

MODELING CLIMATE CHANGE IN THE LABORATORY

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ABSTRACT

In a simple tabletop-size rotating wave tank experiment at the von Kármán Laboratory of ELTE, atmospheric climate change scenarios can be modeled by continuously decreasing the temperature difference between the two sidewalls of the tank, imitating the effect of global warming. As these boundary conditions slowly change, we can observe how the "weather" in the tank reacts to this non-stationary forcing. Such laboratory investigations may support the better understanding of the causal connections between global warming and the increasing number of unusually warm or cold seasons observed coincidentally in the past 30 years at the mid-latitudes of Earth.

INTRODUCTION

Understanding the underlying statistical properties of extreme weather conditions is crucially important to our society. Analogously to the engineering problem of sizing a dam to withstand extreme water levels, decision makers involved in long-term economic or political planning must consider and, if reasonably achievable, mitigate the risks of unlikely but highly hazardous events (e.g. to keep a certain amount of agricultural goods in reserve as preparation for extremely warm and dry Summers, as in the 3,500 year-old Biblical story of Joseph in Egypt). For such strategic purposes assigning odds to extreme events would be essential.

Unfortunately, quantifying such risks is far not trivial, firstly, because – by definition – extreme events are rare, thus reliable measurements are needed over as long time as possible. Even if this was granted, one must keep in mind that climate exhibits significant fluctuations on every imaginable timescale, yielding a power law-type long-range correlated behavior, as demonstrated by merging observational and paleoclimate data sets in, e.g. [1]. This feature implies that, strictly speaking, no data record can be long enough to define a stationary base period to which extremes can be properly compared. Yet, given the fact that only one realization of global temperature time series exists (we have one Earth, and we have no access to climate data from “parallel universes” with the same laws of physics but slightly different initial conditions), finding such “quasi-stationary” periods and taking them as the “golden standards” of climate variability is still the best thing climate scientists can do. It has some serious drawbacks, however, as we will point out.

Fig. 1 shows the monthly global average temperature anomalies of the Earth. By definition, anomalies are compared to the – relatively stagnant – three-decade base period of 1951-1980, whose temporal average is subtracted from the whole time series. As it is apparent from the graph, longer periods without any trend are more like the exceptions than the rule, as far as the past 150 years are considered.

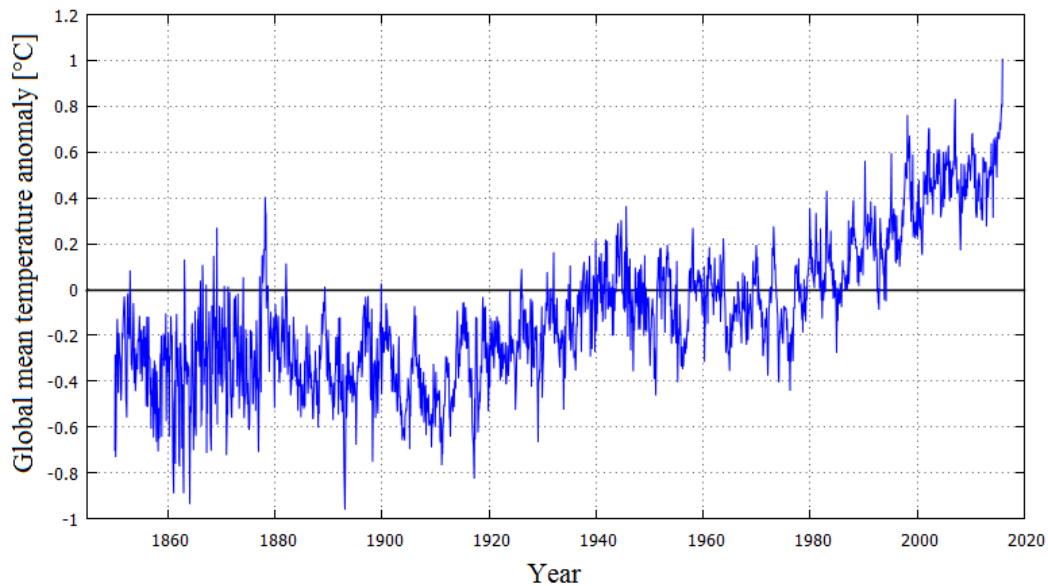


Fig.1. Fluctuations of monthly global mean temperature anomaly, as compared to the average of the 1951-1980 ‘base period’. Source: <https://climexp.knmi.nl>

Widely cited studies, such as [2] have come to the conclusion that coincidentally with the rapid global warming of the past 40 years, the so-called “climate dice”, that describes the chance of unusually warm or cool seasons, has become more and more “loaded”, or in other words, “the distribution of seasonal mean temperature anomalies has shifted toward higher temperatures and the range of anomalies has increased” (compared to their base period).

