



On the role of downstream-developing Rossby waves in concurrent heat extremes

Wolfgang Wicker¹, Georgios Fragkoulidis², Nili Harnik³, Emmanuele Russo⁴, and Daniela I. V. Domeisen¹

¹Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

²Institute of Environmental Research and Sustainable Development, National Observatory of Athens, Athens, Greece

³Earth and Planetary Science Department, Tel Aviv University, Tel Aviv, Israel

⁴European Centre for Medium-Range Weather Forecasts, Bonn, Germany

Correspondence: Wolfgang Wicker (wolfgang.wicker@unil.ch)

Abstract. Spatially compounding extreme events such as concurrent heatwaves pose a growing risk to society. The distance between concurrent events, or more generally their distribution in longitude, can be described in terms of a zonal wavenumber. Estimates of this wavenumber are typically based on stationary Rossby wave dynamics and the properties of a mid-latitude waveguide. A potential link to transient waves remains largely unexplored. We investigate the zonal structure of concurrent heatwaves through a composite analysis, comparing idealized numerical experiments and reanalysis data. In particular, we compare summer and winter in the Northern and the Southern hemispheres. Defining concurrent events on a weekly time scale, the composite mean shows a central peak in concurrent heatwave frequency corresponding to a spatially extended heatwave object, adjacent minima with reduced concurrent heatwave probability, and, depending on the degree of zonal symmetry in the atmosphere, more or less pronounced secondary maxima. Such wavy structures can be interpreted as the temporal mean of a downstream-developing transient wave packet. The distance between the adjacent minima or secondary maxima can be inferred from the stationary wavenumber, which we derive by calibrating a simple dispersion relation with the phase speed and group velocity of the associated wave packets. By linking the structure of the quasi-stationary flow to the local properties of downstream-developing Rossby waves, we offer a new perspective on spatially compounding climate extremes.

1 Introduction

The combined impact of climate hazards in distant regions can seriously harm the global economy. These climate extremes are referred to as spatially compounding extremes (Zscheischler et al., 2020). One prominent example is synchronized crop failure in different regions due to concurrent heat extremes (Kornhuber et al., 2020). Another example is concurrent flooding and drought in the vicinity and at the center of an atmospheric blocking event, respectively (Guo et al., 2025). Large-scale modes of low-frequency variability such as the El Niño-Southern Oscillation (e.g., Singh et al., 2022) and circumglobal Rossby waves (e.g., Jiménez-Esteve et al., 2022) are commonly identified as modulators of spatially compounding extremes.

The spatial structure of these compound events is often characterized in terms of a zonal wavenumber. Estimates of this wavenumber range from 4 to 8 (Yang et al., 2024; Teng et al., 2013; Liu et al., 2025; Kornhuber et al., 2019; Coumou et al.,



2014). The link between a wavy zonal structure of extreme events and different properties of the extratropical waveguide is an area of active research (White et al., 2022). One potential mechanism called quasisresonant amplification (Petoukhov et al., 2013) is based on ray tracing considerations and relies on a specific waveguide definition (White and Mareshet Admasu, 2025). However, the assumptions behind this mechanism and its performance in idealized model experiments have been questioned (Wirth, 2020; Harnik and Wirth, 2025; Mooring and Linz, 2026). Instead of assessing the properties of a zonalized background flow (Wirth and Polster, 2021), we propose a local perspective focusing on synoptic-scale systems. We seek, in particular, to explain the zonal structure of compound extremes based on the properties of Rossby wave packets.

The term Rossby wave packet refers to a representation of the upper-tropospheric circulation that places particular emphasis on local flow characteristics (e.g., Wirth et al., 2018). These systems have been found to generate heat extremes in North America (Castañeda and Wang, 2024), Europe (Fragkoulidis et al., 2018; Noyelle et al., 2025), and Asia (Fang and Lu, 2024). They have also been found to influence heatwave characteristics, whether they are spatially fixed or zonally propagating (Wang et al., 2025). The evolution of Rossby wave packets is commonly described in terms of a phase speed and a group velocity. Typically, the energy or envelope of a wave packet propagates more quickly to the east than the individual troughs and ridges do (i.e., group velocity is larger than phase speed). This situation gives rise to the phenomenon of downstream development (e.g., Simmons and Hoskins, 1979). On the other hand, there is a manifestation of non-linear Rossby wave behavior called atmospheric blocking (Woollings et al., 2018) with a very different character from that of a downstream-developing wave packet. Under certain flow conditions, a persistent anticyclone can act to absorb the horizontal wave activity flux (Nakamura and Huang, 2018; Polster and Wirth, 2023), disrupting the eastward phase and group propagation, and promoting persistent surface weather anomalies (e.g., Kautz et al., 2022). Under these conditions, the value of a group velocity might not be meaningful.

In this study, we investigate the zonal structure of concurrent heatwaves as one form of spatially compounding extreme events. We explore the concept of downstream development in the context of compound extremes, while recognizing the contrasting behavior of atmospheric blocking compared to continuous zonal wave propagation. Specifically, we evaluate to what extent we can model the zonal structure of concurrent heatwaves based on a simple dispersion relation, which we calibrate with the local phase speed and group velocity. The detailed methodology is outlined in Section 2. First, we validate the calibration procedure based on climatological-mean wave packet properties in idealized numerical experiments. Then, we turn to concurrent heatwaves and heatwave-generating Rossby waves. The numerical experiments without thermal memory from interactive land and sea surface conditions (Jiménez-Esteve and Domeisen, 2022) provide a simple test bed where heatwaves are initiated, maintained, and terminated by dry atmospheric dynamics, before we apply our methodology to reanalysis data. Finally, we discuss the link between a localized transient Rossby wave packet and quasi-stationary or circumglobal waves.

