Traffic Bottlenecks: Predicting Atmospheric Blocking with a Diminishing Flow Capacity

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Key Points:

- Flow capacity exceedance events, predictors of blocking onset in the traffic jam theory, are defined and evaluated in climate reanalyses.
- A downstream reduction in flow capacity is ubiquitous for both exceedance and blocking events: lane closures favor traffic jams.
- Blocks are co-located with exceedance events in space but not in time, limiting the utility of the traffic jam theory for prediction.

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Abstract

Atmospheric blocking is characterized by persistent anticyclones that "block" the mid-latitude jet stream, causing temperature and precipitation extremes. The traffic jam theory posits that blocking events occur when the Local Wave Activity flux, a measure of storm activity, exceeds the carrying capacity of the jet stream, leading to a pile up. The theory's efficacy for prediction is tested with atmospheric reanalysis by defining "exceedance events", the time and location where wave activity first exceeds flow capacity. The theory captures the Northern Hemisphere winter blocking climatology, with strong spatial correlation between exceedance and blocking events. Both events are favored not only by low carrying capacity (narrow roads), but also a downstream reduction in capacity (lane closures causing a bottleneck). The theory fails, however, to accurately predict blocking events in time. Exceedance events are not a useful predictor of an imminent block, suggesting that confounding factors explain their shared climatological structure.

Plain Language Summary

An atmospheric block is a large, high pressure weather pattern that blocks the jet stream, affecting many regions in the midlatitudes including North America and Europe. Blocks are notable for their persistence, driving extreme weather conditions for up to a week or longer. Despite their significant societal impact, we don't fully understand the mechanism(s) that generate blocks. A traffic jam theory was proposed, which suggested that the onset of a block is caused by having too much "storm activity flux", which leads to a pile up of storm activity, just as a traffic jam is precipitated by conditions where the vehicular flux exceeding the road capacity, blocking traffic. This analogy is useful for understanding the preferred locations of atmospheric blocks in the time-mean sense, but is not predictive in terms of individual blocking events. We further propose to incorporate additional regional constraints on flux capacity, analogous to "traffic bottlenecks", to improve our understanding of preferred blocking locations.

1 Introduction

An atmospheric block is a large, persistent high pressure system that "blocks" the jet stream, locally reversing the direction of the flow (Berggren et al., 1949; Rex, 1950). It causes a stagnation and re-routing of typically eastward propagating weather systems, which can lead to extreme weather events in the mid-latitudes (Kautz et al., 2022). It has proven difficult to predict the onset of blocking in numerical weather forecast (Woollings et al., 2010, 2018), for example, with the ECMWF Ensemble Prediction System (Pelly & Hoskins, 2003a; Ferranti et al., 2015) or the NCEP Climate Forecast System (Jia et al., 2014). Models used for climate projection generally struggle to capture the frequency and duration of blocking events (Davini & D'Andrea, 2020). The mechanism(s) that trigger blocking events also remain an open question in the field. A better understanding of the dynamics would help focus efforts to improve weather and climate prediction systems, and provide insight into potential changes in blocking in response to global warming.

Nakamura and Huang (2018, hereafter NH18) proposed a novel hypothesis to predict the onset of blocking. They argued that the jet stream has a maximum carrying capacity for storm activity. When this capacity is exceeded, wave activity rapidly backs up, in analogy to a traffic jam, leading to a block. They quantified the storm activity using the Local Wave Activity (hereafter LWA) of Huang and Nakamura (2016), and, after several simplifying approximations of the LWA budget equation, derived an equation that is a close relative of the classical traffic density equation. Thus NH18 suggested that jet stream possesses a capacity for LWA fluxes, and predicted that an exceedance of this capacity results in blocking onset. This result advanced the pioneering work of Swanson (2000, 2001), who argued that the accumulation of wave activity leads to a vanishing group velocity (i.e., a blocked state) in a simpler, barotropic system governed by a single potential vorticity jump.

NH18 provided a formula to compute the spatial pattern of the flux capacity, and argued that blocks are most likely to occur in regions with minimal capacity, which coincide with the exit regions of the Pacific and Atlantic storm tracks. The goal of this study is to explore the predictive ability of the traffic jam hypothesis in the Northern Hemisphere. We ask two questions. First, how well does the flux capacity predict the spatial climatology of blocking in the atmosphere? Second, can the theory be used to predict blocking onset in a forecasting context?

