Anticipating surprises: Climate extremes in the next decade

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Dear rector, ladies & gentlemen,

In this lecture, I will of course discuss the type of research that we do, on extreme weather and on the climate system. But I also would like to reflect more broadly on how climate science has developed over the past 10 years, and how I think it will develop in the years to come. What are the big challenges? Both for us, as climate scientists, but also for society. The next decade will be critical in many ways: We have to make radical changes to our society to limit global warming, and at the same time the impacts from climate change will be felt more strongly around the globe – in the first place via climate extremes.

But let me start with the year 1988. This is the year when the famous climate scientist Jim Hansen testified for the US senate, and he was the first to very clearly state that global warming had started. To use his own words: 'It's time to stop waffling so much and say that the evidence is pretty strong that the greenhouse effect is here"[1]. Those were strong words which were picked up by The New York Times and then by many media all around the globe. And that news also reached me – I was a young teenager at the time, and it was the first time I heard about global warming. I remember my father pointing me to a little article in the newspaper, and then later I started reading more about it in De Kijk, which was a popular science journal for nerdy teenage kids like me. I remember that I was totally intrigued by this. That humans could actually influence such a huge system, and it made me wonder what the implications would be. It would probably make an attractive story to say that since this moment in my teenage years, I have been "a man on a mission". But that story would not be very accurate. Some of you who know me might point out that I actually worked for the oil industry for over 2 years. So it would not make a very convincing story, and in fact I have done all kinds of different things over the last 30 years. Still I do like the idea that back then it planted a little seed in my brains, and that this has guided me at some important decision making moments in life. Whatever it was, here we are now 30 years later, and I am still very much intrigued by climate change. In fact the more I learn about the complexities of the climate system, the more intrigued I get. I am also getting increasingly worried of course. The globe has seen a lot more warming since 1988, in line with the projections made by Jim Hansen at the time[2], and now people are actually starting to notice that the weather is noticeably different than 30-40 years ago. And we particularly notice this in the extremes.

Summer 2010 – a wakeup call

When it comes to extremes, the summer of 2010 was very much a wakeup call for many climate scientists around the globe. That summer saw 2 very devastating extremes: A heatwave over Russia and massive flooding in Pakistan. We had a very wavy Jetstream that brought very hot and dry air towards Russia and Ukraine, which resulted in a harvest failure and also tens of thousands of heat related deaths. At the same time, this wavy jet brought cold Arctic air southwards all the way to Pakistan. Here this cold air collapsed with warm-and-moist air from the monsoon system, triggering very strong rainfall. These events were a wakeup call for many climate scientists and certainly also for myself. At that time I was working as a young postdoc spending my days with C++ programming to build an atmosphere model – truly, a hell of a task. But since that summer I have devoted most of my time in understanding how climate change affects these type of extremes.

We were among the first to argue that global warming is having a strong effect on heatwaves and extreme rainfall. In one of our early articles[3] we actually paraphrased Jim Hansen, stating that 'it is time to stop waffling so much and say that the evidence is pretty strong […] that anthropogenic, unprecedented heat and rainfall extremes are here". This paper had a big impact. It became my most cited paper by far, and not because it was rocket-science - it wasn't - but simply because we stated in clear words what was getting obvious. At that time, this message was still somewhat controversial, but now this has become mainstream climate science.

The reason that this has become mainstream science is because we understand the physics well, and we can clearly find these changes in observational data. In a series of studies, we analyzed data from about 50,000 meteorological stations around the globe, and simply count the number of extremes[4–7]. This showed heatwaves and extreme rainfall increased strongly over the last 30 years. We now have 8x as many monthly heat records, as compared to the 1950s, and 30% more daily rainfall records. If you look at drought, then you see that those regions that already have a relatively dry climate have seen an increase in droughts[8]. So for example, the Mediterranean and Middle East, but also large areas of sub-Saharan Africa have become drier. Also the western United States has become drier, and California has seen some very intense droughts in recent years.

The changes in extremes over the last 50 years – increases in heatwaves, extreme rainfall and drought - that's bad news. The good news is: we at least understand these changes well. They are driven by simple warming of the Earth's surface and lower atmosphere. We can therefore also make good projections for the next decade: the gradual trends over the last decades will continue, as they scale directly with global warming. This is the stuff we know and understand well. But there are also many unknowns.

