2024 TECHNICAL UPDATE

# Guidance on Numerical Weather Prediction

## Models and Data Sources

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**3002027745**

Technical Update, January 2024

EPRI Project Manager
**D. Larson**

**EPRI**
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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# ACKNOWLEDGMENTS

EPRI prepared this report.

Principal Investigator
D. Larson

Project Team
A. Fan
A. Wigington
A. Tuohy

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner: *Guidance on Numerical Weather Prediction: Models and Data Sources.* EPRI, Palo Alto, CA: 2024. 3002027745.

# ABSTRACT

Weather forecasts are a key input to applications across system operations, including for short-term forecasting of load and variable renewable energy (VRE) generation. However, the choice of weather forecast can affect outcomes due to variations in areas such as accuracy, resolution, and update frequency. It is therefore important for consumers of weather forecasts to be informed about the underlying forecast models and data sources. This document summarizes publicly available weather forecast models and data sources and is intended to be used by staff across the electric power industry, including those without backgrounds in meteorology.

## Keywords

Numerical weather prediction (NWP)
Weather forecasts
System operations
Short-term forecasting
Variable renewable energy
Meteorology

# ACRONYMS AND ABBREVIATIONS

ACCESS: Australian Community Climate and Earth-System Simulator

AWS: Amazon Web Services

BOM: Australian Bureau of Meteorology

CONUS: Contiguous United States

DHI: Diffuse Horizontal Irradiance

DNI: Direct Normal Irradiance

ECMWF: European Centre for Medium-Range Weather Forecasts

ENS: Atmospheric Model Ensemble 15-Day forecast

GEFS: Global Ensemble Forecast System

GFS: Global Forecast System

GHI: Global Horizontal Irradiance

HRES: Atmospheric Model High Resolution 10-Day Forecast

HRRR: High-Resolution Rapid Refresh

JAM: Japan Meteorology Agency

KMA: Korea Meteorology Agency

Met Office: United Kingdom Meteorological Office

NAM: North American Mesoscale Forecast System

NCEP: National Centers for Environmental Prediction

NOAA: National Oceanic and Atmospheric Administration

NWP: Numerical Weather Prediction

RAP: Rapid Refresh

RRFS: Rapid Refresh Forecast System

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# 1 INTRODUCTION

Weather can be a key factor for a range of applications and timescales across the electric power industry. For system operations, it is important to have accurate information regarding current weather conditions, as well as forecasts of how the weather will evolve over the next few hours, days or even weeks. This is particularly true for systems with increasing penetrations of variable renewable energy (VRE), e.g., solar and wind. But having accurate weather information is still important for systems without VRE due to, e.g., the relationship between temperature and energy demand.

There are a multitude of data sources for weather observations[1]. For weather forecasts, a common source is numerical weather prediction (NWP). Per the name, NWP involves using numerical models to simulate how temperature, wind speed, solar irradiance, etc. will change over time and space. Figure 1 summarizes the key steps in producing weather forecasts using NWP:

1. **Initialization:** Weather observations are collected and then assimilated to determine the initial conditions and boundary conditions of the numerical model. The observation data can come from a variety of sources, including but not limited to weather stations, geostationary satellites, radar, and aircraft. This is a recurring process, though not all observation data is updated at the same frequency.
2. **Computation:** After initialization, the next step is to execute the model, which numerically simulates how the weather will evolve over space and time from its initial state based on the underlying physics. The computational complexity typically requires the use of a high-performance computing (HPC) cluster to ensure the computation finishes fast enough.
3. **Output:** After a successful run, forecast values from the NWP model are exported as data files and then disseminated.

Despite following the same general process, NWP models can vary significantly. For example, Figure 2 illustrates how three NWP models can cover the same spatial region but have very different spatial grid resolutions. But beyond spatial resolution, NWP models can also vary in spatial domain, time resolution, update frequency, variables being forecasted, etc. As a result, it is important for consumers of NWP data to be aware of what NWP models exist and how to access their data.

The rest of the document is organized as follows. Section 2 summarizes publicly available NWP models—including their key technical specifications—relevant to applications across the electric power industry. Then Section 3 links to public NWP data sources, while Section 4 provides guidance on getting started with NWP data. Finally, Section 5 concludes with key takeaways.

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[1] *Guidance on Weather Datasets for Studies: Data Sources and Use Cases for Historical Datasets.* EPRI, Palo Alto, CA: 2023. 3002024375.

