We know the earth is warming. We know that will stress water in the West. But we don't know how.

Two critical, big-picture questions loom: How much snow will fall in the mountains and how much water will there be for the region's forests, farms and cities.

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Flavio Lehner was a graduate student working with computer models simulating Earth's climate at the University of Berne in Switzerland when he had a chance to join a research vessel collecting sea temperatures and measuring ocean currents between Greenland and Svalbard, Norway.

"As a lifestyle, field work is very agreeable," Lehner said. "But for me, it was a watershed moment. I had to decide which way to go."

Was it to be a life in the real world of ocean voyages or mathematical abstractions?

"They had been measuring ocean currents for 10 years," Lehner said. "In real-world data collection, you look at one fraction of the Earth for a long time. With models, you can look at the big-picture questions."

Two of those big-picture questions are how much snow will fall on the mountains of the West and how much water will be available for the region's forests, farms and cities in a world growing warmer as greenhouse gases build up in the atmosphere.

Today, Lehner, 35, and his colleagues at the National Center for Atmospheric Research in Boulder, are trying to divine answers through a welter of mathematical calculations designed to reflect how the world works.

Those equations are linked together in NCAR's Community Earth System Model, a sort of algorithmic Rube Goldberg machine, which connects a set of algorithms representing the laws of physics that govern the planet – thermodynamics, transfer of radiation and global conservation of momentum and water — and uses them to generate a picture of the future.

Flavio Lehner Project Scientist at the National Center for Atmospheric Research in Boulder

It takes years to construct such a model, and it is hoped it accurately reflects the world. "The models do have deficiencies, and we work on those," Lehner said.

For example, there is a tongue of cold water in the tropical Pacific Ocean near the equator. The position and shape of it don't look realistic in a lot of models, Lehner said, and that in turn, could affect predicted rain patterns.

If you think of a map of the world overlaid by a checkerboard, you get a vision of the "cells" into which the data is distributed – Greenland ocean temperatures into the Greenland cell and Rocky Mountain snowfall into the

Colorado cell. The cells are big — 60 miles by 60 miles to as much as 150 miles on a side.

The smaller the cells the better the resolution in the model and the clearer the picture, but more computer power and detailed data are required.

The model is run on various scenarios to see what will happen to the world. Seeing what happens to rain and snow in the West is trickier.

"Temperature on a regional scale is clear," Lehner said. "If it is particularly warm in Boulder, it is going to be warm in Denver, but it can rain in Boulder and not in Denver."

The mountains make the Western cells even more difficult to model. As a result, predicting what is going to happen to rain and snow in the West is challenging.

The big models don't even agree on whether there will be more or less precipitation in the West as the world warms.

As the air gets hotter, it can hold more moisture – 7% more for each 1-degree Celsius increase in temperature – but whether that translates to more rain or just a few heavier storms is unclear.

Hot air that rises at the equator moves hundreds of miles north and south, descending to create a band of deserts around the world, including the Sahara, Gobi and the American Southwest's Sonoran.

The models show the Southwest deserts advancing north as the world heats up, but by just 10 miles in some, and by 100 miles in others. It is easier to see the movement over the oceans, which are flat, Lehner said, but more complicated once mountains and valleys are added. So, over land it is not always clear what will happen to the rainfall and deserts.

A backpacker pauses to rest near the summit of Stony Pass on the Continental Divide in the San Juan Mountains of south central Colorado. The Rio Grande's headwaters rise on the east side of pass. (Dean Krakel, Special to The Colorado Sun)

To better calibrate the Earth system models, 30 of the big model groups around the world – from Japan to China to Russia to Canada to Boulder – are participating in an exercise called the Climate Model Intercomparison Project, or CMIP, in which they all run the same data set to see where their models differ.

“It isn’t straightforward when you see these models don’t agree,” Lehner said. “Then it’s a lot of detective work to figure out why.”

NCAR’s model is housed in “Eagle,” the center’s supercomputer in Cheyenne, and Lehner can tap into it from his laptop (a bit like checking your bank balance online) and run simulations.

While Eagle is the fastest supercomputer in the world dedicated to energy research – performing 8 million-billion calculations per second — to run the data through the model’s mass of algorithms takes at least 24 hours for a 20-year projection; a century will take weeks.

While modelers try to sort out the glitches and differences, all the models do agree on quite a lot, including the basic fact that as the amount of greenhouse gases in the atmosphere rises, the world will be warmer and in many places drier.