Black swans

There are extremes that we do not understand well. Extremes that do not follow this gradual increase, but that are much more intense than anything observed before. Sometimes we refer to such events as black swans. Going back to Roman times, the phrase 'black swan' was used in Europe to refer to something that was impossible. All swans were simply white. But then in the late 17th century, the Dutch captain Willem de Vlamingh sailed to Australia and he was the first European to see an actual black swan. Since then the meaning of this phrase changed, and now it is used to describe phenomena that are perceived to be impossible, but then can actually happen. In climate science, the black swan phrase is used for extremes that were not anticipated by climate scientists, and that were much more intense than any extreme observed in history. As we do not anticipate such extremes, they present surprises to society and therefore they often have the most damaging impacts. And we have seen several of such surprises in recent years. A good example is last summer.

The summer of 2021 was actually full of such surprises, starting in June when we saw a record heatwave in western Canada. If you look at the temperature of the warmest day of the year in western Canada, you see that this fluctuates between about 28°C and 32°C. The region also experienced a long-term warming of about 2°C since the 1950s, which is very consistent with global warming. But then in 2021, we suddenly jump out of this historic range to a temperature of almost 40°C – a very large jump. This jump is even more pronounced when looking at local temperatures, for example in the town of Lytton. In this town, which was completely destroyed by wild fires, a temperature of almost 50°C was measured, where the previous record temperature was 40°C – so a jump of 10°C. If one compares this to the Netherlands: the warmest temperature measured in the Netherlands is just over 40°C, so this would imply that we would also jump to a temperature of 50°C. That is unheard of, and certainly not something we are anticipating as climate scientists. So, a black swan like event

Only one week after the Canadian heatwave we saw flooding in western Europe. We had very heavy rainfall for several days right at the border between Belgium, Germany and the Netherlands, causing massive flooding, for example in the Ahr river. Several hundred people died, mostly in Germany. Now if you look at rainfall of the wettest day in the warm season in the Ahr river basin over the last century, you find that this typically fluctuates between 20 and 50mm. But then 2021 saw more than 90 mm. Again about one week later, we see dramatic flooding in China. In western Europe we were shocked by 90mm in one day, but the city of Zhengzhou received more than 200mm in only *one hour*. That's an enormous amount of rainfall, and it shattered the previous record for all of China which was about 165mm. Again a very large jump. In 3 days it rained more than 600mm in Zhengzhou causing widespread flooding and 100,000 people needed to be evacuated.

These 3 examples from 2021 all broke previous records by very large margins, and had a massive impact on society. Those two characteristics define a black swan. What particularly interests me, however, is that they were all connected in some way to the dynamics of the Jetstream.

The Jetstream

So how is climate change affecting the jet in summer? We are starting to see some important changes. First, we see that the westerly flow has been weakening over the past 40 years, as also predicted by climate models[9]. Second, we see that so-called double jet states are becoming more frequent and more persistent[10]. There are two jets in the northern hemisphere: a subtropical jet and a polar jet, but very often they are intermingled with each other. Still, sometimes the jets are clearly separated and those situations are often associated with stagnant weather patterns in the mid-latitudes, and thus often heatwaves. These double jet states have roughly doubled in frequency over the past 40 years. I want to stress that there is a quite some uncertainty still with these dynamical changes. But I would like to stress even more that uncertainty here is really not 'our friend' as there are clear risks from dynamical changes in the climate system. Dynamical changes can lead to surprises.

To better anticipate surprises, it is absolutely important that we understand dynamical changes much better. How does global warming affect atmosphere dynamics? This includes the Jetstream, but also circulation patterns in the tropics. What type of extremes can we expect, and what are the key risks for society? If we understand these dynamical aspects better, we can likely also improve early warning systems.

