Dynamics, statistics and predictability of Rossby waves, heatwaves and spatially compounded extreme events

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ABSTRACT: What: A workshop on Rossby waves, heatwaves and compound extreme events was co-organized by the Institute for Atmospheric Sciences and Climate (ISAC) of the National Research Council of Italy (CNR) and the University of Trento, Italy. The workshop gathered experts from different fields, such as extreme events analysis, atmospheric dynamics, climate modeling, Numerical Weather Prediction, with the aim to discuss state-of-the-art research, open challenges, and stimulate networking across different communities.

When: 28-30th November 2023.

Where: CNR Research Area, Bologna, Italy.

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1. Introduction

The low-frequency variability of the atmosphere has long been the subject of intense investigation in the dynamical meteorology community (Benzi et al. 1986; Ghil 1987; Mo and Ghil 1987; Benzi and Speranza 1989; Tibaldi and Molteni 1990; Pelly and Hoskins 2003b,a). Recent decades have seen increasing interest in the complex interplay between the upper-level mid-latitudinal circulation, mediated through Rossby waves, and surface extreme events, such as heatwaves, with their manifold impacts. This topic has been investigated across multiple scales, from hemispheric to local, for various scenarios, from past climates to future projections, and for numerous applications, from predictability in Numerical Weather Prediction (NWP) systems to extreme weather-related impact and risk assessment.

Heatwaves are prolonged episodes of high temperatures, whose duration, from a few days to a few weeks, entails different formation, development and maintenance mechanisms. In the Northern Hemisphere, they are typically associated with high-amplitude upper-tropospheric ridges or blocking anticyclones. These are often embedded in persistent large-scale wave patterns (White et al. 2022) and can lead to "concurrent heatwaves" simultaneously affecting several regions across the mid-latitudes (Kornhuber et al. 2020). These are examples of spatially compounding extreme events, which can lead to extreme socio-economic impacts via hazards co-occurring at multiple locations (cfr. Zscheischler et al. (2020)). See Figure 1 for an example of the association between Rossby wave potential vorticity and temperature anomalies for the concurrent heatwaves of July 2023. Despite the increasing frequency of such concurrent heatwaves (Rogers et al. 2022; Messori et al. 2024) and their improved forecasting in operational NWP systems (e.g., Emerton et al. (2022)), our understanding of their large-scale drivers is limited, yet critical to further improving their predictability, especially at subseasonal-to-seasonal timescales. One crucial open question is the relationship between surface weather extremes and large-scale atmospheric circulation patterns, such as Rossby waves (cfr. Dole et al. (2011); Hoskins and Woollings (2015); Röthlisberger et al. (2019); Ali et al. (2022); Strigunova et al. (2022)) and blocking (Kautz et al. 2022).

While progress has been made on the atmospheric circulation response to climate change, the connection between circulation changes and trends in extremes is an active area of research (Shaw and Miyawaki 2024). On the one hand, high-amplitude Rossby waves have been highlighted as a key driver of concurrent heatwaves in some years (Kornhuber et al. 2019). In fact, Rossby waves

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can interact with extreme events across different timescales. It has been found that the predictability of heatwaves is higher than for milder temperatures or cold extremes (Wulff and Domeisen 2019; Hochman et al. 2022) or for other extreme events (Domeisen et al. 2022), especially if these heat extremes are associated with the occurrence of high amplitude Rossby waves (cfr. Pyrina and Domeisen (2023) and references therein). On intraseasonal-to-seasonal and longer timescales, however, high-amplitude Rossby waves are poorly predicted in weather models (cfr. Teubler and Riemer (2016); Quinting and Vitart (2019); Pérez et al. (2021); Pérez-Fernández and Barreiro (2023)), although, generally, tendencies for hot extremes can be estimated on sub-seasonal forecast horizons (Domeisen et al. 2023) and magnitude becomes certain about a week ahead (Oertel et al. 2023).

On the other hand, over the historical record, heatwaves have increased in most regions of the globe (Russo and Domeisen 2023), with Europe emerging as a key hot spot (Rousi et al. 2022). Despite this observational evidence, climate models significantly underestimate heatwave trends due to atmospheric circulation biases (Vautard et al. 2023). Additionally, activating specific tipping elements like the Atlantic Meridional Overturning Circulation (AMOC) might have a major impact on the statistical and dynamical properties of heatwaves in the European sector (Schenk et al. 2018).