On the one hand, this is definitely a very interesting and important observation from the practical point of view; extremely hot summers can have disastrous effects on agriculture and our society in general. So this is clearly something important to know about, and prepare for. On the other hand, the finding, at least qualitatively, is exactly what one would expect from the simple fact that the time series of Fig. 1 in the considered period (i.e. the past 40 years) exhibits a marked increasing trend: if the mean is shifting upwards, previously rare high values more and more become the norm. The real question is therefore, whether the observed changes in the number of days in the year with “extreme temperatures” is merely a consequence of the shifting mean, while the statistical properties of the fluctuations (i.e. the physical nature of “weather”) remain the same throughout the process, or there is also an inherent amplification within the dynamics of the fluctuations themselves, besides the shifting mean. Looking back to Fig. 1 the change in the past decades seems to be so rapid that even on the typical timescale of a larger fluctuation the trend line increases significantly: the observed process is nowhere near quasi-stationary. So the classic approaches of decomposing the signal to short term and long term components and identifying the former with “weather” and the latter with “climate forcing” can be very misleading.

The schematic drawings in the three panels of Fig. 2 are excerpts from the special report of the UN’s Intergovernmental Panel on Climate Change (IPCC), titled “Managing the risks of extreme events and disasters to advance climate change adaptation” from 2012 [3]. Panel a) drafts the scenario of “shifted mean” in terms of the sketched probability density functions (PDFs) of global average temperature values. The graph corresponding to the base period is marked by solid line and the “climate change” scenario is sketched with the dashed curve. In this case the mean changes, but the fluctuations behave essentially the same way as in the base period. Panel b) shows just the opposite case: even though the mean does not change at all here (“no global warming” on the long term), yet, apparently something happens to the

weather system, because the “tails” of the PDF become thicker (i.e. frequencies of extremely hot or cold days in a year increase). Panel c) represents a similar scenario: the mean stays unchanged, and so does the “left tail” of the PDF, but the probability of hot weather increases, thus the symmetry of the distribution changes.

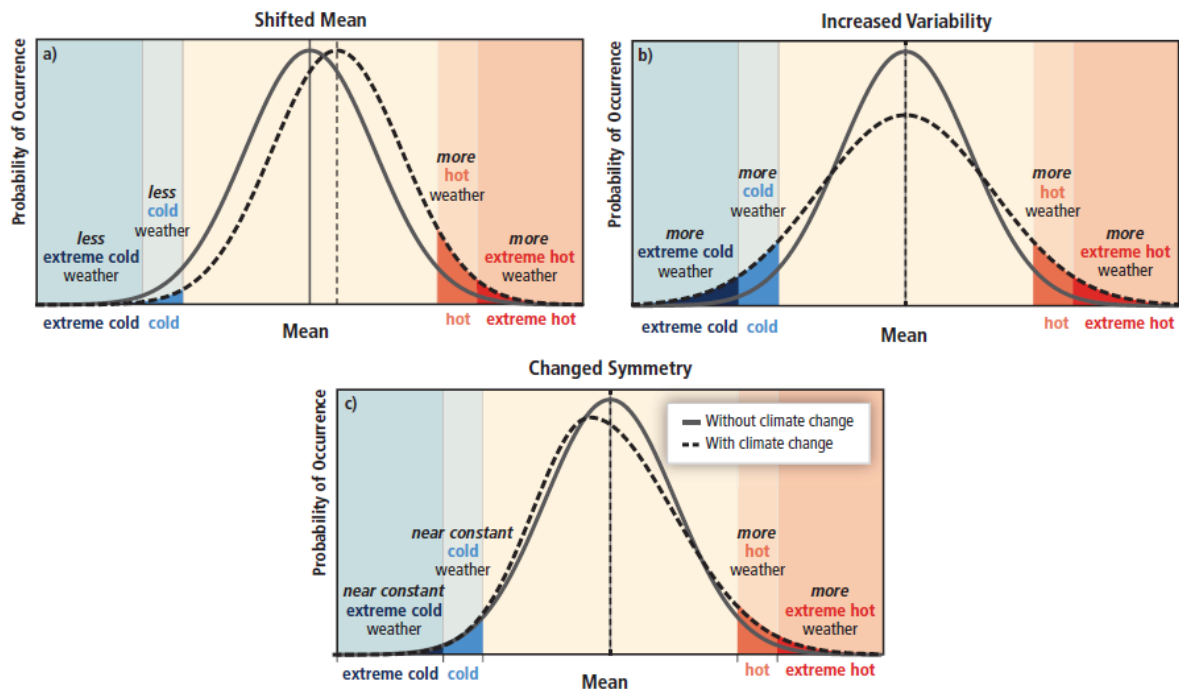


Fig.2. Sketches of probability density functions of the global mean temperatures subject to different “climate change” scenarios: a) shifting mean, b) increased variability, c) changed symmetry (source: [3])

The actual climate change probably cannot be described by any of these conceptual scenarios alone, but more likely as a combination of at least two of them. Yet, based on the available data, where – due to our incomplete understanding the climate system – separating the long-term deterministic components from stochastic fluctuations is practically impossible, therefore, it is hard to tell, which of the scenarios are actually contributing.

