'Forewarned is Forearmed?
Coping with our Changing Climate'

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Introduction

Perhaps the only advantage of getting older, is that you can see the **past** in a better perspective. At the same time, certainly at a university, you need to keep an open view to the **future**, especially for today's theme, climate action.

I started working on the modeling of clouds and climate at KNMI in 1990, now almost 30 years ago. If we look 30 years ahead it will be almost 2050, the year that Europe aims to be CO_2 neutral. Thirty years is also the time that we use define climate: **climate** is **weather** averaged over a period of 30 years.

I will present my modeling perspective on climate predictions in the form of three simple questions:

1. How did we look forward in the past?
2. How are we experiencing climate change today?
3. But above all: how can we look sharper into the future?

1 Looking forward from the past

I will start, however, with an observational story about one of my hero's: ***Charles Keeling***. He actually started his career as a chemist working on a project to measure the amount of carbonate in surface water. In order to do so, as a side effect, he also needed an accurate measurement technique to measure CO_2 concentrations in the atmosphere. And so he developed one.

By accident, he got into contact with a project manager who was organizing the International Geophysical Year planned in 1958. The project manager provided funds for 2 years of monitoring CO_2 concentrations on a new remote observatory on the Island of Hawaii: ***Mauno Loa*****.**
Within 2 years of measurements Charles Keeling made two groundbreaking discoveries:

i) He was the first to observe the seasonal rythm of CO_2 concentrations due to vegetation. In the figure you see the time development of CO_2 concentrations demonstrating the withdrawal of CO_2 from the atmosphere during the plant growth season in summer and the returning of it during winter.

ii) But, more relevant to our theme of today, and actually not anticipated, he also observed a clear upward trend of CO_2 with almost 1 part per million per year as a result of human activities.

The 'Keeling Curve' as we call it nowadays, has just celebrated its 60^{th} anniversary and ranks as one of the top scientific achievements of the 20^{th} century. This demonstrates the importance of long and carefully monitoring, an activity so often underrated in science. The story contains also a message to younger students: allways have an open mind to other applications of your work. You can never plan your career.

Today, the whole world is watching this curve, waiting to see when CO_2 emissions will start to decrease. At the moment, the opposite is still the case: The pink bars show that the increase of CO_2 concentrations is even accelerating. At present, emissions have almost tripled compared to the early days when Keeling started measuring.

Going back now to those early days in the sixties, Keelings early measurements started to trigger the question for scientists, to what extent global temperatures could be affected by the observed increase of CO_2 concentrations.

This question was, in part, answered by a revolutionairy scientific development that took place in the sixties. Thanks to the development of the electronic computers, Joseph Smagorinsky was the first to produce a global simulation of the atmosphere in 1963. This could be done by slicing the atmosphere up into boxes of 500 by 500 km. In each of those boxes, the well-known laws of physics were used, to calculate how wind, temperature and humidity evolve in time.

By coupling this model to a simple ocean model it became possible in the seventies to make also long climate simulations. Syukuro Manabe made in 1975 the first climate simulation experiment in which he doubled CO_2 concentrations compared to preindustrial estimates.

The analyses of these simulations led in 1979 to the first assesment report entitled: 'Carbon Dioxide and Climate'. I would like to bring out three important conclusions of this now famous Charney Report:

1. A most probable estimate 3^0 C of global warming was given as a result of a doubling of CO_2 concentrations

2. Associated with this warming, an increase of the water vapor amount in the atmosphere by 7% per degree warming was predicted. This outcome came as a direct result of the Clausius-Clayperon relation, well known by physicists. It simply states that warmer air can, and in fact will hold more water vapor as we all know from daily experience. As water vapor is an even stronger Greenhouse Gas (GHG) as CO_2, its increase forms a considerable contribution to the 3 degree warming.

3. The large uncertainties in global warming in the report were mainly due to clouds. More clouds reflect more sunlight and can dampen global warming to only 1.5 degree. Less clouds, on the other hand can enhance global warming to values up to 4.5 degrees. How clouds would respond exactly was unkown then and is still uncertain now.

If we go now to the present, all these predictions have come true!!

The Earth has warmed at a rate of almost 2 tenths of a degree per decade since 1980, in line with estimates of 40 years ago. And water vapor amounts in the atmosphere have increased by 7% per degree, especially over the oceans, all for reasons that we physically understand. So the first generation climate models, primitive as they were, were fit to answer the questions they were asked.

