https://doi.org/10.5194/egusphere-2023-2353
Preprint. Discussion started: 19 October 2023

WCD Ideas: Teleconnections through weather rather than stationary waves

Clemens Spensberger[1]

[1]Geophysical Institute, University of Bergen, and Bjerknes Centre for Climate Research, Bergen, Norway

Correspondence: Clemens Spensberger (clemens.spensberger@uib.no)

Abstract. Conventionally, teleconnections in the atmosphere are described by correlations between monthly mean fields. These correlations are supposedly caused by stationary Rossby waves. The main hypothesis explored in this idea is that teleconnections are instead established by chains of events on synoptic time scales, that is by weather. Instead I hypothesise that non-stationary Rossby waves play an important role in establishing teleconnections. If these hypotheses are correct, much of the vast literature on this topic misses an essential part of the atmospheric dynamics leading to teleconnections.

1 Introduction

Conventionally, teleconnections are described by statistical relations between time-mean fields. For example, many teleconnections are defined through EOF analyses based on monthly mean sea-level pressure or geopotential (e.g., Wallace and Gutzler, 1981; Thompson and Wallace, 2000). Thus defined, teleconnections statistically describe spatial relations in how these fields vary.

Teleconnections can be comparatively local. An example would be the North Atlantic Oscillation (NAO), an anticorrelation between the sea-level pressure over Iceland and the Azores. I call these teleconnections “local” because their spatial scale is comparable to that of a single weather system. For example, the anticorrelation defining the NAO can be physically understood as variations in the occurrence of a characteristic weather event (Rossby wave-breaking) over the North Atlantic (Woollings et al., 2008).

Other teleconnections extend over much larger distances. For example, variations in tropical convection in the Indo-Pacific associated with the Madden-Julian Oscillation (MJO) or the El Niño Southern Oscillation (ENSO) influence the North Atlantic weather on monthly to seasonal time scales despite the large distance between these regions (e.g., Fromang and Rivière, 2020; Deser et al., 2017). It is these long-distance teleconnections that are the focus of this idea. They cannot be explained by variations in a single weather event, such that some other process must establish the observed connection between the distant regions.

Teleconnections to ENSO and the MJO are important for the predictability of North Atlantic weather because both ENSO and the MJO are more predictable than mid-latitude weather. Through long-distance teleconnections, these oscillations can be a source of predictability for the North Atlantic on sub-seasonal to seasonal (s2s) time scales (e.g., Scaife et al., 2014, 2017).

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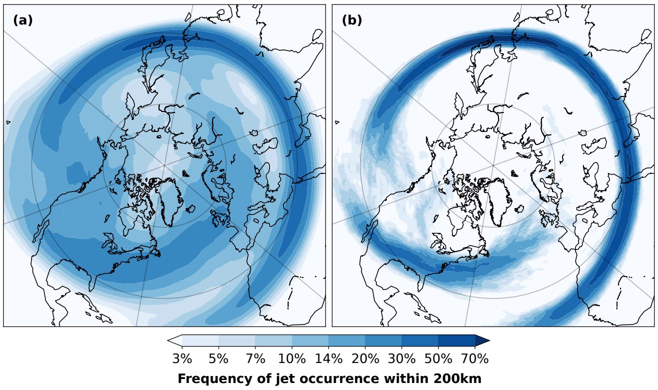

Figure 1. The effect of monthly averaging for detected jet axes. The detections are based on (a) 3-hourly instantaneous winds, or (b) monthly mean winds in ERA5 during winter for the period 1979-2022. Jets in (b) deviate little from their climatological mean position. Jets are detected following Spensberger et al. (2017).

In contrast to several "local" teleconnections, no attempt has been made yet to interpret and understand long-distance teleconnections in terms of variations of weather. Instead, the connection is thought to be established by stationary Rossby wave trains, as often seen in monthly-to-climatological averages, with arguments generally based on the pioneering work by Hoskins and Karoly (1981) and a somewhat more recent conceptual review by Held et al. (2002).

