The Onset of a Blocking Event as a “Traffic Jam”: Characterization with Ensemble Sensitivity Analysis

CHRISTOPHER POLSTER* AND VOLKMAR WIRTH*

* Johannes Gutenberg University Mainz, Mainz, Germany

ABSTRACT: Recently, Nakamura and Huang proposed a theory of blocking onset based on the budget of finite-amplitude local wave activity on the midlatitude waveguide. Blocks form in their idealized model due to a mechanism that also describes the emergence of traffic jams in traffic theory. The current work investigates the development of a winter European block in terms of finite-amplitude local wave activity to evaluate the possible relevance of the “traffic jam” mechanism for the flow transition. Two hundred members of a medium-range ensemble forecast of the blocking onset period are analyzed with correlation- and cluster-based sensitivity techniques. Diagnostic evidence points to a traffic jam onset on 17 December 2016. Block development is sensitive to upstream Rossby wave activity up to 1.5 days prior to its initiation and consistent with expectations from the idealized theory. Eastward transport of finite-amplitude local wave activity in the southern part of the block is suppressed by nonlinear flux modification from the large-amplitude blocking pattern, consistent with the expected obstruction in the traffic jam model. The relationship of finite-amplitude local wave activity and its zonal flux as mapped by the ensemble exhibits established characteristics of a traffic jam. This study suggests that the traffic jam mechanism may play an important role in some cases of blocking onset and more generally that applying finite-amplitude local wave activity diagnostics to ensemble data is a promising approach for the further examination of individual onset events in light of the Nakamura and Huang theory.

SIGNIFICANCE STATEMENT: Blocking is an occasional phenomenon in the mid- and high-latitude atmosphere characterized by the stalling of weather systems. Episodes of blocking are linked to extreme weather but their occurrence is not completely understood. A recent theory suggests that blocks may form in the jet stream like traffic jams on a highway. The onset mechanism contained in the theory could explain why forecasts of blocking are sometimes poor. In this work, we investigate the formation of a 2016 European winter block in the context of the traffic jam theory. Though questions remain regarding the implications for forecast uncertainty, our findings strongly support the notion of a traffic jam onset.

KEYWORDS: Atmosphere; Blocking; Fluxes; Nonlinear dynamics; Rossby waves; Idealized models

1. Introduction

Blocking is an occasional feature of the mid- and high-latitude tropospheric flow. An atmospheric block is formed by a quasi-stationary ridge or cutoff anticyclone and obstructs the usual eastward propagation of weather systems. Episodes of blocking are characterized by a locally strongly meandering jet stream with predominantly meridional and/or cellular flow (Berggren et al. 1949; Rex 1950; Tyrlis and Hoskins 2008; Woollings et al. 2018). The diversion and disruption of the jet is often accompanied by a nonlinear evolution of the flow, in particular wave breaking (Pelly and Hoskins 2003b; Berrisford et al. 2007; Masato et al. 2012). Blocked flow can persist for multiple days or weeks over the same region and cause extreme weather events such as heatwaves (e.g., Black et al. 2004; Schneider et al. 2012; Kautz et al. 2022). Advances in the domains of theory, diagnostics, and modeling have improved our understanding of the life cycle of onset, maintenance, and decay of these weather systems since their discovery in the early twentieth century, but important problems remain open (Woollings et al. 2018; Lupo 2021). Forecasting the onset of blocked flow is a challenging problem in numerical weather prediction (Tibaldi and Molteni 1990; Pelly and Hoskins 2003a; Ferranti et al. 2015) and occasionally leads to exceptionally poor model performance (Rodwell et al. 2013). Numerous influences on blocking onset have been identified. Some proposed onset mechanisms are global in character, involving, e.g., (quasi-)resonance between stationary Rossby waves and zonal waves, wave-vortex interactions, and nonlinear amplification of perturbations. Other hypotheses focus on the role of local processes, such as orographic lifting and baroclinic instability.
waves and different forcings (e.g., Charney and DeVore 1979; Tung and Lindzen 1979; Petoukhov et al. 2013). Other theories are local and concern, e.g., instabilities of the low-frequency circulation (Swanson 2001) or the influence of transient synoptic systems and events like explosive cyclogenesis (e.g., Colucci 1985; Tsou and Smith 1990; Nakamura and Wallace 1993; Altenhoff et al. 2008). The idealized multiscale interaction models of Luo and collaborators can describe full life cycles of eddy-driven blocking (e.g., Luo 2005; Luo et al. 2014, 2023). More recently, attention has been paid to the role of diabatic processes, especially those occurring in warm conveyor belts, as well as the associated upper-level divergent outflow (e.g., Pfahl et al. 2015; Grams et al. 2018; Maddison et al. 2019, 2020; Steinfeld et al. 2020; Neal et al. 2022).

The involvement of Rossby waves in blocking has motivated the use of wave activity diagnostics in the study of the blocking life cycle. Nakamura (1994) composited fields of Plumb’s (1986) wave activity density flux of European blocking events and hypothesized that a self-amplification process may exist in the atmosphere that can facilitate a transition to blocked flow: an initial anticyclonic anomaly in the upper-tropospheric circulation weakens the westerlies, leading to convergence of wave activity density flux associated with propagating Rossby waves upstream. The convergence allows additional wave activity to accumulate and further decelerate the westerly flow, leading to continued convergence and amplification until a point of saturation is reached. In a follow-up study, Nakamura et al. (1997) concluded that the convergence of wave activity density flux associated with low-frequency dynamics plays a major role in the formation of North Atlantic blocks while block amplification over the North Pacific is more strongly influenced by transient eddy activity. Recently, Luo and Zhang (2020) analyzed idealized life cycles of blocking obtained from a nonlinear multiscale interaction model in terms of local wave activity propagation. They found that local eddy-induced wave activity flux is important for the non-dispersiveness of growing blocking Rossby wave packets.

The possibility of an obstruction of the zonal propagation of wave activity was identified in the budget of quasigeostrophic finite-amplitude local wave activity (LWA) by Nakamura and Huang (2018, hereafter NH18). The authors simplified the three-dimensional LWA budget (Huang and Nakamura 2017) to a one-dimensional semiempirical model for the temporal evolution of the zonal LWA distribution in the midlatitudes. They recognized that this simplified model of the zonal LWA budget is analogous to a model of traffic flow. In the same way that a traffic jam forms as a shock in solutions of a traffic flow model (Treiber and Kesting 2013), blocked flow forms as a shock in the zonal distribution of LWA (Nakamura and Huang 2017; NH18). The development of such a shock is governed by a threshold on the amplitude of wave activity, which is a function of the atmospheric background state. When exceeded, a local bottleneck for the zonal flux of LWA appears, leading to further increasing levels of LWA that reinforce the bottleneck.

The process underlying this “traffic jam” mechanism of blocking onset is very similar to that proposed by Nakamura (1994). The theory of NH18 distinguishes itself by its quantitative nature and the finite-amplitude formalism of the quasigeostrophic zonal LWA budget. This formalism originates from the zonally averaged finite-amplitude wave activity by Nakamura and Zhu (2010) and Nakamura and Solomon (2010, 2011). LWA is valid in the presence of arbitrary-amplitude eddies (Nakamura and Zhu 2010; Huang and Nakamura 2016), and, thus, even when the atmospheric flow evolves nonlinearly as it usually does during blocking onset, e.g., in the process of wave breaking (Berrisford et al. 2007; Masato et al. 2012). Notably, while previous studies have highlighted the role of scale interaction for the dynamics of blocking onset (e.g., Luo et al. 2023, and references therein), the traffic jam onset theory is not explicitly dependent on a separation of eddies into different scales.

NH18 supported their theoretical results with reanalysis data composites of 24 high-LWA events over the Atlantic. They saw a gradual buildup and decay of LWA before and after the composite event and an associated deceleration and acceleration of the zonal wind, respectively. The region immediately upstream of the composite LWA maximum experiences a prolonged period of enhanced eastward LWA flux prior to the block formation, while zonal LWA fluxes turn weakly westward within the block after onset. These findings were broadly consistent with numerical simulations from their idealized model of blocking onset, although discrepancies regarding the timing and duration of the periods of enhanced upstream flux remained. Barpanda (2020) produced feature-centered composites of anomalous occurrences of high-amplitude LWA. They found that enhanced eastward LWA fluxes in the North Atlantic preceding the development of LWA maxima mainly occur as short bursts in the immediate upstream for short-lived events while longer-lived events experience comparatively weaker incoming flux but over a substantially longer time before onset.

