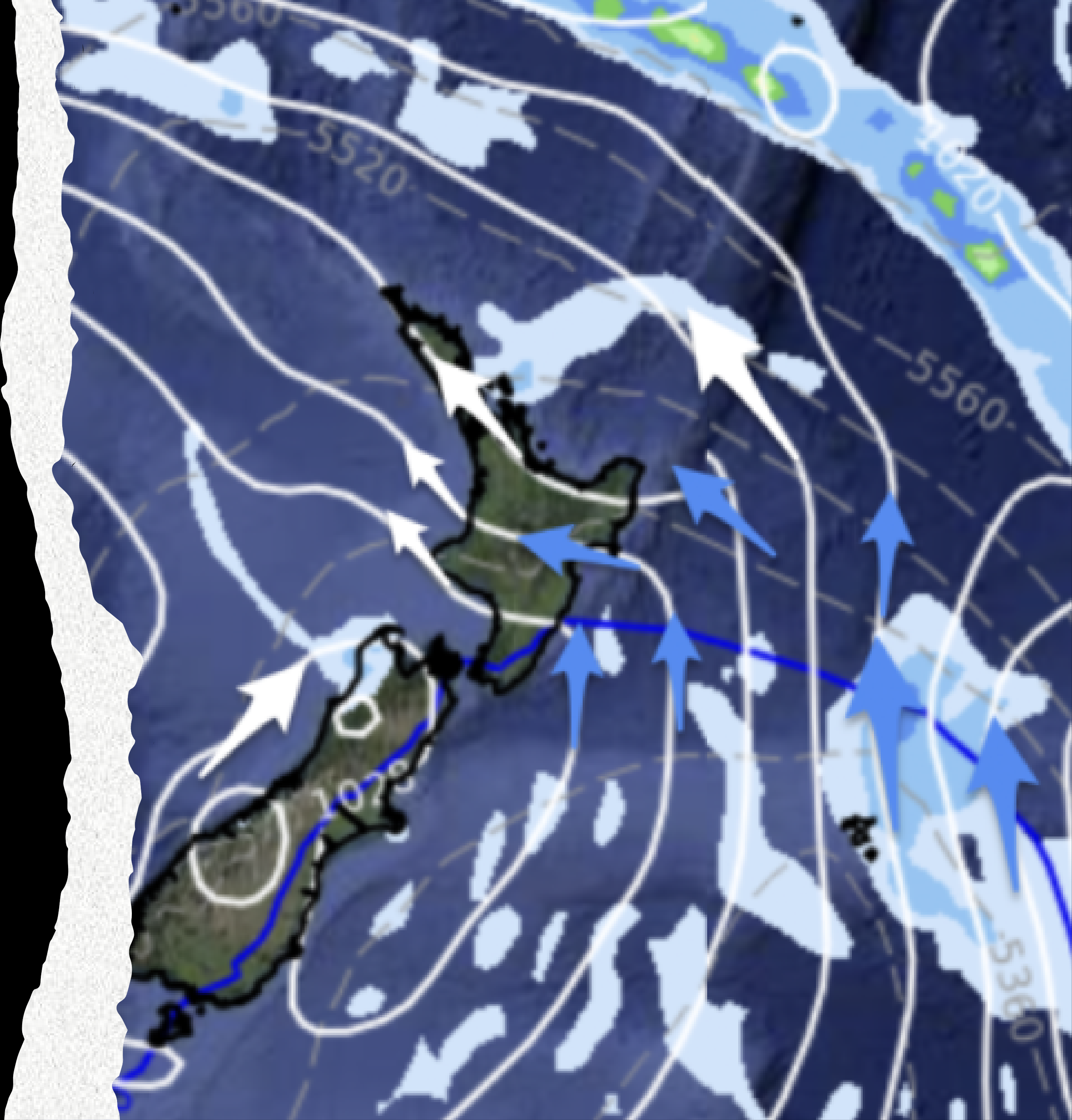
- Small errors "double roughly every five days" according to World of Weather e-education.
- Tiny measurement mistakes become huge prediction errors

Atmospheric Chaos:

- Weather is chaotic - mathematically unpredictable beyond limits
- Complex fluid dynamics equations break down over time

Traditional Limits:

- Forecasts do not exhibit useful skill beyond eight days
- Physics-based models hit a performance wall at day 7-8



Why This Type of Forecasting Important?