2 Methodology

2.1 Idealized experiments and reanalysis data

The idealized experiments are run with the dry-dynamical core of the ICON atmospheric model component (Zängl et al., 2015; Giorgetta et al., 2018), where all parameterized physics are replaced by linear surface friction and a relaxation to an equilibrium



temperature profile (Held and Suarez, 1994). The model does not contain any representation of moisture. The grid configuration corresponds to a horizontal resolution of approximately 160 km, and the experiments are run for 18,000 days under fixed and zonally symmetric boundary conditions. The output, featuring no seasonal cycle and only limited low-frequency variability, is interpolated to a regular $1^\circ \times 1^\circ$ grid.

60 To validate our methodology for two different spectra of synoptic-scale waves, the equilibrium temperature profile is modified following the approach by Butler et al. (2010). In the first experiment, labeled as 'Experiment fast', localized heating in the tropical upper troposphere produces a poleward shift of the extratropical storm track by 4°N compared to a reference simulation with the unmodified Held and Suarez (1994) forcing. A second experiment labeled as 'Experiment slow' is forced by surface-intensified heating in the high latitudes and features a 4° equatorward-shifted storm track. The wavenumber-frequency
 65 spectra in these experiments are linked to the storm track position via the strength of the eddy-driven jet (Wicker et al., 2025), and are such that the peak of the spectrum corresponds to a higher phase speed for the poleward-shifted storm track. The profiles of the equilibrium temperature and the zonally averaged zonal wind are shown in Figure S1 for further illustration of the two experiments.

In the second half of this study, the idealized experiments are compared to ERA5 reanalysis data of meridional wind at
 70 250 hPa and 2m temperature for the years 1959–2024 (Hersbach et al., 2020). For computational efficiency, the meridional wind data is regridded to 2° horizontal resolution, while temperature extremes are identified on a $0.5^\circ \times 0.5^\circ$ grid. To focus on dynamically driven temperature extremes, the ERA5 data is detrended prior to the identification of hot extremes following Wicker et al. (2024).

2.2 Concurrent heatwave frequency

75 Our near-surface temperature diagnostic starts with the identification of persistent hot extremes on a grid-point basis. Focusing on moderate extremes, we choose a 90th percentile threshold to define hot days based on daily-mean temperature at 1000 hPa or daily-maximum 2m temperature in the dry-dynamical model and in ERA5, respectively. In reanalysis, we choose a seasonally varying threshold following the empirical cumulative distribution for a 31-day-of-year rolling window (see, e.g., Russo and Domeisen, 2023). A persistent extreme, or heatwave, is qualified by a minimum duration of 3 consecutive hot days.
 80 After the grid-point-based identification, we define concurrent heatwave frequency based on a composite analysis around every heatwave onset between 30° and 45° latitude. For each central heatwave onset, we count the number of concurrent heatwave onsets within a latitude band of 20° width at each respective relative longitude from 4 days prior to 8 days after the central heatwave onset. Then we average and normalize the count over all central heatwaves. The resulting frequency is in units of concurrent events per season or concurrent events per year for ERA5 and the idealized model, respectively. Note that
 85 this definition of concurrency allows for a separation of up to 12 days between concurrent event onsets. Note, furthermore, that counting along the relative time coordinate bears similarity to a temporal mean of heatwave onset probability.

For an illustration of this definition, take the example of Paris, Berlin, and Moscow with 70, 72, and 70 summer heatwaves in the ERA5 time series, respectively. Paris experienced 35 concurrent heatwaves for a summer heatwave onset in Berlin. The other way around, Berlin experienced 41 concurrent heatwaves, whereas Moscow experienced only 8 events concurrent with



90 a heatwave onset in Paris. Without spatial autocorrelation, one could expect around 10 concurrent summer heatwaves for the ERA5 time series length (see supplement).

2.3 Calibrating a dispersion relation

A dispersion relation $\omega = \omega(k)$ maps the angular wavenumber k to the angular frequency ω . In the idealized example of a barotropic quasi-geostrophic channel model, all parameters in the dispersion relation are determined by the central latitude, the channel width, and the strength of the background flow. Here, in an attempt to model the zonal structure of concurrent heatwave frequency, we calibrate a dispersion relation

$$\omega(k) = Uk - \frac{Bk}{k^2 + (l_0/2)^2} \quad (1)$$

with two parameters, U and B , based on the properties of heatwave-generating Rossby wave packets, where l_0 is the local meridional angular wavenumber. Equation (1) follows the shape of the barotropic quasi-geostrophic dispersion relation, but the parameters U and B are not derived from the properties of the background flow. Instead, the parameters are calibrated ensuring that, at the dominant angular wavenumber k_0 , the ratio $\frac{\omega}{k} \big|_{k=k_0} = c_p$ is the dominant phase speed and the derivative $\frac{d\omega}{dk} \big|_{k=k_0} = c_{gx}$ is the dominant group velocity. Specifically, the parameters are set to

$$B = (c_{gx} - c_p) \frac{(k_0^2 + (l_0/2)^2)^2}{2k_0^2} \quad (2)$$

$$U = c_p + (c_{gx} - c_p) \frac{k_0^2 + (l_0/2)^2}{2k_0^2}. \quad (3)$$

105 The phase speed c_p and group velocity c_{gx} , as well as the zonal and meridional wavenumbers k_0 and l_0 of a wave packet can be diagnosed from the model output or from reanalysis data following the algorithm developed by Fragkoulidis and Wirth (2020). An illustration of the different steps is shown in Figure S2. A Hilbert transform in longitude extracts the envelope and phase of a locally plane wave from horizontally filtered meridional wind anomalies at 250 hPa. Finite differences of the phase in longitude and in time yield estimates of local phase speed and local zonal wavenumber. Estimating the group velocity and the meridional wavenumber involves a Hilbert transform of object-based envelope anomalies in longitude and latitude. Indeed, the unusual factor of 1/2 in equation (1) is linked to the object-based definition of the meridional wavenumber. Fragkoulidis and Wirth (2020) calculate the object-based anomalies after thresholding the envelope with $E_0 = 15$ m/s. Here, we lower the threshold to $E_0 = 0$ m/s because this increases the group velocity (see Results below).