Since neither the true temporal behavior of the driving force (i.e. the climate system’s response to changes in Solar flux, carbon-dioxide emission, etc.) nor the statistical properties of the fluctuations can be determined independently, the only proper way to take them apart would be to observe many realizations (paths) of the same dynamical system, presumably with very similar initial conditions and with exactly the same time-dependent forcing scenarios. Then statistical analyses over such an ensemble can be carried out and thus the separation of deterministic and stochastic terms (and the true properties of fluctuations around the mean) could be, at least theoretically, achieved.

Obviously, since only one realization of the actual climate system exists, ensemble statistics cannot be used there. However, there is a way to imitate climate-like dynamics in a surprisingly simple laboratory experiment. This, being a physical experiment, can be repeated and therefore ensemble statistics can be constructed, as will be discussed in the next sections. It is to be noted that this approach has been successfully applied to numerical climate models of minimal and intermediate complexity in very recent works, e.g. [4]. Surely, the outcomes from simplified laboratory experiments will not solve the problem of separating processes and obtaining proper extreme statistics from the actual global temperature records, yet, they may help to drive attention to some serious methodological issues which inevitably arise when using single-realization statistics instead of an ensemble.

EXPERIMENTAL SETUP AND METHODS

The so-called “differentially heated rotating annulus” is a widely studied experimental minimal model of the mid-latitude weather system. It is “minimal” in the sense that it captures the two most important basic factors that contribute to the formations of cyclones and anticyclones in the atmosphere: lateral temperature difference (between the polar and equatorial regions) and rotation (around the Earth’s axis). If either of these boundary conditions was absent, no weather-like flow patterns would emerge; so the model is “as simple as possible but no simpler”. For more details on the history and the possible variants of rotating annuli, we would suggest the reader to consult our recently published textbook chapter [5].

A schematic drawing and an actual photo of our experimental tank (alongside with a cartoon demonstrating the aforementioned analogy with the terrestrial atmosphere) is shown in Figs.3 b), c) and a), respectively. The annular gap between the coaxial cylindrical sidewalls is filled up with water to height $d = 4.5$ cm (Fig. 3b). The inner cylinder, with a separate working fluid in it, serves to maintain the desired “polar” temperature. It has a radius $a = 4.5$ cm, whereas the outer rim (where the warming occurs) is at distance $b = 12$ cm from the axis of rotation. The radial temperature difference ΔT yields an overturning “sideways convective” background flow, similar to the large convection cells in the actual atmosphere. Due to the rotation of the tank, Coriolis force also acts on the fluid parcels (that otherwise would trace out an azimuthally symmetric, toroidal overturning cell) and drags them towards the respective right hand side of their direction of motion (since, due to our ‘Northern-hemisphere-chauvinism’ counterclockwise rotation is applied here; Australian laboratories typically do it the other way, then the Coriolis force has an opposite sign). For more information on the Coriolis force, and the way it can be taught in high schools, we refer to the paper of Andrea Gróf in the present volume [6].

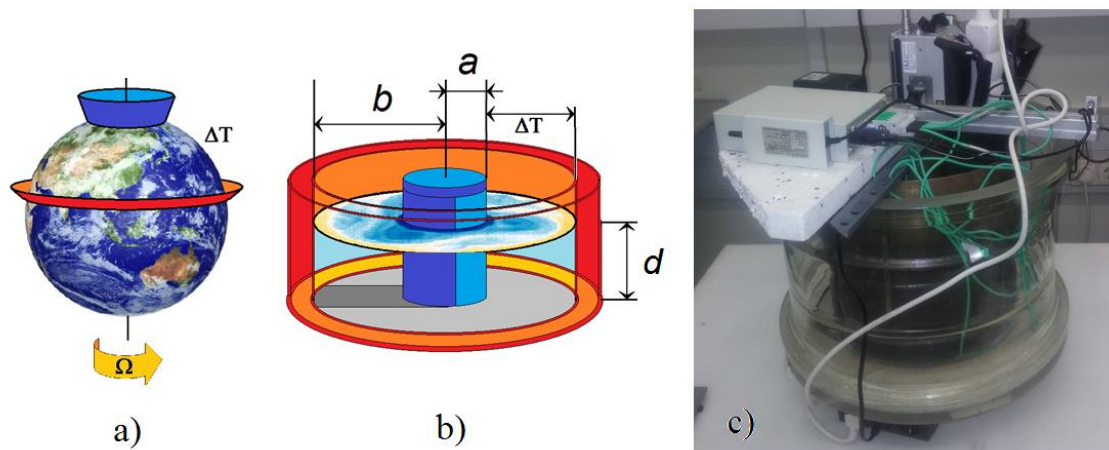


Fig.3. Schematic diagram of the mid-latitude atmosphere (a), illustrating that the basic boundary condition for it is a warm equator (red) and a polar region (blue) colder by temperature contrast ΔT . (b): Sketch of the differentially heated rotating annulus with its geometric parameters for which the boundary condition is similar to that of the real atmosphere: warm outer rim (red), cold inner rim (blue). (c): Photo of the actual experimental tank in the von Kármán lab