The traffic jam mechanism is an attractive theory for the development of blocked flow. It provides a dynamical definition of onset (the occurrence of a wave activity flux bottleneck), contains a process that acts to amplify wave disturbances locally (the accumulation of LWA at the bottleneck) and it can explain the stationarity of blocked flows (the suppressed transmission of LWA flux into the downstream region). The mechanism itself is based on dry dynamics, but it can accommodate the impact of diabatic processes in the form of LWA sources and sinks. Global influence of planetary waves can be incorporated at least one-way as preconditioning of the waveguide or the background-level wave activity.

Paradise et al. (2019) used the idealized NH18 numerical model of the zonal LWA budget to investigate the response of blocking prevalence, frequency, and persistence to changes in the transient forcing of eddies, the stationary wave amplitude, and the jet speed of the background state. They found two climate regimes in the model, one block-dominated and one block-free, separated by a relatively sharp transition region in which blocking statistics are highly sensitive to the control parameters. Such sensitivity might also be relevant for forecasts of blocking events in the medium range. In the traffic jam framework, the state space of midlatitude LWA contains regions where the atmosphere is close to a transition into a blocked state by being close to the mechanism’s onset threshold. We would expect such states to exhibit localized
and high sensitivity of block development to changes in the LWA evolution. This implies that the predictability of blocking is flow dependent and increased sensitivity in onset-adjacent states may lead to large (in both scale and amplitude) forecast errors from initially small perturbations.

The foregoing motivates our present work, in which we examine a block development that occurred in December 2016 over Europe in the context of the traffic jam mechanism with a sensitivity analysis. Our focus is on LWA and the zonal flux of LWA, the variables at the heart of the mechanism, prior to and during the onset event. A forecast ensemble covering the flow transition provides a sample of realistic developments of the block. LWA and related quantities are computed from the three-dimensional atmospheric data produced by the ensemble. Combined with an understanding of the evolution of the flow in the ensemble and a comparison to simulations with the idealized traffic jam model of NH18, we intend to gain a causal, flow-dependent understanding of the sensitivity results.

Ensemble sensitivity techniques have been used frequently in recent years to study the predictability of blocked flows. Magnusson (2017) applied ensemble sensitivity analysis (ESA) and a cluster-difference method to identify source regions of forecast error. In a case of blocking onset, forecast errors over Europe could be traced back multiple days to errors in the development of a trough and an associated surface cyclone farther upstream. Berman and Torn (2019) applied ESA to a ridge development over the North Atlantic. Their analysis indicated that better representation of warm conveyor belts and upstream PV anomalies in models could lead to improved forecasts of the upper-tropospheric flow. Maddison et al. (2019) investigated the influence of cyclones on the predictability of blocking onset with ESA. Their results suggest that improved forecasts of the location and intensity of cyclones may improve the prediction of blocking events. Quandt et al. (2019) explored the predictability of the block associated with the 2010 Russia heatwave. They found sensitivities of the block onset to a precursor upper-level ridge upstream as well as to low-level pressure anomalies and their associated diabatic activity.

In the current work, we use ESA to investigate the role of wave activity and its zonal flux in the transition to blocked flow. The findings of NH18 in the LWA framework and simulations we conduct ourselves with their idealized traffic jam model set our expectations for the characteristics that resemble a traffic jam onset. We quantify the relationship between LWA and the zonal LWA flux based on multiple realizations of the same event obtained from an NWP model. This ensemble-based approach allows us further to explicitly evaluate the sensitivity of the block to incoming LWA flux during the flow transition, giving us insight into the role of the traffic jam theory for the predictability of our chosen onset case. Sensitivities are localized in time and space with ESA and we contextualize them with the evolution of the flow in weak- and strong-block scenarios obtained from a basic clustering.

Our work adds to the climatological composites of NH18 and Barpanda (2020) as well as the recent case investigation of Neal et al. (2022). We employ an NWP model-based ensemble sensitivity approach for the first time in the context of the traffic jam theory and provide a complementary perspective on traffic jam characteristics of blocked flow in a realistic atmosphere during onset. A single-event case study has the potential to illustrate the relevance of the onset mechanism more clearly than an averaged multievent composite, at the cost of generalizability. The ensemble approach further allows us to talk about onset predictability and, as we will argue below, approach the issue of attribution of a transition to blocked flow to an onset mechanism. This is of particular importance because we cannot expect that the traffic jam mechanism plays a major role for all blocking onset events.

This paper is structured as follows: First, a brief review of quasigeostrophic finite-amplitude local wave activity, its zonal budget, and the one-dimensional traffic jam model of NH18 is given in section 2. The section also introduces our data processing procedure, including the ensemble sensitivity analysis setup, and used datasets. Findings from the analysis of the December 2016 blocking event in the European-Atlantic sector are presented in section 3. We describe the block development and its sensitivity to zonal wave activity flux in the upstream region before and in the blocked region during the onset event and discuss results in the context of the traffic jam hypothesis of NH18. Conclusions from the investigated onset event are drawn in section 4.

2. Methods and data

a. Finite-amplitude local wave activity

We adopt the formalism of NH18. In the coordinate system of longitude $\lambda$, latitude $\phi$, and (pseudo)height $z = -\ln(p/p_0)$ for the sphere, with pressure $p$, $H = 7$ km, and $p_0 = 1000$ hPa, quasigeostrophic potential vorticity (PV) $q(\lambda, \phi, z)$ is

$$q = \zeta + f \left[ 1 + e^{-\gamma H} \frac{\partial}{\partial z} \left( e^{-\gamma H} \frac{\partial}{\partial \theta} \right) \right] \left( \frac{\partial}{\partial \theta} \right) \left( \frac{\partial}{\partial z} \right),$$

(1)

where $\zeta(\lambda, \phi, z)$ is relative vorticity, $f(\phi)$ the Coriolis parameter, $\theta(\lambda, \phi, z)$ is potential temperature, and $\theta(z)$ is a reference potential temperature obtained from an area-weighted global average at height $z$. A wave-free reference state $q_{ref}(\phi, z)$ is obtained from PV on each height level through “zonalization,” an area-preserving map that produces a zonally symmetric PV field with contours monotonically decreasing from north to south (Butchart and Rensberg 1986; Allen and Nakamura 2003; Nakamura and Zhu 2010). Defining

$$q_e(\lambda, \phi, z, \phi') = q(\lambda, \phi + \phi', z) - q_{ref}(\phi, z),$$

(2)

finite-amplitude local wave activity $A$ is the expression

$$A(\lambda, \phi, z) = -\frac{a}{\cos(\phi)} \int_0^{\lambda} q_e(\lambda, \phi, z, \phi') \cos(\phi + \phi') d\phi',$$

(3)

where $a = 6378$ km is the radius of Earth and the integral bounds depend a domain of integration from the given
latitude \( \phi' = 0 \) to the latitude of meridional displacement \( \phi' = \Delta \phi(\lambda, \phi, z) \) of the PV contour with the same value as the reference state at the given latitude, i.e., \( q = q_{\text{ref}}(\phi, z) \). The domain can be made up of multiple segments in the presence of contour overturning or cutoffs, in which case \( \Delta \phi \) is multivalued (see the illustrations of Huang and Nakamura 2017; Ghinassi et al. 2018). We obtain column LWA with a density-weighted vertical average up to 25 km height (upper bound set by data availability) and follow NH18 in making a connection to angular pseudomomentum by always considering \( (A) \cos(\phi) \). The vertical integration acts as a weak filter of the phase signal, which is still present in LWA as defined in Eq. (3).

Indices of blocked flow are traditionally based on a deceleration of the westerlies and a reversal in the upper-tropospheric gradient of geopotential height, potential temperature or potential vorticity (e.g., Lejenäs and Okland 1983; Tibaldi and Molteni 1990; Pelly and Hoskins 2003b), and/or the amplitude of anomalies of such variables (e.g., Dole and Gordon 1983; Schwerz et al. 2004). LWA is appropriate as a measure of blocking strength because it combines these approaches: it quantifies PV anomalies relative to the zonally referenced state and is valid even in the presence of finite-amplitude eddies. Furthermore, due to an existing nonacceleration relation (Huang and Nakamura 2016), an increase in LWA is generally associated with a decrease of the zonal wind at the same location.