2.4 The stationary wavenumber

115 After calibrating a dispersion relation, we can infer the stationary wavenumber k_S where $\omega(k_S) = 0$ rad/s. In this study, we hypothesize that this stationary wavenumber will describe the zonal structure of concurrent heatwaves if the dispersion relation is calibrated appropriately. The reasoning behind this hypothesis is our definition of concurrency, and in particular, the similarity between the counting procedure along the relative time coordinate and a temporal average.

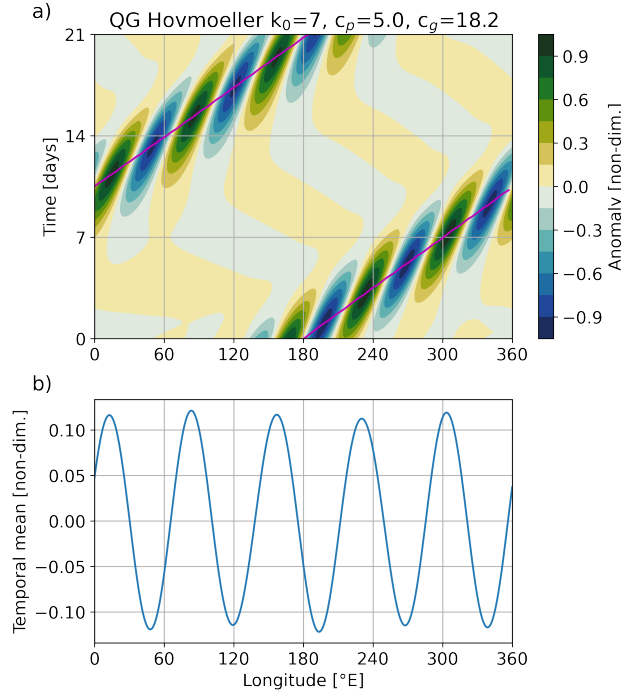


Figure 1. (a) Temporal evolution and (b) temporal mean over 21 days of a Gaussian-shaped wave packet with zonal wavenumber 7 in a linear and barotropic quasi-geostrophic channel model of 5000 km width centered at 37°N with a 13 m/s background flow. The magenta line in panel (a) marks the longitude of maximum wave amplitude.

To illustrate the use of a stationary wavenumber, we initialized a barotropic quasi-geostrophic channel model with a localized Rossby wave packet (Fig. 1a). The downstream development with an eastward group propagation is indicated by the magenta line. The wavenumber spectrum from the initial condition peaks at integer wavenumber 7. The corresponding wavelength of 4600 km describes the distance between two troughs or two ridges in a snapshot. However, since the energy is localized in longitude, the wave packet projects onto a range of wavenumbers that all obey the quasi-geostrophic dispersion relation. For the chosen parameters in Figure 1, the stationary wavenumber amounts to 5.1 (i.e., an angular wavenumber of 1.00×10^{-6} rad/m). The corresponding wavelength of 6300 km describes the distance between two maxima in the temporal mean (Fig. 1b). All harmonics with a larger wavelength are, in fact, retrograding, which can be seen from the backward tilt of the contour lines in the center of Figure 1a.

2.5 Wavenumber-frequency spectra

As an additional step of validation, we will compare the calibrated dispersion relation to the power spectrum of upper-tropospheric meridional wind. The computation of these spectra involves a two-dimensional Fourier transformation in longitude and time. Prior to the transformation in time, we split the time series into 30-day tapered windows following Wicker



et al. (2024). The window length sets the frequency resolution to $2.4 \times 10^{-6} \text{ rad s}^{-1}$. Note that a signal at zero frequency does not correspond to an infinite period but to a 30-day mean anomaly. Finally, we average the spectra meridionally in coordinates of frequency and angular wavenumber between 30°N and 45°N because this latitude range marks the core of the extratropical storm track in the dry-dynamical model. The storm track in ERA5 is located further poleward than in the model, but averaging between 40° and 55° latitude does not change the results substantially.

3 Results

The mid-latitude power spectrum in our idealized numerical model is dominated by synoptic-scale waves (Fig. 2). This range of angular zonal wavenumbers on the order of $10^{-6} \text{ rad m}^{-1}$ is specifically targeted by the zonal filtering in the Rossby wave packet algorithm (Fragkoulidis and Wirth, 2020) for wavelengths between 2000 km and 10000 km. The frequency spectrum is composed of transient and quasi-stationary waves. The spectral peak corresponds to a period of roughly one week for a full phase oscillation. Given the absence of a zonally asymmetric forcing, we identify baroclinic instability and downstream development as the primary mechanism to generate the spectrum of both transient and quasi-stationary waves.

In this study, we present two idealized experiments to assess the calibration for two different power spectra. In addition to power spectral density, Figure 2 depicts dispersion relations (dashed lines) calibrated with the climatological-mean Rossby wave packet properties meridionally averaged between 30°N - 45°N (Fig. S3). This calibration yields parameters $B = 1.0 \cdot 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ and $U = 10.9 \text{ m s}^{-1}$ for the experiment with a high phase speed and $B = 1.9 \cdot 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ and $U = 12.1 \text{ m s}^{-1}$ for the experiment with a low phase speed. For comparison, the meridional gradient of planetary vorticity between 30°N - 45°N amounts to $\beta = 1.8 \cdot 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$. A particular focus lies on the stationary wavenumber where the dispersion relation crosses the abscissa. In comparison to the peak of the stationary power spectrum, the stationary wavenumber is slightly underestimated. Evaluating the quality of the calibration for higher wavenumbers, we have to note that there (Fig. 2) the mismatch between the dispersion relation and the power spectrum increases. This mismatch raises the question of whether the dispersion relation is appropriate. Here, we can note that including a stretching term in the denominator of equation (1) improves the match for high wavenumbers but deteriorates the estimation of the stationary wavenumber. A better fit could be achieved with a dispersion relation, where the meridional wavenumber is not constant but a function of the zonal wavenumber. Similarly, one could argue that a calibration $\frac{d\omega}{dk} \big|_{k=k_0} = c_{gx}$ neglects the contribution of an equatorward group propagation with $c_{gy} < 0$ that contributes to downstream development with

$$\frac{d\omega}{dk} = \frac{\partial\omega}{\partial k} + \frac{\partial\omega}{\partial l} \frac{dl}{dk} = c_{gx} + c_{gy} \frac{dl}{dk}. \quad (4)$$

