REQUEST FOR A SPECIAL PROJECT 2026 - 2028

MEMBER STATE: Netherlands

Principal Investigator: Dr Karin van der Wiel

Affiliation: Royal Netherlands Meteorological Institute (KNMI), Utrecht University (UU)

Address: Utrechtseweg 297, De Bilt, The Netherlands

Other researchers: PhD student (to be hired), Dr Frank Selten, Prof. Dr Daan Crommelin (CWI, UvA), Prof. Dr Wilco Hazeleger (UU)

Project Title: The four seasons revisited (VIVALDI)

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2026	
Would you accept support for 1 year only, if necessary?	YES	

Computer resources required for project year:		**2026**	**2027**	**2028**
High Performance Computing Facility	[SBU]	2 500 000	3 000 000	2 100 000
Accumulated data storage (total archive volume)[2]	[GB]	40 000	100 000	125 000

EWC resources required for project year:		**2026**	**2027**	**2028**
Number of vCPUs	[#]	-	-	-
Total memory	[GB]	-	-	-
Storage	[GB]	-	-	-
Number of vGPUs[3]	[#]	-	-	-

Continue overleaf.

Principal Investigator: Dr Karin van der Wiel

Project Title: The four seasons revisited (VIVALDI)

Extended abstract – project VIVALDI

All Special Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous Special Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 5,000,000 SBU should be more detailed (3-5 pages).

ABSTRACT

Due to the focus of the atmospheric sciences on the extremal seasons (winter, summer), our understanding of the dynamical processes in the atmosphere and of the weather at the Earth's surface is much more limited in the transition seasons (spring, autumn). Project VIVALDI aims to address this gap in our knowledge by studying the atmosphere as a dynamical system in perpetual adjustment to the annual cycle of incoming solar radiation. Instead of investigating the dynamics in pre-defined 3-month seasons (e.g. MAM, SON), we will study the detailed shape of the annual cycle as a whole, with specific focus on the physical processes at play in the transition seasons. Despite the fact that solar forcing is (nearly) perfectly sinusoidal and periodical, the atmospheric response is not. We hypothesize that the 'lag' of the atmospheric response to the instantaneous solar forcing, e.g., due to slow radiative adjustments in the atmosphere, or the slow heating of ocean waters, affects interannual variability of weather at the Earth's surface in the transition seasons. We will conduct idealised experiments of increasing complexity with a state-of-the-art atmospheric model (OpenIFS) and use concepts from the mathematical field of periodically forced dynamical systems. These experiments are designed to gain insights into the time scales, strength and interactions of the physical processes in the Earth system that play a role in the adjustment to the periodical solar forcing. With these insights we will investigate the observed annual cycle and explain the interannual variations in terms of variations in the adjustment to the periodical solar forcing. Finally, we will investigate the influence of anthropogenic climate change on the identified adjustment processes and the shape of the annual cycle using existing climate model projections of our future climate (CMIP6 and EURO-CORDEX). This fresh look at the annual cycle, using concepts from dynamical systems theory, will provide valuable new insights into the origins and dynamics of weather at Earth's surface throughout the entire year, and specifically in the transition seasons. This knowledge will help to improve projections of regional climate change that form the basis for climate adaptation measures taken by society.

KEYWORDS

Annual cycle - Transition seasons - Atmospheric dynamics - Dynamical systems - Climate change

BACKGROUND

The proposed project, VIVALDI, aims to advance scientific knowledge of the annual cycle, particularly focusing on addressing the gap in our understanding of the transition seasons, i.e. spring and autumn. While there is a wealth of research concerning atmospheric or Earth system dynamics in the summer and winter seasons [e.g. 2, 3, 4], the more nuanced characteristics of spring and autumn have not received the same level of scrutiny. This, despite a general recognition that anthropogenic climate change impacts nearly all aspects of weather year-round. VIVALDI will revisit the transition seasons by reconsidering their definition. Traditionally we define four distinct seasons, defined either by the solar cycle ('astronomical' seasons) [5], by monthly assignment (DJF, MAM, etc, 'meteorological' seasons) [6], or through data-driven methods [7, 8, 9]. This approach implicitly assumes that the weather in these seasons is somewhat stationary, an assumption that is at odds with the definition of transition seasons: the periods of the year in which the atmosphere transitions from solar minimum to solar maximum, or reverse. In VIVALDI we will instead investigate the shape of the complete annual cycle and its physical origins. We will take into consideration the sinusoidal shape of solar forcing, the (lagged) atmospheric response (Fig. 1), and the consequences for the observed surface weather in Europe. We will systematically disentangle the dynamical drivers and physical processes that give rise to the detailed regional annual cycle of temperature, precipitation and wind variations, investigate drivers of interannual variability in the annual cycle [1], and their role in regional climate change.

