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A Tool for Exploring Our Fluid Earth

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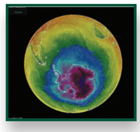

This image signals that this contribution is a featured part of the special collection on "Climate Change and Sustainability in Intro Physics."

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Five years ago, the Byrd Center's Education and Outreach program recognized the need for a new weather and climate visualization for middle school youth and the public. Working across traditional disciplines, the team was able to create a tool that addressed challenges they had identified through delivery of outreach programs and allowed educators to create investigations appropriate for their audience and content.

Inspiring the team were a series of "Challenges Inherent in Teaching Geosciences," articulated by Kastens from the geosciences education research community, that were consistent with Cervenec's science teaching experience over 11 years using the Modeling Instruction method.[1–3] These challenges included (1) that the scale of phenomena were often well beyond the size of the classroom, (2) that there was a need for well-crafted experiences and models that could bridge the gap in scale, (3) that there was regularly a need to depend on data that students could not practically collect themselves, (4) that there was often a need to depend on nonexperimental ways of inquiry that deviated from the often-taught "scientific method," (5) that spatial thinking was critically important, and (6) that understanding how phenomena emerged was aided by conceptualizing Earth systems and their interactions.

The team set out to create a tool, currently named Fluid Earth, that

- displayed information on a digital globe rather than a map, allowing a more accurate depiction of processes, avoiding the "Pac-Man" effect of following off the edge of the map, and allowing polar regions to be displayed with less distortion;
- included global rather than country-specific information, as is often done by weather bureaus, so that large-scale phenomena and patterns may be observed;
- allowed information from the past to be examined, which is seldom done in an accessible way by weather bureaus or commercial weather sites, so that educators can select locally relevant events to use in exercises and lessons;
- displayed multiple, commonly taught weather variables (i.e., temperature, pressure, precipitation, and wind speed) on an intuitive platform, customized for youth with accessible textual information;
- included common climatological variables, such as temperature and precipitation, so that youth may explore differences between locations.

While there were existing tools available for visualizing weather and climate information, including the National Weather Service (https://www.weather.gov) and Windy (https://www.windy.com) for weather and The Climate Explorer (https://crt-climate-explorer.nemac.org/), NOAA View (https://www.nnvl.noaa.gov/view/), and Climate Reanalyzer (https://climatereanalyzer.org) for climate, each of these tools had a limitation that made them challenging to deploy with youth in education settings.[4–8] The National Weather Service visualizations are limited to United States territories, lack animations that show the dynamic nature of weather, and are not easy for youth to navigate when looking at multiple variables. Windy does show the entire globe and is highly intuitive and interactive, but users cannot look at past events, nor can they pin specific locations to share. The Climate Explorer, NOAA View, and Climate Reanalyzer all provide climate data on a separate platform from weather data, requiring youth to learn a second interface. While all three tools are interactive, none display climate data on a digital globe, and youth may be overwhelmed navigating the interfaces and making meaning of the data displayed.

The physics and chemistry education communities might already be familiar with PhET Interactive Simulations, which have demonstrated success in enhancing learning.[9–12] There are a few PhET simulations featuring geosciences content, but there is also a fundamental difference in the design and user experience between PhET and tools such as Fluid Earth. Fluid Earth offers a visualization of actual data sets instead of a simulation operating on a limited set of discrete formulas. Furthermore, most weather and climate concepts cannot be taught in the spatial or temporal scale of a classroom using standard equipment to collect data, so educators are required to use software solutions to provide these experiences. Starry Night and other packages that allow users to explore the motion and behavior of astronomical bodies might be more comparable tools to Fluid Earth.[13] A more in-depth comparison and discussion of different software alternatives is provided in the implications section of Cervenec et al.[14]

Over time, youth and educator feedback inspired additions to Fluid Earth that

- allowed specific locations to be pinned, the numeric information at those locations to be displayed, and the pins and view to be shared via the URL (the URL encodes the location with pins, the time being displayed, and the variable) so that educators may create customized exercises that can be readily shared;
- provided a search tool for users to type in cities, states, and countries of interest to aid in finding locations around the world;
- created a time-lapse feature that generates short animations showing weather patterns over specific intervals of time;
- optimized the code to run quickly on numerous devices, using a range of browsers, with modest Wi-Fi/internet connections so as not to overwhelm school infrastructure or low-bandwidth residential connections, and to take advantage of graphics processing unit (GPU) acceleration to smoothly refresh the view of the data as users interact with the globe.[15]

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Once Fluid Earth was built, the team was able to use it with groups beyond the target audiences, to include high school and university students and researchers from disciplines outside of atmospheric sciences.