The zonal-mean meridional group velocity c_{gy} is on the order of -1 m/s. But the derivative $\frac{dl}{dk}$ is difficult to estimate, and the question does link to the discussion about the refractive index and waveguideability (Wirth and Harnik, 2026). Finally, one might ask whether the group velocity is underestimated by the wave packet algorithm, or whether the meridional and temporal average is appropriate for the calibration. We note that the group velocity is sensitive to the envelope threshold chosen to define the extent of a wave packet. Fragkoulidis and Wirth (2020) found an increase by 1 m/s in reanalysis data

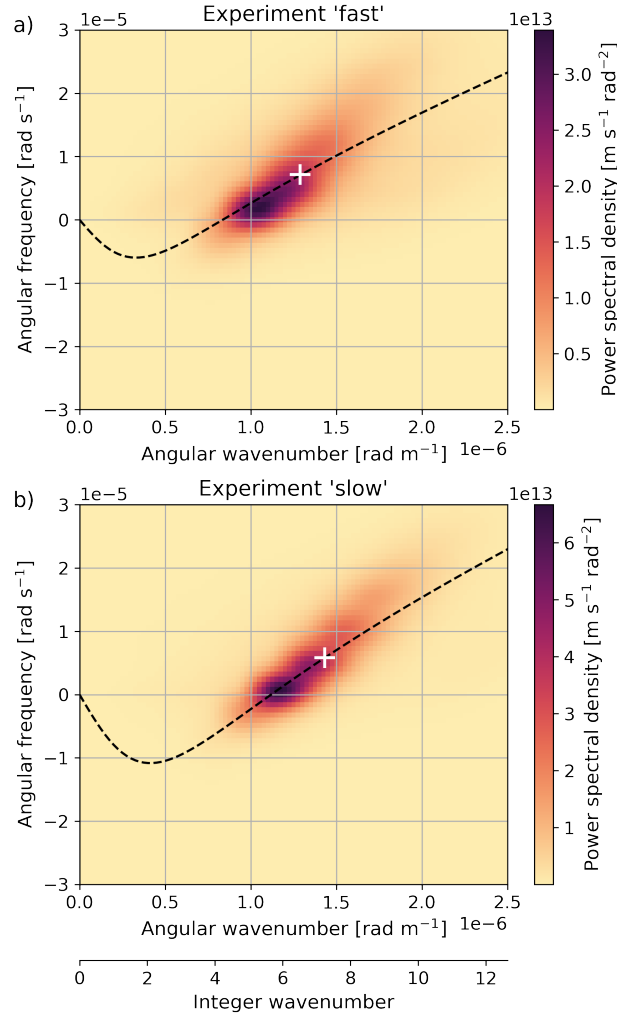


Figure 2. Meridional-mean mid-latitude (30°N–45°N) power spectra of meridional wind at 250 hPa in the idealized experiments with (a) high and (b) low phase speed shown by the color shading. The '+' marker indicates the meridional-mean climatological-mean Rossby wave packet. The dashed line shows the calibrated dispersion relation following equation (1).

when lowering the threshold from 15 m/s to 10 m/s. Here, we omit the thresholding altogether because that choice yields
 165 the highest climatological-mean group velocity. However, with these caveats in mind, we highlight that the difference in the
 stationary power spectrum between the two experiments is well captured by the calibrated dispersion relation. A calibration
 with the climatological mean yields $k_S = 0.8 \times 10^{-6}$ rad/m for Figure 2a and $k_S = 1.1 \times 10^{-6}$ rad/m for Figure 2b. At
 37.5°N, this corresponds to 4.0 and 5.6 in integer wavenumbers.

After this first step of validation, we turn to the zonal structure of concurrent heatwaves as defined in Section 2.2. Our
 170 definition of these events can be illustrated in coordinates of longitude and time by the composite-mean temperature anomalies



around heatwave onsets (Fig. 3). Strong positive temperature anomalies of more than 7 K at 850 hPa in the center of the plot mark the zonal and temporal extent of a central heatwave object. In addition to this central object, we can observe a succession of positive and negative anomalies that resemble the downstream development of a Rossby wave packet, as shown for the quasi-geostrophic example in Figure 1. The spacing of the composite-mean temperature anomalies on the abscissa can be interpreted in terms of a wavenumber, while the tilt of individual anomalies corresponds to the phase speed. As discussed by Wicker et al. (2025), we see the properties of the climatological-mean spectrum (Fig. 2) reflected in a stronger tilt for the experiment with a higher phase speed (Fig. 3a), and in a smaller spacing for the experiment with higher wavenumbers (Fig. 3b). While the composite-mean temperature anomalies show a positive tilt in both experiments, the stationary component is clearly visible.