Coriolis force yields the formation of cyclonic and anticyclonic eddies, which can be seen by dye painting or via observing the water surface with a thermal (infrared) camera. A typical “atmosphere-like” flow pattern is visible in the left hand side of the composite image of Fig.4, alongside a satellite image of Earth as seen from poleward direction.

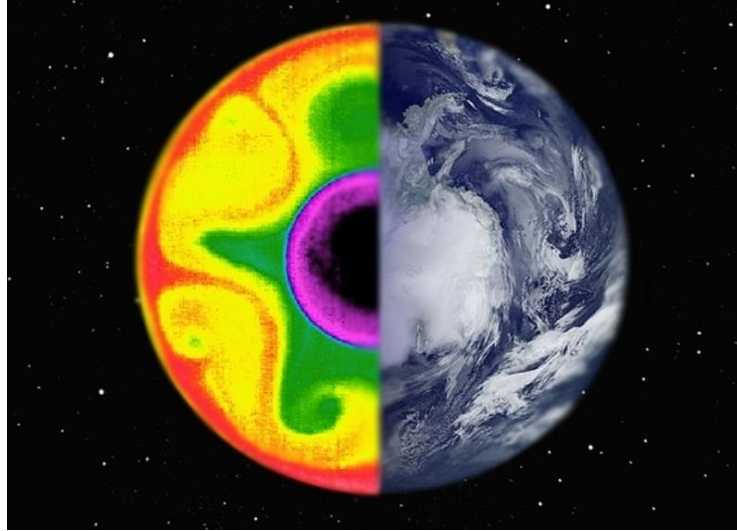


Fig.4. Infrared view of the flow in the laboratory setup (left) and cloud patterns of the Southern mid-latitudes as seen from space, looking down from the axial direction

The analogy between the atmosphere and the experimental configuration is of course far not qualitative only. Studying the equations of motion in both systems, one can derive two non-dimensional quantities that properly describe the possible flow regimes: these can be set in the experiment so that they match the same dimensionless ratios of the atmosphere. One of these parameter combination is known as thermal Rossby number Ro , and is defined as:

$$Ro = \frac{gd\alpha\Delta T}{\Omega^2(b-a)^2}, \quad (1)$$

where Ω is the angular velocity of the rotating tank, a , b , and d are the aforementioned geometric dimensions, α is the coefficient of volumetric thermal expansion of the fluid (water in the experiment and air in the atmosphere) and ΔT is the (“Equator-to-pole”) temperature contrast imposed on the vertical boundaries of the rotating layer.

Besides Ro the kinematic viscosity ν of the medium also plays an important role in the dynamics. Its contribution is parametrized by Taylor number Ta that accounts for the ratio of rotational and viscous effects, and reads as

$$Ta = \frac{4\Omega^2(b-a)^5}{\nu^2 d}. \quad (2)$$

Ro and Ta are used together to characterize the different dynamical regimes in rotating, thermally driven systems, such as planetary atmospheres, oceanic basins and their minimal models in the laboratory. The parameter space with a few typical snapshots of the corresponding experiments is sketched in Fig.5: for smaller rotation rates, where the Coriolis force is of less importance (green shaded area) the flow stays axially symmetric. In an intermediate “anvil-shaped” domain of moderate Ta and smaller Ro values regular three- or four-fold symmetric wave structures emerge (orange domain), and towards higher rotation rates (larger Ta and small Ro) the flow becomes turbulent. The letter is the domain where Earth’s mid-latitude atmosphere also belongs, once its actual physical parameters are plugged in the above formulae of Ta and Ro .