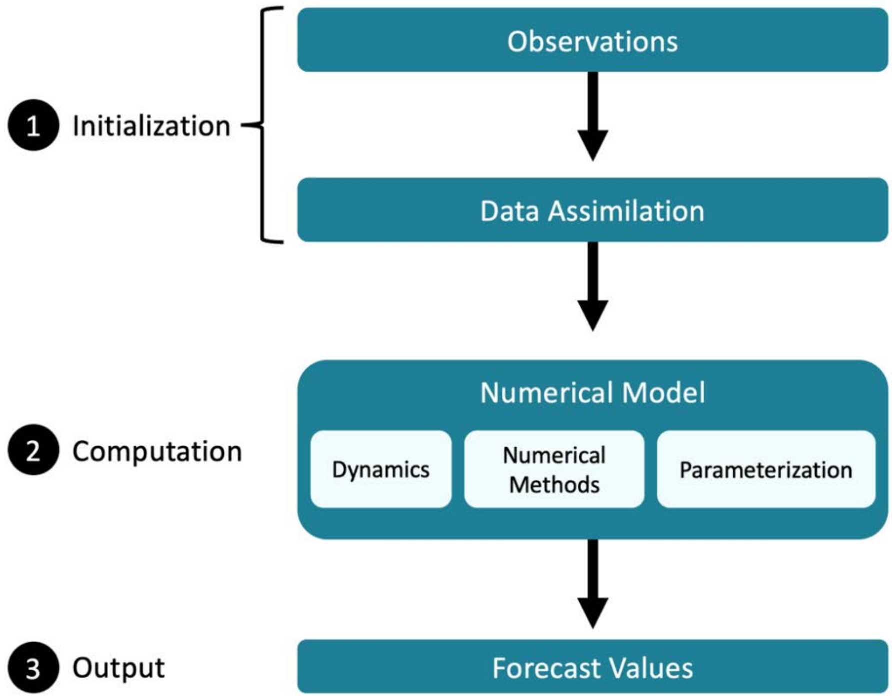


Figure 1. Key steps in the NWP forecasting process.

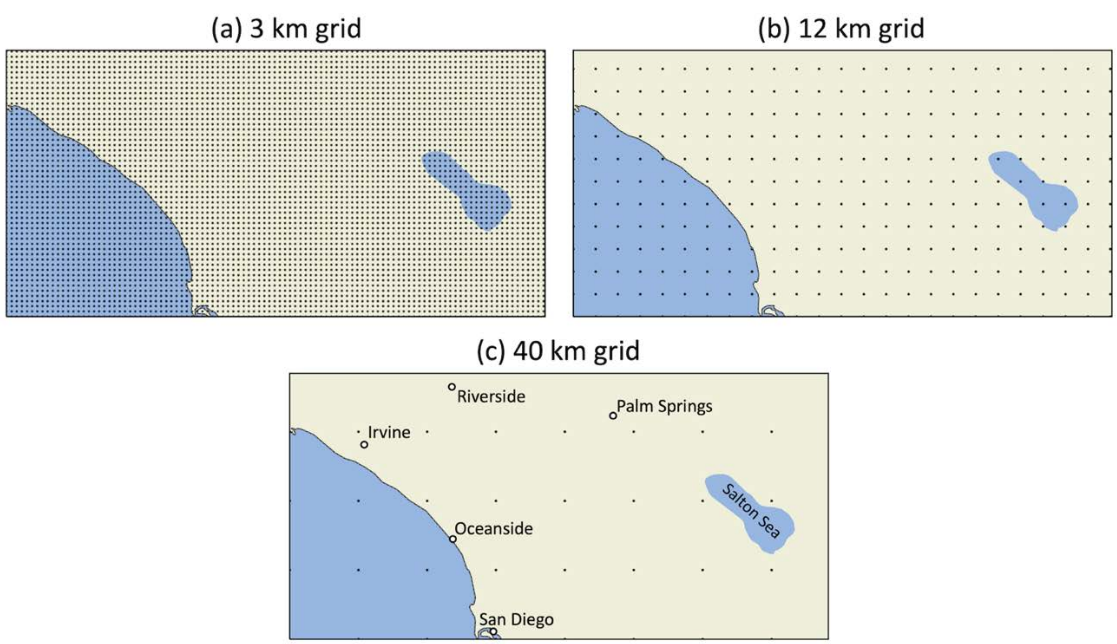


Figure 2. Comparison of spatial grid resolutions overlaid on Southern California. Black dots indicate grid points.

# 2 NWP MODELS

This section provides an overview of NWP models and their parameters. The goal is to not provide an exhaustive list of NWP models, but instead focus on currently available and commonly used models for applications across operational timescales, i.e., hours to days or weeks ahead. The tables include the following information:

1. **Model:** name of the NWP model
2. **Source:** organization responsible for running the model, e.g., NOAA
3. **Spatial Resolution:** spatial resolution of the horizontal grid in km
4. **Time Resolution:** time resolution of the forecast values
5. **Forecast Horizon:** maximum lookahead time of the forecasts, e.g., 84 hours means the forecast output covers 1, 2, 3, …, 84 hours ahead inclusive
6. **Update Frequency:** how often new forecasts are generated, e.g., every hour or once per day

Before proceeding to the tables, a few notes:

- NWP models commonly use horizontal spatial grids defined as functions of latitude and longitude in degrees. For ease of interpretation, we have approximated the spatial resolution of all NWP models in kilometers (km) based on 1 degree latitude being approximately equal to 111 km.
- Most NWP models are defined on 3D spatial grids (latitude, longitude, and altitude). We have elected to ignore the vertical spatial resolution in our overview as many applications only require weather forecasts at the surface. However, for those requiring weather forecasts at multiple altitudes, e.g., 100m for wind turbines, note that vertical grids are sometimes defined in terms of pressure levels rather than meters above the surface.
- The information in the summary tables is based on review of current documentation for each NWP model. Therefore, some of the information in this overview may become outdated as new versions of NWP models are deployed. For example, version 4 of the High-Resolution Rapid Refresh (HRRR) model deployed in 2019 extended the forecast horizon from 18 hours for all cycles to 48 hours for the 00/06/12/18 UTC cycles.
- Weather forecasts from the NWP models in this overview are all considered publicly available and therefore accessible without payment. However, public access may be limited or restricted for individuals outside of specific regions. For example, those in Europe can access all ECMWF data, but those in North America can only access a subset of the data. However, in the case of ECMWF, paid access is also available via commercial licensing.
- While most NWP models provide the same set of weather variables, there can be differences between what weather variables are available and how those variables are defined. For example, the HRRR and NAM models from NOAA both provide GHI forecasts

across CONUS, but HRRR also provides DNI and DHI forecasts. As another example, ECMWF models define GHI and other solar irradiance variables in units of energy density [$J/m^2$], whereas NOAA models use units of power density [$W/m^2$].

## Global Models

Table 1 compares common NWP models that forecast on global spatial domains. Figure 3 visualizes sample forecasts of ambient temperature at the surface for the GFS and HRES models for the same timestamp.

Both GFS and HRES have analogous ensemble models, as described in Table 2. In NWP, ensemble models provide multiple forecasts by perturbing the underlying model. The multiple forecasts—ensemble members—provide insight into the uncertainty of the forecasts. For example, ensemble forecasts are commonly used for hurricanes, where each ensemble member predicts a potential path of the hurricane, as seen in visualizations such as spaghetti plots. Or the variation in the ensemble members is used to indicate the level of uncertainty in the forecasts, e.g., via cone of uncertainty plots.

Note that ECMWF implemented the IFS Cycle 48r1 on June 27, 2023, which upgraded the horizontal resolution of the ENS model from 18 km to 9 km globally. As a result, ENS data before and after the implementation date have different spatial resolution. In addition, Cycle 48r1 updated the forecast models and data assimilation, which has led to better forecast quality for both the HRES and ENS models.[2]

Table 1. Global NWP models.

| Model | Source | Spatial Resolution | Time Resolution | Forecast Horizon | Update Frequency |
|---|---|---|---|---|---|
| Global Forecast System (GFS) | NOAA | 28 km | Hourly (0-120 hours ahead), 3-hourly (123-384 hours ahead) | 284 hours | Every 6 hours (00/06/12/18 UTC) |
| | | 56 km | 3-hourly | | |
| | | 111 km | | | |
| Atmospheric Model High Resolution 10-Day Forecast (HRES) | ECMWF | 9 km | Hourly (0-90 hours ahead), 3-hourly (93-144 hours ahead), 6-hourly (150-240 hours ahead) | 240 hours (every 00/12 UTC cycle), 90 hours (every 06/18 UTC cycle) | Every 6 hours (00/06/12/18 UTC) |

[2] ECMWF upgrade: https://www.ecmwf.int/en/about/media-centre/news/2023/model-upgrade-increases-skill-and-unifies-medium-range-resolutions

Table 2. Ensemble global NWP models.

| Model | Source | Ensemble Members | Spatial Resolution | Time Resolution | Forecast Horizon | Update Frequency |
|---|---|---|---|---|---|---|
| Global Ensemble Forecast System (GEFS) | NOAA | 30 | 28 km<br>56 km | 3-Hourly | 240 hours<br>384 hours | Every 6 hours (00/06/12/18 UTC) |
| Atmospheric model Ensemble 15-Day forecast (ENS) | ECMWF | 51 | 9 km | Hourly (0-90 hours ahead), 3-hourly (93-144 hours ahead), 6-hourly (150-360 hours ahead) | 360 hours (Every 00/12 UTC cycle), 144 hours (Every 06/18 UTC cycle) | Every 6 hours (00/06/12/18 UTC) |