To review scientific advances and identify outstanding challenges and opportunities, the workshop "Rossby waves, heatwaves, and compound extreme events," co-organized by the Institute for Atmospheric Sciences and Climate (ISAC) of the National Research Council of Italy (CNR) and the University of Trento, Italy, was held in Bologna from 28th to 30th November 2023. The workshop was specifically designed to bring together a diverse research community, with experts from different subfields of the broad research ecosystem under the umbrella of "atmospheric and climate sciences" (e.g. extreme events analysis, atmospheric dynamics, climate modeling, NWP).

A focal discussion theme was the connection between Rossby waves and concurrent heatwaves, with contributions on selected case studies, on the different roles of (quasi-)stationary and traveling Rossby waves, on the role of topography and land-sea contrast for the formation of co-occurring heatwaves, and non-linear interactions and wave resonance. These contributions relied on and described a plethora of different methods for Rossby wave identification and characterization (waveguides, PV inversion, Rossby Wave Packets, Local Wave Activity, spectral decomposition, and wave detection methods). Global statistics of Rossby wave energy by Strigunova et al.

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(2022) showed an increased skewness of the spectra of Rossby wave anomalies at planetary scales (k=1-3) during heat waves, with a reduction of intra-monthly variance most pronounced at zonal wavenumber k=3. Furthermore, it was noted that heatwaves are increasing most strongly in specific regions rather than uniformly across all regions.

The workshop also touched on other aspects of the large-scale atmospheric circulation relevant to spatially compounding extremes, such as weather regimes and land-atmosphere and ocean-atmosphere interactions. Riboldi et al. (2023) highlighted that spatially compounding extremes can also result from anomalous zonal large-scale flows rather than anomalous wave activity.

Another focus point was the predictability of heatwaves through the identification of specific precursors at different spatiotemporal scales, such as those related to conditions for Rossby wave amplification and breaking (blocking, the role of upstream latent heat release during moist ascent (cfr. Steinfeld and Pfahl (2019); Oertel et al. (2023); Papritz and Röthlisberger (2023)) or specific weather regimes and teleconnections (e.g., active/inactive monsoon; Garfinkel et al. (2024); Hochman et al. (2021b)).

Statistical methods of heatwave characterizations were also extensively addressed, revealing how the most extreme heatwaves show typicality features (Galfi and Lucarini 2021; Hochman et al. 2021a; Lucarini et al. 2023; Noyelle et al. 2024). According to the concept of typicality (Galfi and Lucarini 2021; Lucarini et al. 2023), if one considers a reference location within the surroundings of an observed heatwave, the majority of foreseeable heatwaves of comparable intensity are expected to exhibit similar features as the observed one, over large - typically continental - spatial scales. Some evidence for the typicality of co-occurring heatwaves was also discussed, indicating a correspondence between the climatic and NWP viewpoints (Lucarini et al. 2023; Fischer et al. 2023).

2. Scientific questions/challenges

Below, we provide a more detailed discussion of scientific questions and challenges that emerged from the presentations and the ensuing discussion:

Rossby wave dynamics for spatially compounding extremes: the nature of Rossby waves involved in spatially compounding extremes, notably heatwaves, is still a subject of discussion. Several studies highlighted the role of specific wavenumbers (such as zonal wavenum-