The weather, and variations therein, impacts European society in all seasons, influencing various aspects of daily life, economy, and overall well-being. Well-known risks include the effects of extreme summer heat and extreme winter cold on morbidity and mortality [e.g. 10], the effects of summer drought on agriculture, shipping, and water quality [e.g. 11, 12], and long-lasting periods of abovenormal rainfall (winter half year) or short-duration extreme convective rainfall (summer half year) leading to (flash) flooding causing property damages and fatalities [e.g. 13]. However, though maybe not quite as obvious, also the transition seasons play a vital role in shaping regional climates and societies, influencing phenomena such as ecosystem dynamics, agriculture, and extreme weather events both in- and outside the transition seasons. For instance, false spring events, where late-season frost damages blossoms and agricultural production [14, 15], or anomalously low precipitation in spring leading to drier than normal soils at the start of summer, which in turn enhance summer heatwaves and summer drought [16]. Ongoing and projected climate change [17] makes understanding the dynamics of weather and its consequences ever more urgent, and it is obvious that this knowledge is needed for all seasons of the year.

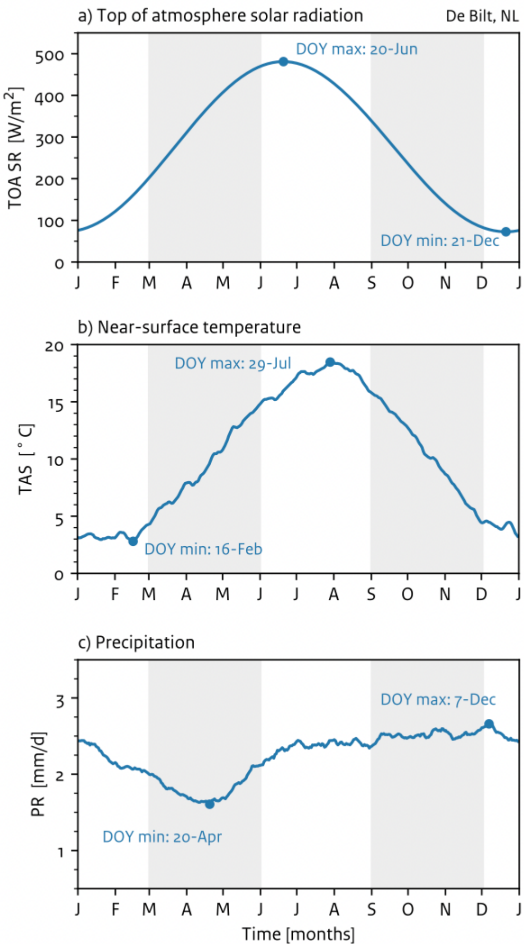


Figure 1 – Annual cycle of (a) incoming solar radiation at the top of the atmosphere (solar forcing, W/m²), (b) near-surface temperature (°C, 7-day running mean applied), and (c) precipitation (mm/d, 60-day running mean applied). Data taken from (a) ERA5, and (b,c) KNMI station De Bilt (1971-2020). Grey/white shading in background shows traditional 3-month meteorological season definition.

By redefining our method of investigation, from the traditional three-month seasons to the broader and complete annual cycle (Fig. 1), we can gain deeper insights into the underlying processes driving seasonal transitions and weather at the surface. **This allows us to view transition seasons as periods of atmospheric transition from solar minimum in winter to solar maximum in summer, providing a more holistic understanding of their dynamics.** Besides providing new insights into the dynamics of weather in the transition seasons, this will also lead to improved understanding of interannual variability [1] (e.g. perceived early starts of spring, or early cold spells in autumn with hefty showers), and valuable information regarding projected regional climate changes.

One of the key challenges in studying transition seasons lies in the complex interplay of direct and indirect drivers. Despite the (near) perfect, repeating, sinusoidal shape of solar forcing at the top of the atmosphere (Fig. 1a), the shape and shift of its imprint at the Earth's surface is not perfectly predictable (Fig. 1b,c, [1]). Rather, it is determined by both fast and slow physical processes in the atmosphere, together leading to an Earth system response in disequilibrium with its instantaneous forcing. The relevant processes here are, for example, radiative-convective equilibrium (O 10^1 d time scales), oceanic heating (O 10^3 d time scales), equator-to-pole heat transport ([18], O 10^2 d time scales), global monsoon-like circulations (Fig. 2, O 10^2 d time scales) [19], and the melting of snow pack and ice on land (O 10^2 d).