The 12-day temporal mean of the composite-mean temperature anomalies is plotted in Figure 4 (dashed lines). Consistent with the idea of downstream development, the temporal-mean anomaly shows a distinct wavy structure with a central peak, adjacent minima, and secondary maxima. These composite-mean temperature anomalies reflect the change in heatwave probability compared to the climatological mean. The frequency of concurrent heatwaves (solid lines in Fig. 4), defined in the sense of a composite mean by counting heatwave onsets along the relative time coordinate from 4 days before to 8 days after the central heatwave onset, shows the same structure of secondary maxima and adjacent minima, while the central peak is more pronounced. The experiment with a high phase speed shows 4 secondary maxima in addition to the central peak (Fig. 4a), whereas the experiment with low phase speed shows 5 secondary maxima (Fig. 4b). As outlined above, we seek to explain the different zonal structure of concurrent heatwave frequency in terms of the stationary wavenumber of a downstream developing wave packet. When calibrating the parameters in equation (1) with the properties of heatwave-generating Rossby wave packets (see details below), we obtain stationary wavenumbers $k_S = 4.1$ for the experiment with a high phase speed and $k_S = 5.6$ for the experiment with a low phase speed. The dotted orange lines in Figure 4 depict a corresponding sinusoid. A calibration with the climatological-mean wave packet properties (Fig. S3) yields almost the same stationary wavenumber. So, we find that the inferred stationary wavenumber does not fully capture the zonal structure of concurrent heatwave frequency, in particular for the experiment with high phase speed. On the other hand, some properties of the zonal structure, such as the distance between the minima adjacent to the central peak, are well captured. In summary, we can explain the zonal structure of concurrent heatwaves that corresponds to a wavenumber lower than the wavenumber dominating the spectrum of transient waves and lower than the wavenumber that we see in a snapshot of the large-scale circulation.

Before applying our methodology to reanalysis data, we would like to elaborate on the input for the calibration, which is heatwave-generating Rossby waves, based on the idealized model. Figures 5 and 6 depict composite-mean Rossby wave packet diagnostics relative to mid-latitude heatwave onsets with substantial variations in longitude and time. The white contours display the amplitude of composite-mean temperature anomalies as in Figure 3a and b to indicate the downstream propagation of the heatwave-generating wave packet. We use the spatial and temporal mean masked by the 2 K contour to define the term ‘heatwave-generating’ and as input for the calibration.

The composite-mean diagnostics show that the properties of heatwave-generating Rossby waves are significantly different from climatology: In both sensitivity experiments (Fig. 5a and 6a), the phase speed reduction is largest around the heatwave

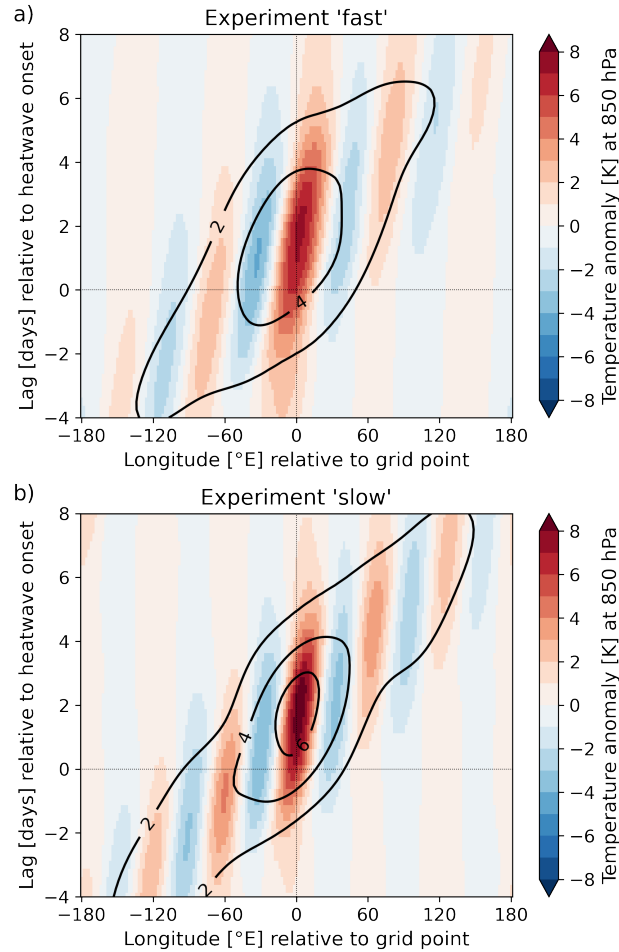


Figure 3. Composite-mean meridional-mean (30°N – 45°N) temperature anomalies at 850 hPa in coordinates relative to the onset of a heatwave for the idealized experiments with (a) high and (b) low phase speed. The black contours depict the amplitude of composite-mean temperature anomalies based on a Hilbert transform after zonal filtering as in the wave packet diagnostics.

onset in the center of the composite and spreads upstream and downstream along the path of group propagation. The reduced phase speed of heatwave-generating circulation anomalies is linked to the construction of the composite and can be interpreted as an increased persistence (Wicker et al., 2024, 2025). The composite-mean zonal wavenumber (Fig. 5b and 6b) is structured similarly to the composite-mean temperature anomalies (Fig. 3), reflecting an asymmetry between troughs and ridges. This asymmetry is linked to the semi-geostrophic nature of Rossby waves and implies a wavenumber reduction around anticyclonic circulation anomalies (Wolf and Wirth, 2015). In addition to the composite-mean anomalies in phase speed and zonal wavenumber that are apparent in both experiments, we also notice a reduction in group velocity and the meridional wavenumber that is stronger in 'Experiment slow' (Fig. 6c, d) than in 'Experiment fast' (Fig. 5c, d). Here, we would like to point out that