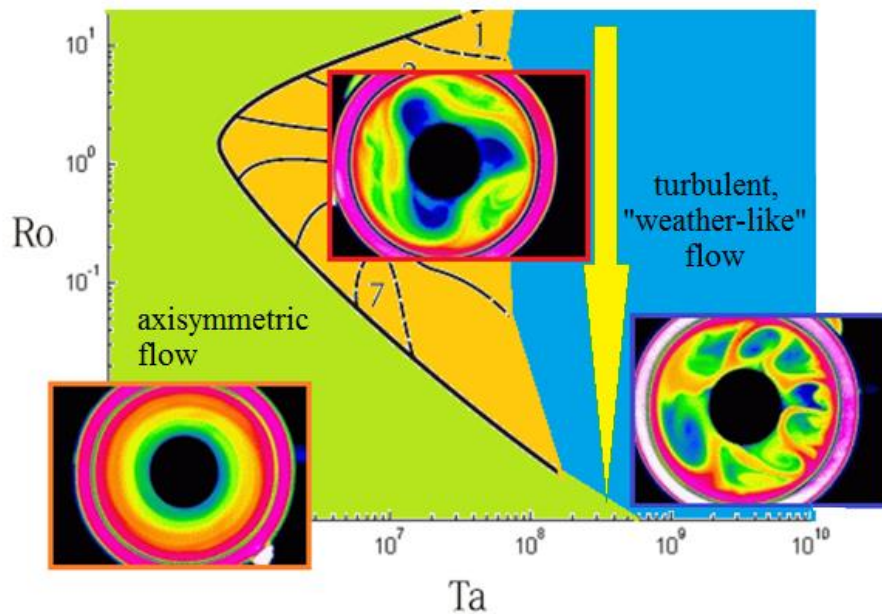


Fig.5. Regimes of the Ta - Ro parameter space with the observed flow patterns (insets). The yellow arrow shows the shift due to decreasing radial temperature contrast

The novelty of our experiments [7] carried out in the von Kármán lab and at the Brandenburg Technical University of Cottbus (Germany) is the following procedure: while keeping the rotation rate, thus, Taylor number Ta , constant – so that a “day” i.e. a full revolution of the tank lasted for 3 seconds – after a true “base period” of ca. 3000 revolutions of constant ΔT , we started to decrease the temperature contrast parameter, by turning off the computer-controlled cooling of the “polar” thermostat. After this change of the thermal boundary conditions we logged the data for another 3000 revolutions of time, corresponding to a “global warming” scenario with gradually increasing polar temperatures.

It is a well-established fact that the ongoing global warming of the Earth affects the polar regions the most in terms of mean temperature (melting sea ice and land ice), whereas in the local records from the equatorial regions the warming trend is not that apparent. Thus, climate change yields gradually *decreasing* mean equator-to-pole temperature contrast; this is what we imitated in the lab by lowering ΔT . Such a “global warming” in our experiment corresponds to a downward motion in the parameter space of the system, marked by a yellow arrow in Fig.5.

We repeated the very same forcing scenario 10 times with the same initial conditions, in order to create a statistical ensemble of virtually identical experimental runs, which only differed in the stochastic aspects of their evolution. We logged mean surface temperature $\langle T \rangle(t)$, defined as the spatial average of temperature signals obtained simultaneously from three digital thermometers placed on the water surface inside the annular gap of the tank. Their sampling rate was 1 Hz, and their temperature resolution was below 0.05 K.

PRELIMINARY RESULTS

Fig. 6 shows time series obtained for four typical experimental runs. In the top panel, the imposed temperature contrast forcing scenarios $\Delta T(t)$ are plotted, as obtained from the differences of measured temperatures at the heated and cooled lateral sidewalls. One can see that the reproduction of the experiments is very good. In each case, time $t = 0$ corresponds to the time instant when the cooling thermostat was switched off. The bottom panel shows the ‘response’ of the mean surface temperature $\langle T \rangle(t)$ in each run (colored curves) and their

ensemble average (thick black curve). As expected, the latter is much smoother than any of the realizations: the stochastic fluctuations of the different runs average out fairly enough. Note also, that the response ensemble average does not exhibit a sharp turning point at $t = 0$; the transition towards “global warming” appears to be a continuous one, even in terms of its derivative, unlike the forcing itself.