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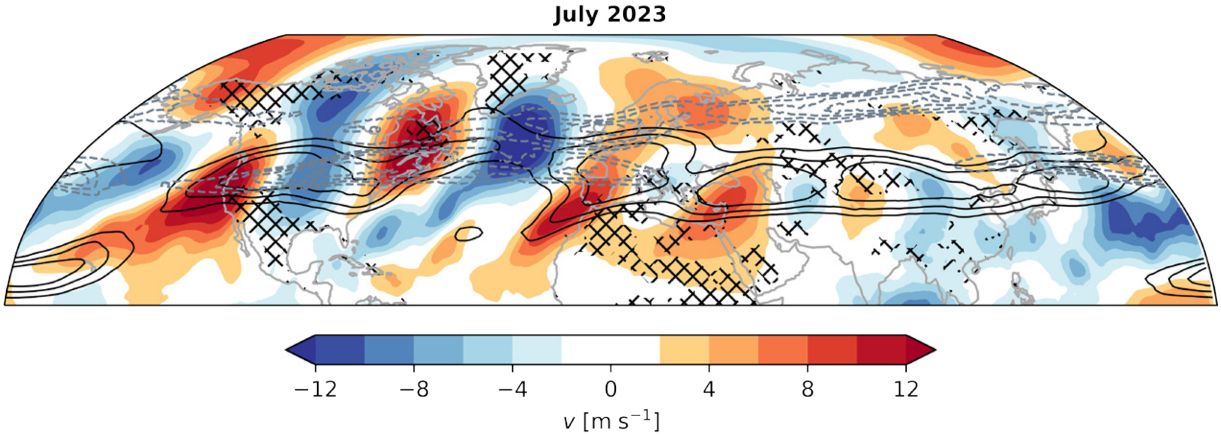

FIG. 1. Northern Hemisphere Rossby waves, waveguides, and heatwave locations for July 2023. Shading shows monthly averaged meridional winds at $200hPa$, with positive values denoting southerly winds. Regions that experienced heatwaves for more than 5 days in a month are denoted with the black hatches. The solid black contours show monthly mean zonal wind U at $200hPa$ and are plotted every $5m * s^{-1}$ from 15 to $30m * s^{-1}$. The dashed gray contours show waveguide occurrence frequency in percentage and are plotted every 10% from 40 to 100%. The waveguide occurrence frequency per grid denotes the number of times the grid experiences $||\nabla \log(|q|)|| > 10^6 m^{-1}$ in a month, where q is potential vorticity in PVU on two different isentropic surfaces ($320K$ and $340K$).

bers k=4-8) organized in quasi-stationary and circumglobal planetary waves (e.g., Petoukhov et al. (2013); Kornhuber et al. (2019)). This view was put into question by other studies (Röthlisberger et al. 2019; Wirth and Polster 2021)) that noted how such wavenumbers are instead associated with transient, non-hemispheric Rossby wave packets. While a possible explanation could involve the interaction between the time-varying upper-level jet stream and geographically fixed large-scale orography (Jiménez-Esteve et al. 2022), more work is needed to confirm or reject this hypothesis. The role of circulation features such as atmospheric blocking or recurrent Rossby wave packets, both known to be related to heatwaves, must also be systematically assessed in this context.

Synoptically-induced Rossby wave amplification: Diabatic outflow in the warm conveyor belt of extratropical cyclones is very important for the non-linear amplification of Rossby waves (e.g., Grams and Archambault (2016); Steinfeld and Pfahl (2019); Oertel et al. (2023)). This happens at the synoptic timescale through extratropical cyclogenesis, which triggers

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persistent ridges often evolving in blocking events (e.g., Riboldi et al. (2019)) associated with heatwaves (Quinting and Reeder 2017; Zschenderlein et al. 2019, 2020). Whether diabatic outflows are systematically correlated to temperature anomalies and extreme events at the surface is still an open question.

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Predictability of heatwaves: Long-range prediction of heatwaves can be related to teleconnections, which are often mediated through Rossby wave trains (Boreal Summer Intraseasonal Oscillation effect on the easterly jet, possibly as a consequence of background El-Niño Southern Oscillation, cfr. Strnad et al. (2023), the impact of diabatic heating of the Tropical Indian Western Pacific on European heatwaves; Ma and Franzke (2021)). Due to their large-scale or global nature, teleconnections can often be interpreted in the context of concurrent or compound extreme events. The predictability of heatwaves is also conditioned by their duration, which needs to be better understood for improved subseasonal-to-seasonal outlooks (Wulff and Domeisen 2019). On synoptic time scales, Oertel et al. (2023) discuss "predictability barriers" due to the interaction of diabatic outflow with the Rossby wave pattern for the prediction of the 2021 North American heat wave magnitude. From a reduced-order model point of view, two competing modes are seen to occur, zonal and blocking modes, and the transitions among them are often determined by the role of noise, making blocking, in particular, very hard to predict in NWP systems (Xavier et al. 2023; Hochman et al. 2021a). In Europe, this noise can take the form of rapidly evolving atmospheric structures (1-2 days) that can convey warm air from the tropics (D'Andrea et al. 2024). Zonal and blocked flows are associated with somewhat different levels of structural instability in the atmosphere (Faranda et al. 2017), challenging our ability to capture their statistics in climate models (Lucarini and Gritsun 2020). Therefore, a systematic underestimation of concurrent heatwave occurrence has been highlighted in climate models (Kornhuber et al. 2023).