It is comforting for science to see that these anticipated changes have actually occurred. But more importantly, the results are highly disturbing not only for policy makers but for society as a whole.

So yes we were forewarned already in the late seventies but did we get forearmed?

The answer is essentially: very very late. Despite the Kyoto protocol of 1997 and the recent Paris agreement signed in 2016, the Keeling curve shows that the increase of global CO2 concentration is even accelerating instead of slowing down. Unfortunately, It is human nature only to take action once a predicted change becomes real.

2 Climate change in the present

Today, climate change is real. In the Netherlands temperature has increased by almost 2 degrees since 1900 and as a result, the amount of water vapor has gone up by more than 12%.

But these are all climatological trends. Society is much more interested to what extent extreme weather events that we experience are related to climate change. Was the long lasting drought of 2018 related to climate change? Was the European heat wave of 2003 a result of climate change? And what about the many extreme precipitation events of the last summer seasons?

To answer such questions we have to realise that what we experience in daily life is **weather** rather than **climate.**

Due to the Earth's rotation, the midlatitudes where we live, are dominated by Westerly winds, bringing a train of low pressure systems with mild maritime weather with clouds and precipitation over our country. These are occasionally interrupted by high pressure systems over the European continent that block this train, causing dryer Easterly winds that bring colder spells in Winter and warmer episodes in Summer. We call these circulation patterns the **large scale circulation** and they determine to a large extent our daily weather.

We can of course not say that a specific weather event, like a heat wave, is a direct result of climate change. Each weather event is unique and heat waves have occured in the past as well as in the present. But, today, we **can** say something about the probability of occurrence. Both westerly and easterly winds have on average become warmer over the last 50 years during summer.

Therefore, it can be calculated that the probability of having a heatwave has **doubled** over the last 50 years. This new branch of climate science, event attribution, calculates these probabilities, metaphorically speaking, by using dices with dots from 1 to 6 for weather without global warming, and modified dices with dots from 2 to 7 for weather for the present warmer climate.

This way, also the increase of extreme precipitation can be related to the warming climate: warmer air contains on average more water vapor: 7% more for each degree warming. So naively, you would expect that intense rain showers would produce a 7% increase in intensity for each degree warming: it's simply like a sponge, the more water it contains the more you can squeeze out.

The reality is even more disturbing: observations show an increase of even 14% extreme precipitation intensity per degree warming. This is likely the result of more vigorous updrafts in these convective rain clouds. The sponge does not only contain more water, it is also squeezed out more strongly. The top six of most intense rain events in the Netherlands all occurred after 2000.

But what about the more longlived events such as droughts? One could argue that the more humid and dominant westerly winds would bring more annual rain an average. But by that simple argument one would expect more annual precipitation over most of Europe and less droughts.

But if we look at the observed trends in mean annual precpitation and droughts, we actually see a **decreasing** trend of annual precipitation and consequently **more** heat waves in Southern Europe and the opposite in Northern Europe, more rain and less droughts. Netherlands is on the borderline between those two oppposite trends.

So how can this happen?

In short, these trends are largely due to **changes in circulation**. **More** Easterly winds for instance cause l**ess** precipitation. And less precipitation cause dryer soils and eventually droughts. This is exactly what is happening in the Mediterranean.

Circulation changes are in general **not** (yet) attributable to climate warming. Observations are not statistically significant and climate models are highly inconclusive about regional circulation changes as a reponse to global warming.

That's why it is not possible to link long-lasting droughts, like the one we experienced last year, directly to global warming. And for changes in annual rain it is a similar story.

A recent model study was carried out with 4 credible state-of-the-art climate models. The set up was simple. A simplified Earth only covered with oceans was simulated for a climate in which the oceans were made 4 degrees warmer. The results were disturbing. All models gave very different regional precipitation changes, especially in the tropics and subtropics where the circulation is less strong bounded by the Earth's rotation.

This all demonstrates that climate models were fit to answer the questions asked in the seventies about global changes, but also that they are inconclusive on providing more precise answers on changes in regional annual precipitation and droughts as a result of global warming, especially in the tropics and subtropics.

3 Looking into the future

If we want to look into the future, climate models are our only tool, simply because we do not have observations of the future.

