[DA-048] GIS&T and Atmospheric Science

Abstract

Atmospheric science studies Earth's atmosphere and its interactions with the land, oceans, and the Sun. It encompasses both weather and climate research—weather being short-term atmospheric conditions and climate representing long-term patterns. Climate change refers to persistent shifts in these patterns over decades, including temperature variations, precipitation changes, and shifts in extreme weather events. Because weather and climate vary across space and time, they are inherently geospatial. Geographic Information Systems (GIS) have become critical to atmospheric science, offering tools for data collection, analysis, modeling, visualization, and real-time monitoring. GIS enables scientists to understand atmospheric processes by integrating diverse datasets and visualizing complex phenomena in maps and models. Although early GIS applications in atmospheric science were limited by technical barriers, advances in GIScience—particularly in managing big, dynamic, and multidimensional data—have greatly expanded their capabilities. Maps, long used by meteorologists and climatologists, are fundamental to GIS, allowing researchers to visualize atmospheric variability across space. GIS tools also allow for detailed spatial and statistical analysis, helping scientists explore interactions among atmosphere, land, water, ecosystems, and society. These insights support informed decisions about risks from weather hazards and climate change impacts on infrastructure, ecosystems, and resources.

Keywords: climate, climate change, netCDF, spatio-temporal data, weather

Author & citation

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Explanation

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1. Introduction

Atmospheric science, in the broader context, is a study of Earth's atmosphere, its processes and interaction with other elements of the Earth System, which include land surface, ocean, and the Sun. Geographic Information Systems (GIS) has become an invaluable tool for atmospheric science, providing tools and geospatial methods for data analysis, modeling, visualization, as well as real-time monitoring of atmospheric phenomena.

Atmospheric science includes weather and climate research. Weather is defined as a temporary state and short-term changes in the atmosphere in a given location. Climate represents average weather conditions for a given area over a long period of time. Climate change refers to changes in average weather conditions that persist over multiple decades or longer (Grade et al. 2023). Changes in climate can be represented by increases and decreases in temperature, shifts in precipitation amounts, changes in frequency and geographic location of severe weather events, and changes to other features of the climate system. Therefore, weather and climate information is inherently geospatial, and GIS tools help to understand how weather and climate vary across space and over time.

GIS applications in atmospheric science have significantly increased in recent decades (Armstrong et al. 2015). Initially, constrained by the interoperability between atmospheric and geospatial data and their respective analytical systems, advancements in GI science and technology with respect to big, dynamic, multidimensional data significantly expanded the range of GIS applications for atmospheric science. Maps have always been essential to meteorologists, climatologists, and atmospheric scientists for visualizing atmospheric phenomena and their variability in space. Maps, being the fundamental part of GIS, have enabled visualization of complex multidimensional atmospheric data, while numerous analytical capabilities of GIS further enhance atmospheric science research and operations through data integration, analysis, and spatio-temporal and statistical modeling. Spatial analysis tools in a GIS help to connect the data from atmosphere, land, water, ecosystems, and human society to explore the interactions between different elements of the Earth system and identify patterns of change or areas of impacts. Informative visualizations can show complex patterns and processes in ways that scientists and practitioners can understand and make informed decisions about weather hazards risks or impacts of changing climate on natural resources or infrastructure.

2. Working with Atmospheric Data in GIS: Key Concepts and Challenges

While atmospheric data, including weather and climate data, are geospatial, there are several considerations that are helpful to keep in mind when working with atmospheric data in a GIS.

2.1 Data Interoperability

Integrating data from different disciplines can be challenging due to differences in data formats, metadata standards, terminology, and the way various domain experts think about their data. Data interoperability between atmospheric science and GIS has been a focus in the research and operational community since the early 2000s. Initially presenting a barrier to data sharing and integration, data interoperability has significantly evolved over the past two decades, allowing for an increased access and use of multidimensional scientific data by GIS users (Boehnert et al. 2016).