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Role of blocking and topography: related to the previous point but deserving of specific consideration is the necessity to improve the understanding of the link between Rossby waves, blocking, and topography, particularly the reproduction of this link in state-of-the-art NWP and climate models. As it has been known for a long time (cfr. Tibaldi and Molteni (2018) and references therein), topography and surface friction critically influence the capability of models to characterize the stability, frequency, and transition phase of blocking events, leading to increased or reduced predictability (Schubert and Lucarini 2016; Lucarini and Gritsun 2020).

Physically justified weather regimes: he existence of weather regimes as recurrent or persistent regional/hemispheric-scale patterns associated with concurrent heatwaves has been assessed statistically (e.g. Yiou and Nogaj (2004)). Physically justified assessments must be conducted and tailored to specific needs and balanced by diverse pattern recognition approaches, such as k-means clustering, Hidden Markov Models, EOFs, and self-organizing maps, including recent machine learning approaches. Statistical models based on circulation analogs are good candidates to emulate persisting features during heatwaves (e.g. Yiou et al. (2023)). A-posteriori assessments of the physical grounding of regimes are also key (Vannitsem 2001; Franzke et al. 2008; Kwasniok 2014; Zschenderlein et al. 2019, 2020; Hochman et al. 2021a; Springer et al. 2024). Depending on the situation, a protocol for the most appropriate method for pattern recognition and clustering is needed.

Statistical treatment of spatially compounding extreme events: the typical trajectory leading to an extreme state refers to the most likely development of the extreme event. The typical trajectory is a theoretical concept: when the extreme event unfolds, the real dynamics fluctuate around the typical trajectory. We call the events that approach this typical trajectory "typical extreme events" (Galfi and Lucarini 2021; Lucarini et al. 2023; Noyelle et al. 2024). But how do we study such "typical" extreme events? How far does this typicality apply to spatially compounding events? How do we extend the probability density function of an observable to sample extremely rare events when we don't have sufficiently large observational datasets? Committor functions informed by stochastic weather generators and data-driven large deviation theory as a complement to classical extreme value theory have been proposed,

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but their applicability has to be assessed depending on the context (cfr. Kwasniok (2015); Galfi and Messori (2023); Miloshevich et al. (2024)).

Interactions with land and ocean surface: Besides their origin from internal atmospheric variability, Rossby waves can be forced by changes in mid-latitude sea surface temperatures (SST) and soil moisture anomalies (cfr. Martius et al. (2021)). Marine heatwaves and droughts can act locally to enhance and propagate temperature extremes on land. More work is needed to disentangle the complex ocean-atmosphere and land-atmosphere Rossby wave interactions and their cause-effect relationships.

Reconciling definitions of persistence: the word "persistence" has different connotations, depending on the various processes and timescales it refers to and the defined framework (Holmberg et al. 2023). One can distinguish between global, state, and episodic persistence, manifesting as either (quasi-)stationarity or recurrence (cfr. Tuel and Martius (2023)). Regarding atmospheric circulation, both the (quasi-)stationarity (e.g., blocking) and recurrence (e.g., recurrent Rossby wave packets) of flow anomalies can lead to prolonged and impactful surface extremes. While agreement on the exact meaning of persistence may not be possible or even relevant, more clarity and nuance are advised when presenting work linked to this concept.