Development

Fluid Earth was developed and refined by a team of educators, computer programmers, atmospheric scientists, and students over five years to fill the need the team had for an intuitive tool to use (1) at science, technology, engineering, and mathematics (STEM) festivals and agricultural events to explain weather phenomena and answer climate-change questions and (2) in classrooms with short exercises to allow students to explore weather phenomena and identify patterns. In addition to user testing with college students, the team did multiple rounds of user testing with youth and families at the Center of Science and Industry (COSI), a science center located in Columbus, Ohio, and at public science outreach events held in Central Ohio. Deployments of Fluid Earth in middle school science classrooms and feedback submitted electronically by educators informed revisions to the design. The team found favorable results on student engagement and perceived learning in a study conducted with middle school youth in science classes.[9] The entire code repository is freely available via a GitHub repository established by Zhan and Gravina[16]; an overview of the code, its structure, and decisions that informed its creation is provided by Gravina et al.[17]

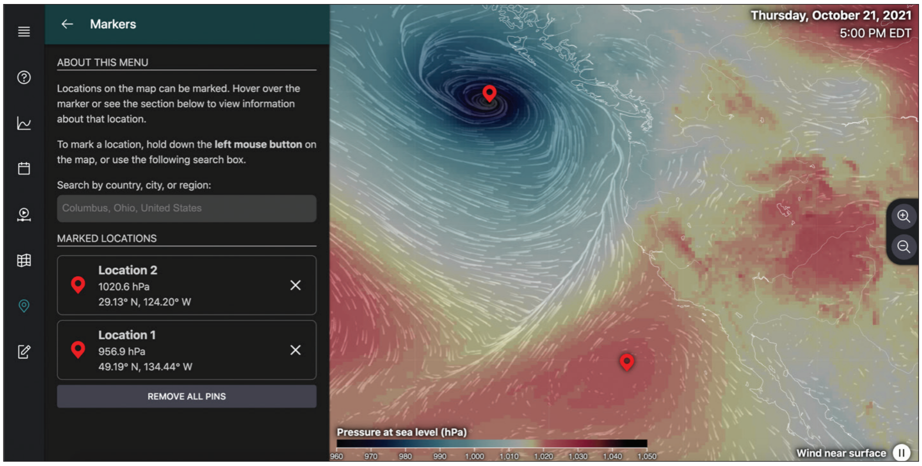

Fig. 1. Pressure analysis of a strong cyclone (top) and anticyclone (bottom) on Fluid Earth. Markers further clarify the high- and low-pressure centers and read off sea-level barometric pressures. Link to date/location: https://go.osu.edu/fev1.

Table I. *NGSS* Disciplinary Core Ideas, Crosscutting Concepts, and Science Practices that may be addressed using Fluid Earth.

Disciplinary Core Ideas	
MS-ESS2-5 Earth's Systems	Collect data to provide evidence for how the motions and complex interactions of air masses result in changes in weather conditions. Grades 6–8
MS-ESS2-6 Earth's Systems	Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates. Grades 6–8
3-ESS2-1 Earth's Systems	Represent data in tables and graphical displays to describe typical weather conditions expected during a particular season. Grades 3–5
3-ESS2-2 Earth's Systems	Obtain and combine information to describe climates in different regions of the world. Grades 3–5
Crosscutting Concepts	
Patterns	Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.
Practices	
1. Asking questions	
2. Developing and using models	
4. Analyzing and interpreting data	
6. Constructing explanations	
7. Engaging in argument from evidence	

Next Generation Science Standards

On its surface, Fluid Earth has applications in formal and informal STEM education experiences involving *Next Generation Science Standards* (*NGSS*) content standards (see Table I). But Fluid Earth's greatest strength is that it allows educators to readily engage students in examining patterns, a crosscutting concept core to weather and climate, both spatially and temporally within the user interface.