Disaster Preparation:

- Hurricane evacuation planning (7-10 day lead time needed)
- For example, ECMWF predicted Hurricane Sandy's landfall "seven days in advance"
- Flood warnings and emergency response coordination

Agriculture:

- Planting and harvest timing decisions
- Crop protection from weather threats
- Irrigation and resource planning

Energy Sector:

- Renewable energy forecasting (wind/solar)
- Power grid demand planning
- Energy trading and pricing decisions

Economic Impact:

- Better forecasts provide better severe event prediction, including tropical cyclone tracking, atmospheric rivers, and extreme temperatures which essentially saves lives

Current Operational Use Cases

Enhanced Weather Forecasting

Enhancing the precision an d lead times of daily predic tions by combining machin e learning with numerical weather prediction (NWP).

Seasonal to Sub Seasonal Prediction

Providing improved long-range outlooks for agriculture, energy, and water resource management, with 2-week to 3-month lead times.

Oceanic and Marine Forecasts

Providing forecasts for sea ice, waves, and oceanic cur rents,all of which are essen tial for offshore activity such as fishing and shipping.

Emergency Manageme nt

Predicting extreme weat her conditions, such as heat waves, storms, and floods, to aid with early warning systems and di saster readiness.

Climate Change Implications & Extreme Weather Prediction

Climate Change Implications

- More accurate evaluations of regional climate impacts
- Enhanced comprehension of feedback proces ses, such as Arctic amplification
- Calculating the degree of uncertainty in poten tial warming paths

Advances in Extreme Weat her Prediction

- Earlier identification and more precise predicti ons of hurricane intensity
- Improved readiness for tornadoes and powerf ul thunderstorms
- Enhanced systems for early warning for droug ht and floods

Machine learning Forecasting models

- Traditional NWP models (Numerical weather predictions) didn’t use historical data.
- NWP was using simple linear techniques guided by scientific expertise rather than using a statistical method, but MLWP uses approaches like random forests or neural networks.
- These new systems use deep learning neural network models for image generation.
- It helps in generating image which have high resolution and can forecast to a spatial resolution of 28*28km and longitude resolution of 0.25 degrees using GNNS (Graph neural network).

MLWP models in use

- Different weather prediction models: Graphcast, Fourcast.
- GraphCast : takes as input the two most recent states of Earth’s weather—the current time and 6 hours earlier—and predicts the next state of the weather 6 hours ahead.
- GraphCast is implemented as a GNN (graph neural network) architecture, based on GNNs in an “encoder-processor-decoder”.
- Encoder encode the grid like representation using mesh like graph representation which maps regions on the earth. Processor updates each mesh and decoder decodes it back into grid like representation.

Challenges Yet to be Overcomed

Demands on Computation

- Exascale computing is necessary because to the sheer volume of data and the complexity of the models, which presents serious infrastructure issues.

Integration and Data Quality

- Incorporating various observational data sources (in-situ, satellite, and ground-based) into models and guaranteeing data quality via international networks.

Clarity of the Model

- Gaining trust and improving practical parameterizations require an comprehension of the "black box" elements of sophisticated AI models.

Integration and Data Quality

- Integrating territorial and local effect models (such as flash floods and urban heat islands) with climate models worldwide in a seamless manner.

Upcoming Future Actions to be Taken

Transformation Capability:

- Hybrid modeling is transforming the forecasts of world's system

Practical Actions:

- Improved forecasting and climate estimation assists in nationwide curial decision makings

Collaborative Future:

- Necessity to address the remaining difficulties such as diverse research, computer investment and worldwide cooperation

Summary

- These new systems are multi fold faster than the traditional models, taking same energy as traditional models and then minimum energy for the tuning, with better lead times.
- These models match the traditional NWP models forecasting accuracy for large scale variables and outperform small scale variables.
- Future is to generate under a minute weather forecast, generating images at 9 km resolution.
- Target is to achieve under a minutes and generating image at 0.1 degree latitude.