The first question is motivated in particular by further development and application of the traffic jam hypothesis by Paradise et al. (2019), who investigated a one-dimensional idealized traffic jam model forced with noise. This allowed them to examine blocking statistics with varying parameters (such as stationary wave amplitude, transient eddy forcing, and jet speed), exploring how the blocking climatology changed with modulation of the capacity. They found that blocking consistently maximized in regions of minimum capacity. Here, we take a complementary approach, computing the flux capacity directly from atmospheric reanalysis, and comparing its structure with that of blocking statistics. While we find that blocking is favored in regions of minimum capacity, there is an upstream shift in blocks relative to the (inverse) capacity. This suggests that blocking is favored not just in regions of low capacity, but regions where the capacity decreases downstream. In analogy with a traffic jam, we argue that lane closure causes a "traffic bottleneck", where merging causes a pile up before the road is most narrow. Our work emphasizes that not just a low LWA capacity, but also a reduction in the flux capacity contribute to exceedance formation and atmospheric blocking.

The second question is motivated by case studies in NH18, where they showed that events of excessive zonal wave activity flux preceded blocking development (their Fig. 5). An additional case study was performed by Polster and Wirth (2023), where ensemble sensitivity analysis of a 2016 winter European block through the lens of the traffic jam mechanism identified a collocation between target blocking and enhanced upstream flux 2.5 days prior to onset. To determine whether an exceedance of the jet's carry capacity can be used as a predictor for imminent blocking, we define objective criteria for "exceedance events" to quantify the time and location when the LWA exceeds the flux capacity. We adopt a flexible definition to mark exceedance events. We find that blocking is indeed often preceded by a minor exceedance of the flow capacity, but such minor exceedance events happen on a near daily basis, and so cannot be used to flag blocking: the false positive rate is prohibitively high. If we look for major exceedance events, defined so that they are similarly as rare as blocking events, the relationship between exceedance and blocking is lost. We conclude that while flow exceedance and blocking share the same spatial climatology, the former cannot effectively be used as a harbinger of the latter.

2 Data and Methodology

NH18 argued that an exceedance of the carrying capacity of the jet stream precipitates a blocking event. To define exceedance events, one requires the LWA flux capacity, a climatological property of the atmosphere, and the time varying LWA flux, an instantaneous measure of storm activity movement. We follow the methodology of NH18 exactly to calculate the LWA, denoted $A(x, y, t)$ (a function of longitude, latitude, and time x, y, t), flux $F(x, y, t)$, and flux capacity $F_C(x, y)$. We followed the direct regression approach outlined in NH18 to compute F_C, but compared our results with their approximate flux capacity, which yielded similar conclusions. Calculations were done using 6-hourly, 1.5° by 1.5° grid data of 1979-2016 DJF winter temperature T and zonal and meridional wind u, v from ERA-interim (European Centre for Medium-Range Weather Forecasts, 2009).

To identify blocking events, we follow Martineau et al. (2017) and Liu and Wang (2024), using daily, 1° by 1° grid data of 1979-2016 DJF winter geopotential height z_{500} extracted from ERA5 (Copernicus Climate Change Service, 2023). This LWA-based blocking definition was chosen for optimal compatibility with the traffic jam theory, but yields similar results to B-index (Pelly & Hoskins, 2003b); see Liu and Wang (2024) and the supplementary materials for more detail.

The traffic jam theory predicts the onset of a blocking event when the LWA flux value exceeds the flux capacity, i.e., $F(x, y, t) > F_C(x, y)$. Figure 1d shows the fraction of time when this criterion is met over the northern midlatitudes in winter. We see immediately that the fraction is quite large, often above 30%. Blocking events, however, occur much less frequently (Figure 1e). We therefore require criteria to identify the times and locations when the flux capacity is *meaningfully* overwhelmed: an exceedance event.

We require that the flux exceeds the capacity by a tunable threshold, ΔF over a synoptic scale region:

$$\overline{F(x, y, t) - F_C(x, y)} > \Delta F, \tag{1}$$

where the overbar denotes an average over a 12° by 12° patch of the midlatitudes. We experimented heavily with choice of the bounding box and threshold ΔF, and found the results to be robust, provided the two parameters were varied together: when the bounding box is increased, the threshold needs to be decreased to keep the same frequency of events. In the results to follow, we highlight two thresholds, $\Delta F = 100$ and 1200 m^2s^2. The low threshold was chosen to capture the nearly daily events where the LWA flux exceeded the jet capacity over a storm-sized patch of the atmosphere. The high threshold was chosen to limit the number of exceedance events to a number comparable to blocking events.