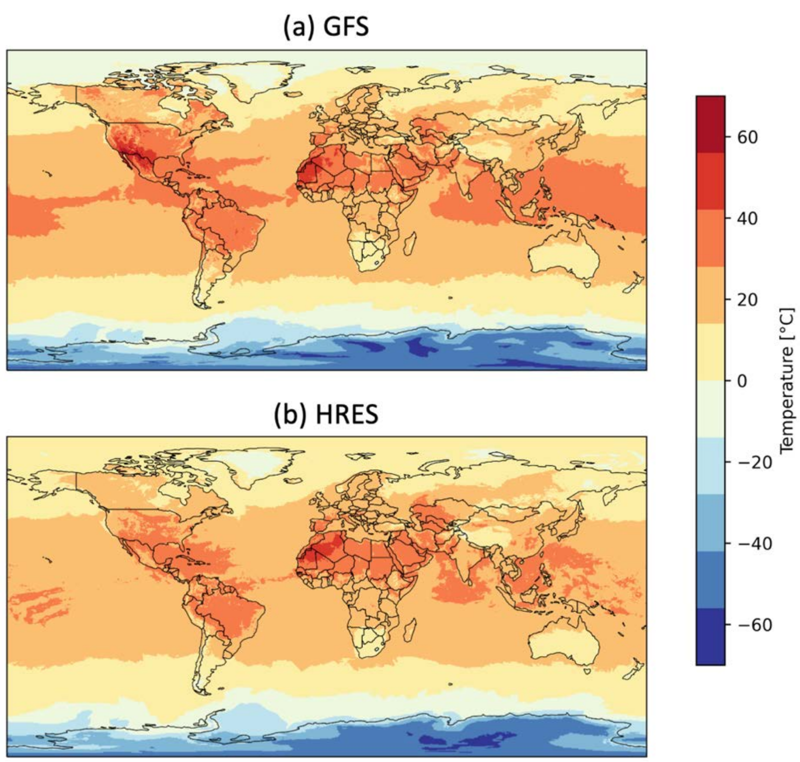


Figure 3. Temperature forecasts on July 10, 2023, at 18:00 UTC from two global NWP models: GFS and HRES.

## Regional Models in North America

Table 3 summarizes regional NWP models from NOAA for North America. For ease of comparison, we have also included models whose spatial domain covers a subregion of North

America, e.g., CONUS or Hawaii. See Figure 4 and Figure 5 for visual comparisons of the spatial domains. Additionally, there are multiple models with the same spatial domain, but differing spatial resolutions, forecast horizons, etc. For example, Figure 6 compares forecasts from three NWP models with the same domain (CONUS) but with varying spatial resolutions: HRRR (3 km), NAM NEST (5 km) and RAP (13 km).

Note that NOAA is developing the Rapid Refresh Forecast System (RRFS), a next generation regional NWP model that will replace HRRR, RAP and NAM. While RRFS is not expected to be operationally available until late 2024, experimental data from RRFS is already available on AWS S3.[3] Additionally, NOAA has indicated they will discontinue running the NWP models that RRFS replaces, e.g., HRRR, within less than 6 months of when RRFS becomes operationally available.

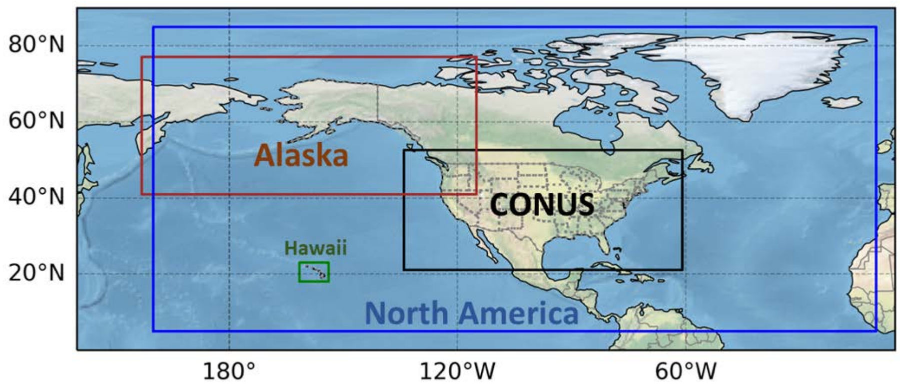


Figure 4. CONUS, Alaska, Hawaii, and North America spatial domains of NWP models from NOAA.

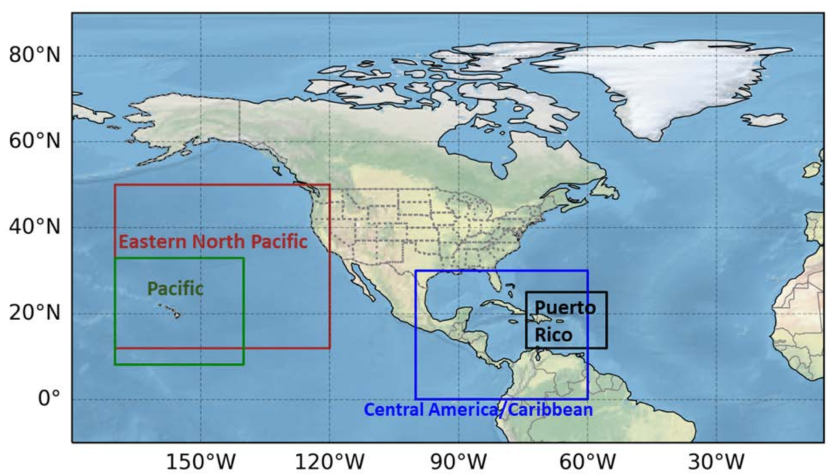


Figure 5. Eastern North Pacific, Pacific, Central America/Caribbean, and Puerto Rico spatial domains of NWP models from NOAA.