Data dimensionality is one of the challenges that had to be addressed in improving interoperability between GIS and atmospheric data, especially data generated by numerical weather prediction and Earth system models. Traditional GIS data describe a geographic location on the Earth's surface using geographic coordinates, X (longitude) and Y (latitude), in a two-dimensional (2D) flat plane. Atmospheric science data (e.g., weather, climate, air quality) inherently contain information that is multidimensional, represented through space (X,Y), time (T), and pressure level in the atmosphere (Z) (Figure 1). Therefore, atmospheric science data formats (e.g., netCDF, GRIB, Zarr) have been designed to accommodate multiple dimensions in the data. GIS tools, initially designed to work with 2D geographic data, have evolved over the past decade to handle multidimensional data. Advancements in the GIS tools’ ability to visualize and analyze multidimensional data and atmospheric data formats, such as netCDF, expanded GIS applications in weather and climate research and decision support (Xu et al. 2016).

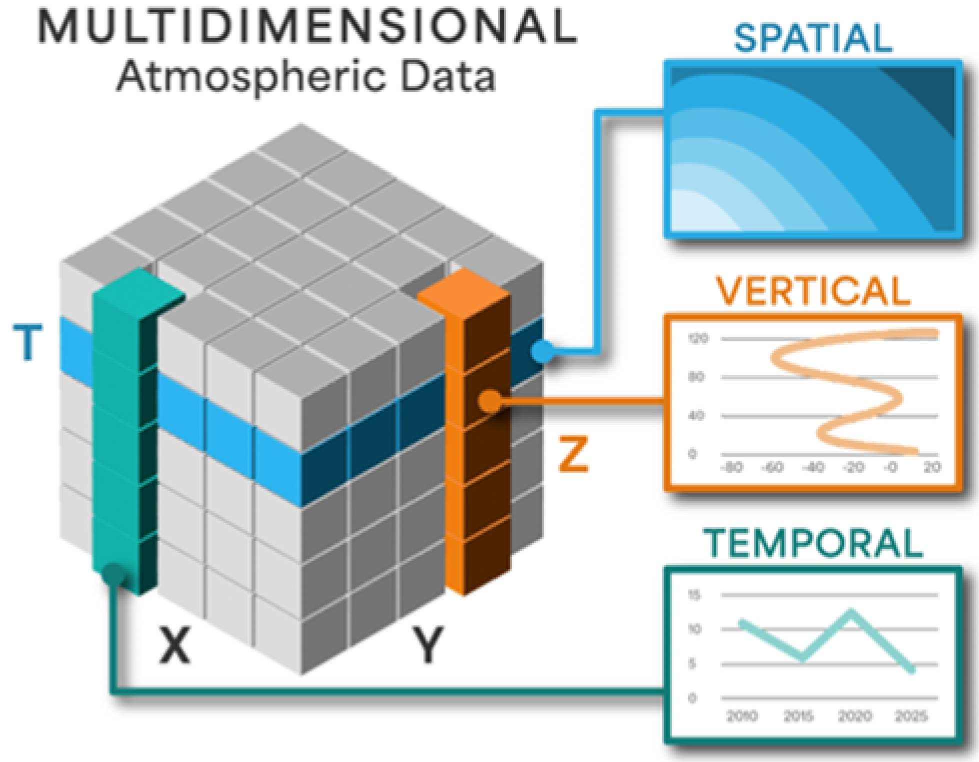

Figure 1. Atmospheric data, stored in a multidimensional data format, such as netCDF, includes spatial dimension (e.g., near surface air temperature across geographic area for a given time), vertical dimension (e.g., air temperature profile for the lower levels of atmosphere in a given location and time), and temporal dimension (e.g., time series of measured or modeled near surface temperature in a given location). Source: authors.

2.2 Spatial Referencing

Spatial referencing can be another challenge when working with atmospheric data, especially model outputs, in GIS. Coordinate systems can be geographic or projected. Geographic coordinate systems define locations on the Earth’s surface based on a 3D spheroidal model and latitude-longitude coordinates. Projected coordinate systems are based on a 2D coordinate plane derived from mathematically transforming the geographic coordinates (latitude and longitude) from a curved surface to a flat map. The foundation for location of both types of coordinate systems is the shape of the underlying spheroidal Earth, called the Datum. Spatial data, such as elevation or land cover types are commonly based on the spheroidal (i.e., elliptical) Earth models. However, most atmospheric numerical models assume Earth’s surface is a perfect sphere shape, to simplify calculations. When working with weather and climate model outputs, it is important to understand and define the proper shape of the Earth before integrating atmospheric model outputs with other geospatial datasets. The difference between a spheroidal Earth and the atmospheric model's perfect sphere can lead to geolocation discrepancies, especially at midlatitudes (Monaghan et al. 2013).