We use the hn2016_falwa Python package (Huang et al. 2021) to compute LWA and related quantities in the QG framework. Documentation for the numerical procedures is found in the supplementary material of NH18, who used the same data processing and whose analysis serves as a reference frame for our investigation. The simpler construction of LWA based on geopotential used by Chen et al. (2015) and Martineau et al. (2017) lacks exact theorems and relationships, e.g., between wave activity and its fluxes, and is therefore not well suited for our analysis. LWA for the primitive equations (Ghinassi et al. 2018) is associated with technical challenges related to the background state (see Nakamura and Solomon 2011; Methven and Berrisford 2015) and a less advanced formalism, so we stick to QG theory.

b. LWA budget in the midlatitudes

We approximate the wintertime midlatitude column-LWA budget (Huang and Nakamura 2016, 2017) by

\[
\frac{\partial (A)}{\partial t} \cos(\phi) \approx - \frac{1}{\cos(\phi)} \frac{\partial (F_s)}{\partial A} + (A) \cos(\phi),
\]

On synoptic time scales, the local temporal evolution of LWA is dominated by the convergence of the zonal LWA flux \( F_s \) (NH18; Valva and Nakamura 2021). We further consider nonconservative sources and sinks \( A \) of LWA. Equation (4) condenses the midlatitude dynamics on synoptic and larger scales into a one-dimensional transport problem for LWA with forcing. This approximation is valid to the extent that there is a strong midlatitude jet that acts as a zonal waveguide.

The vertically averaged zonal LWA flux \( F_s \) is

\[
(F_s) = \left( \frac{u_{\text{ref}} A \cos(\phi)}{\hat{F}_1} \right) - a \left( \int_0^{\Delta \phi} u_q e \cos(\phi + \phi') d\phi' \right)
\]

\[
+ \frac{\cos(\phi)}{2} \left( v_c^2 - u_c^2 - \frac{R e^{-\kappa H} \partial n}{\hat{H} \partial \theta \partial \omega} \right),
\]

with zonal wind \( u \), meridional wind \( v \), \( R = 287 \text{ J kg}^{-1} \text{ K}^{-1} \), and \( \kappa = 0.286 \). In \( F_s \), \( \Delta \phi \) denotes the same integration domain as in Eq. (3) and \( u_c \) is defined analogously to \( q_e \) in Eq. (2). The definitions of \( v_c, u_c, e \), and \( \hat{\theta} \) in \( F_s \) also take the form of Eq. (2) with \( \phi' = 0 \) held constant. The required reference states \( u_{\text{ref}}, v_{\text{ref}}, e \), and \( \hat{\theta}_{\text{ref}} \) are obtained with a PV inversion procedure from \( q_{\text{ref}} \) and appropriate no-slip boundary conditions (Nakamura and Solomon 2011; Huang and Nakamura 2017).

The three terms that make up \( F_s \) can be associated with physical processes (Huang and Nakamura 2016; NH18). The advection of local wave activity with the background state zonal wind and the zonal component of the generalized Eliassen–Palm flux are represented by \( F_1 \) and \( F_2 \), respectively. Together, these terms describe group propagation in the case of linear Rossby waves and are referred to as the “group propagation terms” throughout this work. The flux arising from the Stokes drift is encapsulated in \( F_3 \), which gains significance when waves reach a nonlinear finite-amplitude stage. The effect of \( F_2 \) on the total zonal LWA flux was found to be essential for the traffic jam mechanism by NH18.

c. Idealized model of the LWA budget

NH18 propose the partial differential equation

\[
\frac{\partial \hat{A}}{\partial t} = \frac{\partial \hat{F}}{\partial x} + \hat{S} - \hat{A} \tau + \kappa \frac{\partial^2 \hat{A}}{\partial x^2}
\]

as an idealized, one-dimensional model for transient Rossby waves on the midlatitude jet stream. For a periodic domain in longitude \( x \), the model has the structure of Eq. (4), with the total LWA field \( A = \hat{A}_s + \hat{A} \) split into a stationary and a transient component, respectively. The LWA flux is approximated as a nonlinear function of transient LWA:

\[
\hat{F}(x, t) = \left[ C(x) - \alpha A(x, t) \right] \hat{A}(x, t),
\]

where \( C(x) = u_{\text{ref}} + c_g - 2 \alpha A_s(x) \) is the background group velocity modulated by the stationary wave and \( \alpha \) is an empirically determined parameter that quantifies the interaction of waves and the zonal flow. Nonconservative sources and sinks of LWA as well as other terms in the LWA budget are represented by a forcing term \( \hat{S} \) and linear damping with a time scale of \( \tau \). The last term on the right-hand side of (6) provides weak diffusion to stabilize the numerical solution. See the appendix for information about our numerical setup and choice of parameters.

The nonlinear dependence of \( \hat{F} \) on \( \hat{A} \) in (7) enables the formation of persistent local LWA maxima in the solution of (6) when

\[
\hat{A}(x, t) \approx \frac{C(x)}{2\alpha} = \hat{A}_c(x)
\]

Unauthenticated | Downloaded 11/26/23 11:03 PM UTC
Traf\-fl ow as a measure of the strength of the developing blocked
value\textsuperscript{ti}.

Eqs. (6) and (7) constitute an idealized model for blocking
ons
t.\nh\nwhose sensitivity we intend to quantify. Here, we aggregate
taken from the ensemble forecast, where

\[ \text{corr}(T, S_{\lambda,\phi}) = \frac{\text{cov}(T, S_{\lambda,\phi})}{\sqrt{\text{var}(T)\text{var}(S_{\lambda,\phi})}} \]  
(9)
of \( T \) and the “source” vectors \( S_{\lambda,\phi} = [s_1(\lambda, \phi), \ldots, s_n(\lambda, \phi)] \)
taken from the ensemble forecast, where \( s_i(\lambda, \phi) \) is the value
of field \( s \) at longitude \( \lambda \) and latitude \( \phi \) of ensemble member \( i \).

This correlation is computed for every grid point of the source
field, resulting in a spatial field of correlation coefficients. A
straightforward interpretation is possible: positive (negative)
correlation at some location means that an increase of the
value of the source field at that location is associated with
an increase (decrease) of the target metric according to the
ensemble.

The identification of coherent regions of positive or negative
values in these correlation maps allows us to localize sen-
sitivity in space. By introducing a temporal offset between the
valid times of the data in the source and target vectors, sensi-
tivities can be traced through time. The temporal and spatial
evolution of regions of sensitivity can further be contextual-
ized with the dynamical evolution of the atmosphere in the
ensemble. Thus, sensitivities can be associated with dynamical
processes, e.g., Rossby wave propagation. Source and target
remain connected through the evolution of the atmospheric
state as simulated by the forecast model that generated the
ensemble, so a causal interpretation of events is approachable
even though the correlation analysis itself only detects statisti-
cal relationships. This could be seen, e.g., in the case studies
of Magnusson (2017), who complemented ESA with relaxation
experiments that targeted regions identified earlier in a
sensitivity analysis and found model responses consistent with
the expectations set by the ESA.

For the investigation in section 3, four consecutive forecast
ensembles are combined in their overlapping forecast ranges
into an “augmented” ensemble for the statistical analysis, as
illustrated in Fig. 1. Quandt et al. (2019) have shown that
ESA can be successfully applied to multimodel ensembles.
Here, we apply it to multiple ensemble forecasts of the same
model, initialized at different times and merged into a single
ensemble. The source and target vectors for a given valid time
in our sensitivity analysis are therefore made up of values ob-
tained from different lead times of the forecasts. This is ac-
tceptable to us since we are not interested in evaluating model
performance at a fixed forecast horizon. We have found that
the statistical robustness of our results is considerably en-
hanced when combining consecutive ensemble runs compared
to an analysis based on a single ensemble only.

Source fields from the forecasts are considered only if their
lead time exceeds 2 days in order to ensure that the “memory
of the initial perturbations” (Hakim and Torn 2008) is lost.
Data in the augmented ensemble are evaluated only if they
are available from all four original ensembles and not beyond
lead times of 11.5 days. Statistical significance is estimated

---

**Fig. 1.** For the sensitivity analysis in section 3, we combine four consecutive forecast en-
sembles, here labeled ENS1, ENS2, ENS3, and ENS4, into an augmented ensemble. The target met-
ric is evaluated at 8.5-, 8-, 7.5-, and 7-day lead time for ENS1, ENS2, ENS3, and ENS4, re-
spectively (solid vertical line). The dashed vertical line marks the initial time of the last included
forecast (ENS4) and therefore the earliest valid time for which the full combined ensemble can be
constructed. Only data from the shaded region are used for the sensitivity analysis. Dates are
specified relative to the target evaluation time (upper time axis) or given directly for the case anal-
yzed in section 3 (lower time axis).
with a bootstrap method (Wilks 2011) similar to that used by Gombos et al. (2012) in the context of ensemble regression. For each sensitivity map, we draw (with replacement) 1000 one-hundred-member ensembles from the original 200-member ensemble and recompute the sensitivities to obtain a distribution for the correlation coefficient at every grid point. Only grid points at which this distribution has a standard deviation smaller than or equal to 0.09 are classified as significant. The issue of field significance (Wilks 2011, 2016) is addressed by always drawing complete forecasts instead of sampling at every grid point independently.