[3] Experimental data from RRFS is available on AWS S3: https://registry.opendata.aws/noaa-rrfs/

Table 3. NWP models from NOAA for North America.

| Model | Domain | Spatial Resolution | Time Resolution | Forecast Horizon | Update Frequency |
|---|---|---|---|---|---|
| High-Resolution Rapid Refresh (HRRR) | CONUS | 3 km | Hourly | 48 hours (00/06/12/18 UTC cycles), 18 hours (all other cycles) | Hourly |
| | Alaska | | | 48 hours (00/06/12/18 UTC cycles), 18 hours (03/09/15/21 UTC cycles) | Every 3 hours |
| | CONUS (sub-hourly)[4] | | 15 minutes | 18 Hours | Hourly |
| | Alaska (sub-hourly) | | | | Every 3 hours |
| Rapid Refresh (RAP) | CONUS | 13/20/40 km | Hourly | 51 hours (03/09/15/21 UTC cycles), 21 hours (all other cycles) | Hourly |
| | North America | 32 km | | | |
| | Alaska | 11 km | | | |
| | Puerto Rico | 16 km | | | |
| | Eastern North Pacific | 44 km | | | |
| North American Mesoscale Forecast System (NAM) | CONUS | 12 km | Hourly | 85 hours | Every 6 hours (00/06/12/18 UTC) |
| | North America | 32 km | | | |
| | Alaska | 6/11/40 km | 3-Hourly | | |
| | Central America/Caribbean | 12 km | | | |
| | Pacific | 12/40 km | | | |
| NAM NEST | CONUS | 5 km | Hourly | 61 hours | Every 6 hours (00/06/12/18 UTC) |
| | Alaska | 6 km | | | |
| | Hawaii | 3 km | | | |
| | Puerto Rico | 3 km | | | |

[4] HRRR has a sub-hourly version where predictions are made for the forecast hour as well as 15, 30, and 45 minutes prior to the forecast hour. The sub-hourly HRRR has fewer model levels, fewer parameters, and a shorter forecast horizon compared to the hourly HRRR forecast.