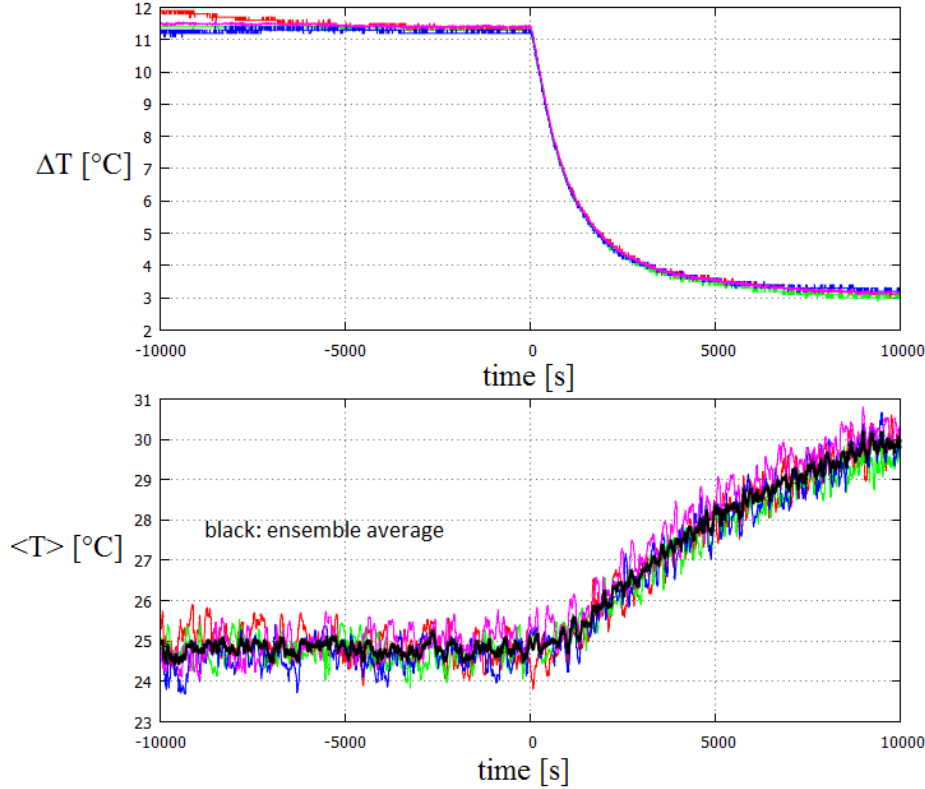


Fig.6. Time-dependence of temperature contrast $\Delta T(t)$ in four experimental runs (top) and the resulting records of “global warming” $\langle T \rangle(t)$ from the same experiments (bottom). The ensemble average is marked with black curve (data from our experiments at BTU-Cottbus)

To demonstrate our main point here, let us consider one of the realizations – namely, the red curve of Fig. 6, repeated in Fig. 7 – and treat it the same way as climate scientists analyse actual atmospheric data. Pretending that we do not have any *a priori* knowledge of the underlying forcing scenario, the best we can do to analyse fluctuations is to apply polynomial de-trending of the temperature record. This is achieved by fitting a polynomial function to the time series $\langle T \rangle(t)$ and subtract it from the original record afterwards. Two such polynomial fits are shown in the top panel of Fig. 7: a sixth-degree (green) and a tenth-degree one (blue). The ensemble average is repeatedly plotted here, too (black curve).

In the next step – as a measure of variance – we calculated the 1001-point, or 300 revolution-long (centered) moving standard deviations of $\langle T \rangle(t)$ defined as

$$\sigma_{1001}^{(i)} = \sqrt{\frac{1}{1001} \sum_{i-500}^{i+500} (\langle T \rangle^{(i)} - m_{1001}^{(i)})^2}, \quad (3)$$

where index i is running from the 501th measured value of time series $\langle T \rangle(t)$, up to $i = N - 501$, N being the total number of data points in the record. $m_{1001}^{(i)}$ is the moving mean in the same window, obtained as

$$m_{1001}^{(i)} = \sum_{i-500}^{i+500} \frac{\langle T \rangle^{(i)}}{1001}. \quad (4)$$

The moving standard deviations of the original time series $\langle T \rangle(t)$ are shown with red in the bottom panel of Fig. 7. This can be understood as an estimated measure of “atmospheric variability”: the larger its value, the more the time series fluctuates around the running mean. This is no surprise that here, without detrending, the variability increases instantly from around $t = 0$ on due to the increasing trend.