3 Results

Figure 1 shows winter climatologies of the key quantities in the traffic jam theory of blocking onset. The time-mean LWA A, panel (a), reveals key features of the storm tracks. A maximum in LWA over the eastern North Atlantic and Europe is associated with the Atlantic storm track, while a more diffuse maximum over the North Pacific, flanked by peaks in wave activity over East Asia and the Western US, is associated with the Pacific storm track. The climatological LWA flux F, panel (b), even more closely matches traditional storm track measures, highlighting the regions storms travel across the North Pacific and North Atlantic. The flux capacity F_C, shown in Figure 1c, on the other hand, is more strongly associated with the jet streams, and peaks upstream of the storm tracks where the zonal winds are strongest off the coast of East Asia and diagonally across the western North Atlantic. Regions of low flux capacity are associated with a higher frequency of times when the LWA flux exceeds the capacity (Fig. 1d). Consistent with the traffic jam mechanism, these regions where the flow capacity is most often exceeded are co-located with regions where the flow is most often blocked (Fig. 1e).

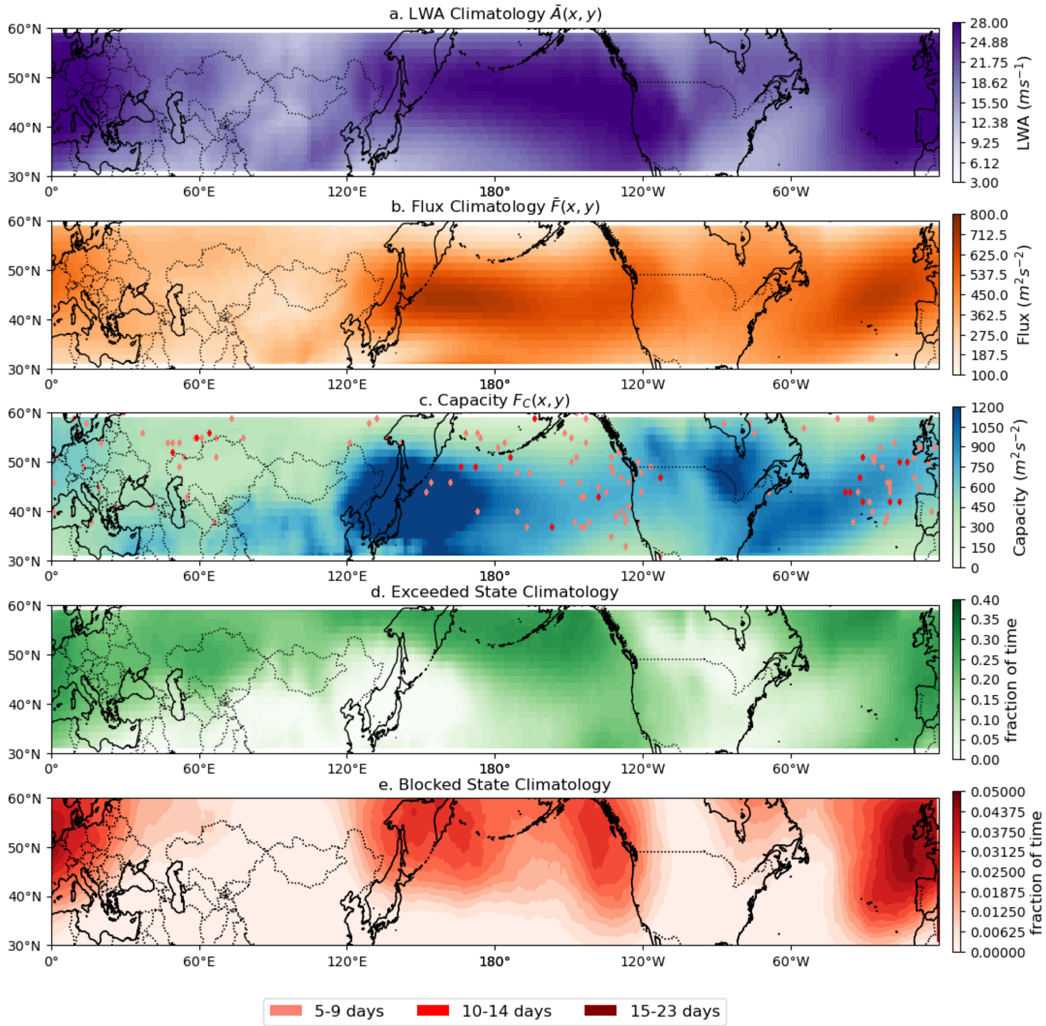

Figure 1: Key quantities of the traffic jam mechanism for blocking, computed for boreal winter, 1979 to 2016. (a) the climatological LWA $\overline{A}$. (b) the climatological LWA flux $\overline{F}$. (c) the LWA flux capacity F_C. (d) the climatological exceedance frequency, computed as the time fraction that the LWA flux of a grid point exceeds F_C by any amount, $\Delta F = 0$ in equation (1). (e) the blocking frequency, computed as the time fraction that a grid point experiences a blocking event.

Figure 2a allows a more quantitative comparison: meridional averages of the exceedance and blocking frequency are plotted with the inverse of the flux capacity $-F_C$. We find a robust anticorrelation between the exceedance and blocking frequency with the flux capacity, but also observe an upstream shift of exceedance and blocking frequency relative to minima in the flux capacity, particularly in the Atlantic region.

While the lowest flux capacity is found over Eurasia (from the prime meridian to approximately 120°E), the exceedance and blocking frequency peak slightly west of the prime meridian. The upstream shift in the maximum in exceedance events suggests that it is not just a minimum in the carrying capacity that increases the likelihood of a traffic jam, but also its zonal gradient. Exceedance of the jet capacity is not only favored by low carrying capacity, but also a downstream reduction in the capacity. In analogy with a traffic jam, we argue that lane closures lead to a bottleneck in traffic. Furthermore, the carrying capacity of the jet is rarely exceeded over Eurasia, despite the low carrying capacity of the jet. The dearth of exceedance and blocking over Eurasia is consistent with low wave activity in this region (Fig. 1a). A traffic jam analogous interpretation is that the chance of traffic congestion on a narrow but little used roadway are low.