We complement ESA with an examination of the clusters formed by the 15 highest- and lowest-ranking forecast members according to the sensitivity target. For our purposes, these are the strongest and weakest blocked members, respectively. This approach is very close to ESA as demonstrated by Torn et al. (2015) and Magnusson (2017), who produced maps very similar to correlation sensitivity maps by taking the difference of the mean fields of such rank-based clusters. Here, mean fields of the rank-based clusters are used to assess the evolution of the atmosphere at the two ends of the block development spectrum in the ensemble. They provide the reference frame to examine sensitivity signals in the context of the evolution of the atmospheric state. Finally, where a linear approximation of sensitivity as obtained from correlations is insufficient, we examine the nonapproximated relationship between two variables with a scatterplot for a region of interest.

d. Data

Forecast data were obtained from the operational archive of the European Centre for Medium-Range Weather Forecasts (ECMWF). To cover the investigated blocking onset event, 50 perturbed members of the Integrated Forecasting System (IFS) Ensemble Prediction System were obtained for each of the four consecutive runs initialized at 1200 UTC 9 December, 0000 and 1200 UTC 10 December, and 0000 UTC 11 December 2016 (cf. Fig. 1). At the time, IFS model cycle 43r1 was operational (ECMWF 2022). From the forecast data, we use fields of temperature $T$ and the horizontal wind components $u$ and $v$ every 6 h of lead time out to 12 days with a horizontal resolution of 2° in both latitude and longitude. Fields were downloaded for vertical levels 10, 50, 100, 200, 250, 300, 400, 500, 700, 850, 925, and 1000 hPa. Computations are performed on a different, higher-resolution ln($p$)-based vertical grid set up by the hn2016_falwa functions onto which the model output temperature and wind data are interpolated.

The values of $T$, $u$, and $v$ were retrieved with the same configuration from the ERA5 dataset (Hersbach et al. 2018, 2020). The reanalysis data are used as a reference for the actual evolution of the atmospheric flow in the considered period.

3. The December 2016 blocking event

The 4-day period from 16 to 19 December 2016 was identified by NH18 as being simultaneously in the top 5th percentile of column-averaged LWA and in the bottom 5th percentile of average zonal wind at 45°N, 9°W in a 1979–2016 dataset (their Table S1, event 24). Maddison et al. (2019) found that an ensemble forecast initialized on 9 December 2016 contained one of the 20 most uncertain block onsets in the Euro-Atlantic region in their dataset. Following these recognitions as a notable period of blocking and forecast uncertainty in earlier studies, we choose to further analyze this December 2016 blocking event.

a. Episode overview

A block is formed by an anticyclonic wave overturning pattern in the upper-tropospheric PV field on 18 December 2016 (Fig. 2a), created by an excursion of low-PV air north of the Iberian Peninsula. We can expect easterly wind to locally replace the usually westerly jet stream at around 50°N due to the meridional PV gradient reversal over Western Europe. Farther to the west and all the way back to the Rocky Mountains, the PV contours are generally zonally oriented and dense, suggesting a strong gradient. In contrast, a weak gradient is found over eastern Europe in the remnants of a ridge that was situated over Europe previously (not shown).

Collocated with the blocked flow in Fig. 2a is an LWA maximum with values exceeding 100 m s$^{-1}$. The maximum is centered between the northern and southern PV anomalies of the block and constitutes the largest-amplitude signal in the domain. Weaker secondary LWA maxima are found north of the troughs at 40° and 100°W and in the region of weakened PV gradient over eastern Europe. We can see that LWA quantifies meanders in the PV field effectively, including the nonlinear overturning of the PV contours in the block. The temporal evolution of LWA averaged meridionally in the midlatitude range of 35°–65°N (Fig. 2b) shows that the maximum on 18 December represents the initial peak in a period of enhanced LWA in the European sector that lasts until 23 December. The local wave activity feature associated with the block moves eastward by about 40° longitude in that period. Enhanced LWA is already found in Europe prior to 18 December, with 60 m s$^{-1}$ exceeded multiple times around the prime meridian from 11 to 17 December. This first phase of enhanced LWA is accompanied by overall weak zonal fluxes of LWA in the region upstream of Europe (Fig. 2c). On 16 December 800 m$^2$ s$^{-2}$ of flux is exceeded, and two strong maxima of $\langle F_u \rangle$ are seen over the Atlantic during the second phase of enhanced LWA after 17 December. Flux maxima generally propagate faster across the Atlantic than the wave activity maxima over Europe drifting eastward.

Comparing the evolution of LWA and its zonal flux in Figs. 2b and 2c to the multievent composite of NH18 (their Figs. 5A and 5C), we find similar values of LWA in the blocked region, although there is less eastward movement of the maximum in the composite. The evolution of the flux is rather different, with the largest values of flux found here just before and during the blocking episode, while NH18 found enhanced flux for the whole two weeks prior to onset. Negative values are virtually absent from Fig. 2c, but are found in the composite block. However, NH18 looked at a single latitude only while we apply meridional averaging. The existence of a residual eastward
flux in our case is furthermore consistent with the eastward drift of the blocking system. For the purpose of our analysis in the LWA framework, we consider 17 December 2016 as the onset day of a blocking event. It falls within the period identified by NH18 (16–19 December) but is after the 15 December onset date chosen in the study of Maddison et al. (2019). While the earlier ridge identified by Maddison et al. (2019) is of large amplitude, it is not associated with a significant change in midlatitude LWA over Europe (Fig. 2b). In contrast, values of LWA almost double during 17 December and enhanced zonal LWA flux arrives from the upstream region (Figs. 2b,c). Further inspection reveals that the earlier ridge has strongly differing characteristics from the later blocking pattern (not shown), in particular a lack of the strong PV overturning seen after onset on 18 December.

To quantify the strength of the block at any time with a scalar metric, we consider a “target region” from 35° to 65°N and from 30°W to 10°E (dashed box in Fig. 2a). The temporal evolution of reanalysis-derived LWA, aggregated in this region with an area-weighted average is shown in Fig. 3a. Values of 50 to 57 m s⁻¹ are seen until 17 December, when the LWA

Fig. 2. Overview of the blocking event discussed in section 3 based on ERA5 data. (a) Contours of PV q on the 7-km height level (1 × 10⁻⁸ and 2 × 10⁻⁸ s⁻¹) and vertically averaged local wave activity (A) cos(φ) (shading) for 0000 UTC 18 Dec 2016. The dashed box encloses the target evaluation region used in the assessment of block strength in the sensitivity analysis. (b),(c) Longitude-time Hovmöller diagrams of (A) cos(φ) and local wave activity flux (Fₚ) = F₁ + F₂ + F₃, respectively. The meridional dimension is reduced by area-weighted averaging between 35 and 65°N. The horizontal dashed lines indicate the target evaluation time. For comparison with Figs. 5a and 5c of NH18, the black contours in (b) indicate 60 m s⁻¹ and the gray and black contours in (c) indicate 0 and 600 m² s⁻², respectively.

Fig. 3. (a) Time series of the target metric (used to quantify the strength of the blocked flow pattern) in the sensitivity analysis time period (see Fig. 1), evaluated with data from reanalysis (bold black line) and all members of the forecast ensemble (gray, red, and blue lines). The vertical dashed line indicates the target evaluation time. The red- and blue-colored lines highlight the 15 top- and bottom-ranking ensemble members in the distribution of the target metric at the target evaluation time, respectively. (b),(c) Mean fields of PV at 7-km height (contours, as in Fig. 2a) and LWA (shading) of the 15 top- and bottom-ranking ensemble members, respectively, at 0000 UTC 18 Dec 2016. The contour levels, color bar, and target evaluation region box (dashed) are identical to that of Fig. 2a.
average increases by 20 m s\(^{-1}\), reaching a peak of 75 m s\(^{-1}\) on 18 December. Values drop soon after the peak and continue decreasing throughout most of the depicted time period, consistent with the weakening and eastward drift of the LWA maximum (Fig. 2b).