Despite the widespread use of the Hoskins and Karoly (1981) arguments to explain teleconnections[1], this perspective has severe limitations in explanatory power, which so far have remained largely unaddressed. The Hoskins and Karoly (1981) arguments are based on a time-mean perspective and require the definition of a basic state on which small-amplitude perturbations propagate linearly. They further require spatial variations in the mean state to be gentle enough to not interfere with wave propagation. Given these strong assumptions, linear stationary wave theory following Hoskins and Karoly (1981) is surprisingly successful in describing observed time-mean states (Held et al., 2002; Potter et al., 2013). Despite this success, however, this description remains only self-consistent in that it cannot explain how the time-mean state with apparently linear wave perturbations can emerge from chaotic, non-linear weather. There is no obvious link from a time-mean state back to the instantaneous weather from which it emerged.

On the contrary, inferences about wave propagation based on a time-mean state can be misleading. As Potter et al. (2013) demonstrated, small changes in the flow structure can be enough to cause large changes in wave reflection, and thus the direction of wave propagation. As illustrated by Fig. 1, there are typically large differences between instantaneous and time-mean flow. In monthly means, jets deviate hardly at all from their climatological position. On shorter time scales, however, jets occur over a wide range of latitudes. Rossby waves tend to propagate in the direction of the jet (e.g., Martius et al., 2010), such that it seems highly unlikely that the instantaneous wave propagation can be inferred from a time- mean state, and thus that stationary wave theory can provide a causal explanation for the emergence of teleconnections.

[1] On 10 January 2022 Google Scholar listed 2837 citations of Hoskins and Karoly (1981), of which 773 citations in the five years 2017-2021.

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2 Hypotheses

The missing causal explanation calls for a reinterpretation of long-distance teleconnections in terms of weather. As the basis for this reinterpretation, I hypothesise

1. Teleconnections are established through (chains of) events on synoptic time scales, i.e., "weather".
2. These chains of events are orchestrated by predominantly non-stationary Rossby waves.

While the scope of these hypotheses is global, first step could be focussing on tropical- extratropical teleconnections involving the North Atlantic. These specific teleconnections are an ideal testbed because (a) the North Atlantic is storm track is very well studied, and (b) significant but weak correlations with the tropical Indo-Pacific suggest large variability within the teleconnection. Consequently, I hypothesise

3. Predictable forcing from ENSO or the MJO is communicated to the North Atlantic by weather events.

Analogous hypotheses have been shown to be correct for air-sea and air-ice interactions. Here, the interpretation of (monthly) mean fluxes can be quite misleading (Ogawa and Spengler, 2019) because brief bursts dominate the climatological exchange and its variability in the mid-latitudes. For example, Greenland tip jets, short-lived mesoscale wind maxima, shape deep ocean convection in the Irminger Sea (e.g., Pickart et al., 2003; Piron et al., 2016). Similar bursts in the air-sea exchange are associated with extratropical cyclones (Sorteberg and Kvingedal, 2006; Sampe and Xie, 2007), polar lows (Condron and Renfrew, 2013) and cold-air outbreaks (Papritz and Spengler, 2017; Aemisegger and Papritz, 2018). If weather events dominate the climatology of these exchange processes, it seems plausible that weather events also dominate the exchange, for example, between the tropics and extratropics, or within teleconnections.

Hypotheses 1-3 however provide no guidance on why the dominant stationary-wave perspective on these teleconnections appears so immensely successful (cf., citations of Hoskins and Karoly, 1981; Held et al., 2002). Stationary Rossby waves appear ubiquitously in monthly, composite, and climatological means, and have with some success been applied to study s2s predictability of the North Atlantic (e.g., Scaife et al., 2017).

To clarify the relation between the weather-based and stationary wave-based perspectives on teleconnections, it is useful to consider an analogy between the time-mean perspective and geostrophy. In both geostrophic balance and the stationary-wave perspective, information about causality is lost. Neither causes the geostrophic wind the pressure gradient, nor vice-versa. Analogously, there is no causal relation from a time-mean state back to the instantaneous events from which it emerged. Further, causal relations in the evolution of weather do not translate to, for example, the succession of monthly averages. I therefore hypothesise

4. Stationary waves do not cause teleconnections, they are an expression of their existence in a time-mean perspective.

Following the analogy, both geostrophy and stationary wave theory are indispensable fundamental concepts for understanding mid-latitude flow. Nonetheless, it is essential for many applications to look beyond geostrophic balance. In essence, all my hypotheses can be summarised by the claim that the same is true for stationary wave theory.