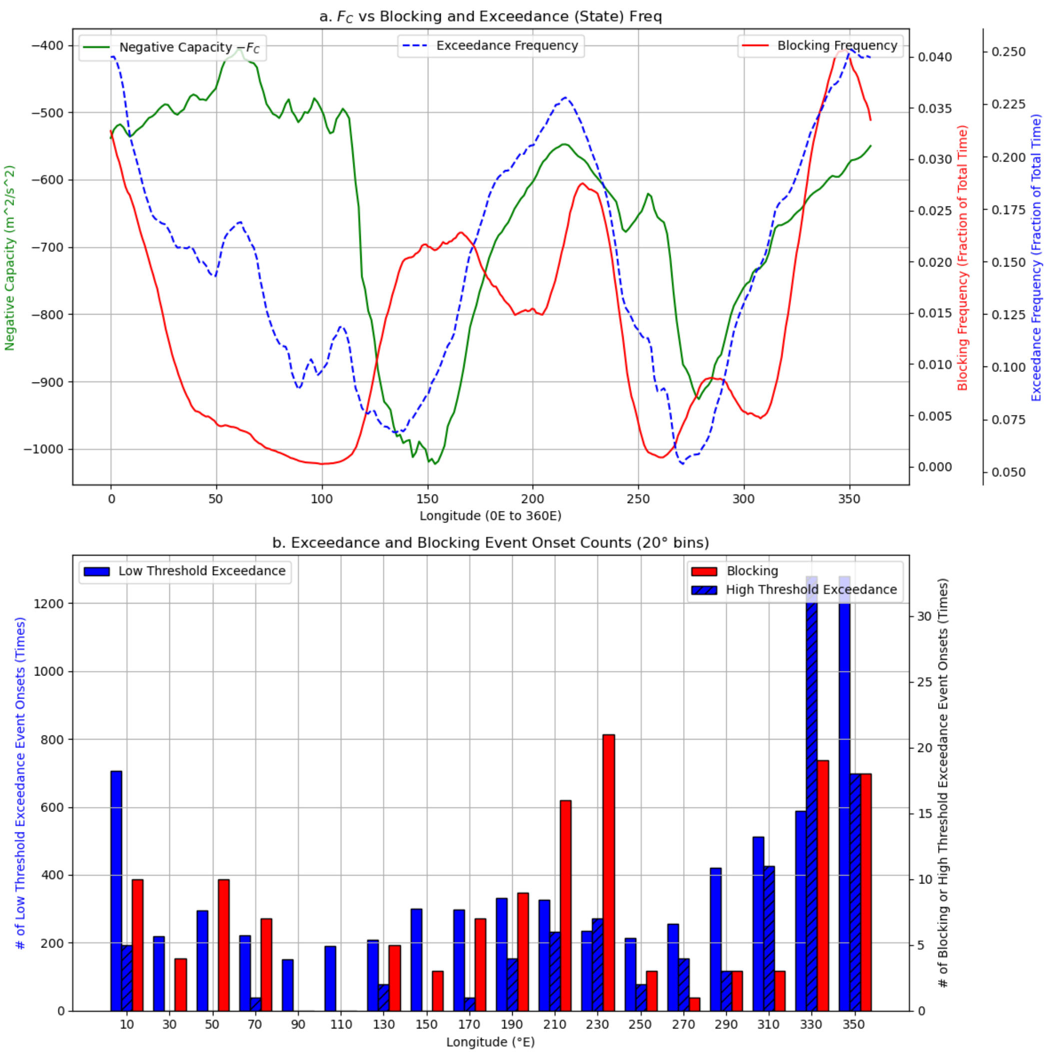

Figure 2: (a) the meridional average flux capacity (solid green, left green axis scaling, inverted for comparison) against the blocking frequency (solid red, right red axis scaling) and exceedance frequency (dashed blue, right blue axis scaling) in the boreal midlatitudes during winter. Each quantity is meridionally averaged from 30 to 60° N. The exceedance frequency is defined as the pointwise LWA flux capacity exceedance satisfying inequality (1) with $\Delta F \geq 100 m^2 s^{-2}$. (b) event onsets of low threshold exceedance (in solid blue, left axis scaling, $\Delta F \geq 100 m^2 s^{-2}$), high threshold exceedance (in striped blue, right axis scaling, $\Delta F \geq 1200 m^2 s^{-2}$), and blocking onsets (in red, right axis scaling). The Atlantic sector is more likely to be blocked than Pacific by ∼30%, as shown in (a), but the number of blocking events are similar in each sector, with a slight maximum in the Pacific region (230°E) as shown in (b). This seeming contradiction is due to the fact that Atlantic blocks are more persistent: the same number of events yields more blocked days.

Despite the upstream shift, the climatological structures of capacity, exceedance, and blocking strongly support the NH18 traffic mechanism. Blocking is indeed found where the flow is most likely to exceed the carrying capacity. There is, however, a significant mismatch in the magnitude of the exceedance frequency compared with blocking frequency. In the North Atlantic peak, the LWA flux exceeds the flux capacity about a quarter of the time, while