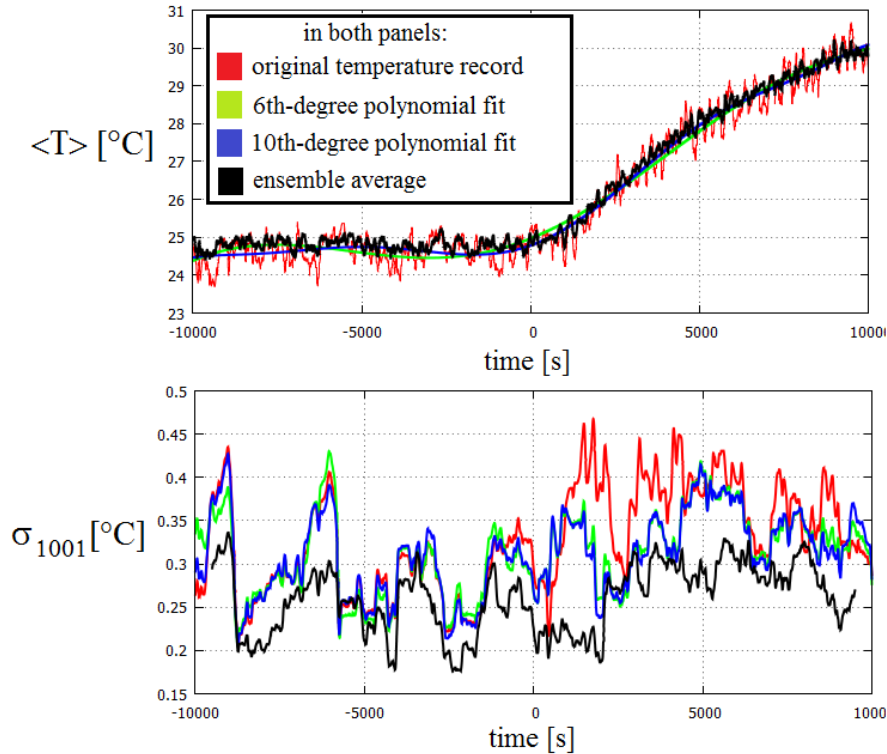


Fig.7. Top: A single realization of the mean surface temperature $\langle T \rangle$ (red), its polynomial fits (green and blue) and the ensemble average (black). Bottom: standard deviations of the original record (red), those of the detrended records (green and blue), and those obtained after subtracting the ensemble average from the temperature record (data from our experiments at BTU-Cottbus)

Afterwards, we carried out the same procedure with the *detrended* records as well: the moving standard deviations and moving averages were calculated in the same manner as written in formulae (3) and (4), but instead of the original $\langle T \rangle(t)$ now the detrended time series were evaluated. The results are plotted in the bottom panel of Fig. 7: the green and blue curves represent the moving standard deviations of the sixth and tenth-degree detrended records, respectively. We found in both cases that the average variabilities are significantly higher in the $t > 0$ range than before, although clearly, immediately after $t = 0$ these detrended records yield smaller fluctuations than the values of the red curve. Therefore, if these were real global temperature data and this would be the only known realization, a climate scientist would come to the conclusion that the internal variability of the system indeed increased coincidentally with the warming, as compared to the stationary base period ($t < 0$).

However, if we use the ensemble average (shown as black curve in the bottom panel of Fig. 6 and in the top panel of Fig. 7) for detrending, i.e. subtract its values from the original $\langle T \rangle(t)$ and calculate the moving standard deviations of the obtained detrended time series (black curve in the bottom panel of Fig. 7), we get a different result. Apparently, these variabilities appear to be systematically below and more uniform than, both polynomial residuals. In other words, fluctuations of the mean temperature around the ensemble average

are *smaller* than even around the record's own polynomial trend. The other important observation is that unlike in the cases of polynomials, detrending with the ensemble average does not yield significant difference between the mean fluctuations in the base period ($t < 0$) and the “global warming” phase ($t > 0$), demonstrating that even high-degree detrending – based on the considered realization only – can produce “artificial” changes in the variability.

SUMMARY AND CONCLUSIONS

Experiments in the von Kármán Laboratory offer a unique insight into the large-scale dynamics of flows in the atmosphere and the ocean. In the present work the behavior of atmospheric variability in a changing climate has been studied in an experimental ‘toy model’ of mid-latitude atmosphere. Unlike in the case of real climate, in laboratory experiments it is possible to run the same scenario several times, thus creating a statistical ensemble. A large enough data pool enables the separation of the deterministic and stochastic aspects of temperature variations in the system. This was demonstrated by using standard tools of time series analysis on temperature records of several identical experiments. We concluded that if the fluctuations of an individual realization are compared to the proper (constantly shifting) ensemble average, no significant changes occur in their variability, as compared to a stationary base period.

These results have a certain methodological or demonstrational value and may help to increase awareness in the climate community of the fact that – as long as the underlying complex processes are not properly understood *a priori* – fluctuations and deterministic trends can hardly be separated, and therefore they may well yield statistical artifacts that can easily be misinterpreted.

ACKNOWLEDGMENTS

The present work was supported by EuHIT (European High Performance Infrastructures in Turbulence) and by OTKA grant, no.: NK100296. Highly useful discussions with Tamás Tél are very much acknowledged.

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APPENDIX: THE VON KÁRMÁN LAB

The von Kármán Laboratory for Environmental Flows of the Institute of Physics at the Eötvös University (ELTE) of Budapest is one of the very few of its kind in Europe. Based on the principles of hydrodynamic similarity, large-scale atmospheric and oceanic phenomena (shallow-water waves, tsunamis, weather fronts, atmospheric convection, cyclones, tornados, etc.) can be accurately modelled and demonstrated here in relatively simple, table-top-size experimental setups [1].

Our laboratory was founded in 1998, when a group of enthusiastic physicists, namely V. Horváth, I. M. Jánosi, G. K. Szabó, and T. Tél – by then already internationally recognized experts in their own fields, ranging from chaotic dynamics to materials science – developed an interest in the surprisingly nontrivial and modern field of geophysical fluid dynamics. ('Modern' is meant in the sense that the proper theoretical framework of atmospheric dynamics was mainly developed after the 1920s, and even later for oceanic flows. Thus, being a contemporary of quantum mechanics, it can indeed be rightfully regarded as 'modern classical physics'.)