2.3 Metadata Standards

Metadata plays an essential role in data interoperability. To improve interoperability of atmospheric science data with GIS tools, a significant effort has been made through the use of international standards in spatial data formats, metadata conventions, and storage and management. Using data and metadata formats recognized by the Open Geospatial Consortium (OGC) for multidimensional data was the first step in making atmospheric data interoperable. OGC has adopted the climate and forecast (CF) convention to promote the sharing and integration of netCDF data from the atmospheric science domain with other geospatial domains (Nativi and Domenico 2013). For example, when working with netCDF data formats, the way in which the spatial information (X,Y) is stored and the projection information is defined within the netCDF dataset can make a big difference in the ability to use and integrate this dataset with other geospatial data within a GIS platform.

2.4 Scale and Resolution

In the GIS world, there are two types of scale. Spatial scale can be divided into scales of measurement and scales of variation. Scales of measurement relate to the ratio between a distance on a map or in a GIS viewer to that same distance on the actual ground. Small scale refers to phenomenon that occurs over large areas, whereas large scale refers to phenomenon that occurs over much smaller areas. Global Earth system models, for instance, are typically completed at small scales (global coverage), though large-scale climate modeling does take place regionally (i.e., regional climate models). Scales of variation relate to data and the sampling framework and have to do with horizontal resolution. Global-scale Earth system models are typically going to have a coarser resolution as compared to regional-scale climate models. Figure 2 illustrates representation of air temperature at different spatial scales, as simulated by global, regional, and urban scale climate models. Horizontal resolution in these examples varies from 100 km to 1 km.

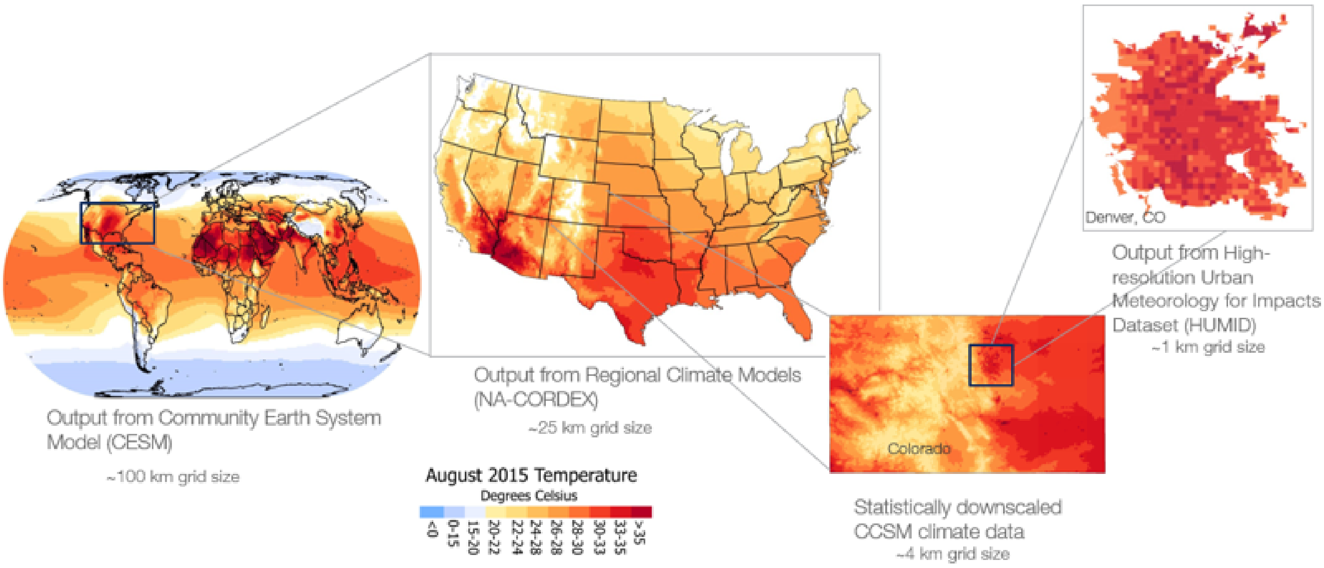

Figure 2. Scale and resolution in climate models can affect how the data are used and for what applications. Figure shows climate models' simulations of air temperature for August 2015 at different resolutions, ranging from 100 km to 1 km. Source: authors.