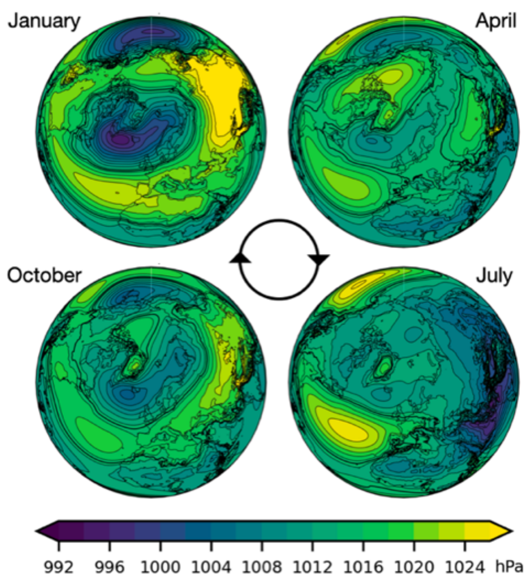


Figure 2 – Seasonal re-distribution of atmospheric mass. Monthly mean sea level pressure (hPa, colours) in January, April, July and October, data: ERA5 1991-2020.

When viewed from a dynamical systems approach, the atmosphere is never in statistical equilibrium with the instantaneous solar forcing, so that there is an energy imbalance due to the changing solar forcing pattern and the time-lag of the atmospheric response. **We will conduct several idealised experiments with OpenIFS, a state-of-the-art climate modelling system, to unravel the impact of this energy imbalance on the dynamical motions in the atmosphere.** We will study the absorption of solar energy by the atmosphere and the Earth's surface (ocean and land), the redistribution of mass and heat, and its consequences for the transition of a wintertime to summertime typical jet stream structure (different in strength, position, and meandering behaviour), and changes in the surface energy balance (determining temperature, feeding precipitation). We aim to identify the dominant drivers, physical mechanisms and feedback processes that ultimately determine the weather at the Earth's surface which, in turn, impacts nature and society.

In summary, VIVALDI proposes an effort to deepen fundamental understanding of seasonal transitions, ultimately allowing us to improve projections of regional climate change. By adopting an innovative approach and leveraging state-of-the-art methodologies, we aspire to make significant contributions to the field of atmospheric science, while addressing pressing societal challenges associated with a changing climate.

WORKPLAN

The research will be split in three sequential work packages, most of the requested computer resources will be used in WP1.

<u>WP1: Earth's atmosphere as a dynamical system in transition</u>

Objective	To understand the dynamical atmospheric response in the North Atlantic-European sector to continuously varying solar forcing.
Methodology	We will conduct various idealised experiments with the OpenIFS climate modelling system designed to unravel the specific (lagged) response of different physical processes to solar forcing. The complexity of these experiments will systematically be increased to build understanding of the atmospheric response in the full complex Earth system.
Expected Outcome	Quantification of key processes driving atmospheric motions throughout the year. Focus will be on how these differ between the transition seasons (spring, autumn) and the extremal seasons (summer, winter), and on quantifying the energetic imbalance of the atmosphere and the instantaneous solar forcing.

We will use the OpenIFS model (https://confluence.ecmwf.int/display/OIFS) for our idealised experiments. We will conduct several of such experiments with the aim to quantify the time scales, the strength and the interactions of different physical processes in the Earth system in response to solar forcing. In short, the experiments planned:

- Aquaplanet experiments with slab oceans of varying thickness – In a configuration of Earth without continents, spatial inhomogenities in surface heat capacity are removed. This will remove global-scale movements of atmospheric mass from relatively cool continents to warm oceans (in winter), or vice versa in summer (Fig. 2). Varying the depth of the model's slab ocean will influence the (slow) heat uptake in the ocean, and therewith the magnitude of the energetic imbalance between atmosphere and solar forcing.
- Annual cycle experiments with perpetual solar forcing – In the real world solar forcing is continuously changing, increasing from winter solar solstice to summer solar solstice, then decreasing again, etc. Earth's atmosphere and oceans respond to this forcing, though are likely never in a state of equilibrium with the instantaneous forcing. We will perform different experiments in which we apply constant solar forcing [20], to create perpetual winter solstice, perpetual summer solstice and perpetual equinox (mid spring/autumn, in this idealised form the same) simulations, and compare the outcomes to equivalent data from experiments with varying solar forcing (i.e. comparing to days around the solstice/equinox in 'normal' runs).
- Continental configuration experiments – The influence of land-ocean heating differences and orography will be tested. We will compare an experiment with continents to the aquaplanet experiments. Similarly, the influence of perpetual solar forcing on continental heating and atmospheric motions will also be studied.
- Water vapour experiments – We will prescribe the climatological distribution of atmospheric water vapour in the calculation of short- and long-wave radiation transports. Water vapour is a potent greenhouse gas and plays an important role in the timescale of adjustment to a change in radiative forcing.