The rise of Big Data in climate sciences

Those are big challenges, but there are also big opportunities. The increase in compute power and the amount of climate data available to us, enables us to study the climate system in exciting new ways. Moore's law has continued to double compute power every 2.5 years over the last decade. We now reach exascale compute power, which is a billion times a billion operations per second – that is quite unbelievable. Climate models are therefore becoming ever more realistic, also in terms of extreme weather events. Higher resolution, for example, enables to produce Hurricanes accurately. Also we run climate models not for one year, but for thousands of years, such that we can search for very rare extremes. This is of course creating massive amounts of climate data, from climate models but also from observations like satellites, radar, and many more sources. The total volume of climate data is now estimated at 100s of petabytes. In addition we have tons of relevant impact data. Crop data derived from satellites or critical infrastructure derived from open street map, to give just two examples. This data and compute power provides enormous opportunities. But the real challenge will be to create actual new knowledge from this deluge of data. Stuff that we humans can actually understand again.

Mining knowledge from Big Data

So how can we do that? How can we harvest new knowledge, new insights, from all of this big data? Luckily, there are several new methods from the Data Sciences that can help us here, and I am really excited about these three: Explainable Artificial Intelligence (AI), Causal Discovery methods, and Dynamical System Analyses. I believe that if we systematically apply such methods for different regions and different type of extremes, we can achieve some very important scientific goals, including: 1. Regional projections of extremes and associated societal risks; 2. (Sub) seasonal forecasting including impact-based forecasting (thus not forecasting the weather, but forecasting the impacts from the weather); 3. Attribution of extremes, including attribution of the impacts from extremes. I will discuss one example study for each of these three methods to illustrate how they can give new insights, and new process understanding of teleconnections and extremes.

Let me start with dynamical system analyses. In the summer of 2018, Europe was hit by a very intense drought. What was particularly surprising in 2018 was the persistence and recurrence of warm and dry weather conditions. The question is how such long weather persistence can happen in a chaotic system. The god-father of chaos theory, Edward Lorenz, actually proposed a mechanisms that might explain this, and it's called intransitivity[11]. Lorenz developed equations for simplified chaotic systems and those systems are prescribed by a so-called attractor. An attractor tells you the possible states of the system, but also how it evolves over time following specific pathways. The butterfly attractor forms the mathematical basis for chaos theory. The basic idea for intransitivity is that different summers can be governed by different attractors. They can be different in terms of their preferred state or in the part of the phase space that is accessible and which part is not accessible. The well-known butterfly attractors are valid only for very simple chaotic systems consisting of only three dimensions. Circulation over Europe is much and much more complex, and it is a very difficult exercise to try to estimate the attractor of European summer weather. But Ruud Sperna Weiland[12] was brave enough to give it a try. He used 2000 summers from a climate model and an advanced method to trace the evolution of European summer weather and find the preferred pathways through phase-space. And he succeeded in estimating what the attractor looks like, which is a very important result (see Fig. 1). Let me try to give you the essence of it: Each coordinate in phase space represents a possible weather state over Europe. On one end of the phase space, we have an east-west oriented Jet (coordinate E5) that brings relatively cold and wet conditions to Europe. At the other end, we have a wavy Jetstream state (coordinate K11) and therefore hot-and-dry conditions. The arrows show the preferred pathways of the system, so how the system preferably migrates from one weather regime to the next. Also, when you leave the right boundary of the phase space you enter again from the left and likewise for the top and the bottom. So one should actually project the phase space on a sphere. The cool thing here is that the pathways are not showing transitions from one day to the next, but instead 10 days ahead. So they capture the slow moving evolution beyond weather variability, and we are learning here that the system has much longer memory than typically thought – on the order of a month. And it gets even more interesting in that, the attractor for dry summers (right panel of Fig. 1) is very different from the one for wet summers (left panel of Fig. 1). For wet summers, the

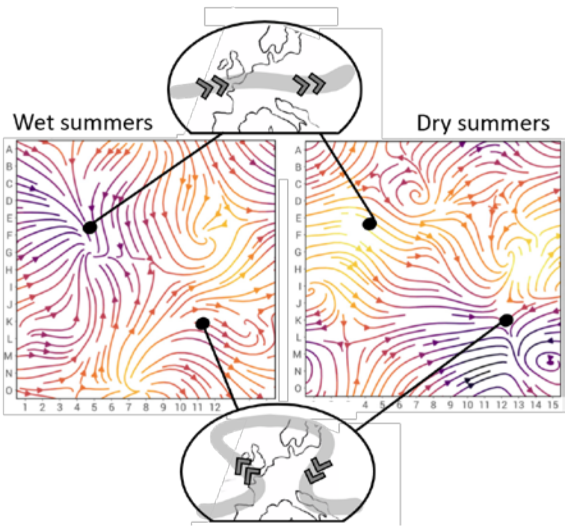

Fig 1: 10-day transition tendencies for European summer weather (adapted from ref 12)