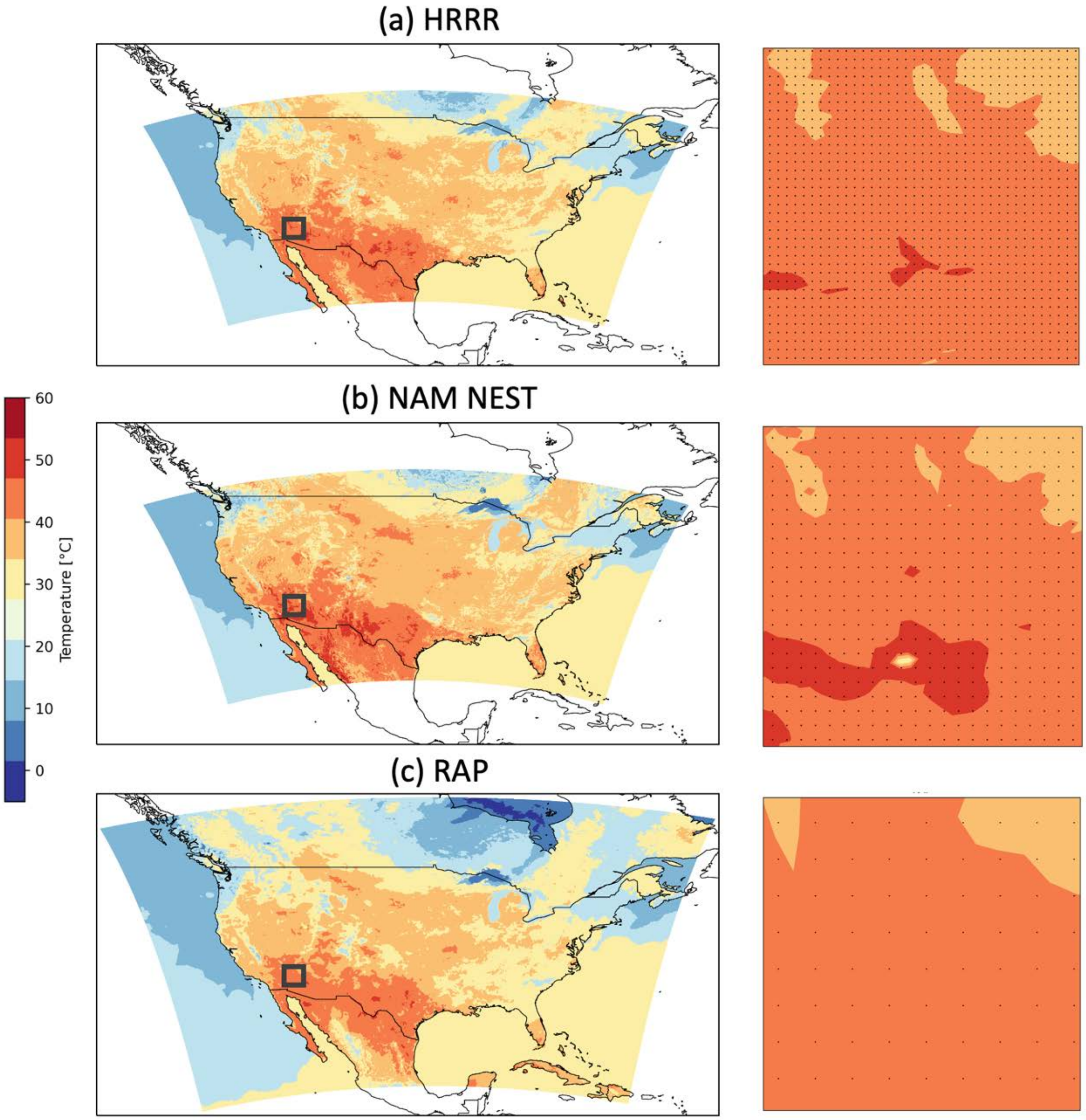


Figure 6. Temperature forecasts on July 10, 2023, at 19:00 UTC from three NWP models for CONUS. The right subplots show zoomed-in views of ~110 km x ~110 km.

## Regional Models Outside of North America

Table 4 lists NWP models for regions outside of North America. Note that the table does not include all regions of the world, nor does it include all NWP models available for each of the included regions. And for regions lacking a regional NWP model, users could instead use a global NWP model, e.g., GFS or HRES.

Table 4. Regional NWP models outside of North America.

| Model | Source | Domain | Spatial Resolution | Time Resolution | Forecast Horizon | Update Frequency |
|---|---|---|---|---|---|---|
| Meso-Scale Model (MSM) | JMA | Japan | 5 km | Hourly | 78 hours (00/12 UTC cycles)<br>39 hours (all other cycles) | Every 3 hours |
| Local Forecast Model (LFM) | JMA | Japan | 2 km | Hourly | 10 hours | Hourly |
| Very Short-Range Forecast Model (KLAPS) | KMA | Korean Peninsula | 5 km | Hourly | 12 hours | 144 times/day |
| UK Atmosphere (UKV) | Met Office | UK and Republic of Ireland | 1.5 km inner domain, 4 km outer domain | Hourly (0-48 hours ahead), 3-hourly (51-120 hours ahead) | 120 hours (03/15 UTC cycles), 54 hours (all other run) | Every 3 hours |
| ACCESS-R | BOM | Australia | 12 km | 3-hourly | 72 hours | Every 6 hours<br>(00/06/12/18 UTC) |
| ACCESS-A | BOM | Australia | 12 km | 3-hourly | 48 hours | Every 6 hours<br>(00/06/12/18 UTC) |
| ACCESS-T | BOM | Australia, SE Asia, SW Pacific, Fiji | 37.5 km | 6-hourly | 72 hours | Every 12 hours (00/12 UTC) |

# 3 NWP DATA SOURCES

NWP data can be access through multiple sources. Table 5 lists official sources and cloud archives which provide public access to NWP data files. For more information on the listed NWP models, see Section 2.

Table 5. Data sources for NWP models from NOAA and ECMWF.

| Model | Access link | Date Availability |
|---|---|---|
| HRRR | NCEP HRRR Products Inventory | Past 2 days |
| | AWS<br>• Bucket of Grib2 files<br>• Bucket of ZARR files | 2014–present |
| | Google Cloud | 2014–present |
| | Microsoft Azure | 2021–present |
| RAP | NCEP RAP Products Inventory | Past 2 days |
| | NWS/COMET archive of RAP hybrid (native) grids | Current year |
| | AWS | 2021–present |
| | Google Cloud | 2021–present |
| | Microsoft Azure | Past 30 days |
| NAM | NCEP NAM Products Inventory | Past 8 days |
| | AWS | 2021–present |
| | NOAA Website | 2007 until 2 days ago |
| GFS | NCEP GFS Products Inventory | Past 10 days |
| | NCEI Server | Current year |
| | AWS | 2021–present |
| | Google Cloud | 2023–present |
| | Microsoft Azure | Past 30 days |
| GEFS | NCEP GEFS Products Inventory | Past 4 days |
| | AWS | 2017–present |
| | Microsoft Azure | Past 30 days |
| HRES and ENS | ECMWF | Past 4 days |
| | AWS | 2023–present |
| | Microsoft Azure | Past 30 days |

## Official Sources

The organizations responsible for each publicly available NWP model maintain an official archive for accessing data files. Generally, these official sources are the most reliable and up to date, with the smallest time lag between when an NWP run is scheduled and when data files are available. However, these official sources also tend to only provide data for the most recent few days.

## Cloud Providers

Data from several NWP models is available via cloud providers. Many factors could influence the choice between using an official source vs an archive on a cloud provider, as well as between cloud providers. For the purposes of this document, we will only note a few practical differences between archives on three of the largest cloud providers: Amazon Web Services (AWS), Google Cloud and Microsoft Azure.

### *Amazon Web Services*

Amazon Web Services (AWS) has continuously updated archives of most NOAA models (HRRR, NAM, etc.) and some ECMWF data. Users can browse and download individual files via their web browser without needing to sign-up or install any additional software. Alternatively, users can programmatically access data using tools such as the official AWS Command Line Interface (CLI)[5], AWS Software Development Kit (SDK) for languages such as Python[6], or other open-source tools such as the Herbie package for Python.