<u>WP2: Interannual variability due to the lagged atmospheric response</u>

Objective	To understand the role of lagged atmospheric responses to solar forcing in setting the magnitude of interannual variability in the North Atlantic-European sector.
Methodology	We will analyse interannual variability in the idealised experiments (WP1), and quantify the role of the atmospheric energetic imbalance on the magnitude of interannual variability. The insights will then be related to the real world to explain observed historical variability.
Expected Outcome	New insights into the processes leading to interannual variability in the transition seasons. Quantification of the role of the (lagged) atmospheric system response in observed historical variations in seasonality.

We will revisit the outcomes of the OpenIFS idealised experiments set up in WP1, but here focusing the analysis on quantifying observed interannual variability. Depending on the outcomes of WP1, some of the experiments might be extended to allow better quantification of (the processes leading to) interannual variability. After investigating the processes and effects in the idealised experiments, we will apply the knowledge created to the explain observed variability in the real world.

<u>WP3: Projections of climatic changes in seasonality</u>

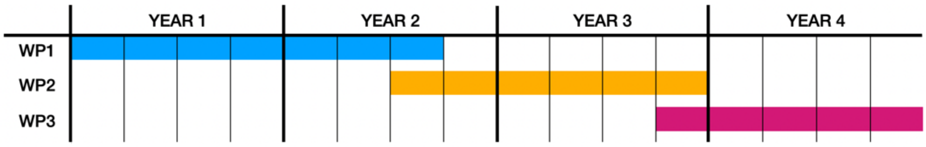
Objective	To evaluate the impact of climate change on the dynamics of the annual cycle and seasonal transitions in western Europe.

Methodology	We will compare the shape of the mean annual cycle and the magnitude of interannual variations in simulated projections of future climate (CMIP6/EURO-CORDEX). Projected changes will be attributed to changes in the driving mechanisms of the annual cycle (identified in WP1 and WP2).
Expected Outcome	Improved projections of the impact of climate change on shifts in the timing, intensity, and variability of seasonal transitions in western Europe.

Finally, we will apply the improved dynamical understanding of the atmospheric response to solar forcing, and its influence on the shape of the annual cycle, to improve regional climate projections. We will use data from openly available, state-of-the-art, multi-model archives of global and regional climate model simulations (CMIP6, EURO-CORDEX). In this data we will look for evidence of changes in the shape of the annual cycle in a number of variables. We will investigate whether the processes identified in WP1 and WP2 play a part in driving the changes. Possibly, we will repeat some of the idealised experiments of WP1 with higher greenhouse gas forcing, to identify changing physical processes or relationships.

COMPUTATIONAL RESOURCES

The idealised simulations with OpenIFS described in WP1 will take up the largest quantity of the computational resources requested in the special project. These are planned to be executed over the first two years (2026, 2027) of the PhD project. As stated, more simulations may be undertaken to complement the analyses in WP2 and WP3, but these will likely be much smaller (in terms of SBUs) than those of WP1. Therefore, the bulk of the request of computational resources will be for 2026 and 2027.



Though the details of the simulations will be decided on during the project, likely we don't need high resolution data to gain understanding for the large scale dynamical processes of interest. As such, we will assume runs at Tl255 (~80km) at 91 levels here. A 10 year integration of atmosphere-only then uses 60 kSBU, for the four envisioned types of experiments we would need an approximate:

- Aquaplanet experiments with slab oceans of varying thickness – 5 thicknesses x 50 years = 250 years
- Annual cycle experiments with perpetual solar forcing – 3 forcings x 50 years + 1 control x 50 years = 200 years
- Continental configuration experiments – 4 experiments x 50 years = 200 years
- Water vapour experiments – 1 experiment x 50 years = 50 years

That makes, in total, for WP1, approximately 700 simulation years = 4.2 MSBU (4.200.000 SBU). For additional simulations in WP2 and WP3 we count 2 x 200 years = 2.4 MSBU (2.400.000 SBU). Finally, some computing hours for testing experimental setups and configurations etc. (estimated at 1 MSBU, 1.000.000 SBU). As such, total request is for 7.6 MSBU, divided over the three special-project years (note that PhD education is a four year process in the Netherlands).

