Lost Connection between Data and theory

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Introduction

This story is an edited and extended version of an online presentation to the members of the German "ClimXtreme Research Network" on 25 May 2021. It is drawn from my personal 40-year experience as a scientist and teacher. My scientific career started in the year that I published my first scientific paper together with my master thesis supervisor and later PhD thesis supervisor, Hans Oerlemans (van Delden and Oerlemans, 1982). This paper describes and interprets the results of numerical simulations of several life cycles of a population of shallow cumulus clouds in the atmospheric boundary layer. This interpretation is rather superficial and not well routed in theory. I was acutely aware of this, even at the time of publication. Moreover, I was not so sure about the realism of the numerical result. What role did the imposed boundary conditions play in determining the numerical result? We should perhaps have been more careful and critical about these results.

Later in my career I discovered that my first scientific paper is in fact a typical paper of its time in Climate Science in which a numerical model is used to identify a result from a large data set. This result, which seemed interesting and new, was not anticipated on the basis of a hypothesis or a theory beforehand. Many research papers of this kind have appeared since the 1980's. These papers with little or no grounding in theory, have flooded the Climate Science literature and have made it increasingly difficult, if not impossible, to keep up with this scientific literature. The idea that theory is not needed in this "Age of Big Data" is unfortunately gaining a strong foothold in Climate Science. At the same time, theorists have retreated into their own world, which is very much determined by mathematics. This is especially true in Theoretical Physics.

But let me start my story with a critical look at the new science of "Weather and Climate Extremes", the central theme of the "ClimXtreme" project.

A new discipline: Science of "Weather and Climate Extremes"

What are "weather extremes"? Is the frequency of occurrence of so-called "weather extremes" increasing? If so, can we attribute this increasing frequency to human induced climate change? These research questions are part of the new "*Science of Weather Extremes*".

This new discipline is a serious business **(figure 1)**, considering the fact that a journal with the title, *Weather and Climate Extremes*, launched in 2013, is now ranked higher, in terms of short-term *impact factor*, than well-known traditional journals, such as *Monthly Weather Review*, *Journal of the Atmospheric Sciences* and *Quarterly Journal of the Royal Meteorological Society*, which represent the older discipline of "*Dynamical Meteorology*". Nevertheless, in my opinion, the new "*Science of Weather Extremes*" cannot exist without the theoretical framework of "*Dynamical Meteorology*".

I will illustrate this assertion with an example, which is concerned with explaining the spectacular change of winter climate in Central-Western Europe over the past 50 years **(left panel of figure 2)**. In the Netherlands this winter climate change is manifest in a rise of the monthly average surface temperature in January at a rate of 3.8°C per century, which is much faster than the rate of rise of *global* average surface temperature in the same period.

The spectacular warming in January in the Netherlands is associated, to a large degree, with a transition to a more equable winter climate. It appears that persistent cold extremes are gradually vanishing out of the winter climate of Western Europe **(right panel of figure 2)**! Extremely cold winters were much more frequent in the far past.

Figure 1. Papers published in the journal, *Weather and Climate Extremes*, have a higher (short-term) impact than papers published in well-known old scientific journals representing the mother discipline of Dynamical Meteorology.

Are winters in Western Europe becoming more equable and if so why?

Winter temperatures in The Netherlands used to have a bi-modal distribution. This is especially clear when we look back in time as far as into the little ice age **(left panel of figure 3)**! The transition to more equable winter temperatures over the past 50 years, if true, may be connected, not only *directly* to the increasing CO_2-concentration, but also to a changing atmospheric circulation pattern, which is revealed in a more positive winter average North Atlantic Oscillation (NAO)-index over the past 50 years. A significant correlation exists between surface temperature in winter in the Netherlands and the NAO-index **(right panel of figure 3)**. Cold months, with an average surface temperature below zero, are mostly associated with a negative NAO-index, which is associated with more easterly winds over central Europe, bringing the cold from Russia.