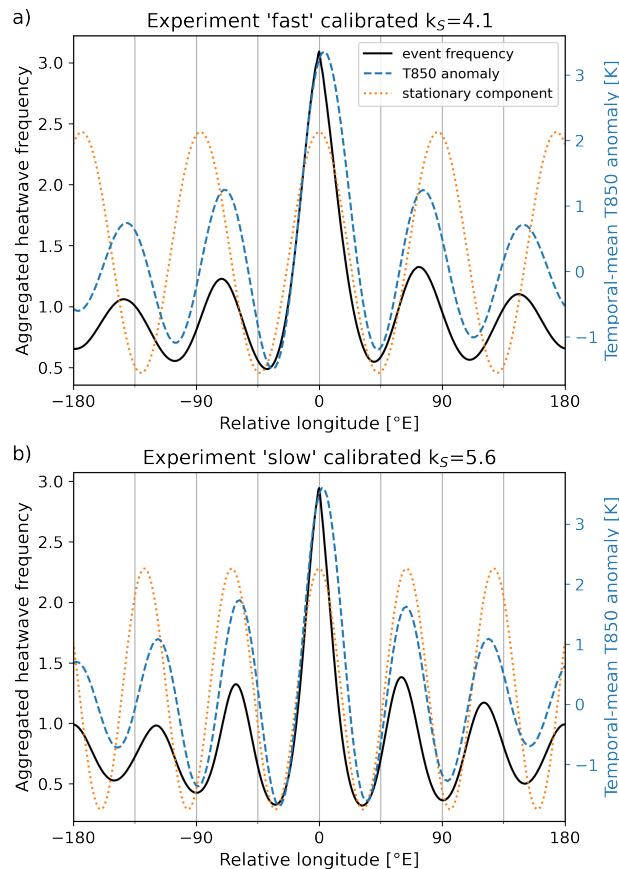


Figure 4. Concurrent heatwave frequency (solid line), in units of concurrent events per year, for a central heatwave between 30°N-45°N and the associated temporal-mean composite-mean temperature anomaly at 850 hPa (dashed line) from the idealized experiments with (a) high and (b) low phase speed. The dotted orange lines depict a sinusoid to illustrate the stationary wavenumber from the calibrated dispersion relations.

group velocity as well is linked to the persistence of circulation anomalies as well (Wicker et al., 2025) and that the meridional
 215 extent of jet meanders has been linked to their stationarity (e.g., Francis and Vavrus, 2012; Babaei et al., 2026).

Another interpretation of the anomalous composite-mean wave packet properties could be the onset of blocking. As outlined
 in the introduction, atmospheric blocking plays an important role in the generation of hot extremes in both the idealized model
 (Jiménez-Estevé and Domeisen, 2022) and reanalysis (Pfahl, 2014). The reduction in group velocity is directly linked to the
 wave activity flux and could point towards an exceedance of the flux carrying capacity, as argued by the 'traffic jam' theory
 220 (Nakamura and Huang, 2018). The reduction in meridional wavenumber or increase in meridional wave extent might be seen
 as a sign of wave breaking, an important process in blocking formation (Altenhoff et al., 2008; Masato et al., 2012). This
 interpretation is noteworthy in the context of this study since the idea of a blocked atmospheric flow contradicts an eastward
 group propagation and downstream development. While the flow might be blocked for an important number of heatwaves,



Experiment 'fast'

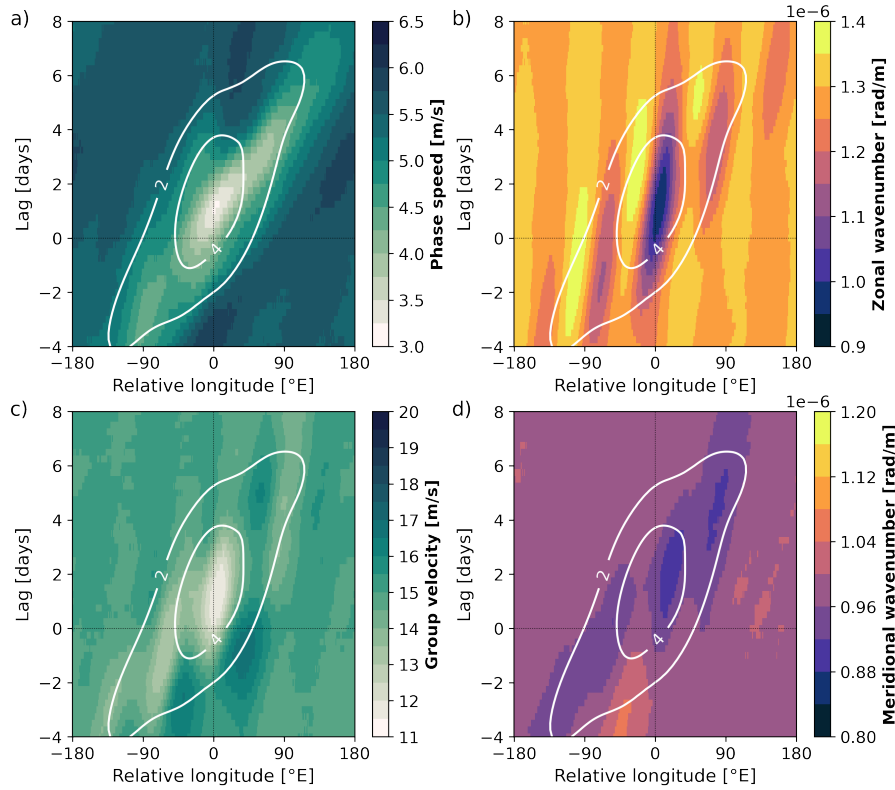


Figure 5. Composite-mean meridional-mean (30°N–45°N) Rossby wave packet diagnostics relative to the onset of a heatwave in the idealized experiment with high phase speed. Specifically, we show (a) the composite-mean local phase speed c_p , (b) the local angular zonal wavenumber k_0 , (c) the local zonal group velocity c_{gx} , and (d) the local meridional angular wavenumber l_0 . The white contours depict the amplitude of composite-mean temperature anomalies as shown by black contours in Figure 3a.

it is remarkable that downstream development is still adequate to describe the temporal evolution and zonal structure of the composite mean (Fig. 3).