the flow in this region is only blocked about 1/25th of the time. To use exceedance as a predictor of blocking onset, we require an event-based definition, a measure to quantify when the flow sufficiently exceeds the capacity to forecast an imminent blocking event.

To motivate our event definitions, Figure 3 shows the evolution of daily averaged LWA flux F for three winters. The climatological tendency for exceedance events and blocks to occur in the storm tracks, especially the North Atlantic, shows up clearly in these 3 years, as seen in Figures 1 and 2. The temporal connection between these events, however, is muddier.

The block on 13 Feb 1984 supports the NH18 mechanism. An exceedance anomaly (black contour) begins near 120°W on 7 Feb, building up and propagating eastward through 12 Feb, just before the block occurs on the 13th. A second block, just a week later on 19 Feb, however, does not appear to be associated with any preceding exceedance anomalies. Indeed, many of the blocks in these three years are not readily associated with a significant exceedance anomaly.

The LWA flux exceeds the capacity by 100 $\mathrm{m}^2\mathrm{s}^2$ quite often, particularly in the North Atlantic region. While some blocks are associated with them, clearly a minor level of exceedance cannot be used to forecast blocking onset. Major anomalies where F exceeds F_C by $1200 m^2 s^{-2}$, such as that in the North Atlantic on 25 Dec 1983 or in the North Pacific on 24 January 1986, occur less frequently. In these three years, however, none of these major exceedance events led to a block.