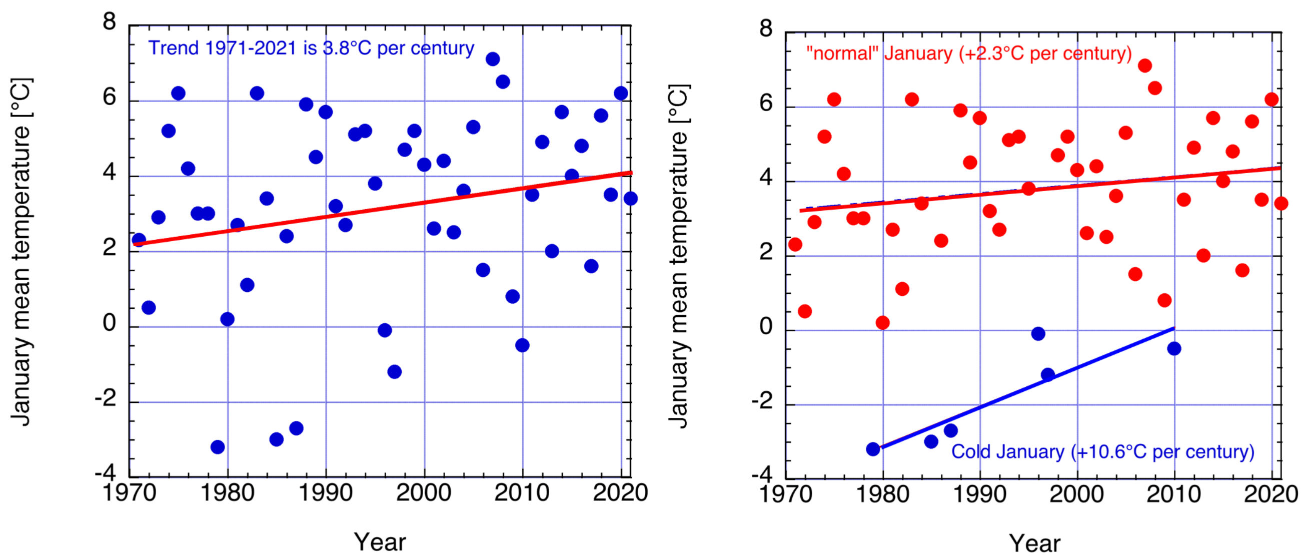

Figure 2. Left panel: Monthly mean surface air temperatures at De Bilt in January between 1971 and 2021. Right panel: same as left panel but with mild months highlighted in red and cold months highlighted in blue, somewhat subjectively emphasizing the bimodal distribution of winter temperatures and the differing temperature trends. Source of the data: https://www.knmi.nl/nederland-nu/klimatologie/maandgegevens.

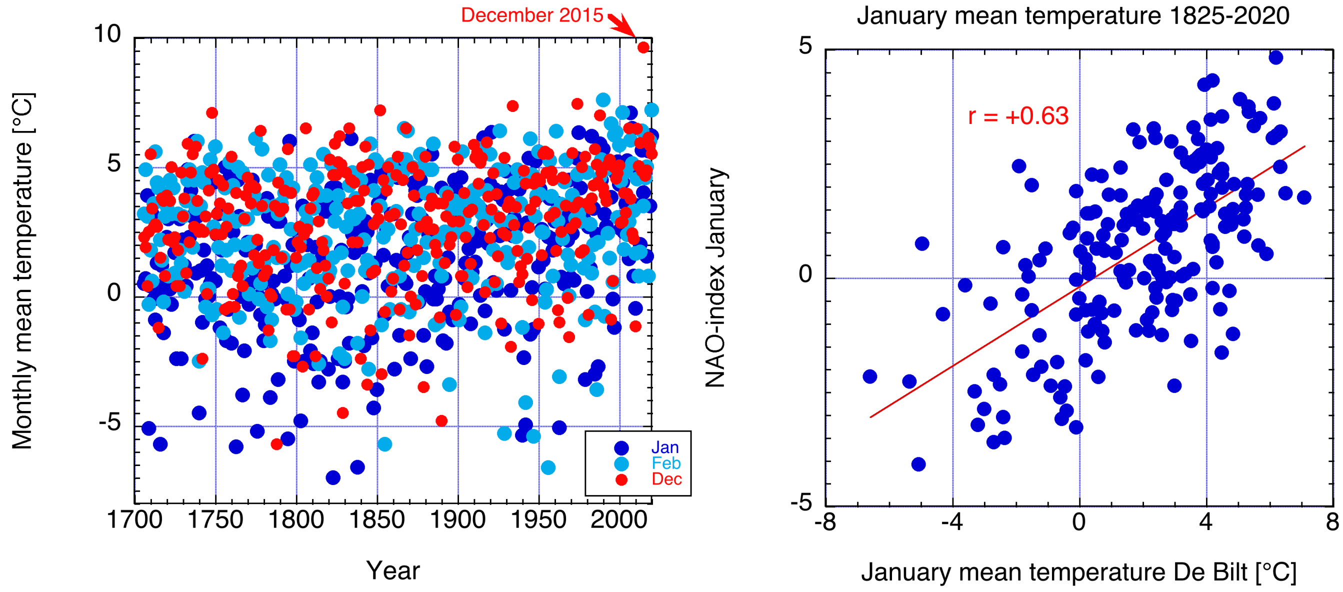

Figure 3. Left panel: Monthly mean surface air temperatures at De Bilt in December, January and February between 1706 and 2020, based on Delft/Rijnsburg (1706-1734), Zwanenburg (1735-1800 & 1811-1848), Haarlem (1801-1810) and Utrecht (1849-1897), reduced to De Bilt', and De Bilt (1898-now, homogenised 1906-2020). Source: Climate Explorer ("Labrijn time series"). Right panel: Scatter plot with best linear fit of January mean surface air temperatures at De Bilt against the NAO-index for the period 1825-2020. Correlation coefficient is 0.63. The NAO-index is based on the pressure difference between Gibraltar and Iceland: https://crudata.uea.ac.uk/cru/data/nao/.