So far, we compared two idealized simulations with two different power spectra and argued that downstream development can explain the different zonal structures of concurrent heatwaves. Next, we will look at reanalysis data, compare summer and winter, and the Northern and Southern Hemisphere mid-latitudes. In comparison to the dry-dynamical model, the wavenumber-frequency spectrum from ERA5 is much broader (Fig. S4), reflecting zonal asymmetries as well as intraseasonal and interannual variability. In contrast to the model, ERA5 shows substantial power for stationary waves with smaller than synoptic-scale wavenumbers. When comparing the four spectra, the angular frequency associated with the climatological-mean wave packet in Northern Hemisphere summer (white marker in Fig. S4a) is about half of the angular frequency in Northern Hemisphere winter and in the Southern Hemisphere (Fig. S4b–d). A strong contrast between Northern Hemisphere summer mid-latitudes

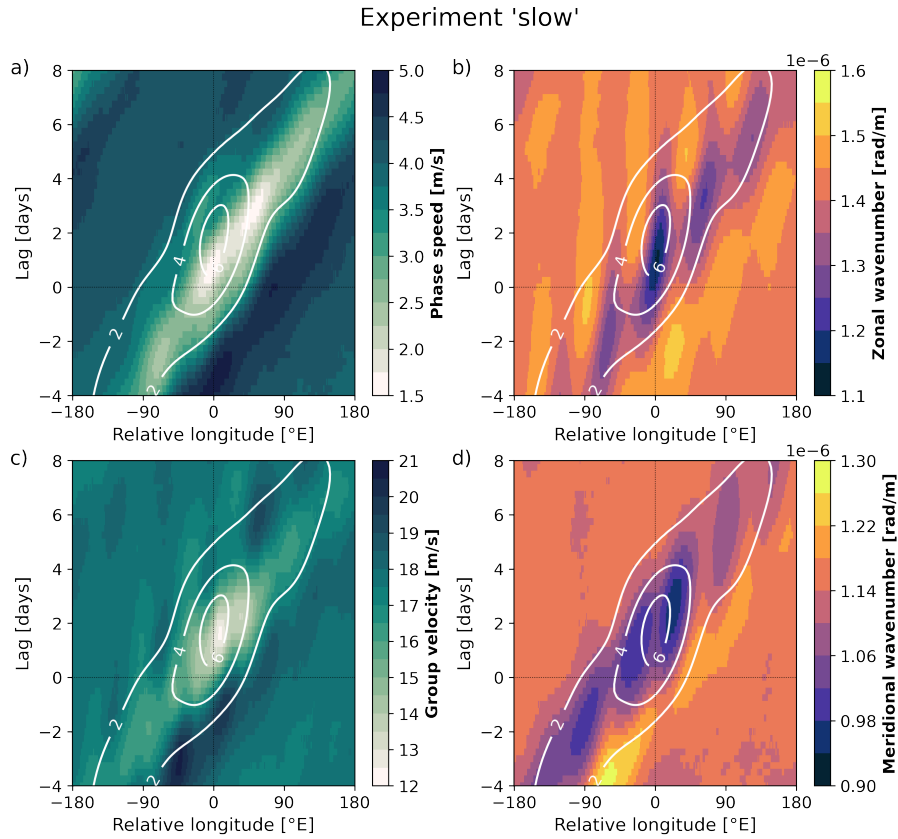


Figure 6. As in Figure 5 but for the idealized experiment with low phase speed. The white contours depict the amplitude of composite-mean temperature anomalies as shown by black contours in Figure 3b.

and the other three cases can also be seen in the properties of heatwave-generating Rossby waves (Fig. S5-S8). In the Southern Hemisphere (Fig. S7, S8) and during Northern Hemisphere winter (Fig. S6), a phase speed reduction along the path of downstream development is clearly visible, although the composite-mean is much closer to climatology than in the case of the dry-dynamical model (Fig. 5, 6). During Northern Hemisphere summer, the phase speed reduction is less clear and a reduction in group velocity is more prominent (Fig. S5). Different properties of the heatwave-generating Rossby waves are reflected in differing stationary wavenumbers for the calibrated dispersion relation. We infer $k_S = 4.9$ for Northern Hemisphere summer, compared to $k_S = 3.6$ and $k_S = 3.7$ for the other three cases (Fig. 7).

The closest resemblance to the dry dynamical model can be seen in Southern Hemisphere summer (Fig. 7c) with a pronounced wavenumber-4 harmonic. Indeed, the properties of transient Rossby waves are the most zonally symmetric in the Southern Hemisphere summer mid-latitudes (Fragkoulidis and Wirth, 2020). Consequently, the calibrated dispersion relation models the zonal structure of the concurrent heatwave frequency, defined in the sense of a composite mean, very decently. In Southern Hemisphere winter, with an equatorward-shifted subtropical jet, the South Pacific shows a double jet structure that

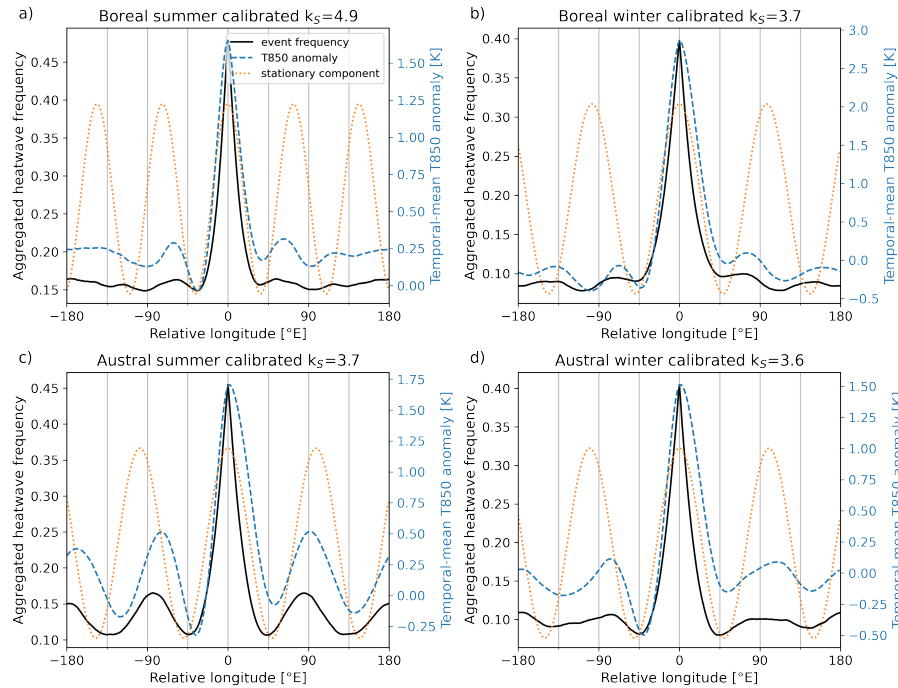


Figure 7. As in Figure 4 but for ERA5 data in the Northern (panel a-b) and Southern Hemisphere (panel c-d) for December-February (panel a, d) and for June-August (panel b-c), respectively.