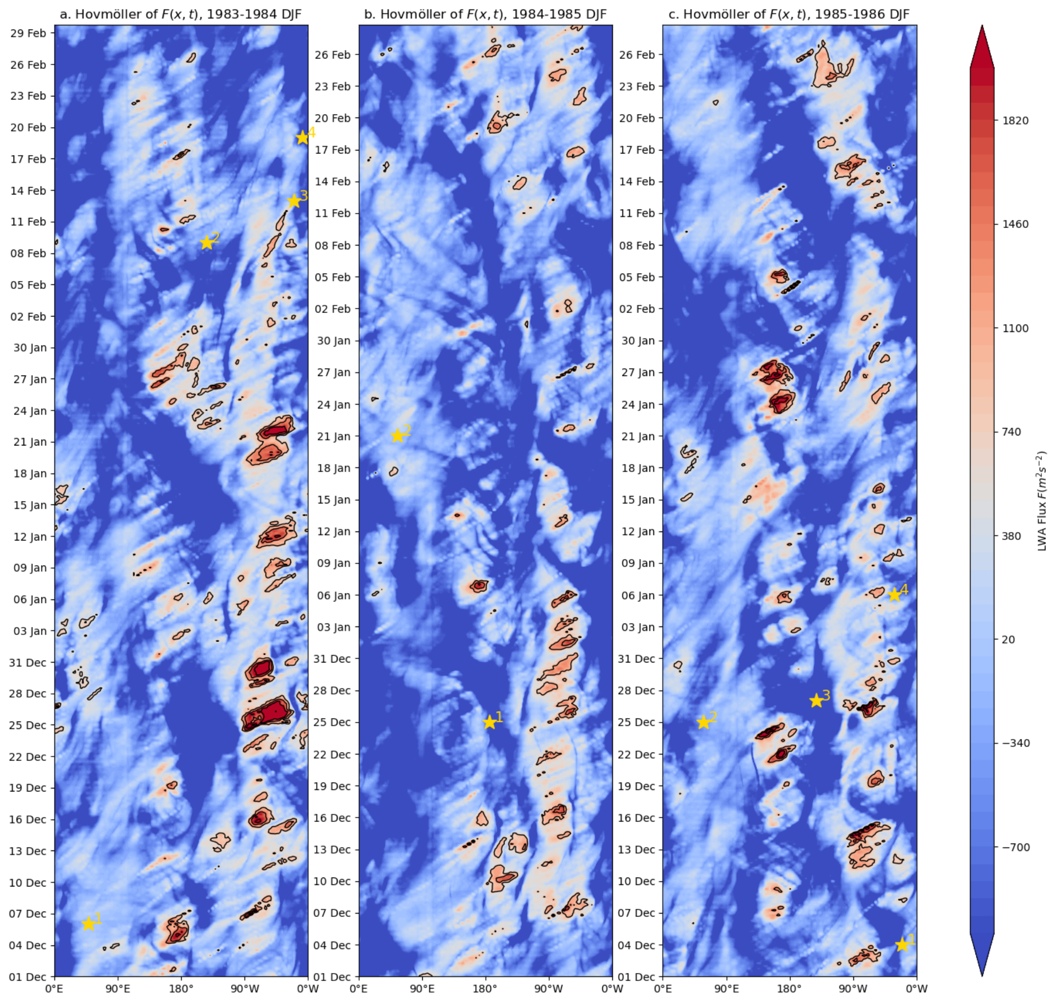

Figure 3: The evolution of meridionally averaged (from 30°N to 60°N) LWA flux F overlaid by flux exceedance contours ($F - F_C$) for three winters. The contour levels represent ΔF levels of $100, 650, 1200$ m^2s^{-2}, respectively. All solid contours indicate minor exceedance events, with earliest contour date being the exceedance event onset. Blocking events are marked by gold stars at the onset location and time. (a) a Hovmöller diagram from 1 Dec 1983 to 29 Feb 1984, with 4 blocking events, (b) 1 Dec 1984 to 28 Feb 1985 with 2 blocking events, and (c) 1 Dec 1985 to 28 Feb 1986 with 4 blocking events.

To provide statistical evidence behind these anecdotal observations, we consider all events where the LWA flux exceeded the capacity in the ERA-Interim record. We identified and tracked 8842 minor events and 98 major events that exceeded $\Delta F = 100$ and 1200 $m^2 s^2$, respectively. Their longitudinal distribution is shown in Figure 2b, alongside that of 139 blocking events. All event distributions have pronounced longitudinal structure, peaking in the exit regions of the north Pacific and Atlantic storm tracks. Minor and major exceedance events, however, are more strongly preferred in the North Atlantic relative to blocking, especially the major events. Minor exceedance events are more uniformly distributed in longitude, occurring all around the globe, while blocks and major exceedance events have never been observed at some longitudes over eastern Asia. The largest difference, however, is reflected by the different y-axis scale; over the North Atlantic, minor events are as much as 60 times more frequent than blocking. All of these differences have implications for prediction.