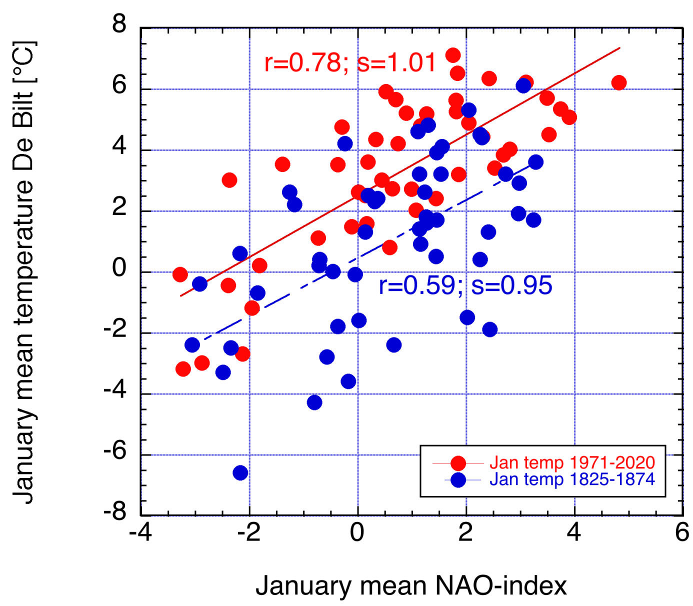

Figure 4. January mean temperature in De Bilt in the 50-year period, 1971-2020 (red dots), and in the 50-year period, 1825-1874 (blue dots, as function of the NAO-index. Also shown are the best linear fits and associated correlation coefficients and slopes. Data sources: see **figure 3**.

Are values of the NAO-index becoming more extreme? Of the one hundred January-mean values of the NAO-index plotted in **figure 4**, the highest five values occurred in the recent 50-year period between 1971 and 2020. Yet, the lowest two values of the NAO-index also occurred in that same recent period. Is the variability (the variance) of the NAO-index increasing?

Is the NAO in its positive phase more frequently in recent years? The NAO-index was positive in 35 out of 50 years in the period 1971-2020, while it was positive in 32 out of 50 years in the period 1825-1874. Can we conclude from this that the NAO-index has been in a more positive phase in the last 50 years? I think not.

We can, nevertheless, be reasonably certain that the relation between NAO-index and surface temperature has changed over time (**figure 4**). The two straight lines in **figure 4** represent the best linear fits to the observational data of each 50-year period. Note that these lines are practically parallel. The top line, corresponding to the most recent period, is simply displaced vertically by 2°C with respect to the bottom line, which corresponds to the mid-nineteenth century. This means that January-mean temperatures in the

Netherlands have systematically risen by about 2°C, no matter what the exact value of the NAO-index. Very probably, this reflects the direct effect of higher greenhouse gas concentrations on surface temperature.

The remaining observed warming, of about 2°C over the 145 years, separating the two 50-year periods under discussion here is unexplained. Is it associated with the demise of cold extremes, and is this, in turn, associated with more frequent westerly winds over Central/Western Europe in the recent period?

Indeed, an interesting research question at present concerns the influence of enhanced greenhouse gas concentrations on the polar winter vortex. In theory, more CO_2 will cool the stratosphere, which will intensify the polar winter *stratospheric* vortex. Will this also intensify the westerly winds in the troposphere? In other words, are we indeed going to see more winters with a very positive average NAO index, characterised by very strong westerly winds, more equable (mild) temperatures and abundant rainfall in North-Western Europe with simultaneous winter drought in the Mediterranean region? Or can we expect a different bimodal distribution of winter temperatures with recurring extreme *warm* winter months in North-Western Europe, like December 2015, now still an unlikely outlier (left panel of **figure 3**).

Some researchers, think that the recent strong warming of the Arctic, known as "Arctic amplification", has led and will lead to more weather extremes in middle latitudes, because Arctic amplification, they say, induces planetary waves with larger meridional amplitudes (for example, see the paper, due to Jennifer Francis, entitled "*Meltdown*" in *Scientific American* of April 2018). The unlikely high temperatures in December 2015 were indeed associated with a deep stationary trough over the Eastern Atlantic Ocean with a so-called *Atmospheric Moisture River* bringing moisture from the subtropics and abundant rainfall to the UK. On the other hand, large amplitude planetary waves are also associated with persistent high-latitude blocking anticyclones, a negative NAO-index and low winter temperatures in Western Europe.