pathways (arrows) converge towards the east-west oriented jet, so that is the preferred state. In contrast, for dry summers, the pathways converge towards the wavy-jet state. So this suggests that dry summers and wet summers have different attractors and thus behave dynamically differently. Or in other words, summers can be intransitive. There is a lot more to say about this – and there are many underlying assumptions - but I find this a very important fundamental insight. It is important for understanding how summer drought might change in the future. It is of course also important for predictability.

This brings me to another study where we really focused on improving predictability of European summer weather[13]. We want to forecast summer temperature 1 month ahead. This is challenging: Europe is a difficult region for predictions and summer is a difficult season. We start by taking a seasonal forecast from a climate model. Then we train an AI to apply corrections to what the model is forecasting. So it is searching for systematic errors. This is somewhat similar to an AI that checks our grammar in a word-document – something we are all familiar with. But the exercise with climate data is more complex as we do not know all the grammatical rules of the climate system. In fact, we actually want to learn those rules. And that's where *explainable* AI comes in, as it can tell you why the AI made a particular correction. This way we can learn which "grammatical rules" the climate model is missing. I hope this make any sense to you. If not – don't worry - let me just explain what we learnt with this approach: We see that the AI needs to apply an upward correction (i.e. the climate model is too cold) during situations when a wavy Jetstream pattern is present over Europe that brings warm weather to western Europe and cold weather to eastern Europe. And we learn that these situations happen during El Nino events. A downward correction (i.e. the climate model is too warm) is needed when this wave in the Jetstream is shifted eastwards, with the warm anomaly now over eastern Europe, and those situations happen during La Nina events. This I find a very important insight. El Nino – La Nina variability is known to be important in influencing weather worldwide, but classically it is thought that this is not the case for Europe, and not in summer. Here we are learning that El Nino-La Nina variability *is* actually important for European summer weather. Also we learn that the climate model apparently does not capture this link from the Pacific towards Europe, as the AI needs to make a correction. That's two important insights. In general, the cool thing is that we as humans, as scientists, can now learn new stuff from an AI.

A third powerful way to mine knowledge from big data are causal discovery algorithms. This builds upon classical work by Judea Pearl, about 20 years ago, who introduced new concepts for causal reasoning and how this can be applied to big data[14]. So this gives us tools to extract cause-effect relationships from big data sets – these tools have revolutionized many science fields, and have also many climate applications. Here we apply them to predict heatwaves over the eastern US, but also understand the underlying driving mechanisms. We find that temperature in the eastern US correlates with a wave-pattern in the Jetstream, but also sea surface temperature (SST) anomalies over the Pacific, Atlantic and Indian ocean. Now when we apply the causality step, we filter out all spurious correlations, and that shows that only the Pacific sea-surface temperatures are the causal drivers of eastern US heat waves. We call this the horse shoe SST pattern, and with this pattern we can predict eastern US heatwaves up to 60 days ahead[15]. So these AI-based forecasts can give us forecasts much further into to the future as compared to weather models.

Impact-based forecasting using AI

The fun thing with these AI-based forecasts is that one can easily adapt them to forecast impacts as well. So instead of forecasting temperature or rainfall, we can try to forecast harvests. And this actually works very well. The eastern US is a major soybean producer and we know soybeans are very sensitive to heatwaves. In recent work, we have shown that US soybean harvest failures are predictable 3 months before sowing[16]. And, interestingly, forecasting harvest failures works even better than forecasting heatwaves. We often think as climate scientists that including crops, or impact variables in general, makes things much more complex – but here we find that sometimes it can actually make life easier. We have seen this also for other regions and other crop types. And that is quite powerful of course as crop forecasts are directly relevant for society.