LWA diagnostics are based on dry dynamics but account for nonconservative processes implicitly when evaluated with data that include their effect. To assess the role of diabatic LWA sources and sinks in our blocking onset event, maps of LWA change in the 2.5 days prior to 18 December 2016 for the individual terms of the budget Eq. (4) are shown in Fig. 4. Consistent with the evolution seen in Fig. 3, LWA increases in the target evaluation region in the considered period (Fig. 4a). Convergence of the zonal LWA flux is collocated with the region of largest LWA increase (Fig. 4b). Large values of \(\langle F_3 \rangle\) are situated just upstream of the convergence region, transporting LWA eastward from a region south of Greenland, where strong divergence and negative LWA change are found. Nonconservative processes act as an LWA sink in the target evaluation region prior to and during onset and as an LWA source upstream in the North Atlantic (Fig. 4c). This picture is similar to the one seen by Neal et al. (2022), who investigated a summer block associated with a Pacific Northwest heat wave in terms of the LWA budget.

The presence of a diabatic source of LWA upstream of the developing block gives additional weight to previous studies that emphasize the role of diabatic processes in blocking onset. However, from Fig. 4 and the spatial correlation of each budget term with \(\Delta(A)\cos(\phi)\), we conclude that the zonal LWA flux is most directly associated with the increase in LWA at the block location while the diabatic processes act as an upstream LWA forcing. Thus, we focus on LWA transport as the main influence on the block development in the following.

b. Forecast overview

We use the value of the LWA-based metric of the strength of blocking at 0000 UTC 18 December 2016 as the target of our sensitivity analysis. The evolution of the target metric for the 200 members of our augmented ensemble approximately follows the reanalysis time series in Fig. 3a with some spread but few major deviations until 15 December. Spread then increases in the following two days, with more forecast members deviating toward lower values of LWA than toward higher values compared to the reanalysis. Simultaneous with the increase in LWA during 17 December, the ensemble spread increases further and remains high throughout the rest of the forecast period. On 18 December, the ensemble members show a variety of block strengths according to our LWA-based metric, from values of about 40 m s\(^{-1}\) up to about 80 m s\(^{-1}\), exceeding the reanalysis value.

Figure 5 shows the evolution of forecast uncertainty of all ECMWF ensembles initialized in the 10 days prior to the establishment of the block. The majority of forecasts initialized prior to 1200 UTC 12 December underestimate the block strength as measured by our LWA-based metric, though the reanalysis value is almost always inside the range of values produced by the individual forecast ensembles. After 12 December, ensemble means deviate from the reanalysis value only by a few m s\(^{-1}\). The characteristics of the ensembles included in our augmented ensemble are generally similar and interensemble variability dominates interensemble variability. Our 200-member ensemble should therefore represent the medium-range forecast variability associated with the block onset well. We have verified that all following results can be reproduced from each of the four ensembles individually, albeit at lower levels of statistical significance.

We want to gain further insight into the differing evolutions of the ensemble by clustering members according to their rank in the distribution of the evaluated target metric on 18 December. The 15 forecasts with the highest values are grouped into a “top-rank” cluster and considered to be the most (strongly) blocked members, while the 15 members with
the lowest values are grouped into a “bottom(-rank) cluster” and considered to be the least (strongly) blocked. Members from both clusters are highlighted in Fig. 3. The top-rank cluster generally follows the reanalysis data well until the LWA peak (Fig. 3a), after which increased spread becomes noticeable. The bottom-rank cluster members evolve consistently below the reanalysis curve from 16 through 18 December. A few members in the bottom cluster show a delayed onset of LWA growth and peak on 19 December. Others experience a much weaker or no LWA increase. Spread remains high after 19 December.

Figures 3b and 3c show maps like Fig. 2a but for the means of the top- and bottom-rank clusters, respectively. The pattern formed by the mean PV contours of the top cluster closely resembles that of the reanalysis data. In particular, it contains the anticyclonic overturning in the target region and a collocated LWA maximum exceeding 100 m s$^{-1}$. In the bottom-rank cluster, a weak ridge is situated over the eastern North Atlantic and the Iberian Peninsula. There is little indication of contour overturning and the trough south of Greenland is less pronounced compared to the top cluster mean PV field. Cluster-mean LWA does not take on values larger than 60 m s$^{-1}$ in the target region. Outside of the Atlantic and western European regions, PV and LWA show few differences between the two clusters and reanalysis. PV contours are predominantly zonal over North America and a weak PV gradient is found east of the target region.

We find that the members of our augmented ensemble evolve into both strongly and weakly blocked configurations over Europe on 18 December 2016, with some members able to capture the actual evolution as determined by the reanalysis well during the blocking onset. The ensemble is therefore suited for performing ESA with respect to the block strength on 18 December.

c. Idealized simulations

We see an enhanced zonal LWA flux from upstream into the target region prior to 18 December (Fig. 2c) and find that the convergence of this flux correlates well with the LWA increase in the target region (Fig. 4). Now, we further investigate the role of this local wave activity flux in the flow transition. Before applying the sensitivity techniques to our augmented NWP ensemble, we first obtain a baseline for our expectations in the traffic jam framework. We set up the 1D idealized model of NH18 to resemble the December 2016 blocking episode (see the appendix for details) and run 25 simulations with varying strength of upstream LWA forcing and, thus, varying strength of upstream LWA flux. The sensitivity of block development to the upstream flux is determined with ESA and a scatter analysis based on this idealized ensemble. With the onset threshold $\hat{A}_C$ known in the idealized setting, the model experiment allows us to characterize how the traffic jam mechanism leaves an imprint on our variables of interest.

Figures 6a and 6b show the ensemble-mean evolution of LWA and LWA flux, respectively, in our idealized simulations. All simulations start with a local maximum of LWA over Europe, which preconditions the region for blocking onset. A burst of LWA flux from days $3 \rightarrow 0$ transports LWA from the region of prescribed LWA forcing across the Atlantic. With the arrival of the flux over Europe, the preexisting LWA maximum intensifies. Members with strong prescribed forcing develop a shock front at the leading edge of the LWA maximum (not shown), an indication of block formation and wave breaking in the atmospheric context (Nakamura and Huang 2017). LWA associated with the block decays gradually after day $+1$. LWA flux remains positive inside the block, a limitation of the 1D model (NH18). The idealized evolution of LWA and LWA flux in Fig. 6 is not unlike the evolution in the December 2016 blocking episode (Fig. 2). The simulations are smoother in space and time (except for the shock formation) but capture and isolate the features of interest in our analysis.

As a first test of the sensitivity analysis, we correlate block strength, measured by averaging LWA over western Europe on day 0, with the LWA flux (Fig. 6c). The largest positive correlations are collocated with the occurrence of the upstream LWA flux prior to day 0 and with the western side of the block after. Given our model setup, this is the expected signal: ESA associates strong blocking with stronger upstream fluxes. A closer look at the connection between block strength on day 0 and upstream LWA flux on day $−2$ reveals that their relationship is weakly nonlinear (Fig. 6d). LWA accumulation in the blocking region appears to be slightly more effective for stronger than for weaker upstream forcing. At around 600 m$^2$ s$^{-2}$ of LWA flux or 72 m s$^{-1}$ of LWA, a saturation effect sets in. In these strongly forced scenarios, the leading edge of the block has already propagated to the west of 30°W by day 0 and with it the region where LWA accumulates.

In the idealized setting, we can compute the threshold $\hat{A}_C$ for the onset of an atmospheric “traffic jam.” Simulations where the onset threshold is exceeded are marked in Fig. 6d.
Traffic jam blocks at +0 days are found above 67 m s\(^{-1}\) aggregated LWA in the blocking region or above 55 m s\(^{-1}\) for traffic jams occurring on day 0 or later. Notably, the transition between nonblocked and threshold-exceeding simulations in the LWA-flux relationship is smooth. Exceedance of the traffic jam threshold changes the development of the solution qualitatively and determines if a block develops. However, because the accumulation of LWA during onset is governed by the availability of LWA flux from upstream, the threshold behavior does not translate into a discontinuous LWA-flux relationship.