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The analogy also reveals wide gaps in our understanding. While geostrophy is well-founded (a) on scaling arguments that explain why the balance exists and (b) on geostrophic adjustment theory that explains how geostrophic balance can be attained in practice, neither of these ingredients exists for stationary wave theory. Neither do we know why we should expect time mean states to apparently follow linear wave theory, nor do we know how chaotic, non-linear weather can reduce to an apparently linear time-mean state.

If correct, hypothesis 2 provides the missing conceptual foundation. Non-stationary finite-amplitude Rossby waves regularly propagate approximately linearly over large distances (e.g., Wirth and Eichhorn, 2014; O'Brien and Reeder, 2018). They further have a clear influence on the non-linear evolution of mid-latitude weather, for example by determining the predominant locations of cyclogenesis (Holton and Hakim, 2013). It thus seems plausible that they constitute the ordering principle that links the non-linear instantaneous weather to a linear mean state.

3 Conceptual risks and potential impact

These hypotheses challenge the dominant paradigm of how long-distance teleconnections arise. This paradigm has been prevailing since the pioneering work of Hoskins and Karoly (1981) and has generally successfully been applied to link zonal asymmetries and mid-latitude variability to faraway orography and diabatic forcing (e.g., Held et al., 2002; Scaife et al., 2017). There is thus a considerable conceptual risk that the hypotheses will need to be refuted despite my above arguments.

If, however, the hypotheses turn out to be true, we need to conceptually reframe how long-distance teleconnections are established in the atmosphere, shifting the focus from monthly and longer time scales to synoptic time scales. This reframing is synonymous with a deeper physical understanding because it transforms teleconnections from statistical relations to a causal chain of events, in which each link in the chain depends on well-defined conditions. The deeper understanding of teleconnections provides the basis for a better understanding of the potential and limits for predictability through these teleconnections. In a time-mean perspective the link from, for example, the MJO to the North Atlantic can only be analysed as a whole, whereas the weather perspective allows to follow the causal chain of events link by link. This is advantageous because for every link in isolation it is much easier to physically understand the conditions under which it is effective than for the teleconnection as a whole.

This perspective on the conditions for predictability will also help unravel the so-called predictability paradox (Scaife et al., 2014; Scaife and Smith, 2018). The paradox is rooted in s2s ensemble predictions systems being too dispersive, leading to the rather paradoxical result that members in the ensemble are better at predicting reality than each other (Scaife and Smith, 2018). If the hypotheses are correct, this paradox implies that at least one of the links in the chain of events that constitutes the teleconnection is simulated as much more uncertain than this link actually is. Following the chain of events link by link will help identify the processes that might be misrepresented in the prediction systems, thereby leading to the paradox.

But even if the hypotheses will need to be refuted, efforts to systematically test them would have a considerable scientific impact. The approach envisioned to test the hypotheses entails the compilation of a comprehensive dataset showing both stationary and non-stationary Rossby wave activity during the past decades. This dataset provides a new avenue to address

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long-standing issues on the relation between the near-stationary and transient circulation, as well as the relation between waves and weather. By conceptually linking waves and weather, this avenue also constitutes a bridge between the synoptic and weather event-based perspective prevalent in dynamical meteorology and the eddy-mean flow perspective prevalent in climate dynamics. Finally, the dataset of Rossby wave activity will be valuable to clarify the link between Rossby waves and extreme events suggested by many case studies of (in particular) flood events (e.g., Massacand et al., 1998; Enomoto et al., 2007; Martius et al., 2008; Wirth and Eichhorn, 2014; Röthlisberger et al., 2016).