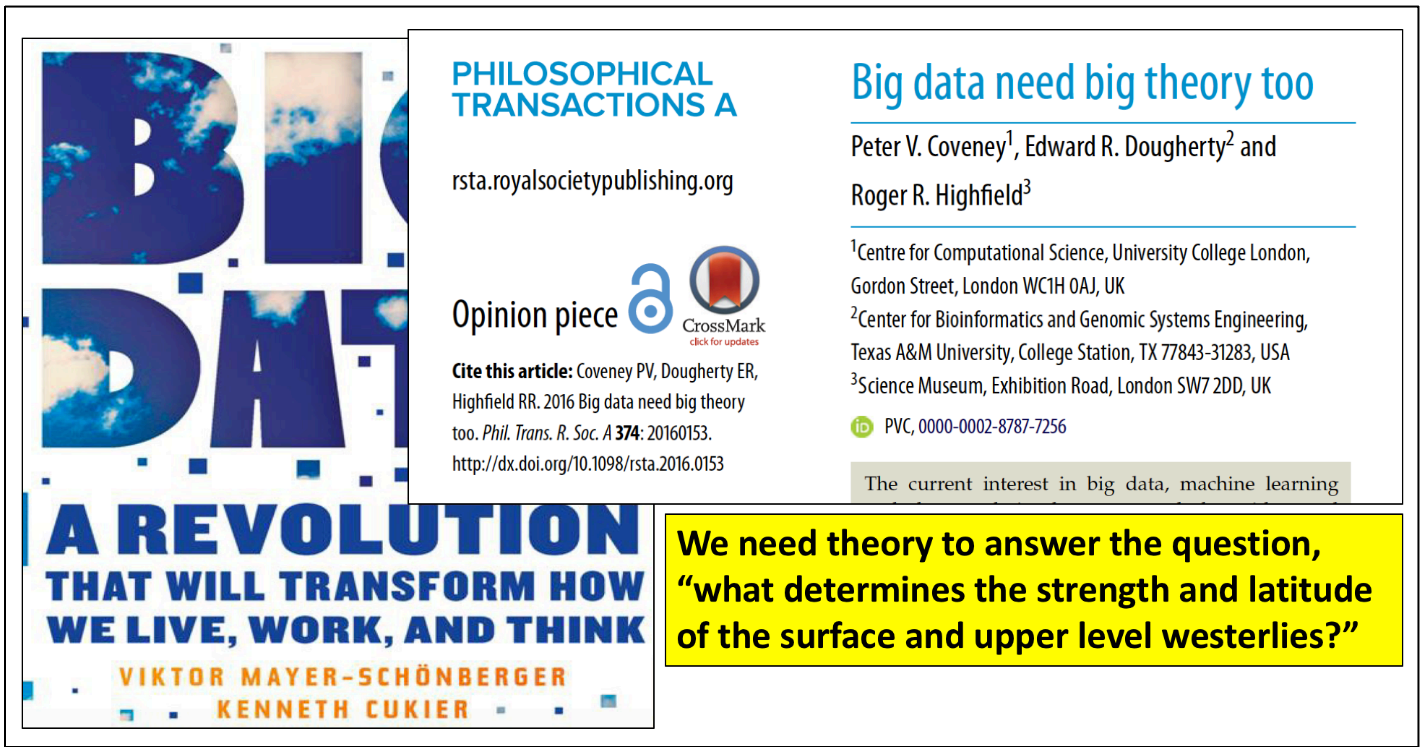

Figure 5. A slide in defense of combining "Big Theory" with "Big Data".

Is the new generation of climate researchers equipped with enough knowledge of Atmospheric Dynamics, Radiation Transfer Theory, the Water Cycle and the Physical, Chemical and Biological Processes occurring at the Earth's Surface to tackle the research questions of the "*Science of Weather Extremes*"? I am not so sure about this. Present day Climate Science seems to be dominated too much by only "Data and Statistics". But, in my opinion, a statistical result is no more than "Useful Information requiring a Theoretical Interpretation", as, three computer scientists pointed out recently (Succi and Coveney, 2019) (**figure 5**). "Theory" turns "Useful Data" into "Knowledge and Wisdom". Here I wish to make a passionate plea for the "Theoretical Interpretation" of data analyses, hopefully also pointing the way to new "Theory Development". By far the most valuable datasets in this context are the reanalysis datasets.