The occurrence of wave breaking and meridional and vertical variations in LWA and LWA transport complicate the translation of concepts from the idealized 1D model to a realistic 3D setting. It is therefore nontrivial to obtain a precise value of the traffic jam threshold from reanalysis or NWP forecast data. Instead of attempting to estimate \(\hat{A}_c\) in the following, we carry out a simple perturbation experiment with the 1D model here and assess how uncertainties in the model parameters are likely to affect our results below. Figure 6d shows the response of the LWA-flux relationship to perturbations of \(u_{ref} + c_g\) and the timing of the upstream forcing \(t_{up}\). We find the qualitative behavior unchanged by the perturbed parameters. Less (more) flux at day \(-2\) is required to reach the same level of LWA if the upstream forcing sets in earlier (later) or if the background state group velocity is smaller (larger). We do not control for the timing of the upstream LWA flux, the blocking onset date or the influence of the background state in the following analysis. The idealized simulations suggest that this will lead to increased scatter in our assessment of the relationship between LWA and LWA flux. When we quantitatively compare idealized and NWP model data, conclusions drawn from such comparisons can only be of qualitative nature.

d. Analysis of the upstream region

With more precise expectations for the influence of the upstream LWA flux on the block development obtained from the idealized experiment, we return to the ensemble of NWP model forecasts for the December 2016 blocking episode. LWA aggregated in the target region on 18 December is used to assess the strength of blocking and serves as the sensitivity target. Source fields are obtained from \(\langle F_s \rangle\) at various times around onset. For the correlation maps shown in Fig. 7, this means positive (negative) correlations indicate regions where an increase of the zonal LWA flux is associated with a more (less) pronounced blocked flow pattern on 18 December according to the ensemble statistics. Contours of the mean zonal LWA flux from the top-ranking cluster are plotted to provide additional context.

The sensitivity map for both source and target valid at 0000 UTC 18 December (Fig. 7a) shows positive correlations in a region stretching westward from Scandinavia to the British Isles and southeastern Greenland. Collocated is a region of
large positive values of $\langle F_h \rangle$ in the top cluster mean. To the south sits a smaller region of negative correlation over and west of the Iberian Peninsula. The LWA flux in the top cluster mean at these latitudes is weak but positive. Only smaller and weaker patches of correlations compared to these signals over western Europe are visible in other regions of the map. Notably, no sensitivity to a top cluster flux maximum found at the U.S. East Coast is detected.

The sensitivity map associated with $\langle F_h \rangle$ evaluated 24 h before the target evaluation time (Fig. 7b) also shows the negative correlation signal over the Iberian Peninsula, although weaker. The northern region of positive correlation can be tracked back to the upstream region of the developing block over the Atlantic. Secondary maxima of both top cluster mean flux and correlation exist to the west over Newfoundland and Quebec and to the east over Scandinavia. Considering that both LWA and its zonal flux retain phase information from the underlying eddies, this pattern invokes the image of a Rossby wave train extending across the North Atlantic. The wave train pattern, weaker but with little change in location, also exists at a time difference of −2 days between source and target (Fig. 7c). Both positive and negative correlations over most of western Europe and the North Atlantic are weaker and the strongest sensitivity is now found in the western flux maximum of the top-rank cluster in northeastern Canada. We further examine the sensitivity signal at −2 days below. Correlations are generally small at a time difference of −3 days (Fig. 7d).

Averaging over the meridional extent of 35°–65°N, we can capture major features of this development with a Hovmöller diagram (Fig. 7e). Positive correlations of our target metric evaluated at 0000 UTC 18 December and the meridionally averaged zonal LWA flux fields are collocated with regions of enhanced flux upstream of the block in the top cluster up to 2.5 days earlier. This is consistent with the similar evolution of the top cluster and reanalysis noted above, which also shows this enhanced flux (Fig. 2c). The associated sensitivity found in the ensemble suggests that the arrival of LWA in Europe with this flux is important for the subsequent block development. The same general pattern of upstream LWA flux and collocated sensitivity signal was found in the idealized experiment (Fig. 6c). Notably absent from the Hovmöller plot is the strong positive correlation signal at the block location on 18 December. Here, the positive and negative correlations in

![Sensitivity maps for the period prior to and around block onset.](image)
upstream similar in both clusters. The stark difference in strength of over Europe and the downstream regions in Asia look overall positive correlations found in the sensitivity maps. The ridges associated pattern across the Atlantic in the bottom cluster mean (Fig. 8b).

In comparison, we investigate the in activity and (Fig. 8a), we can conrm that the previously identified sensitivity and flux pattern across the Atlantic is associated with an upper-tropospheric Rossby wave packet. The troughs located at 70°–80°W and 10°–20°E. The associated fluxes are weaker as well, consistent with the positive correlations found in the sensitivity maps. The ridges over Europe and the downstream regions in Asia look overall similar in both clusters. The stark difference in strength of upstream \( \langle F_h \rangle \) between the two clusters exists from 1200 UTC 15 December to 0000 UTC 17 December (Fig. 8c). No differences between the clusters is seen before 15 December and members of the bottom cluster reach significantly enhanced levels of LWA flux in the Atlantic only during 17 December, when both clusters begin to integrate into the overall spread of the ensemble.

To gain more insight into the functional relationship of upstream LWA flux prior to the blocking onset and the block strength, we aggregate \( \langle F_h \rangle \) in the region marked in Fig. 7c as well as Figs. 8a and 8b. In a scatterplot of the aggregated flux on 16 December against the target metric on 18 December (Fig. 8d), positive correlation can readily be identified from visual inspection of the point cloud. Higher values of \( \langle F_h \rangle \) are generally associated with stronger blocking. The actual value of correlation is 0.66 which is larger than the correlation found in most of the aggregation region in Fig. 7c. The aggregation appears to enhance the sensitivity signal for the entire region. Points from the top-rank cluster show higher values of aggregated flux than all but one member of the bottom-rank cluster. The reanalysis is centered inside the top cluster.

Data from the NWP ensemble are scattered around the simulated LWA–flux relationship from the idealized setting in Fig. 8d. As in the 1D experiment, the transition from non-blocked to blocked scenarios is continuous and does not exhibit strong nonlinearity. Considering the large differences in model complexity as well as parameter uncertainty in the 1D model setup, the NH18 traffic jam theory of blocking onset provides a reasonable fit to the NWP data. It suggests that the upstream LWA flux prior to 18 December was strong enough to trigger an atmospheric traffic jam in some forecasts of the ensemble. The comparison to the idealized simulations is valuable as a qualitative result, but we caution against a quantitative overinterpretation of the traffic jam model data in the context of Fig. 8d. This particularly pertains to the threshold value, which can be quite sensitive to details of the idealized

---

**Fig. 8.** Further analysis of the sensitivity of the target (block strength) to \( \langle F_h \rangle \) in the upstream region at 0000 UTC 16 Dec 2016. (a),(b) Cluster-mean fields of the zonal LWA flux for the top- and bottom-rank forecast member clusters (shading). The 7-km-height PV field is shown as well (contours; as in Fig. 2a). (c) Evolution of the zonal LWA flux \( \langle F_h \rangle \), averaged with area weighting in the region 35°–65°N, 90°–15°W from 14 to 18 Dec. The aggregation region is highlighted by the box in (a) and (b) as well as in Fig. 7c. (d) \( \langle F_h \rangle \) at 0000 UTC 16 Dec 2016, averaged as in (c), plotted against the value of the target metric at 0000 UTC 18 Dec 2016 for every ensemble member and for reanalysis data. The correlation value for the ensemble data is stated above the top-right corner. The line shows the reference simulations from the idealized experiment in Fig. 6d. The solid section of the line corresponds to simulations where \( \hat{A}_c \) is exceeded after day 0, and the dotted section where \( \hat{A}_c \) is never exceeded.
analog setup and, as mentioned previously, is a difficult concept to translate into a realistic three-dimensional atmosphere.

**e. Analysis of the blocked region**

In Fig. 7, we saw a meridional dipole develop at the block location in the correlation field of the blocking strength and the zonal flux of LWA. According to the ensemble, block-dominated members are associated with weaker flux in southwestern Europe but stronger flux at around 60°N. We now investigate this phenomenon further by splitting (F̃) into the terms F1 + F3 and F2. The LWA flux due to F1 + F3 can be associated with Rossby wave group propagation, while F2 quantifies the nonlinear modification of the flux due to the presence of large-amplitude waves (see above; NH18). Repeating the previous analysis for both contributions to the total flux individually, sensitivity can be associated with the corresponding physical processes. We shift focus from the upstream region to the development of the blocked flow pattern over Europe.