"In the political realm, if we don't have the answer for sure, we don't know anything," Lehner said. "We don't yet know with any certainty what will happen to precipitation over the Southwest, but we can anticipate that in a warmer world — and a warmer world is certain — we will see more stresses on water resources."

Reframing the big picture to get a local forecast

To get a better sense of what will happen at a regional level, researchers take the data from Earth system models and "downscale" it to smaller models.

United States Geological Survey researcher Gregory McCabe, for example, constructed a hydrological water balance model – taking into account variables such as precipitation, temperature, soil moisture and snow accumulation and melt. The cells in this model were approximately 2½ miles by 2½ miles.

The model showed that since 1980 there have been lower-than-average snow conditions in the western U.S. that are "unprecedented within the context of 20th century climate."

When the model was applied to the Upper Colorado River Basin with a future average temperature increase of 0.86 degrees Celsius, stream flow declined by 8%. When the average temperature was increased to 2 degrees Celsius, stream flow dropped 17%.

“We’ve seen a shift in peak runoff to earlier in the year,” McCabe said. “So, the water is coming off sooner in several places in the West … that has implications of how much water there will be in the river in July.”

Models can be run backward into the past as well into the future. Using paleoclimate data from tree rings going back to 1490, McCabe and his colleagues reconstructed snowfall and stream flow in the Upper Colorado River basin which includes parts of Colorado, New Mexico, Utah and Wyoming.

Using the historical record, they concluded that under the warmer temperatures used in the hydrology model, the basin is likely to experience periods of water shortage more severe than anything in the past 500 years.

The headwaters of the Rio Grande arise on the Continental Divide in the San Juan Mountains of south central Colorado on the east side of Stony Pass at an elevation of 12, 592 feet. From these small beginnings the river flows 1,896 miles to the Gulf of Mexico. (Dean Krakel, Special to The Colorado Sun)

Lehner was part of a team that did a similar paleo study of the Upper Rio Grande Basin looking at how much of the snow made it into the river and concluded that the current, steep declining trend is "unprecedented in the context of the last 445 years."

Katrina Bennett, a hydrologist at the Los Alamos National Laboratory in New Mexico, downscaled Earth system model output into a hydrological model (with cells about 3.7 miles a side) to look at what would happen to stream flows as forests were lost to fire and pests in the San Juan Basin and found that that their disappearance alone could reduce stream flows in basin 6 to 11%.

“Over the next 50 to 100 years as forests are replaced with shrubs and the water balance shifts,” Bennett said, “the question is how far?”

MORE: Climate change is transforming Western forests. And that could have big consequences far beyond wildfires.

Between 2000 and 2014, the Colorado River suffered the worst 15-year drought on record. Bradley Udall, a research scientist at Colorado State University, and Jonathan Overpeck, at the University of Arizona, sought to parse what was happening to the river.

Using the temperature-water flow sensitives of a hydrological model, they concluded that while droughts in the past were driven by a lack of rain and snow, this drought was in large part caused by high temperatures.

About a third of the lost flow was the result of record-setting temperatures that caused evaporation from streams and soils, as well as evapotranspiration as plants suck up water. By 2050, they projected heat could reduce the

Colorado River flows 20%.

“You can already see the effects of heat,” Udall said. “I spent a week hiking in the Red River Valley in Utah at 10,000 feet. We’d had a wet winter, but by September, it was extremely dry. Streams were dry, marshy wetlands crunched underfoot.”

McCabe’s work on stream flows, Lehner’s centuries’ look back on the Rio Grande, Bennett’s examination of the interplay of San Juan forests and streams and Udall’s assessment of the impact of heat on the Colorado River are each smaller pictures of what is happening and what may happen in the future.

“Science is reliant on models from big global climate to smaller hydrology models,” Udall said. “What we’ve learned out of these global climate models are the extremes, the best and worst case. It gives you the sense of the range, but not what is most probable.”

“The struggle of what we know and what we don’t know should not paralyze us,” he said. “We know a lot, and it should tell us to be cautious. Since 2000, we’ve learned a lot, and it is mostly bad.”

CORRECTION: ***This story was updated at 1:42 p.m. on Jan. 22, 2020, to correctly describe the states in the***

Upper Colorado River basin included in Gregory McCabe's research.

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