Study employs deep learning to explain extreme events

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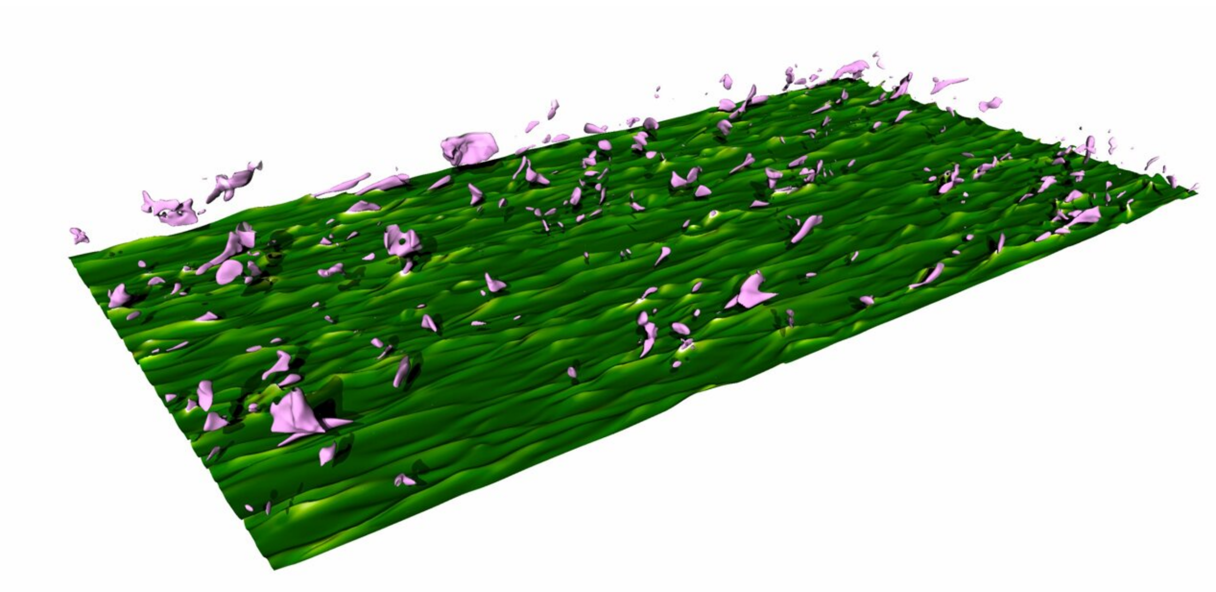

Credit: FAU College of Engineering and Computer Science

Identifying the underlying cause of extreme events such as floods, heavy downpours or tornados is immensely difficult and can take a concerted effort by scientists over several decades to arrive at feasible physical explanations.

Extreme events cause significant deviation from expected behavior and can dictate the overall outcome for a number of scientific problems and practical situations. For example, practical scenarios where a fundamental understanding of extreme events can be of vital importance include rogue waves in the ocean that could endanger ships and offshore structures or increasingly frequent "1,000-year rains," such as the life-threatening deluge in April that deposited 20 inches of rainfall within a seven-hour period in the Fort Lauderdale area.

At the core of uncovering such extreme events is the physics of fluids—specifically turbulent flows, which exhibit a wide range of interesting behavior in time and space. In fluid dynamics, a turbulent flow refers to an irregular flow whereby eddies, swirls and flow instabilities occur. Because of the random nature and irregularity of turbulent streams, they are notoriously difficult to understand or to apply order to through equations.

Researchers from Florida Atlantic University's College of Engineering and Computer Science leveraged a computer-vision deep learning technique and adapted it for nonlinear analysis of extreme events in wall-bounded turbulent flows, which are pervasive in numerous physics and engineering applications and impact wind and hydrokinetic energy, among others.

The study focused on recognizing and regulating organized structures within wall-bounded turbulent flows using a variety of machine learning techniques to overcome the non-linear nature of this phenomenon.

Results, published in the journal Physical Review Fluids, demonstrate that the technique the researchers employed can be invaluable for accurately identifying the sources of extreme events in a completely data-driven manner. The framework they formulated is sufficiently general to be extendable to other scientific domains, where the underlying spatial dynamics governing the evolution of critical phenomena may not be known beforehand.

Using a neural network architecture called Convolutional Neural Network (CNN) that specializes in uncovering spatial relationships, researchers trained a network to estimate the relative intensity of ejection structures within turbulent flow simulation without any a-priori knowledge of the underlying flow dynamics.

"Understanding and controlling wall-bounded turbulence has long been pursued in engineering and scientific discoveries, yet from a fundamental viewpoint, there is much that remains unknown," said Siddhartha Verma, Ph.D., senior author and an assistant professor in FAU's Department of Ocean and Mechanical Engineering.

"Our findings indicate that with the specific modifications we made, 3D CNNs coupled with the modified multi-layer GradCAM technique can prove to be immensely useful for analyzing nonlinear correlations and for revealing salient spatial features present in turbulent flow data."

The general framework the researchers employed leverages a combination of 3D CNNs and the newly modified multi-layer GradCAM (gradient-weighted class activation mapping) technique, which provides an explainable interpretation of a CNN's learned associations related to ejection events in wall-bounded turbulent flows.

"While identification using techniques like the ones employed in this study is an important goal, control and regulation of these coherent structures has countless scientific and practical applications, like reducing drag on ships or efficiency in utility infrastructure," said Eric Jagodinski, Ph.D., a doctoral alumnus of FAU's College of Engineering and Computer Science and principal AI engineer at Northrop Grumman.

"However, control of turbulent flows has been a challenging problem because of the inherent nonlinear evolution of the coherent structures, thus accurately identifying them is crucial."

FAU researchers modified the CNN architecture and GradCAM technique to make them more suited to analyzing turbulent flow structures. Using the modified CNN-GradCAM framework, they examined intermittent ejection events, which are known to influence the generation of turbulent kinetic energy within boundary layers.

"This important study provides a new understanding of wall-bounded turbulent flows using deep learning," said Stella Batalama, Ph.D., dean, FAU College of Engineering and Computer Science. "The techniques developed by our researchers allows for the discovery of non-linear relationships in massive, complex systems like data found frequently in fluid dynamics simulations."

More information: Eric Jagodinski et al, Inverse identification of dynamically important regions in turbulent flows using three-dimensional convolutional neural networks, *Physical Review Fluids* (2023). DOI: 10.1103/PhysRevFluids.8.094605

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