Figures 9a–d show sensitivity maps for the group propagation terms F1 + F3. A region of positive correlation is collocated with a central flux maximum moving toward Europe in the top-rank cluster during the flow transition (−24 and 0 h). Significant regions of negative correlations are found dotted around the edges of the Atlantic F1 + F3 maximum. From a comparison of the top- and bottom-rank cluster mean flux fields (not shown) we find that the top-cluster Atlantic F1 + F3 maxima, while stronger, are more spatially compact with stronger gradients at the edges that give rise to the surrounding negative correlations. At 0 h, the flux contours and sensitivity patterns look qualitatively different to the full flux (cf. Fig. 7a and Fig. 9b). The northward shift of the maximum on 18 December in the top cluster is less pronounced and no negative correlations are found at 40°N over western Europe. Correlations weaken in the target region in the further evolution and only the downstream edge of the flux maximum between 40° and 60°N over Europe exhibits notable positive correlation (Fig. 9a). F1 + F3 is positive almost everywhere in the top-rank cluster mean.

Values of the target metric at 0000 UTC 18 Dec to F1 + F3. (e)–(h) Sensitivity to F2. Filled contours show correlation, and the stippling shows statistical significance. The black contours indicate the mean fields of the respective parts of the flux of the top-rank cluster. Contours of negative values are plotted as dashed lines. The valid time offset of the sensitivity source fields with respect to the target evaluation time is given above the top-right corner of each panel. Valid time advances from bottom to top.
is negative throughout most of Europe in the top cluster, with a weak negative correlation signal over western Europe. A dipole in both flux and sensitivity appears on 17 December, with positive $F_2$ and positive correlations in a region south of Iceland, while the negative flux over the continent intensifies and with it the negative correlations. The maximum of the dipole moves to the Norwegian Sea on 18 December (+0 h) and amplifies to over 800 m$^2$ s$^{-1}$ of flux in the top cluster. Meanwhile, the zonally elongated southern part of the $F_2$ dipole also intensifies together with its associated negative correlations. The dipole then weakens and drifts eastward slowly and collocated correlations decay simultaneously (+24 h). Because correlations have the same sign as $F_2$ throughout the dipole, we can associate stronger blocking with a more intense dipole pattern.

The meridional structure apparent in the evolution of $F_2$ around the onset time and the associated sensitivity dipole stand in contrast to the overall meridionally homogenous behavior of $F_1 + F_3$ in the midlatitudes. From a comparison of the top cluster-mean zonal LWA fluxes and the ensemble sensitivity patterns of the full flux (Figs. 7a–c) to those of $F_1 + F_3$ (Figs. 9b–d) and $F_2$ (Figs. 9f–h), it can be concluded that the term $F_2$ plays a major role in shaping the full flux during and after the blocking onset. $F_2$ counteracts the positive contribution of $F_1 + F_3$ to $(F_1 + F_3)_s$ around 40°N over western Europe and is the main contributor to the northern positive flux maximum over Europe.

These features of $F_2$ appear to be associated with the upper-tropospheric flow, as illustrated in Fig. 10 which depicts the $F_2$ mean fields together with PV contours for the two rank-based clusters on 18 December. The top-rank cluster mean (Fig. 10a) shows that the dipole in $F_2$ is embedded into the high-over-low PV pattern that characterizes the block. Negative flux is found in the southern part where the PV contours curl back and zonal flow reversal can be expected. Positive flux is collocated with the anticyclonic PV anomaly pushing north- and eastward in the Norwegian Sea. The bottom cluster mean (Fig. 10b) shows negative $F_2$ over continental Europe and a positive flux in the northernmost part of the ridge, but amplitudes are much weaker compared to the top cluster. The differences between the two clusters reflect that $F_2$ is the nonlinear flux term, quantifying the impact of large-amplitude eddies on the zonal LWA flux. The overturning of PV contours found in the strongly blocked ensemble members is a nonlinear process and $F_2$ responds strongly to it, while the rather linear evolution of the ridge in the bottom-rank cluster does not lead to much flux due to the term $F_2$. For NH18, the negative $F_2$ inside the block, counteracting the group propagation terms, was essential in the derivation of the traffic jam mechanism.

We have seen before in Fig. 2 for the reanalysis data and Fig. 7 for the top-rank cluster mean fields that the full flux does not completely vanish or reverse in this blocking event. A residual eastward flux remains, consistent with the observed eastward drift of the blocking system. In the top-rank cluster mean fields of $F_2$ in Figs. 9c–g and 10a we see contributions of either sign to the meridionally averaged $(F_1)_s$ at the block location. Negative $F_2$ constitutes an obstruction for Rossby wave propagation in the southern part of the block while positive $F_2$ provides a redirection of some of the LWA “traffic” in the northern part and thereby weakens the obstruction in the meridionally averaged full LWA flux. Here, our analysis goes beyond the capabilities of the idealized traffic jam model. The evaluation of LWA and associated variables with 3D NWP data does not restrict us to the onset phase or a meridionally averaged view and we obtain deeper insight into the balance of contributions to the LWA evolution along the waveguide.

f. The LWA–flux relationship

NH18 assessed the relationship between LWA and its zonal flux at jet exit locations in the eastern Pacific and Atlantic (their Fig. 4). Based on these data, they drew parallels to the “fundamental diagram” of traffic flow (Treiber and Kesting 2013) and set up a simplified one-dimensional model of the midlatitude LWA evolution that encapsulated the traffic jam onset mechanism for blocking. As in Fig. 8, we can use the ensemble to map the relationship of LWA and its flux at the location of the block analogously to NH18. Instead of each data point corresponding to a different 4-day period in a reanalysis dataset, each point now represents the forecast of a different ensemble member for the same 4-day period.

Figure 11 summarizes the relationship of LWA and the zonal flux of LWA in the augmented ensemble for the period from 16 to 19 December 2016 and a 10° × 10° region centered on 45°N, 10°W. Note that this region contains 45°N, 9°W, the Atlantic jet exit location analyzed by NH18. A positively sloped, linear relationship between LWA and the sum of the
is seen in the climatological study of NH18. \( \langle A \rangle \cos(\phi) \) in the ensemble only varies between 40 and 90 m s\(^{-1}\) in contrast to the 20–100 m s\(^{-1}\) in the NH18 winter climatology. Some predictability remains at the 5–10-day forecast lead times considered here (Ferranti et al. 2015; Matsueda and Palmer 2018) so a narrower range of outcomes from our ensemble covering a single case compared to a multidecade climatological dataset is to be expected.

A literal interpretation of the NH18 fit for the full flux in Fig. 11 suggests that most, though not all, ensemble members exceed the traffic jam threshold of \( \langle A \rangle \cos(\phi) \approx 55\) m s\(^{-1}\) determined by the maximum of the fitted curve. This is consistent with our comparison between the idealized simulations and the NWP data in Fig. 8d, which suggests that a majority of the ensemble members exceed the threshold on 18 December or thereafter. Again, we do not find discontinuous behavior around the estimated threshold value or elsewhere in the LWA–flux relationship in Fig. 11. As before, we are cautious about such quantitative comparisons to threshold values intended for a realistic atmosphere. Ultimately, it is the linear relationship of \( \langle A \rangle \cos(\phi) \) and \( F_1 + F_2 \) at the block location and the effect of term \( F_2 \) to reduce the total zonal LWA flux with increasing levels of LWA, which constitute the essential features that enabled NH18 to draw an analogy to the fundamental diagram of traffic flow. We find them here in our ensemble just as they did in a climatological analysis.

### 4. Summary and conclusions

We have carried out an analysis of a December 2016 blocking onset event in the quasigeostrophic finite-amplitude local wave activity framework of Huang and Nakamura (2016, 2017). With a 200 member ensemble, constructed from four consecutive initializations of 50-member forecasts from an NWP model, we conducted a sensitivity analysis to understand the role of wave activity and zonal wave activity flux in the upstream and formation regions prior to and during the block formation, respectively. Particular attention was paid to features expected from an onset process governed by the traffic jam mechanism of NH18.

The sensitivity analysis showed that enhanced zonal LWA flux in the Atlantic immediately preceding the flow transition had a substantial impact on the development of the block. A significant positive correlation between the block’s strength just after onset and zonal LWA fluxes from North America was found for lags of up to 2.5 days. While this stands in contrast to the enhanced LWA flux seen throughout approximately 2 weeks before onset in the NH18 Atlantic composite study, we could not access the same temporal range as the NH18 composite due to limitations in our ESA setup. The rather short temporal scale of features seen here agrees better with results from the one-dimensional traffic jam model, superficially also with the composite of Nakamura (1994) and in particular with the characterization of short-lived North Atlantic blocking events by Barpanda (2020).