One unique feature of the AWS archives is that the HRRR data is available both in its original grib2 file format and the cloud optimized Zarr format. For consumers of NWP data, using Zarr enables more efficient data access by allowing the user to query the full dataset in the cloud but then only pulling the final selection of data. For example, consider the case where a user wants surface air temperature forecasts from HRRR for the entire state of Alabama. If using grib2, the user will need to download grib2 files from AWS containing forecasts for all of CONUS and all variables (~140 MB per timestep), load the data file, and then select only the air temperature forecasts over Alabama. In contrast using Zarr, the user can select only the air temperature forecasts over Alabama and then only download that portion of the dataset (<1 MB per timestep).

Unfortunately, the Zarr version of HRRR data on AWS does have downsides. First, the Zarr data is updated ~3 hours after each HRRR run due to the time it takes to process the grib2 files into Zarr format. Second, the Zarr data files have some missing data due to a processing error. For example, the Zarr files lack the GHI, DNI and DHI variables. Third, the Zarr data has the x and y coordinates in the native Lambert Conformal Conic projection instead of latitudes and

[5] AWS Command Line Interface: https://aws.amazon.com/cli/

[6] AWS SDK for Python: https://aws.amazon.com/sdk-for-python/

longitudes. However, users can convert the coordinates via standard projection techniques using, e.g., Python.

## *Google Cloud*

Google Cloud has a continuously updated archives of the HRRR, RAP, and GFS models from NOAA. Similar to AWS, users can browse and download files using their web browser or programmatically access data using the Google Cloud CLI[7] or open-source software such as the Herbie package for Python. However, users must first sign into or create a Google account.

## *Microsoft Azure*

Microsoft Azure has continuously updated archives of most NOAA models (HRRR, GFS, etc.). However, unlike the AWS and Google Cloud archives, users cannot browse files in the Azure archives using a web browser. Instead, users must programmatically interface with the archives on Azure, e.g., using Python. But like AWS, users do not need to sign up before downloading data.

Lastly, ECMWF data is also available on Azure. However, the Azure archives only contain the last 30 days of ECMWF data.

## Other Sources

The University of Utah hosts a publicly available archive of HRRR data. The ease of downloading historical data has made this archive popular among researchers and those getting started with NWP data. However, this is not an official archive and there are no guarantees of availability or technical support provided. Therefore, this archive is not recommended for any non-research applications. We note the existence of this University of Utah archive to preemptively answer questions given the archive continues to be used and cited by the research community.

There are also commercial vendors who offer weather forecast data as a service, including VRE generation forecast providers. The specifics and costs can vary, but this weather forecast data often is either derived or taken directly from public NWP models. For example, there are VRE generation forecast providers who offer an application programming interface (API) that allows downloading of weather forecasts—on demand—from specific NWP models, e.g., a day-ahead forecast of temperature from HRRR. However, a survey of commercial forecast providers is beyond the scope of this report.

[7] Google Cloud CLI: https://cloud.google.com/storage/docs/access-public-data#command-line

# 4 GETTING STARTED WITH NWP DATA

Here we provide notes to help get started with using NWP data. The included code examples are based on Python 3 and open-source Python packages. However, NWP data can also be accessed using other programming languages, e.g., MATLAB, R and Julia. But to the best of our knowledge, the binary file formats used to store NWP data, e.g., grib2, cannot be directly opened in Excel, Power BI, Tableau, or other general-purpose data tools. Instead, a user would need to first convert the NWP data files into a compatible format, e.g., CSV.

## Opening NWP Data Files

NWP data is typically provided in binary file formats designed to efficiently store gridded datasets. The most common formats include grib2, netCDF, and HDF5. Figure 7 provides an example of opening a single grib2 file—containing forecasts from the HRRR model—using the Xarray package for Python[8]. Once loaded into memory, the forecast data can be queried, plotted, etc. in a similar fashion to other array data.

(a) Code

```python
import xarray as xr

ds = xr.open_dataset(
    "hrrr.t00z.wrfsfcf00.grib2",    # filename
    engine="cfgrib",                # grib2

    # additional kwargs required for this file
    filter_by_keys={
        "typeOfLevel": "surface",
        "stepType": "instant",
    },
)
print(ds)
```

(b) Output

```
> python 1_xarray.py
<xarray.Dataset>
Dimensions:     (y: 1059, x: 1799)
Coordinates:
    time        datetime64[ns] ...
    step        timedelta64[ns] ...
    surface     float64 ...
    latitude    (y, x) float64 ...
    longitude   (y, x) float64 ...
    valid_time  datetime64[ns] ...
Dimensions without coordinates: y, x
Data variables: (12/36)
    vis         (y, x) float32 ...
    gust        (y, x) float32 ...
```

Figure 7. Example of opening an NWP file (grib2 format) in Python. The output is clipped for readability purposes.