To assess the ability of exceedance events to predict blocks, we classify three cases, (i) a flux exceedance event preceded by blocking onset: a true positive prediction, (ii) an exceedance event that is not followed by a blocking onset: a false positive, and (iii) a blocking event despite no flux exceedance occurrence: a false negative prediction. All three types of events are observed in Figure 3a. In the 1983-84 winter alone, the 7 Feb exceedance event preceded a block on 13 Feb, the 25 Dec exceedance event did not precipitate a block, and the 19 Feb block materialized without any prior exceedance event, demonstrating the three cases, respectively. A systematic comparison requires an objective threshold that a block be associated with an exceedance event. We experimented with many criteria, and here use a fairly loose rule that a block must occur within the range of between 1 day ahead to 5 days after the onset of the exceedance event, anywhere within the latitude and longitude range of the exceedance patch throughout its entire lifetime.

For minor events, there are 60 true positives and 79 false negatives: not quite half of the blocks fit the traffic jam mechanism. 8,782 false negative predictions, however, limit the utility of these forecasts. For major exceedance events, the number of false negatives drops to 95, but at the expense of being able to predict true positives (only 3) or avoid false negatives (136). We experimented with a range of thresholds, in addition to modifying the spatial scale of the exceedance, and found this trade off unavoidable. Up to half of blocks are associated with very minor flux capacity exceedance, but at these low thresholds, the false positive rate is unacceptably high (by an order of magnitude). When we require a more substantial exceedance of the flux capacity to avoid all the false positives, we lose the connection to blocks.

These statistics suggest that the spatial correlation between exceedance events and blocking in Figures 1 and 2 reflects a confounding link between the two, one that gives them very similar climatological structure, but not temporal coherence. To probe this spatial structure further, we explore composites of the LWA flux F and flux capacity F_C associated with blocks and exceedance events in Figure 4.

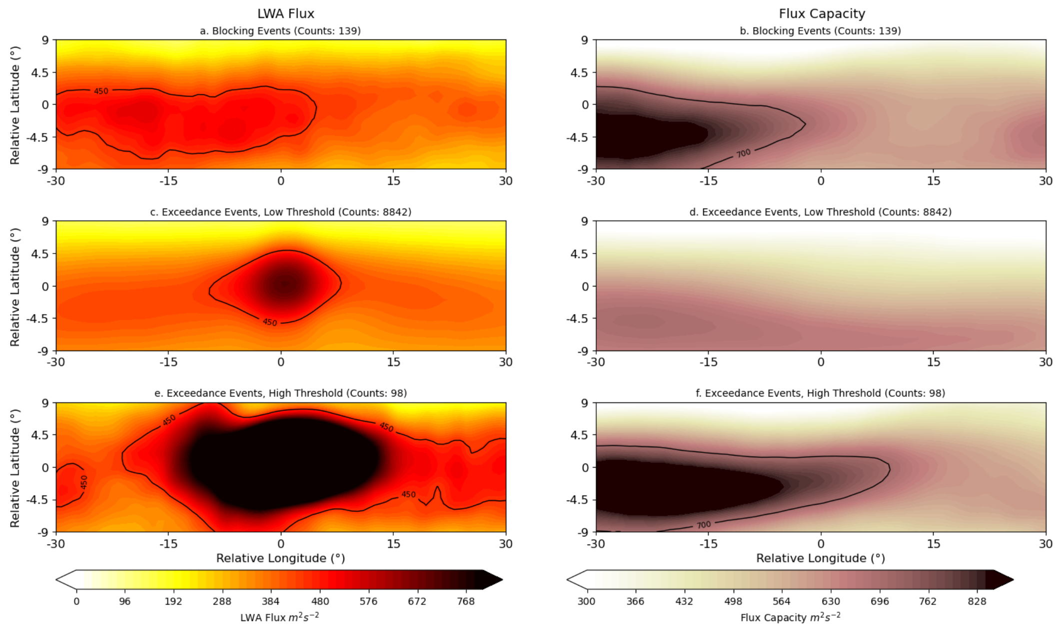

Figure 4: Composites of (left) LWA flux F and (right) flux capacity F_C around blocking and exceedance events. The upper row shows composites from all blocking events, centered around the onset location (0°, 0°). The middle row shows composites based on minor exceedance events ($\Delta F \geq 100 m^2 s^{-2}$). The bottom column shows major exceedance events ($\Delta F \geq 1200 m^2 s^{-2}$).