But climate simulations have uncertainties. The last report of the Intergovernmental Panel on Climate Change (IPCC) from 2013 describes 2 scenario's. One agressive scenario, prescribing high CO_2 emissions, where we do not commit ourselves to any climate action measures. Climate models fed with this scenario give on average 4^0 C global warming compared with 2000.

A low emission scenario in which CO_2 emissions actually start to decrease strongly from 2020 onwards and are reduced to 0 by 2070, gives an additional warming of 1 degree compared to 2000, more or less fulfilling the 2 degree Paris agreement. Which scenario will unfold in the future, depends on the succes or failure of the energy transition that we are facing.

But for both scenario's the climate model uncertainties are huge. For the high scenario it is between 3 and 5.5 degrees, while for the low scenario it is between almost 0 and 2 degrees. And regionally the uncertainties are much larger, because climate simulations predict very different changes in circulation patterns.
Perhaps, surprisingly enough, these uncertainties are just as large as reported in the first Charney climate report 40 years ago. And clouds are still the prime source of this uncertainty. But more about this later.

Because of these uncertainties, KNMI presented 4 different climate scenario's for the Netherlands in the 21th century. A moderate warming scenario where the global temperature has increased by 2 degrees in 2100 and a stronger warming scenario with global warming of 4 degrees in 2100. For each of these scenario's there is another option: one with a small change in regional circulation over Europe and one with a larger circulation change with more Easterly winds.

Policy makers of course would like to know which scenario is the most probable. Unfortunately there is at present no way to answer this question. This is all we know at the moment.

One might argue, why bother? We need to take climate action anyhow. But in order to take action we need to know how the climate change wil further unfold in the future. So we need the best estimates for how fast sea level rise will keep increasing, and how precipitation and droughts will change on a regional scale. Which places on Earth will become first inhabitable because of heat stress? And above all, how much time is there left before we reach a 2 degree or even a 1.5 degree warming?

It has recently been estimated that if we could reduce this climate model uncertainty by 50% , it will have an economic value of trillions of euros, but only if this uncertainty reduction is achieved within the next decade.

So what is the reason for this nagging uncertainty in climate sensitivity and circulation that has not reduced over the last 40 years? And more importantly, what can we do about this?
The answer to the first question is embarrasingly simple. It is mainly the clouds. Clouds are subtle, as the water in the clouds is just a tiny fraction of the water vapor in the air: clouds are like the visible tip of the iceberg.

Even worse, clouds act on the kilometre scale while global climate models today still operate using boxes of one hundred kilometres. Therefore as a result, the impact of clouds is approximated in climate models with simple statistical descriptions called parameterizations. And these come with large uncertainties. Moreover, these errors amplify to the larger scales as clouds strongly influence the circulation. For this reason, uncertainty in climate sensitivity has not decreased over the last 40 years.

So can we do anything to improve this frustating situation? I **firmly** believe the answer is yes, and I will in conclusion discuss 2 pathways forward.

The first pathway is from a global perspective. There is strong evidence that climate models will start converging at least on prediciting changes in the circulation patterns once we reach the 1 km resolution. Only at these resolutions we start to resolve the deep convective cumulus towers that so strongly influence our large scale circulation patterns.

So we must build the best climate models that can operate at these 1 km resolutions.

Thanks to the ever increasing computer resources, this is now starting to become feasible with the most powerful supercomputers that exist today. It is already possible to create global simulations on a near 1km resolution scale for a short period of 10 days.

But in order to make climate simulations on timescales of a century, we need an increase in computational power by a factor of 1000, compared to the fastest traditional supercomputers today. This can not be done by just building a larger supercomputer with more processors. The energy consumption of such systems will simply become too large. So this requires a new archicture of a dedicated supercomputer that will run largely on graphical processor units, called GPU's rather than on the traditional central processor units or CPU's. These GPU's, developed by the gaming industry, are making tremendous progress in computing capability, are low in energy consumption, and are more and more being used for computational challenges such as climate and weather modelling.

This will also require improved efficiencies for scalable computer codes and new numerical flow solvers to make optimal use of such machines. Technology such as is available at TU Delft at the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) is crucial for these developments. Since Climate science is becoming real big science, this can only be done at a collaborative European level and many European institutes are trying to achieve this now through a European Flagship enterprise.

The second pathway is from a more local perspective and is the path that I followed for a large part during my scientific career.