4 Overall approach

To test the hypotheses one needs to systematically assess the time scales at which predictable forcing from the MJO and ENSO is communicated to the North Atlantic. If the hypotheses are correct, we expect synoptic time scales to dominate over monthly and longer time scales. In particular we expect non-stationary Rossby waves to dominate over near-stationary Rossby waves. The main objective thus requires a systematic assessment of the role of all Rossby waves in the climatological momentum exchange between the tropics and extratropics as well as from the North Pacific to the North Atlantic.

The current state-of-the-art diagnostics designed to capture Rossby wave activity (Takaya and Nakamura, 2001) are unfortunately unsuitable for the task because they require strong physical assumptions about the flow. These diagnostics require an a-priori separation of the atmospheric state into a slow-evolving or stationary mean state and transients. Such a separation is highly problematic. The shorter the averaging period, the less is the near-stationarity assumption fulfilled. At the same time, the longer the period, the less representative is the mean of the instantaneous conditions. Often a period of one month is used (Orlanski and Katzfey, 1991; Teubler and Riemer, 2016), which is long enough to bring with it all the conceptual limitations of the stationary wave perspective discussed above.

There are alternative diagnostics which avoid these particular assumptions, such as the Rossby wave packet diagnostic reviewed in Wirth et al. (2018). This diagnostic however comes with its own set of limitations. For example, the region and direction of Rossby wave propagation must be defined a-priori, which renders the wave packet diagnostic, too, unsuitable.

Because of this lack of a suitable diagnostic, a I would propose an alternative approach to diagnose Rossby wave activity which does not require any physical assumptions. The approach is based on using data assimilation in conjunction with an idealised atmospheric model. Data assimilation was originally developed for numerical weather prediction as a tool to derive a state that is optimally consistent with the prediction model given the available observations of the real atmosphere.

The application of data assimilation here would be similar. Given observations, the goal is to determine the optimally consistent state and evolution of the atmosphere represented by an idealised atmospheric model which contains nothing but Rossby waves. To avoid the tremendous complexities of dealing with actual observations, I would suggest to use existing reanalyses instead of observations. The result is an *idealised reanalysis*, which represents the best estimate of Rossby wave activity during the past decades.

In addition to the state and evolution of Rossby wave activity, the assimilation procedure yields a best estimate of the forcing required to keep the idealised model in sync with the input reanalysis. This forcing represents all processes initiating

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or damping Rossby wave activity that are missing in the idealised model. Linking this forcing to weather events in the input reanalysis allows to isolate processes that systematically modify Rossby waves while they propagate between the tropical Indo-Pacific and the North Atlantic.

5 A specific plan to test the hypotheses

Following the suggested approach would require four main steps. Step I contains the implementation of the data assimilation procedure and of the adjoint model, providing the idealised reanalysis datasets and model tools used in Steps II-IV. Step II systematically explores the relationship between transient and near-stationary waves, thus mainly addressing hypothesis 4. Step III complements Step II by linking near-stationary and transient wave activity to weather events such as cyclones, jets, and cold-air outbreaks. Step III thus directly targets hypothesis 2, and will, in combination with Step II, allow to assess the validity of hypothesis 1. Finally, Step IV assesses the predictability of these teleconnections, targeting hypothesis 3. A brief description of each step follows.

Step I: Implementation of the data assimilation procedure and construction of the idealised reanalyses. Suitable idealised models are readily available (e.g., Bedymo, see Spensberger et al., 2021), but will generally need to be extended by a data assimilation component. To minimise the associated risk, and to have preliminary versions of the idealised reanalyses available early-on, the data assimilation procedure can be bootstrapped, starting from spectral nudging. From a data-assimilation perspective and with the “observations” being another reanalysis, nudging is equivalent to a 3D-variational data assimilation (3D-Var) with the assumption that the error covariances (statistical representations of the model dynamics) of the two models are identical. 3D-Var is thus a natural extension of nudging, accounting for differing error covariances between the input reanalyses and idealised model. Guidance on how to construct these error covariance matrices is available from the numerical weather prediction community. With 3D-Var, each state in isolation is consistent between the input and idealised reanalyses, but differences in the evolution of the underlying models are ignored. Taking these into account, we arrive at 4D-variational data assimilation (4D-Var), the final step in the bootstrapping sequence.