As in the North Pacific case study of Neal et al. (2022), we identified a nonconservative upstream LWA source as a major contributor to the LWA flux converging in the region of

![Fig. 11. The relationship of LWA and its zonal flux presented similarly to Fig. 4 of NH18. \( \langle A \rangle \cos(\phi) \) vs \( F_3 \) (total: blue, gray, and red) and \( \langle A \rangle \cos(\phi) \) vs \( F_1 + F_3 \) (orange), averaged in the region of 40°–50°N, 15°–5°W (shown in the map panel in the top left) for 0000 UTC 18 Dec 2016. Each dot represents one forecast from the augmented ensemble. Points showing the LWA–\( F_3 \) relationship have been colored red or blue if the corresponding forecast member belongs to the top- or bottom-ranking cluster, respectively. The reanalysis data point is additionally shown as a star. To aid comparison, the plot also shows the linear (orange) and quadratic (black) fits to the point clouds of LWA vs \( F_1 + F_3 \) and \( F_3 \), respectively, from NH18 (reprinted with permission from AAAS). Note that the assignment of LWA and the fluxes to the axes is inverted compared to Fig. 8c.](attachment:image.jpg)
the developing block. Both large-scale sources of wave activity, e.g., downstream dispersion of energy during the decay of the North Atlantic Oscillation (Luo et al. 2007; Yao et al. 2016), and smaller-scale latent heat release, e.g., in warm conveyor belts (Pfahl et al. 2015; Steinfeld et al. 2020) or mesoscale convective systems (Rodwell et al. 2013), are known precursors of blocking over Europe. Our study quantified the wave activity flux associated with such upstream processes and reinforces the notion that Rossby wave developments over North America and the North Atlantic can lead to European blocking. The nature and predictability of the wave activity sources consequently affects the predictability of blocking onset (Magnusson 2017; Grams et al. 2018) and, importantly, renders it flow dependent.

The idea that forecast uncertainty may be enhanced if the atmosphere approaches the onset conditions of a blocking onset mechanism motivated our study. We considered this idea in the traffic jam framework of NH18, though other onset conditions, e.g., based on energy saturation (Tanaka and Terasaki 2006) or phase matching of eddies (Luo et al. 2014), could have also been considered. The transition to blocked flow on 17 December 2016 investigated here is characterized well by the traffic jam framework. Despite the threshold behavior inherent in the traffic jam onset mechanism, the relationship between upstream LWA flux and the block strength after onset was found to be continuous in our variables of interest for both idealized and NWP simulations. The growth of the block is approximately proportional to the available incoming LWA flux, though other factors, e.g., the atmospheric background state, modulate the relationship. Our results suggest that the change to block development after exceedance of the traffic jam onset threshold is better viewed as a qualitative change of flow regime, but further characterization is required.

By decomposing the zonal LWA flux into terms representing group propagation and nonlinear modification, we could attribute sensitivity signals to specific dynamical processes in the LWA framework. We found that the nonlinear term $F_2$ shapes the major features of the total LWA flux during the flow transition. It suppresses the flux in the southern part of the block, making it essential in creating the obstruction for LWA transport that enables the traffic jam mechanism. At the same time, the meridional dipole structure of $F_2$ embedded into the wave breaking pattern provides a path to partially “redirect” eastward LWA flux around the obstruction in the northern part of the block. This northern flux path could be of further interest for a future investigation of stationarity and eddy-driven maintenance during the mature phase of blocking from the LWA perspective.

The LWA framework of Huang and Nakamura (2016, 2017) proved to be effective for our quantitative investigation of blocking onset. We were able to examine the evolution of the block structure realistically based on gridded model data and also during the nonlinear wave breaking stage, where the simplified one-dimensional traffic jam model of NH18 is applicable with substantial caveats only. The source regions and propagation of the precursor Rossby wave packet as well as the strength of the block were determined with LWA and its flux, facilitated by the more wave packet–centered nature of LWA, e.g., when compared to eddy kinetic energy (Huang and Nakamura 2017; Wirth et al. 2018). We thus obtained a succinct and integrated view of the synoptic and large-scale atmosphere, making the finite-amplitude local wave activity framework a compelling choice for blocking studies. Our findings could furthermore be explicitly evaluated in terms of the characteristics of the traffic jam onset mechanism.

We can of course make only limited statements about the general validity or impact of the NH18 traffic jam hypothesis in the atmosphere based on a single case study. Restricted by the range of scenarios produced by the ensemble and without explicit consideration of the influence of the background state, we do not fully assess the sensitivities of our chosen blocking onset event. Still, we identified suppression of the zonal LWA flux in the blocked region and rapid accumulation of LWA simultaneously with an amplification of the blocked flow. These are essential characteristics of the traffic jam mechanism. Together with the remarkable agreement of the LWA–flux relationship between the ensemble for our specific case, our idealized 1D experiments and the climatological study of NH18, we must consider the possibility that the traffic jam mechanism played an important role in the onset of this December 2016 blocking event. That does not mean every onset of blocked flow must be similarly influenced by the mechanism nor do we claim that every onset is due to a “traffic jam” in the first place. Future investigations may benefit from the combination of ensemble forecast data and the LWA tools of NH18 as demonstrated in this work to approach the attribution of individual blocking events to the traffic jam mechanism.

Acknowledgments. We thank three anonymous reviewers and the editor for their comments, which were very helpful to improve the content and presentation of this work. We are grateful to C. S. Y. Huang for creating and maintaining the open source hn2016_falwa software. The research leading to these results has been done within the Transregional Collaborative Research Center SFB/TRR 165 “Waves to Weather” funded by the German Science Foundation (DFG).

Data availability statement. All results in this work were derived from Copernicus and ECMWF data; no new datasets were created. The code to reproduce all figures of this article is available online (Polster 2022). The repository also contains a MARS script for retrieval of the ensemble data from the ECMWF archive of operational forecasts. Access to these data is restricted; check ecmwf.int. ERA5 data (Hersbach et al. 2018) were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store. The results contain modified Copernicus Climate Change Service information 2022. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.
APPENDIX

Traffic Jam Model Setup

We run numerical simulations with the traffic jam model (6) using an exponential time-differencing fourth-order Runge–Kutta scheme (Cox and Matthews 2002; Kassam and Trefethen 2005) with a time step of 300 s. The periodic domain from $x = 0$ km to $x = 28000$ km is discretized with 1024 grid points and mapped to longitude such that $x = 0$ km corresponds to $\lambda = -180^\circ$. Spatial derivatives are evaluated in spectral space. The implementation is included in our code repository (Polster 2022).

Let

$$H_{n,0}(x) = \begin{cases} \cos^2\left(\frac{x - x_0}{w}\right) & |x - x_0| \leq w/2, \\ 0 & \text{otherwise} \end{cases}$$

For our simulations, we set $\alpha = 0.4$ (NH18; after the correction from 23 April 2020), $\tau = 10$ day and $\kappa = 3.26 \times 10^5$ m$^2$ s$^{-1}$ (Paradise et al. 2019). The background state is constructed with $u_0 = 60$ m s$^{-1}$ and $A_0(\lambda) = 19 \times H_{n,10,15}(\lambda)$ m s$^{-1}$, such that $A_c = 56$ m s$^{-1}$ at the maximum of $A_0$ and $A_c = 75$ m s$^{-1}$ in the regions where $A_0 = 0$ m s$^{-1}$. We start simulations from $A = 0$ m s$^{-1}$ everywhere and run the model for 200 days with only a constant base forcing of $\bar{S}(\lambda) = \bar{S}_0 = 1.825 \times 10^{-5}$ m$^2$ s$^{-1}$. After this spinup phase, the transient LWA $\bar{A}$ has reached a steady state and we set time to $5$ days. We then change the forcing to include a transient term in addition to the base forcing $\bar{S}(\lambda) = \bar{S}_0 + \bar{S}_u \times H_{n,25,75}(\lambda) \times H_{n,1.5}(t)$ and run the model for 8 days. For the reference simulation, $t_u = 2$ days. The peak transient forcing strength is varied from $\bar{S}_u = 0$ m$^{-1}$ to $\bar{S}_u = 0.0007$ m$^{-1}$ in 25 uniform steps to generate the 25 simulations that form an ensemble.

REFERENCES


Pfahl, S., C. Schwierz, M. Croci-Maspoli, C. M. Grams, and H. Wernli, 2015: Importance of latent heat release in ascending...