My work as a teacher and a researcher: in search of explanations

Let me introduce myself: my education and the motivation of my research. I grew up in Barcelona, Spain, where I received an English language school education. At the age of 18 I went to the Technical University of Twente, very near to the German-Dutch border, to study *Electrical engineering* and *Technical Physics*. I will not digress into an analysis of why I did not follow my interest in meteorology! After first overcoming the shock caused by the short gloomy winter days in the Netherlands, and missing the “big city” (Barcelona), I indeed quickly discovered that I did not want to become an engineer. Therefore, I moved to the University of Utrecht to focus on Geophysics, specifically Meteorology. In Utrecht I did a PhD-research project, supervised by Hans Oerlemans and Sjef Zimmerman, on *Cellular Convection in the Atmosphere,* which still serves as the inspiration for my part of a third-year bachelor course *on Turbulence in Fluids* in Utrecht. After getting my PhD, I worked as an assistant professor in the department of Meteorology at the Free University of Amsterdam, which specialised in doing and evaluating measurements as part of large international meteorological field experiments. After the retirement of its two professors (Hans Vugts and Henk Tennekes), meteorological research in Amsterdam was gradually transformed into climate (change) research. This led to the formation of the *Institute of Environmental Studies of the Free University of Amsterdam*, which focuses on climate change and the impact of climate change on society and the economy.

At present I am an associate professor in Utrecht. Perhaps I am an "old-fashioned" professor, because my research is unfettered and curiosity-driven. I am attracted to “fundamental questions”. The topic of my research is inspired by what I think I should teach the students. Students should learn to program a computer. At present, Python is the programming language of our choice in the *Climate Physics* master programme in Utrecht, because it is most suitable for analyzing *and* visualizing Big Data. Students should also learn about how to formulate a research question. They should learn to present their work, both in oral and in written form.

Students should, of course, also hear about the most recent developments in theory and practice. My attempts to combine teaching and research have led to a rather surprising discovery that some fundamental problems, which are presented in textbooks as "solved problems", with "very polished theories", are not actually solved or explained. Worse: some questions, which should be fundamental, are in fact avoided in standard textbooks. The question of the *cause, intensity and position of the sub-tropical jet stream* (STJ) is one of these unsolved problems, In standard textbooks the STJ is treated very superficially. Its strength is usually explained by applying the principle of *angular momentum conservation* to air parcels moving poleward in the upper leg of the "zonally symmetric" Hadley circulation cell. This is obviously not correct. Large-scale tropical eddies and waves have a large influence on the the circulation, in particular also on the STJ! Yvonne Hinssen and myself (van Delden and Hinssen, 2012) provide an explanation of the STJ, which does not refer to the Hadley circulation.

Students should be made aware of the fact that theories, even textbook theories, could be incomplete or even incorrect. Students should hear about scientific controversies. Why do tropical cyclones receive so little attention in standard textbooks on Atmospheric Dynamics? This is because it is a controversial topic in the research community, which, since the end of the 1980’s, has been divided on the question of the best theory to explain the growth, or intensification of a tropical cyclone. The disagreement on the correct theory of tropical cyclone intensification is the reason why tropical cyclones are treated very superficially in textbooks.

I spend much time on designing and preparing courses, such as the first-year master course on *Dynamical Meteorology*, which I have given for more than 25 years. This year I also give courses on the *Simulation of Ocean, Atmosphere and Climate*, on *Turbulence in Fluids* and on *Boundary Layers Transport and Mixing*. The latter course includes a course on the role of transport of radiation, water, heat, mass and vorticity in shaping the *General Circulation of the Atmosphere*. This includes the question of the formation of atmospheric jet streams.

I am open to students about research questions that are still unanswered . I am honest to students about theories that I do not understand, or believe, such as certain aspects of the interpretation of the quasi-geostrophic theory of Eliassen-Palm fluxes, which have led to an oversimplified interpretation of the influence of planetary waves on the polar vortex and the STJ. You can find my lecture notes at https://webspace.science.uu.nl/~delde102/AtmosphericDynamics.htm.

The trouble with Physics in Utrecht

In 2014 I became programme-leader of the master programme, *Climate Physics*. For the past three years I have also been director of education of the *master programme of physics* in Utrecht, which includes programmes in *Theoretical Physics* and *Experimental Physics*.

Research in Physics in Utrecht is united under the name, "*Extreme Matter and Emergent Phenomena*". But in my experience, we seem to have very little in common. Communication between the representatives of the three research directions has been difficult, to say the least. The master programme in *Theoretical Physics* has a solid reputation, due to the Nobel Laureates, Martinus Veltman and Gerard 't Hooft. *Theoretical Physics* is built on two core courses: *Quantum Field Theory* and *Statistical Field Theory*, together 20 ECTS. Remarkably, these courses are not mandatory in the *Experimental Physics* programme. Are these courses too specialised and difficult for students of *Experimental Physics*?

Despite its difficulty, *Theoretical Physics* is immensely popular with the graduate students from the physics bachelor programme in Utrecht. *Theoretical Physics* receives more than 60 students per year, while *Experimental Physics* has only 15 students per year. This difference in the popularity of the two related master programmes cannot be healthy.