The spatial structure of the LWA flux F (Fig. 4, left column) captures the synoptic conditions associated with events. Blocks (panel a) are associated with elevated flux over a wide region upstream, extending more than 30° of latitude, as highlighted by the 450 $m^2 s^{-2}$ contour. This is consistent with the hypothesis that a pile up wave activity upstream of the block favors a large, stationary pattern Swanson (2000). Exceedance events, on the other hand, are associated with elevated fluxes centered about the event, especially for minor exceedance events (panel c). This could be anticipated from their definition: a larger flux F helps overcome F_C. Major events are naturally associated with larger anomalies which extend over a wider region (panel e), more like blocks.

The spatial structure of the flux capacity F_C (Fig. 4, right column) reflects the background jet state around the events. Blocks and major flux exceedance events are favored in regions with decreasing flux capacity, near, but upstream of a local minimum in capacity, as highlighted by the 750 m^2s^{-2} contour in panels b and f. This bottleneck structure of the flux capacity permits a large upstream flux, which runs up against the diminishing jet capacity, generating both exceedance events and blocking events – but generally not at the same time. Minor exceedance events, on the other hand, are more uniformly distributed around the globe, and therefore less sensitive to flux capacity (panel d).

4 Conclusions

We have performed a critical assessment of the flux-exceedance, or "traffic jam" hypothesis of Nakamura and Huang (2018), exploring the utility of LWA flux and flux capacity as predictors for the onset of atmospheric blocking. To test this mechanistic model for prediction, we introduced the concept of exceedance events, synoptic scale developments where the LWA flux exceeds the carrying capacity of the jet. In support of the traffic jam theory, we find that the climatology of the LWA flux capacity is consistent with blocking climatology: low capacity regions correlate with high blocking frequencies. Predicting individual blocks using the flux-exceedance hypothesis, however, is not practical, as the temporal relationship between exceedance events and blocking onsets is tenuous.

Case studies, such as Polster and Wirth (2023), suggest enhanced zonal LWA fluxes are present 2-3 days ahead of some for North America blocking events. Yet, when we look at statistics across multi-decadal reanalysis records, we find that false positive predictions, i.e., exceedance without blocking events, to be orders of magnitude more frequent than true positives. If one waits for a more significant level of flux exceedance, however, to reduce the false positives, the connection to blocking effectively vanishes. Major flux exceedance events share the same climatological distribution as blocks, but do not lead to blocking onset.

While blocking and flux exceedance events appear to be distinct processes, the similarity of their spatial structure suggests shared dynamics. They are favored in regions of low capacity in the exit region of storm tracks. This structure suggests the importance of both a ready supply of storm activity and a decrease in jet strength (flow capacity) to the dynamics. We liken it to a "traffic bottleneck", as visualized in Figure 4, to emphasize the importance of downstream reduction in flow capacity to both phenomena. Just as a small road doesn't precipitate a traffic jam in a sparsely traveled region, overwhelming the flow capacity of the jet requires both a constriction of the capacity and a strong inflow of wave activity. Blocking requires similar dynamics, the slowing of the flow encouraging a stalling of eddies, while the ready upstream supply fuels the magnitude of the block.

Once a block is formed, how does it persist, and ultimately dissipate? Could the periodic behavior of the baroclinic annular mode, as argued in Liu and Wang (2024), give us even further predictability using the temporal variation of the regional structure of the flux capacity? More work is needed to connect the intraseasonal variation of the LWA flux capacity with the 20-30 day periodicity in the midlatitude atmosphere. Lastly, to better understand the observed regional climate change, as discussed by Shaw et al. (2024), future work will explore a wide range of spatial and temporal features of fluxes, blocks, and flow capacities, and how their interactions change in a warming climate.

5 Open Research

The authors acknowledge the use of codes in Huang et al. (2024) which uses ERA-Interim reanalysis (European Centre for Medium-Range Weather Forecasts, 2009), and the use of ERA5 reanalysis (Copernicus Climate Change Service, 2023). Codes are available in the open repository (Yan, 2024).

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