Furthermore, with Fluid Earth (vs. digital weather products available from government weather bureaus or weather information businesses), educators and students have great autonomy over the locations, times, and variables for which they view data and use that data to investigate phenomena. Fluid Earth is readily customizable to their circumstances, and the user interface is designed to be visually compelling and easy to navigate. This opens opportunities for practices in earth science that are difficult to explore with tabular data for specific locations, static maps for particular variables and time periods, and laboratory exercises and demonstrations that may only be conducted at the classroom scale. A list of *NGSS* Science Practices[18] that may be addressed using Fluid Earth is provided in Table I.

Example exercises

There are countless exercises that can be developed using Fluid Earth to convey both disciplinary core and crosscutting concepts to students of all ages. The team developed a handful of lessons for use over 50 minutes with youth in classroom settings and after-school programs. The two lessons provided here offer examples of how Fluid Earth could be used in educational settings and are consistent with Modeling Instruction.

Example 1. High- and low-pressure systems

Cyclones and anticyclones, otherwise known as "low-pressure" and "high-pressure" systems, are the larger-scale triggers for weather around the world. Highs and lows frequently anchor the "pattern" of weather in a region, with high-pressure systems typically ushering in calm, clear weather vs. low-pressure systems, which are usually cloudy and stormy. The centers of these systems can easily be identified in Fluid Earth using the animated wind streamlines and/or pressure overlays (Fig. 1). Wind speed and precipitation overlays can also be used to help guide students toward what weather these systems may be producing or what impacts may occur.

Key questions

- How is the air moving around each pinned location? What pattern do you notice?
- Now look at the larger scene: how does the air move in between each feature?
- Using other variable overlays, what are conditions like around each location?

Discussion

- Summarize the things you have seen when analyzing each feature. What can we conclude?

Takeaways

- Low-pressure systems have counterclockwise wind flow toward the center of the system.
- High-pressure systems have clockwise wind flow away from the center of the system.
- Wind tends to flow from high pressure toward low pressure.
- Lows and highs have contrasting weather patterns: cloudy, windy, and stormy for lows and quiet and clear for highs. This is a result of the previously discussed wind patterns around the pressure systems, with converging air around lows resulting in uplift that triggers clouds and precipitation.

Reinforcement

- Explore other areas of the world on the same date/time. Can you find any other features comparable to the two introduced? Do the patterns of pressure, wind, or precipitation hold firm?

Example 2. Weather front analysis

Fronts are the focal point of a variety of weather across the globe. In the United States, they can bring disruptive and occasionally severe weather regardless of the season or time of day. Fronts come in both "warm" and "cold" varieties, named generally after the types of air masses that settle in after their passage. In Fluid Earth, fronts can be analyzed by using temperature, wind speed, and precipitation overlays coupled with animated wind direction streamlines (Fig. 2). Markers can be used to help determine the temperature at specifically chosen locations on each side of the frontal boundary to identify the type of front and what weather it brings to the region (Fig. 3).

Key questions

- Using multiple different overlays: What are some similarities of each pinned location? What are some differences?
- Which way is the wind blowing at one location? At the other?
- Why might the conditions at each location be different? In other words, why might one spot be warmer and one colder? Or why might it be raining in one location and dry in the other?
- Can you make a guess as to what both locations will be like in 12 hours?

Discussion

- Summarize the things you have seen when analyzing this feature. What can we conclude? What is the feature called?

Takeaways

- Fronts can be identified by turning or converging winds.
- Fronts can also be noted by large changes or contrasts in temperature.
- These features are focal points for weather. Some weather can even be severe or congeal into long lines.
- Two types: warm fronts usher in warmer air masses, and cold fronts bring in cooler air masses.