Why is *Theoretical Physics* so popular? One reason might be, because *Theoretical Physics* has a reputation of being difficult. To many students, doing *Theoretical Physics* represents a real aptitude test. *Experimental Physics*, especially Sub-Atomic Particle Physics, on the other hand, is going through an identity crisis due to lack of new experimental data. Experimentalists in Utrecht are now reorienting their research agenda, finding new challenges in Gravitational Physics and Biophysics under the new logo, "*studying the extremes of matter and space-time*", and soliciting help from theorists. But theorists are not very responsive, not wanting to jeopardize the carefully built reputation of *Theoretical Physics* in Utrecht. A significant part of the crowd of Theoretical Physicists seems to be guided, not by experiments, but by *Mathematics*, as has been noted by many in recent years, most recently by Sabine Hossenfelder (2018). Last year's Physics Noble laureate, Roger Penrose, has a lot to say about the relation between mathematics and physics in his books entitled, "*Fashion, Faith and Fantasy in the New Physics of the Universe*", published in 2016, and "*The Road to Reality*", published in 2004.

The trouble with Climate Physics

The third master programme of Physics in Utrecht is *Climate Physics*. Over the past few years this programme has welcomed 30-40 students per year, many from outside Utrecht. *Climate Physics* is an application of *Classical Physics*, such as Fluid Mechanics and Thermodynamics. Starting in the 1950's much effort in this field has gone into developing numerical models for weather prediction and for studying earth's climate. An impressive family of global models has emerged. These models solve the set of non-linear coupled equations of Fluid Mechanics and Thermodynamics, based on the laws governing the budgets of mass, momentum and energy, which were developed by the theoretical physicists before the beginning of the twentieth century, and applied to a rotating, stratified fluid, such as the atmosphere or the ocean.

The latest development in *Climate Physics* is the so-called "Earth System Model", which includes the atmosphere, including its chemistry, the ocean, the cryosphere and the biosphere. The outcomes of these models require an interpretation. However, even though the theoretical framework, needed for this interpretation, is available, little use is made of it, in my opinion. For example, as far as Atmospheric Dynamics in concerned, we can and should go further and deeper than the traditional quasi-geostrophic approximation. Joseph Smagorinsky (1964), one of the pioneers of the General Circulation Model, formulates this problem as follows.

"Our lack of theoretical understanding of the model elements is perhaps a more serious deterrent than the lack of adequate computational apparatus."

The problems associated with numerical modelling of complex systems, like Earth's climate, which were so succinctly identified by Smagorinsky in the early days of General Circulation Modelling, are still valid today (Held, 2005) (Jacob, 2014). Smagorinsky, who was the mentor of this year's Physics Nobel Laureate, Syukuro Manabe, was an advocate of applying Ockham's razor as a guiding rule to developing models to understand the General Circulation of the atmosphere, as the final words of his 1964-paper demonstrate:

"We must guard against the massive outputs of high-speed computers with understanding. The computer at best is a very convenient laboratory tool – but it is not the end in itself. The design of experiments and the devising of perceptive methods for diagnosing and interpreting the results are still primitive. However, experience in the past few years indicates that numerical methods potentially have an elegance comparable to that of traditional analytical methods – but that its full realization is yet to be achieved. ...

Finally, as we isolate the essential processes responsible for the characteristics of the general circulation, ultimately one would expect to be able to dispense with unnecessary and irrelevant detail – thereby reversing the trend toward more complex models and larger computers."

The Ice and Climate Research Group in Utrecht has an excellent reputation for conducting field experiments on Glaciers and Ice Caps and devising (remote sensing) equipment for continuous unattended automatic measurements of all kinds of meteorological variables in cold and inhospitable regions, such as Antarctica and Greenland. Unfortunately, it is increasingly difficult to obtain financial support for this experimental work, because it is not considered as "original" by funding agencies. A new focus of research has now emerged: Earth System Modelling.

I am afraid that *Climate Physics* is dominated too much by research employing large climate models, which produce huge data sets, the statistical analysis of which may have less to do with reality than desired. The community of theoreticians in Climate Physics is relatively small, and is not benefitting very much from this work, or is just not interested, which means that comparatively little theoretical progress is being made in *Climate Physics*, especially in *Dynamical Meteorology*. At the same time, experimental work in Climate is becoming less popular, because of lack of financial support for this type of work.

My interest in extreme weather

I used to be a weather-amateur in my younger years. Weather amateurs are interested in the statistics of weather, in particular of extreme weather. So was I. At a young age I was fascinated by thunderstorms. Thunderstorms in the east of Spain, and also elsewhere in the western Mediterranean, at the end of summer, especially in September, are frequently accompanied by torrential rain. Flash floods in the heavily populated Llobregat river valley, near my hometown, just outside Barcelona, regularly caused much destruction and many casualties, simply because of lack of protective measures against these floods (**figure 6**).