is strongly reflected in the phase speed and group velocity of Rossby wave packets. In the Northern Hemisphere, the large land masses create strong zonal asymmetries (Fragkoulidis and Wirth, 2020). Here, the approximation from equation (1) is useful mostly for modeling the width of the central peak and the distance between the adjacent concurrent heatwave frequency minima.

250 4 Conclusions

In this study, we investigate the horizontal structure of spatially compounding hot extremes through the lens of synoptic-scale atmospheric dynamics and provide a new perspective to a discussion that is focused on waveguide dynamics (White et al., 2022). We highlight similarities between concurrent heatwaves in a dry-dynamical atmospheric model without zonally asymmetric forcing, thermodynamic feedbacks from the lower boundary, or pronounced low-frequency variability, and concurrent
255 heatwaves from reanalysis data. The zonal structure of concurrent heatwave frequency in mid-latitudes features a central peak representing the extent of a contiguous heatwave object, adjacent minima with reduced heatwave probability, and multiple more or less pronounced secondary minima. The adjacent minimum corresponding to an upstream trough is often noted and dynamically linked to the central heatwave object (D’Andrea et al., 2024; Pappert and Martius, 2026). Our analysis reveals strong symmetry and a downstream trough, indicating that the central heatwave can act as a precursor to downstream hazards



260 (Guo et al., 2025). The overall wavy structure and the similarity between the idealized model and reanalysis are presumably linked to our definition of concurrency, as the maximum lag between concurrent heatwave onsets of 12 days corresponds to the time scale of downstream development. On longer time scales, we would expect land and sea surface feedbacks to become more important (Pappert et al., 2025). A concurrency between extreme events in distant regions on a daily time scale is more likely to occur by chance.

265 The literature on resonant amplification (Petoukhov et al., 2013; Harnik and Wirth, 2025; Mooring and Linz, 2026) seeks to explain the wavy structure of spatially compounding climate extremes based on the properties of a zonalized basic state. This basic state is usually inferred directly from atmospheric data through, for example, a zonal average or a rolling zonalization (e.g., White and Mareshet Admasu, 2025). Here, instead, we calibrate a dispersion relation based on the properties of the localized and transient disturbances which generate temperature extremes. While the dispersion relation assumes the existence
270 of a basic state, the deduction of its nature is indirect. After calibration, we can infer the stationary wavenumber to describe the zonal structure of concurrent heatwave frequency. This wavenumber is effective in explaining differences in concurrent heatwave frequency between different climatologies derived from the idealized numerical model, or between different seasons and hemispheres in reanalysis data. As in Section 2.2, let us use the example of Paris and Moscow for illustration. The separation between Paris and Moscow of 35° longitude corresponds well to the position of the adjacent minima in concurrent heatwave
275 frequency for a stationary wavenumber of 4.9. The number of concurrent summer heatwaves for Paris and Moscow is below the expected value for a spatially and temporally uniform distribution. For a lower stationary wavenumber, the same longitudinal difference would yield more frequent concurrent events. Indeed, during boreal winter, Paris and Moscow experience more than twice as many concurrent heatwaves as during boreal summer.

The features of the atmospheric circulation that relate to the stationary wavenumber derived from a calibrated dispersion
280 relation can be referred to as quasi-stationary waves (Wolf et al., 2018) or as recurrent Rossby wave packets (Röthlisberger et al., 2019; Ali et al., 2022). These two diagnostics, which define a metric based on low-pass filtered meridional wind anomalies, are clearly related to the temporal mean of a Rossby wave packet. Indeed, the concept of a transient but downstream developing wave packet can be seen as complementary to the notion of quasi-stationary circumglobal waves. Any transient wave packet will have a stationary component, as long as its energy is localized in space, and its eastward group velocity
285 exceeds its phase speed. With this study, we seek to draw a line between the properties of quasi-stationary waves and local processes that contribute to the phase and group propagation of transient waves. The role of diabatic processes, in particular, deserves further attention. Early works indicate that large-scale condensation increases the wavenumber and the phase speed of baroclinic unstable waves (Mak, 1982; Bannon, 1986). More recently, computational and methodological advances promote an investigation of diabatic processes for the mid-latitude circulation using object-based and Lagrangian techniques (Schemm
290 et al., 2013; Attinger et al., 2021). Overall, it becomes clear that a smaller-scale perspective can advance our understanding of spatially compounding climate extremes.



Code and data availability. A code repository to replicate the analysis will be published together with final version of the manuscript. The ERA5 reanalysis data can be downloaded from the Copernicus Climate Data Store (<https://doi.org/10.24381/cds.bd0915c6>, Hersbach et al., 2023). The output from the idealized experiments is available from the authors upon request.

295 *Author contributions.* WW and DD conceptualized the study, ER ran the idealized model experiments, and GF provided software for the wave packet diagnostic. DD and NH contributed supervision. WW investigated the data, visualized the results, and wrote the original draft. DD, GF, and NH contributed to the review and editing. DD secured the funding.

Competing interests. Two co-authors are members of the editorial board of Weather and Climate Dynamics.

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