In recent years we have started to apply this AI-driven, impact-based forecasting in different projects in Africa with partners like the World Food Program. We are in the process of grounding a spin-off company, S2SAI, that aims at bringing these AI-driven forecasts to stakeholders around the globe. This can be both non-profit activities in the Global South, but also for-profit activities in the energy and agricultural sector in Europe or US. Personally I find this super fun to do. You get to meet very different people – including people who don't really care about waves in the Jetstream – and that is very refreshing. I also think it could be a very powerful way to bring our science and innovations to society. In the last years there has been a true explosion in start-ups active in climate services and climate analytics[17]. I think IVM is well positioned to have a very active role in this, given its broad experience with stakeholders. And not many people know this maybe but 'societal impact through entrepreneurship' is actually one of the focus areas of the VU, and the VU gives a lot of support for start-ups. So I think for junior scientists this can make a great career path, and there are many opportunities right now in this field.

Food prices in 2022

Back to Africa, and specifically the Horn of Africa as there is currently a humanitarian tragedy unfolding here. The region has suffered from several drought years in a row (2020, 2021, 2022), and this has already caused starvation of cattle, and is now also putting millions of people at risk of hunger. An important factor here too is the record food prices on the global markets. The war in Ukraine – a major exporting breadbasket – is a prime reason behind these record food prices. Now what worries me, is that, climatically, 2022 is developing in a very similar way as 2010. So this brings me back to the beginning of my lecture where I discussed the Russian heatwave and Pakistan flooding in 2010, connected via this wavy jet. We know now that the sea surface temperature patterns of 2010 were very important in creating this wavy jet[18]. This caused harvest failures in Russia and Ukraine, but also below-normal harvests in the US breadbasket. Those harvest failures drove food prices in 2011, as captured by the FAO food price index, which has been linked to the Arab spring.

This year, we have very similar conditions over the Pacific ocean as in 2010: a multi-year La Nina (cold anomalies over the equatorial Pacific) and what we have called "the horse-shoe pattern" over the northern Pacific. So that is worrying, and might indicate that those breadbaskets (Russia/Ukraine and the US) might do poorly this year, which would further drive global food prices. This is of course not a true forecast – one should not even call it a forecast. But rather it is connecting some dots and seeing some first signs developing in the climate system. But I think that in the coming years, we will further push the science such that we will be able to make such forecasts, and make them in a more quantitative and confident way.

The next decade

In the next decade we will have to make an enormous societal transition happen in order to limit global warming. Western nations typically aim at halving their emissions by 2030 – that's a huge challenge. At the same time, one gets the feeling that we are jumping from crisis to crisis: First the pandemic, then war in Ukraine, this again triggering a food crisis and energy crisis. What's next? We also know that in the next decade the impacts from climate change will be felt more strongly around the world – in the first place via extreme weather. So this is a rather sobering picture. And Fabienne, my wife, regularly wonders why my job is not depressing me (you should maybe realize she is a therapist). And to be honest, I am not very optimistic about the future, but, on the other hand, I am also not pessimistic. There is certainly also a more optimistic story to tell: renewables have become very cheap, and many governments have set ambitious targets. At the same time, the recent crises also show us how much we can achieve as a society if we really have to. So that gives some hope. Purely on a personal level, I was intrigued by all of this as a teenager and I still am, and that is very motivating. Also, I find it very fulfilling to work on such relevant topic.

That eagerness to learn, and at the same time, wanting to make a positive impact on society, that I recognize in all of my colleagues. That makes it enormously inspiring to collaborate with all of you. I am very grateful with my current position, bridging the more fundamental science of the climate system at KNMI with the more impact-oriented science at IVM. I like to thank all people who made this position possible, both at KNMI (Gerard, Werenfried) at IVM (Jeroen), and also the Board of the Faculty of Science at VU. I am also very thankful for the collaborations with all the smart and fun people at these institutes. Some do fundamental science, others applied science, others again work with stakeholders in the field – and that diversity in skills makes it really a strong team. What ultimately unites us, I believe, is that we do care a lot: about the environment, about the world and that we want to make it a better place. I certainly see that spirit in this group, but I also encounter it when speaking at external events for different sectors, like the agriculture sector, energy sector, and yes, even in the finance sector. And that spirit gives a lot of hope that we can deal with the challenges of the next decade. As a society we need to overcome those challenges already for this generation but even more so for the next generation.

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