"Immigrants" from other parts of Spain, attracted by work in the growing textile industry around Barcelona in the 1960's, were living in quickly erected neighbourhoods on the ephemeral flood plains of the Llobregat river. The most severe flash flood in this area occurred on 26 September 1962, exactly one week after the birth of my younger brother in Barcelona. In a recent paper in *Journal of Hydrology* (Martín-Vide and Llasat, 2018), it is concluded that this event, which was the worst ever to take place in Spain, in terms of loss of life and destruction, was not an outlier, nor was it extreme, in terms of total rainfall, return period and discharge. It was extreme because of the damage it caused, which was due to bad and irresponsible "urban planning".

Figure 6. Images of the destruction of the bridge over the *Llobregat river*, at Molins de Rei (Barcelona), a few kilometres from my home, as a result of a torrential rain event in December 1971. The bridge was part of the main road between Madrid and Barcelona. These images are taken from my scrapbook, which I made in my teens, as a "weather amateur".

In my teens I was also fascinated by tornadoes and tropical cyclones. I was interested in more than just the statistics of tornadoes and tropical cyclones. What makes huge volumes of air rotate in such an amazingly coordinated fashion to form a tropical cyclone? During my PhD-years I could not refrain from investigating this theoretical question, even though it was officially not part of my PhD-project. I wanted to understand the physics of tropical cyclones. This led to the writing of a paper *on the deepening and filling of balanced cyclones by diabatic heating* (van Delden, 1989). The tropical cyclone research community in 1989 was in the middle of a heated debate about the question of the growth of tropical cyclones. I was framed by one reviewer of my paper as a defender of the old theory of the growth of tropical cyclones, which, in fact was due to two giants of dynamical meteorology: Jules Charney and Arnt Eliassen. Nevertheless, ultimately, I managed to get my paper published. I am still proud of this paper, but I also acknowledge that the main message of this paper, namely that warm core cyclones intensify by diabatic heating, whereas cold core cyclones weaken by diabatic heating, was unfortunately buried in technical detail. I discovered that a paper should have a simple message and that this message should be conveyed as clearly and concisely as possible. I also discovered that it is very difficult to get your work accepted in a specialised research community if you do not, or cannot, invest a much time in going to the corresponding specialised conferences, in this case conferences on tropical cyclones, and write more papers on the same topic. A scientist has to invest time in advertising his/her work. Presumably, I have not done this sufficiently.

In the 1990's I turned to *severe convection* as a subject of research. I was particularly interested in the *Synoptic Setting of Thunderstorms*. What are the right or optimal conditions for the formation and long lifetime of convective storms? Three basic ingredients are needed to produce a thunderstorm: **(1)** potential instability or CAPE, **(2)** high levels of moisture in the atmospheric boundary layer and **(3)** forced lifting of the potentially unstable air.

The principal research question was: what type of large-scale flow configuration is conducive to produce these ingredients simultaneously? Finding the answer to these questions requires, not only data, but also knowledge of Atmospheric Dynamics, which includes an understanding of the potential mechanisms that forces air to move upwards to overcome the potential barrier, which is usually present in the form of an inversion at the top of the atmospheric boundary layer.

About 20% of the students that come to study *Climate Physics* in Utrecht are most interested in weather. This certainly includes the topic of severe convective storms! Many students have performed a master-research project on severe convective storms under my supervision. We took advantage of the first high quality relatively high-resolution gridded analysis of the past state of the atmosphere, now known as "re-analysis", together with high quality data from the UK lightning detection array. Papers based on these master research projects (e.g. Haklander and van Delden, 2003) have been cited many more times than my 1989 - tropical cyclone paper or any other of my theoretical papers. I suspect that it is due to our work on severe convection that I am now giving this presentation, as member of the Scientific Advisory Board of this large German research project on Climate Change and Extreme Events.

Extreme weather research should not neglect "explanation and understanding"

Climate Change broke through on the research agenda after James Hansen's US-Congressional testimony on climate change in 1988. Funding of Climate research grew explosively in the 1990's. In the past years the Dutch National Meteorological Institute (KNMI), is trying to fit weather research into this research agenda. KNMI has adopted the phrase, "Extreme weather due to climate change", to attract the attention of the Dutch government, and has recently obtained a large sum of money to erect a so-called "*Early-Warning Centre*" (**figure 7**).

On the first page of the website of the Dutch *Early-Warning Centre* it states:

"*Climate is changing rapidly. This makes weather extremes more common*".

However, I do not think that there is unequivocal proof that weather extremes are getting more common. It also depends on what kind of weather event. In my opinion, the "Science of Extreme Weather" derives its importance from our increased vulnerability to the *ever-present* risk of extreme weather in this overcrowded world.