The second type of scale is temporal scale, which relates to the duration of time (times or dates). Temporal GIS is still a relatively new, but increasing, capability in GIS for combining temporal information with geographic location and attribute data. Temporal scale can include data on specific events, such as lightning strikes or tornado impacts, as well as longer-scale events such as annual drought outlooks or 30-year climate normals.

In application, spatial and temporal scales are often considered simultaneously. For instance, cross-scale interactions can naturally signify where and when weather- or climate-related phenomena take place, covering different spatial dimensions and time spans. It is worth mentioning that global-scale climate projections are not indicative of local-scale weather patterns. When planning for climate mitigation and adaptation at local levels, the issue of scale and uncertainty (discussed below) must be considered.

2.5 Uncertainty

All spatial data contain some degree of uncertainty. Weather forecasts and climate projections are inherently uncertain as they describe the future state of the atmosphere either days or decades into the future. Given the complexity of the Earth system and existing limitations in observational data or computational power, Earth system models have various sources of uncertainty. Uncertainty in the models can result from model parameterization, different initial conditions, external forcing, and future emissions scenarios (Morrison, 2023). Uncertainty in climate projections can be presented by a range of scenarios, often from using an ensemble of global or regional climate models. These could include data on temperature or precipitation under different greenhouse gas emission pathways (e.g., Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs). Uncertainty can also be represented by an ensemble of model simulations, using different initial conditions for each ensemble member within one model, for different RCPs or SSPs.

GIS can play an important role in communicating uncertainty. There are many techniques for visualizing a range of possible scenarios, including the use of color and symbols, showing different data layers for different scenarios, connecting maps and time series plots, and showing the ensemble mean and the range of possible outcomes. Use of GIS for visualization of uncertainty could help make the results more understandable, allowing decision-makers to see the range of possible outcomes and plan for extreme weather conditions or future climate.

2.6 Real-time data

Real-time weather data can be collected from multiple sources including weather stations, satellites, buoys and even citizen scientists. These data help inform forecast decisions and are used to initiate numerical weather prediction models. GIS can incorporate real-time data in a variety of formats that allows for analysis and visualization. However, challenges and technical considerations include reliable and high-speed internet access, data latency, post-processing, and platforms for dissemination.

3. Common Applications of GIS in Atmospheric Science

There are several shared themes in the use of GIS in atmospheric science and the use of atmospheric data in GIS.

3.1 Visualizing multidimensional data

Weather, climate, and atmospheric phenomena are inherently dynamic and volumetric, thus requiring various data visualization approaches. GIS tools allow researchers and practitioners to investigate patterns and trends in the multidimensional atmospheric data through 2D maps, 3D maps and models, and four-dimensional (4D) visualizations, such as animations. Average climate conditions (e.g., annual average temperature or total precipitation), for example, can be viewed in 2D on a map. This could be either a static map or an interactive map. GIS animation capabilities can be added to a 2D map to allow for viewing time-varying phenomena across a geographic area, such as hourly changes in weather conditions (e.g., precipitation or wind speed) or decadal changes in climatic conditions (e.g., average annual temperature).

A 3D visualization in a GIS can add a vertical dimension (height or depth), which can be helpful for visualizing atmospheric data at different pressure levels. For example, 3D visualizations of air temperature at different pressure levels could reveal temperature inversions, which in turn can affect spatial patterns of air pollution. Visualizing smoke plumes from wildfires in 3D helps to see the data from multiple angles and to assess the height, density, and direction of smoke and investigate its potential impacts. 3D visualizations in GIS can also be used to display flooding scenarios, such as flooding from hurricane storm surge or from sea level rise (Figure 3). GIS-based 3D visualizations of flooding such as these can help communicate risks and inform preparedness and response decisions.