I started to 30 years ago in 1990 at KNMI working on the role of clouds in climate. I was lucky to share a room with Hans Cuijpers, a PhD student under Frans Nieuwstadt, who was a professor at TU Delft then. Through him I started working with a Large Eddy Simulation model. This is a model that takes exactly the opposite appproach to a global climate model.

With large eddy simulations, the atmosphere is sliced into tiny boxes of only 100 meter so that all the relevant turbulent atmospheric motions can be resolved, including clouds. That way, we could accurately simulate the dynamics of clouds, but of course at the price that this was only possible on a embarrisingly small domain of 5 by 5 km, due to the computer resources in those days.

We kept developing this model, by including rain formation, radiation and adding soil and vegetation, thanks to intensive collaborations between various different faculties of the TU Delft, KNMI, University of Wageningen and the University of Utrecht.
As a result, in 2015 we managed at TU Delft, as the first research group in the world, to make a realistic 100 meter resolution that runs over a domain as large as the Netherlands.
This work was made possible, especially due to collaboration of our group Geoscience and Remote Sensing together with the Faculty of EEMCS, and by using the already mentioned Graphical Processor Units.

Now, the simulation applications are endless. For instance, by simulating an observed extreme precipitation event of today and comparing this with a 4 degree warmer climate, we can now explore realistically and in great detail how extreme rain intensity is changing with temperature.

Such **future weather simulations** show that rain showers not only get more intense, but also that they cluster in fewer but larger cells. This is work we do together with Geert Lenderink from KNMI, and is the PhD work of Kai Lochbihler.

The results are becoming now so realistic that TU Delft's Harm Jonker and Remco Verzijlbergh started a spinoff company called Whiffle in 2016. Having made a commercial version of DALES running on GPU's, their company now provides the best one day wind forecasts for the wind energy sector, an application I could have never dreamed of when I started doing these simple 5 km simulations 30 years ago.

But in the end, simulations are only as good as the observation that are needed to verify them. And high resolution simulations require high resolution observations.

Luckily, since the seventies, we have a unique observatory in the Netherlands, the Cabauw Experimental Site for Atmospheric Research, in short CESAR, which is situated between Delft and Utrecht. The centerpiece of that site is a 200 meter tall tower along which temperature, humidity and wind is measured.

But much more is being measured: the water in the soil and the evaporation, the radiation that hits and leaves the surface. Radars from TU Delft measure the clouds and precipitation in great detail, while Raman lidar systems with laser beams accurately measure the water vapor profiles in the air. Together these instruments measure the complete atmosphere, including aerosols and CO_2 concentrations in a vertical straw above Cabauw. Many universities and research labs in the Netherlands have brought their instruments to this site. This makes it one of the few places in the world where atmospheric processes can be measured in such a complete way.

In addition, since a few years, we also use DALES to simulate the weather at 100 meter resolution around this observational site so that we have an even more complete picture of the atmospheric dynamics on a 25 by 25 km domain around the site. And, equally important, we verify DALES in detail with the observations.

This observatory and the daily simulations we run around that site, inspired Herman Russchenberg to a dream. And as a scientist it's always good to have a dream. The dream was to boldly measure and simulate the atmosphere and soil below at the 100 meter scale for the whole of the Netherlands.

This resulted in a proposal for what we now call the **Ruisdael Observatory** in which all the partners of the CESAR consortium participate. This Ruisdael proposal, coordinated by Herman Russchenberg, received 18 milion euros from NWO in 2018. With this, starting this year, we will build a nation-wide observatory.

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This will be done by not only measuring in Cabauw, but at many different locations in the Netherlands, characterised by different environments. It includes urban areas like the city of Rotterdam, forests like in Loobos on the Veluwe, and coastal areas like Ludjewad in the North of the country. All these locations will be equipped with scanning radar systems so that they not only look upward but also in a circle of 50 km around the sites. Together with simulations of 100 meter over the whole of the Netherlands we will paint the next decade a modern version of Ruisdael artistic interpretation of the skies over the Netherlands.

In summary, if global simulations at the 1 km scale will become real the next decade, the Ruisdael observatory will provide a detailed looking glass for the atmosphere over the Netherlands and will enable us to monitor, simulate, understand and predict the weather, air quality and climate over the Netherlands in an unique way for the next decades.

So the opportunities for science to get better forewarned are bright. But it is up to society and to all of us to get better forearmed!