Next to the announcement of the Early Warning Centre on the homepage of KNMI **(figure 7),** we read the following question:

"*Is extreme weather due to climate change*?"

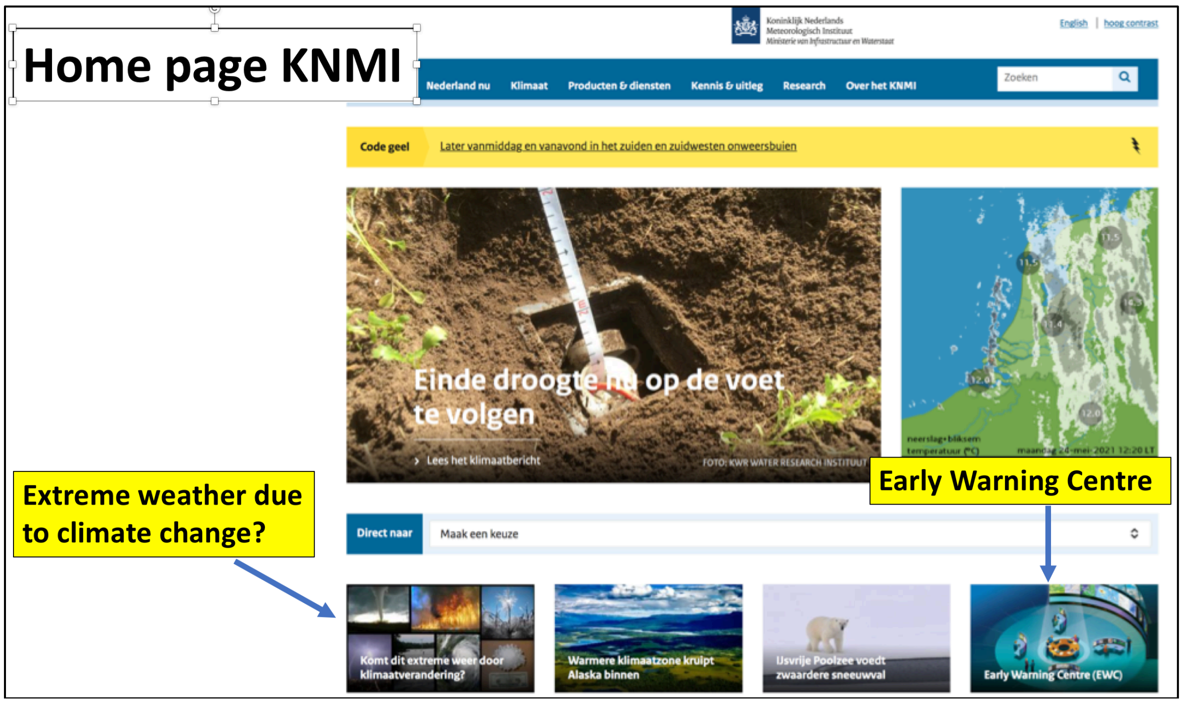

Figure 7. Homepage of the Dutch National Meteorological Institute (KNMI) on 24 May 2021.

A mouse-click on this question, which clearly is still open to debate, leads us to a web-page, presenting the *World Weather Attribution consortium* (WWA), an international team of scientists, which has drawn up a roadmap for the *attribution of weather extremes*. This roadmap consists of answering the following questions.

1. What events are we going to investigate?
2. Which aspects of the extreme weather event were most relevant?
3. How rare was this event and how has this changed?
4. Which models can represent extreme weather conditions?
5. Which part of the observed trend can be attributed to climate change?
6. What is the overall picture of the role of climate change?
7. How important are other (social) factors?
8. How do we ensure that the results are communicated both comprehensibly and truthfully?

These research questions largely overlap with the two central questions of ClimXtreme.

1. Has past climate change caused more extreme weather events?
2. Will future climate change modify the occurrence of extreme weather events?

Is this the complete roadmap for the *attribution of weather* extremes? I think not. Answers to the above-listed questions will not tell the whole story They will not yield a satisfactory feeling of understanding of the physical mechanisms behind extreme weather events. We need studies, which try to uncover the mechanisms behind changing circulation patterns. Can we explain physically, why the North Atlantic Oscillation is in its positive phase more frequently since 1970, while record negative values of the NAO-index are also observed in the same period? We need the theoretical framework of Dynamical Meteorology and Climate Dynamics for this explanation. I am especially interested in the results of **module A of ClimXtreme**, which aims to produce explanations of the “Physics and Processes of Extreme Weather Events”. These explanations should definitively go deeper than oversimplified and short explanations in the media, which go no further than to attribute the German floods of July 2021 to enhanced greenhouse warming by simply stating that "because a warmer atmosphere can "hold" more water vapour, extreme precipitation events will occur more frequently".

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