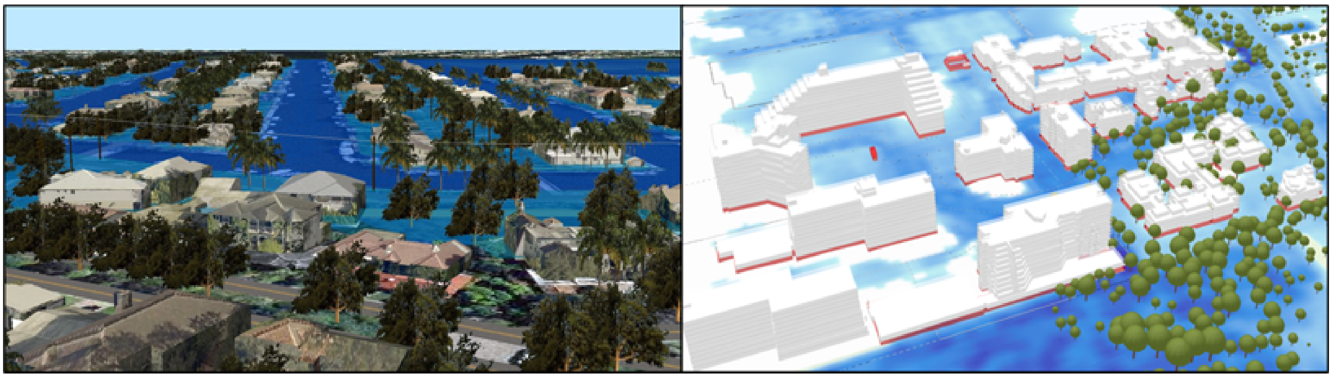

Figure 3. Examples of 3D visualization with GIS. Figure A (left) displays a realistic scene of a local coastal neighborhood showing a storm surge scenario. Detailed 3D building models, infrastructure and vegetation are included to make the scene easily identifiable to the decision maker. Figure B (right) is more of an abstract scene showing sea-level rise scenarios and which portions of the buildings (highlighted in red) could be impacted. Source: authors.

Adding a temporal dimension to a 3D model creates a 4D visualization, by combining space and time. For example, time-enabled weather or climate data in GIS can show changes in sea level and its impacts on coastal communities, movement of a hurricane along the storm's path, or rapid inundation from a storm surge. Often, 4D data are incorporated into GIS-based animations.

3.2 Data processing and analysis

We can explore numerous questions about weather and climate in GIS. GIS analytical tools allow users to process, analyze, and interpret data to understand patterns, relationships, and trends. Because atmospheric data are often large and complex and can contain multiple dimensions, data processing is often required before atmospheric data can be analyzed in GIS and integrated with land surface, hydrology, or population datasets.

A common method for processing large atmospheric data into more manageable information is using scripting languages such as Python. There are many Python libraries such as, netCDF4, GDAL, MetPy, Numpy, SciPy, xarray, and pandas to name a few, that are effective in reading, manipulating, and analyzing multidimensional data (Lin, 2012). Key processes in Python may include reading netCDF files with xarray, or performing calculations on large datasets using Numpy arrays or pandas. Additionally, Jupyter Notebooks are widely used to explore, plot and interact with atmospheric data.

Python contains analysis libraries for working with atmospheric data, however, traditional GIS platforms also can read and analyze multidimensional datasets. GIS platforms enable the integration of various datasets, such as shapefiles, satellite imagery, and multidimensional data, adding geographic context and linking atmospheric phenomena to specific locations and geographic features. Analytical functions like overlay, spatial joins, proximity analysis, spatial interpolation, hot spot analysis, or change detection can be applied, revealing new insights and enhancing the understanding of weather and climate phenomena. Data processing and analysis workflows help to streamline and, where possible, automate the process. An example of such a workflow is discussed below.

A workflow example: Exploring population vulnerability to extreme heat

Figure 4 illustrates a workflow for exploring population vulnerability to extreme heat. In this example, we use climate model projections of daily air temperature (a gridded dataset) and the Python scripting tools to compute the number of hot days per year (i.e., days with maximum daily temperature exceeding 90^{0}F). This same Python code is used to process daily data from model simulations representing present-day climate as well as climate simulations representing climate of the middle of the 21st century (around 2050). This step allows us to compare the number of hot days in present and future climates, as simulated by a climate model, for each model grid cell. The next step in the workflow applies spatial statistics to aggregate this information to administrative boundaries, such as counties. This step results in a dataset showing counties with varying numbers of hot days across two time periods. To estimate population vulnerability to heat, in the next step of the workflow, these data can be combined with other datasets, such as population vulnerability index, to develop a composite index of extreme heat vulnerability. This workflow can be modified by using different climatic thresholds and spatial boundaries for data aggregations to investigate trends, assess risks, and develop risk reduction strategies.