The then-newly constructed campus and the relocation of the Institute of Physics to it from its previous historic building (where even Eötvös himself used to work around the turn of the last century), provided a very fortunate once-in-a-lifetime opportunity to obtain two rooms and financial support for creating such a laboratory in the new building. In the almost 18 years since then, von Kármán lab has matured indeed, and evolved into a superb educational and demonstrational hub, where – as a part of their standard curriculum – bachelor and master students in physics, meteorology or environmental science regularly attend classes, participate in laboratory practices, and some of them eventually end up doing their thesis work here.

Besides education, however, the lab, first and foremost, is a research institution. Even during a regular laboratory practice here, students often face problems for which the solution is simply not known yet. They help us collecting data points for active research projects and in turn, they get a glimpse into how science works, where pretty often even the teacher or laboratory assistant cannot predict the outcome of a given experiment either. Several research topics that started here as bachelor's or master's projects later have actually evolved into publications in peer-reviewed international scientific journals. Three PhD degrees have been earned in our lab (one by the author) so far, and currently our regular staff consists of two senior researchers, one post-doc, a PhD student, and a BSc student. As of today, we are running five different environmentally motivated research projects (three of which are collaborative efforts, involving international partners), see the collage of snapshots in Fig.8, one of which has been discussed in the present work.

It is fair to say that the results coming from the von Kármán lab are of comparable quality to those from any environmental fluid dynamics laboratory in the world; similar research facilities are located at the Universities of Oxford, Cambridge (UK), Aix-Marseille (France), the Brandenburg Technical University at Cottbus (Germany), and at MIT (USA).

The laboratory is open for high school groups to visit at any previously agreed-upon time (preferably Fridays): a typical 'lab tour' lasts for ca. 40 minutes and an ideal group consists of up to 12 students. As Fig.9. shows there is practically no lower limit for the age when a lab tour can be interesting for the children: here a group of kindergarten kids are apparently mesmerized by a demonstration of internal waves in a stratified fluid tank. We can say it with confidence that these experiments can be interesting for toddlers and university professors alike.

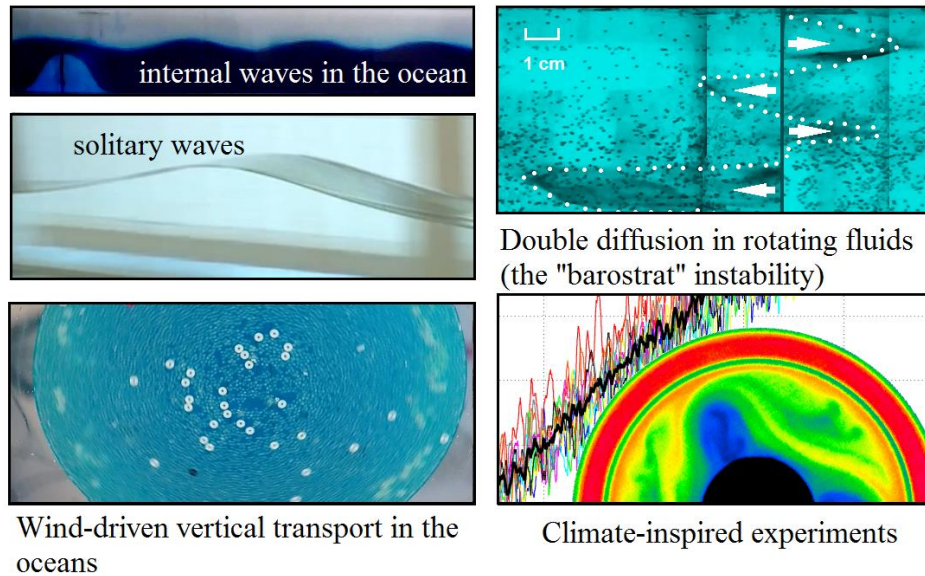


Fig.8. Snapshots from some of the currently active research areas in the von Kármán laboratory



Fig.9. “Visiting researchers” from a kindergarten (and the author) observe internal wave propagation in the von Kármán lab (2015)

Finally, it is appropriate to mention here that – to our great pleasure – the von Kármán lab is not any more the ‘only place in its 800-kilometer radius where large-scale environmental flows can be demonstrated experimentally’, as we used to claim. We refer to the paper of A. Vörös in the present volume [2], which describes somewhat similar experiments for educational purposes at the Babes-Bolyai University of Cluj-Napoca, Romania, and their usage to demonstrate tsunamis, weather fronts and cyclones for high school pupils.

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