For 4D-Var as well as for Step IV in this plan, an adjoint for the idealised model is required. An adjoint model complements a given model by tracing backwards in time how a particular state came to be, rather than predicting forward in time how this state is evolving (Errico, 1997). The adjoint can either be constructed through algorithmic differentiation (using for example TAPENADE, Hascoët and Pascual, 2012), or through manual derivation and implementation of the adjoint equations. Irrespective of this choice, the derivation of the adjoint model will be more straightforward than for most other atmospheric models because no parameterisations are required beyond linear relaxation and biharmonic diffusion. For all remaining terms in idealised model equations, well-tried standard recipes to derive the adjoint are available and can be followed.

Step II: From transient to stationary waves. The Rossby wave-only reanalysis produced in Step I provides the foundation for the two main analyses in Step II. First, this reanalysis can be used to decompose the Rossby wave vorticity budget into a near-stationary and a transient component following Cai and Van Den Dool (1994) and Feldstein (1998). If the traditional stationary wave perspective is correct, the near-stationary component should evolve largely independently from the transient

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component. If, in contrast, hypothesis 4 is correct, one would find scale interactions to be an important contributor to the near-stationary circulation. Second, one could use the Rossby-wave only reanalysis to diagnose vorticity transports due to Rossby waves. Like wave-activity fluxes, the vorticity transport highlights dynamical connections between regions, but its calculation does not require physical assumptions. The time scales on which the Tropical Indo-Pacific and the North Atlantic are connected can then simply be derived by decomposing the transport into different frequency bands.

Step III: From chaotic weather to linear waves. Hypotheses 1 and 2 in combination imply a synergetic relation between Rossby waves and weather events in creating teleconnection patterns. To test the hypotheses, one could detect weather events in the reanalysised used as observations using established detection algorithms, and then relate them to Rossby wave activity, initiation, and damping using composite analyses.

Step IV: Predictability through teleconnections. Finally, one can apply the results from Steps II & III to the problem of predictability through teleconnections. Starting from the event to be predicted (e.g., the occurrence of a certain phase of the NAO), one can use the adjoint model to trace back predictability by identifying those processes to which the event is most sensitive (following, e.g., Galanti and Tziperman, 2003; Heimbach et al., 2011). Such processes could be scale-interactions of Rossby waves or the occurrence of a specific kind of weather event, as identified using the diagnostics of Steps II & III. Repeating the procedure using the occurrence of these key process(es) as the event to be predicted, one can thus work one's way backwards and extract chains of processes and events that in combination yield predictability for the original event. If hypothesis 3 is correct, these key processes act predominantly on synoptic time scales.

6 Further applications of the idealised reanalyses

The idealised reanalyses created following the overall approach have many potential applications beyond the one outlined here. For example, the idealised model Bedymo (Spensberger et al., 2021) could easily be configured to be a dry 3-layer primitive equation model. The corresponding idealised reanalysis would then be ideally suited to assess the influence of diabatic effects on the storm track. This allows to directly address the long-standing question on their role for mid-latitude dynamics and predictability. Expanding on this idea, a hierarchy of idealised reanalyses accompanying each step in the Held (2005) hierarchy of models would simplify considerably the search for a minimal model required to represent a phenomenon of interest because its representation could then simply be compared across existing datasets without requiring a new set of model simulations.

Author contributions. n/a (single-author submission).

Competing interests. I declare no competing interests.

https://doi.org/10.5194/egusphere-2023-2353
Preprint. Discussion started: 19 October 2023

Acknowledgements. This idea is based on a research proposal submitted for an ERC Starting Grant 2021 and 2022, which is in turn the result of discussions with many colleages over several years. Of these colleagues I want to specifically thank Thomas Spengler and Madlen Kimmritz as they had a particularly large influence in shaping the ideas expressed herein. Nevertheless, all mistakes and misguided hypothesis are mine, not theirs.

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