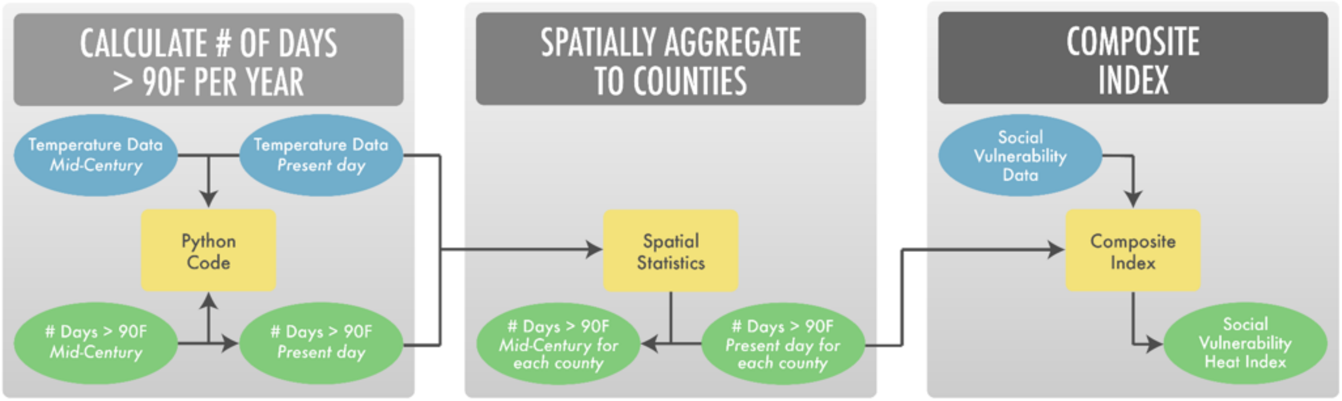

Figure 4. An analytical workflow to explore exposure and vulnerability to extreme heat, using climate model simulations, Python and Esri ArcGIS Pro tools. Source: authors.

3.4 Science Communication

As discussed above, climate and atmospheric science often involves complex data related to weather patterns or long-term temperature and precipitation changes. GIS allows to reduce dimensionality and complexity in atmospheric data (Figure 1) and to present information in easy-to-understand maps, graphs, and interactive visualizations. These visualizations can help explain complex atmospheric science concepts in ways that are engaging and understandable.

For weather hazards preparedness and response, public health interventions, and infrastructure planning, GIS can provide actionable information. For example, by visualizing storm surge or severe weather forecasts in real time, GIS helps the public to stay informed and make timely decisions about protective actions. Maps and visualizations that combine climate data with demographic and infrastructure information can help counties, cities, and communities plan for extreme heat and precipitation events or flooding, thus enabling informed decision-making.

GIS tools such as story maps and dashboards help to convey weather and climate information in an accessible and meaningful way. Dashboards allow for connecting maps to graphs and charts and exploring spatio-temporal patterns in data. The Story Maps allow sharing maps and 3D visualizations of atmospheric phenomena along with a narrative text and other multimedia (e.g., images, videos). Dashboards and Story Maps are used by many academic, government and non-profit scientific organizations to share data and stories about weather and climate. For example, the 5th National Climate Assessment included an ArcGIS Story Map to provide insight into future climate conditions and inform planning for a more resilient future (Crimmins 2023).

4. Summary

GIS for atmospheric science is a growing and evolving field with new numerical models and analytical geospatial tools to support multidimensional data being developed and applied in research and practice. Recent advances in GI science and technology and improved interoperability between atmospheric and geospatial data and tools are making it possible to answer new and complex questions about climate and weather phenomena, analyze trends and patterns through the integration of GIS data and tools. Along with the advances in cloud computing, AI, GeoAI, and real-time data integration, the future questions about the Earth system that can be answered in GIS will continue to expand.

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