## Downloading NWP Data

Figure 8 provides an example of downloading NWP data from cloud-based archives using the Herbie package for Python[9]. NWP data files can be downloaded in the same way one downloads, e.g., a CSV file. But the Herbie package provides a convenient interface for downloading NWP data from NOAA, wherein the user specifies desired model, forecast issue time, forecast horizon, etc. and then the package handles acquiring the relevant data files. Additionally, Herbie interfaces with Xarray.

[8] Xarray Python package: https://docs.xarray.dev/en/stable/

[9] Herbie Python package: https://herbie.readthedocs.io/en/stable/


Figure 8. Example of downloading NWP data in Python using the Herbie package. The output is clipped for readability purposes.

Figure 9 illustrates downloading ECMWF models using the ecmwf-opendata package[10]. The process is similar to Herbie wherein the user specifies the model, forecast issue time, forecast horizon, etc. and then the package handles pulling the relevant data files.

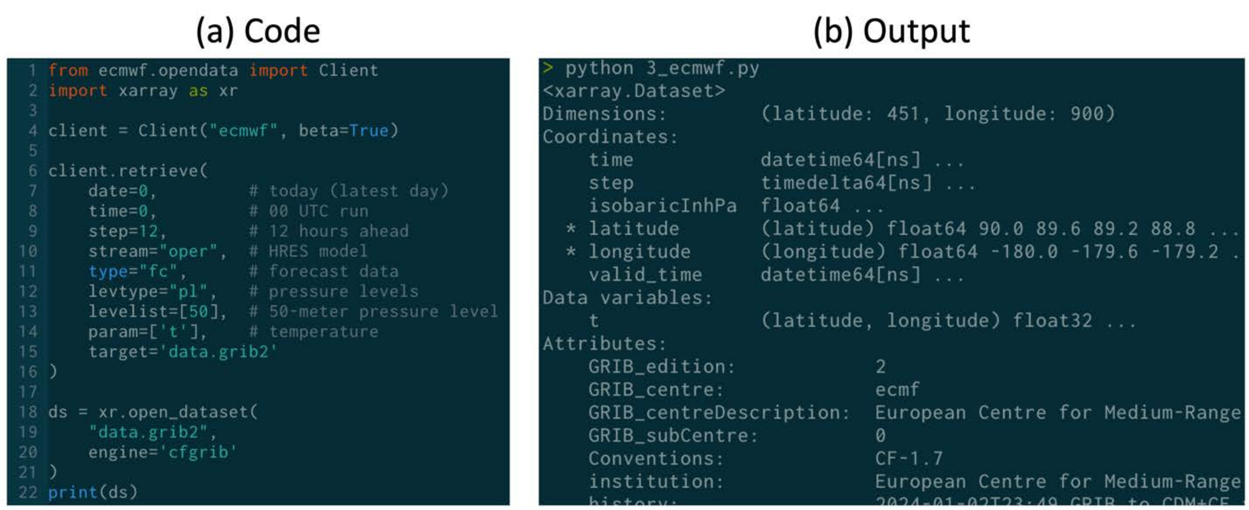


Figure 9. Example of downloading NWP data in Python using the ecmwf-opendata package. The output is clipped for readability purposes.

[10] ecmwf-opendata Python package: https://github.com/ecmwf/ecmwf-opendata

# 5 SUMMARY

Weather forecasts continue to be a key consideration for many applications across system operations. As the choice of weather forecast can impact application outcomes, it is important for consumers of weather forecasts to be knowledgeable about available data and therefore able to make informed decisions. This document summarized numerical weather prediction (NWP) models, which are the most common source of weather forecasts for operational timescales of hours to days or weeks ahead. Additionally, this document provided guidance on getting started with NWP data, including publicly available sources for both real-time and historical data access.

The follow are key takeaways:

1. **NWP models:** There are a multitude of NWP models that continuously provide gridded weather forecasts for regions across the globe. The models can vary in terms of spatial domain, spatial resolution, forecast horizon, update frequency, weather variables, and other factors. Additionally, there is active research and development efforts to improve upon existing NWP models, including for specialized subjects such as extreme weather and wildfire smoke.
2. **Data availability:** NOAA in the US, ECMWF in Europe and other organizations across the globe provide public access to weather forecasts from their NWP models. Many of these weather forecasts are already in use across the electric power industry, including by commercial tools and forecast providers. But anyone can access and use these public data sources directly.
3. **Getting started:** NWP data is typically stored in binary file formats such as grib2 or netCDF, which cannot be opened directly with general-purpose data tools such as Excel, Power BI, or Tableau. However, there is a rich ecosystem of existing software, including open-source packages in Python and other popular programming languages, that new and experienced users alike can leverage. Additionally, users can get started without prior backgrounds in meteorology.

Further work in this area may explore how to blend weather forecasts from multiple NWP models—or multiple forecasts more generally—to achieve more accurate forecasts compared to a single source. Another topic could be to examine the interplay of weather forecasts and operational decisions during low frequency but high impact events, e.g., Winter Storm Elliot.

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EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com