The data storage needs for these simulations will be quite large, as we will analyse both 2D surface fields as 3D atmospheric fields. The estimated data load of these simulations is 100 GB per year, in total accumulating to 125 TB.

REFERENCES

1. S Pezzulli, DB Stephenson, and A Hannachi. The variability of seasonality. Journal of Climate, 18(1):71–88, 2005.
2. DM Smith, R Eade, MB Andrews, H Ayres, A Clark, S Chripko, C Deser, NJ Dunstone, J GarcÅLıa-Serrano, G Gastineau, et al. Robust but weak winter atmospheric circulation response to future Arctic sea ice loss. Nature communications, 13(1):727, 2022.
3. RJ Haarsma, FM Selten, B van den Hurk, W Hazeleger, and X Wang. Drier Mediterranean soils due to greenhouse warming bring easterly winds over summertime central Europe. Geophysical research letters, 36(4), 2009.
4. D Coumou, K Kornhuber, J Lehmann, and V Petoukhov. Weakened flow, persistent circulation, and prolonged weather extremes in boreal summer. Climate Extremes: Patterns and Mechanisms, pages 61–73, 2017.
5. A Berger, Q Yin, and Z Wu. Length of astronomical seasons, total and average insolation over seasons. Quaternary Science Reviews, 334:108620, 2024.
6. KE Trenberth. What are the seasons? Bulletin of the American Meteorological Society, 64(11):1276–1282, 1983.
7. S Cheng and L S Kalkstein. Determination of climatological seasons for the East Coast of the US using an air mass-based classification. Climate Research, 8(2):107–116, 1997.

8. P Alpert, I Osetinsky, B Ziv, and H Shafir. A new seasons definition based on classified daily synoptic systems: an example for the eastern Mediterranean. International Journal of Climatology: A Journal of the Royal Meteorological Society, 24(8):1013–1021, 2004.
9. CJ Lolis and G Kotsias. The use of weather types in the definition of seasons: the case of southern Balkans. Theoretical and Applied Climatology, 142:1199–1219, 2020.
10. P Masselot, M Mistry, J Vanoli, R Schneider, T Iungman, D Garcia-Leon, J-C Ciscar, L Feyen, H Orru, A Urban, et al. Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe. The Lancet Planetary Health, 7(4):e271–e281, 2023.
11. K-J Dietz, C ZÅNorb, and C-M Geilfus. Drought and crop yield. Plant Biology, 23(6):881–893, 2021.
12. MTH van Vliet, J Thorslund, M Strokal, N Hofstra, M FlÅNorke, H Ehalt Macedo, A Nkwasa, T Tang, S S Kaushal, R Kumar, et al. Global river water quality under climate change and hydroclimatic extremes. Nature Reviews Earth & Environment, 4(10):687–702, 2023.
13. O Petrucci. Factors leading to the occurrence of flood fatalities: a systematic review of research paper published between 2010 and 2020. Natural hazards and earth system sciences, 22(1):71–83, 2022.
14. CJ Chamberlain, BI Cook, I GarcÅLıa de CortÅLazar-Atauri, and EM Wolkovich. Rethinking false spring risk. Global Change Biology, 25(7):2209–2220, 2019.
15. Jay Ram Lamichhane. Rising risks of late-spring frosts in a changing climate. Nature Climate Change, 11(7):554–555, 2021.
16. R Vautard, P Yiou, F D'andrea, N De Noblet, N Viovy, C Cassou, J Polcher, P Ciais, M Kageyama, and Y Fan. Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. Geophysical Research Letters, 34(7), 2007.
17. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2021.
18. Ilai Guendelman and Yohai Kaspi. The key factors controlling the seasonality of planetary climate. AGU advances, 3(5):e2022AV000684, 2022.
19. KE Trenberth, DP Stepaniak, and JM Caron. The global monsoon as seen through the divergent atmospheric circulation. Journal of Climate, 13(22):3969–3993, 2000.
20. FW Zwiers and GJ Boer. A comparison of climates simulated by a general circulation model when run in the annual cycle and perpetual modes. Monthly Weather Review, 115(11):2626–2644, 1987.