3. Interdisciplinary approaches

The workshop program was designed to leave ample space for open discussion. Overall, the need to foster collaborations across disciplinary boundaries was emphasized as key to achieving progress with recommendations for coordinated action around several focal points:

Integration, harmonization and consistent use of different metrics for Rossby wave characterization: waveguides, PV-approach, local wave activity, phase speed for storm track propagation, jet stream, kinetic or mechanical energy, latent heat release/atmospheric rivers, persistence;

Different approaches for the study of concurrent extremes: coincidence analysis, large deviation theory (LDT), extreme value theory (EVT);

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Comparisons of different spectral approaches: Fourier coefficients, Hough harmonics, Wavelet, Hayashi, stationary vs. traveling, planetary vs. synoptic;

Integration of methodologies from dynamical systems theory: analysis of unstable periodic orbits, Lyapunov analysis of the tangent space, model reduction via Markov chain modeling;

Clever use of the model hierarchy: large ensembles, Quasi-Geostrophic (QG) models, dynamical cores, convective permitting regional climate models (CORDEX), data-driven models (coral reef optimization method);

Impacts perspective: what extremes are most relevant for droughts, heat stress, energy consumption, and power-grid resilience, regionally and on hemispheric scales? Which timescales are interesting for risk preparedness and decision-making across different social and industrial sectors?

4. Outlook and conclusions

Despite, but also thanks to the diversity of represented expertise, a common vision emerged from the workshop community for pushing forward our understanding of the complex interaction between atmospheric Rossby waves and spatially compounding extreme events. We identified collaborative efforts leveraging various approaches and tools as the most promising avenue for rapid scientific advances. All participants acknowledged the workshop as an essential step towards achieving these goals, and there is ongoing discussion on how to transform this venue from a one-off event to a continued and sustainable effort.

Some cutting-edge questions identified as more amenable to future progress are listed below. The first necessary step is developing a common framework to distinguish between concurrent heatwaves mediated by a common driver, from a set of individual events happening concurrently by chance, due to physically distinct large-scale atmospheric dynamics. Events caused by common drivers, which could occur under amplified, zonally extended Rossby waves "connecting" the various mechanisms, characterized by their predictability and statistics, deserve an in-depth analysis from an atmospheric circulation perspective.

As shown during the workshop, state-of-the-art climate models struggle to reproduce concurrent heatwaves. This model deficiency is a crucial issue, as concurrent heatwaves are becoming

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increasingly frequent compared to isolated heatwaves (Rogers et al. 2022). A modeling approach should focus on characterizing high-intensity and moderate extreme events that might become the median event in a future climate. The amplification and increase in frequency of extreme events with climate change has been, in fact, directly related to mechanisms responsible for the development of Rossby waves (cfr. for instance, the "fast-get-faster" paradigm, a direct consequence of the Clausius-Clapeyron relationship; Shaw and Miyawaki (2024)).

There is a pressing need to enhance the predictability horizon of extreme heatwaves, and probabilistic approaches seem to be particularly promising, especially regarding heatwave duration (Pyrina and Domeisen 2023). Sensitivity studies on the direct or indirect role of topography or surface friction in the development of blockings and the modulation of amplified Rossby waves might provide further crucial insights into the drivers of concurrent heatwaves (Jiménez-Esteve et al. 2022; Jiménez-Esteve and Domeisen 2022).

Whereas both individual and concurrent heatwaves are prone to become more frequent in future climate change scenarios, it is unclear whether the new events will simply be an intensification of already observed extreme heatwaves (typical extreme events or "gray swans") or will follow completely different trajectories, thus being perceived as freak events or black swans (cfr. Fischer et al. (2023)). Note that the latter option is not unlikely, considering the effect of global warming on the atmospheric circulation. Given that these two extreme events may be statistically and dynamically different, we need various analysis tools. While approaches like EVT, LDT, and typicality analysis are adequate for understanding typical extreme events and how these will change with global warming, we need different approaches to analyze black swans. Computational tools such as rare event sampling algorithms, ensemble boosting, and some machine learning methods are promising. However, proper theoretical approaches, which are currently missing, are also critically needed.

Identifying large-scale precursors for local extreme heatwave events by exploiting data-driven models and machine learning algorithms is a promising field of research, as demonstrated by recent work from workshop contributors (e.g., Dorrington et al. (2024)). However, statistical assessments involving classical EVT or LDT (cfr. Kwasniok (2015, 2019)) and purely data-driven technologies must be complemented by physically justified arguments shedding light on the involved mechanisms. Beyond observational constraints, this process-oriented approach is key in correctly

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and systematically evaluating existing model biases in representing spatially compounding events (Bevacqua et al. 2023).

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