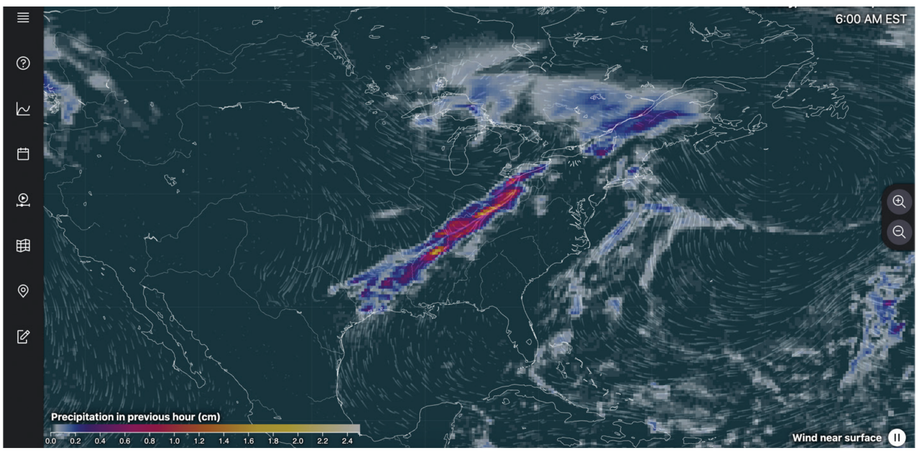

Fig. 2. Fluid Earth's precipitation overlay showing rain and storms over the Great Lakes and Mississippi River valley along a frontal system.

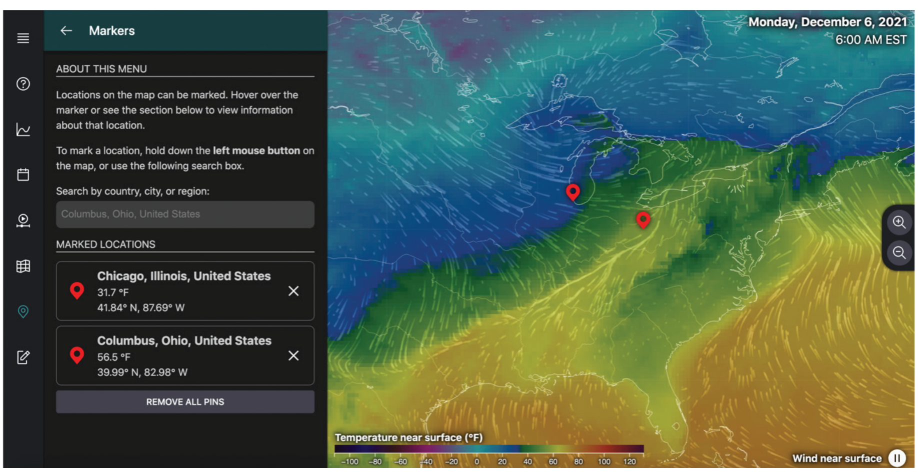

Fig. 3. Markers in Fluid Earth combined with different overlays can help pinpoint exact data at a certain location(s). Here, markers at Columbus, Ohio, and Chicago, Illinois, display a drastic difference in surface temperatures. Combined with changes in streamline angles, this heralds a cold front. Link to date/location: https://go.osu.edu/fev2.

Reinforcement

- Find another cold front somewhere in the United States on September 21, 2022. Mark the leading edge of the boundary with five pins and list the evidence you used to identify it. Date link: https://go.osu.edu/fev322.

Accessing Fluid Earth

Fluid Earth is freely available online for use on desktop and laptop computers with most web browsers as well as with Chromebooks and iOS tablets.[19] A brief tutorial video highlighting features is available for viewers.[20]

For facilities interested in creating an affordable, easy-to-manage interactive weather kiosk—such as at science museums, nature centers, and other informal STEM spaces—a basic Windows computer may be configured as a kiosk, connected to a touch-screen display, and set to visit Fluid Earth's Kiosk Mode.[21] The kiosk version has been scrubbed of all weblinks, guaranteeing that users will remain on the Fluid Earth website, and set to refresh to a new location on the planet every few minutes, ensuring that new users will start with an uncluttered screen. For institutions and users who want to access and customize the raw computer code for their own circumstances, it is accessible at no cost in a GitHub repository.[10]

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