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Key Points:

- Gulf Stream (GS) moisture flux suppression reduces atmospheric blocking across the Northern Hemisphere
- GS moisture fluxes generate larger jet stream perturbations, fostering faster westward-propagating Rossby waves
- Higher resolution models enhance signal transport from the boundary layer to the upper troposphere

Supporting Information:

Supporting Information may be found in the online version of this article.

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Gulf Stream Moisture Fluxes Impact Atmospheric Blocks Throughout the Northern Hemisphere

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Abstract In this study, we explore the impact of oceanic moisture fluxes on atmospheric blocks using the ECMWF IFS. Artificially suppressing surface latent heat flux over the Gulf Stream (GS) region reduces atmospheric blocking frequency across the Northern Hemisphere by up to 30%. Affected blocks show a shorter lifespan (−6%), smaller spatial extent (−10%), and reduced intensity (−0.4%), with an increased number of individual blocking anticyclones (+17%). These findings are robust across various blocking detection thresholds. Analysis reveals a qualitatively consistent response across all resolutions, with Tco639 (~18 km) showing the largest statistically significant change across all blocking characteristics, although differences between resolutions are not statistically significant. Exploring the broader Rossby wave pattern, we observe that diminished moisture fluxes favor eastward propagation and higher zonal wavenumbers, while air-sea interactions promote stationary and westward-propagating waves with zonal wavenumber 3. This study underscores the critical role of the GS in modulating atmospheric blocking.

Plain Language Summary In our study, we investigated how changes in oceanic moisture, specifically from the Gulf Stream (GS), affect atmospheric blocking events using the ECMWF Integrated Forecast System. By artificially reducing the moisture flux from the GS area, we observed a notable decrease in the occurrence of atmospheric blocks across the Northern Hemisphere-up to 30%. These blocks also showed changes in their characteristics: they had shorter durations by 6%, were 10% smaller in spatial size, and had a slight decrease in intensity, alongside a 17% increase in their detection rates. Our findings were consistent across different methods of identifying blocks. We also discovered that the model's resolution influences the observed changes, with coarser resolutions (larger than approximately 18 km) not showing significant alterations in some blocking traits despite the overall frequency reduction. Further analysis into Rossby wave patterns revealed that reduced moisture flux tends to favor faster eastward-moving patterns with shorter wavelengths, whereas interactions between the air and sea support more stationary or westward-moving waves, particularly those with a zonal wavenumber of 3. This highlights the crucial role that moisture from western boundary currents like the GS plays in the development and behavior of atmospheric blocking patterns.

1. Introduction

Understanding the mechanisms governing the formation and persistence of large-scale anticyclonic anomalies, commonly known as atmospheric blocks, is crucial for advancements in weather forecasting (Grams et al., 2018) and predicting the associated extreme temperatures (Pfahl & Wernli, 2012). Nearly a decade ago, Pfahl et al. (2015) linked these synoptic-scale features to upstream latent heating, an observation later substantiated by Steinfeld et al. (2020). Their experiment, suppressing latent heating along the warm conveyor belt of a cyclone, resulted in the subsequent suppression of atmospheric blocks, with some blocks failing to form at all.

The ocean's role as a primary moisture source for atmospheric blocks was highlighted by Yamamoto et al. (2021), with theories by Mathews and Czaja (2024) suggesting that western boundary currents, like the Gulf Stream (GS), modulate atmospheric blocking. This link was evidenced by increased blocking following heightened GS heat transport, leading to warm water anomalies that boost surface latent heat flux (SLHF), and consequently moisture, aiding block formation by transporting anomalously low potential vorticity (PV) air from lower to upper levels (Wenta et al., 2024).

Emphasis has also been placed on both oceanic and atmospheric resolution to accurately represent air-sea interactions in coupled models (Hewitt et al., 2017). Notably, Famooss Paolini et al. (2022) found that models with atmospheric resolution coarser than 50 km exhibited an entirely different response to sea surface temperature anomalies, showing weakened vertical motion and meridional transient eddy heat transport.

In this study, we examine the impact of moisture fluxes from the GS region on atmospheric blocking in the Northern Hemisphere (NH) through a sensitivity experiment conducted using the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS). While this study emphasizes changes in atmospheric blocks, we also examine the effect on the broader Rossby wave spectrum. The paper is laid out as follows: Section 2 describes the model setup and the diagnostic methods used. Section 3 shows the effects GS moisture suppression has on the upper troposphere, followed by our conclusions in Section 4.

2. Data and Methodology

2.1. Model Set Up

The results in this study are based on coupled ensemble reforecasts using the ECMWF IFS cycle 47r3 (ECMWF, 2023), configured as follows. The atmosphere is set up with 15 ensemble members, 137 model levels and run on Tco639, Tco319, and Tco199 cubic octahedral reduced Gaussian grids, corresponding to resolutions of approximately 18, 32, and 50 km, respectively. The IFS is coupled hourly to a 75-level NEMO v3.4 ocean model (Madec et al., 2017) and an LIM2 sea ice model (Bouillon et al., 2009; Fichefet & Maqueda, 1997), both utilizing the ORCA025 tripolar grid with a grid spacing of approximately 0.25°. The ocean and atmosphere are fully coupled throughout the 46-day forecast, producing output every 12 hr. Fifteen reforecasts are used, and the initial dates are listed in Table S1 of Supporting Information S1. This results in a total of 690 forecasted days, with 414 falling in extended winter (NDJFMA) and 276 in extended summer (MJJASO). The atmospheric, land, and wave fields were initialized from ERA5 (Hersbach et al., 2020), while the ocean and sea ice fields were initialized from OCEAN5 and ORAS5 respectively (Zuo et al., 2019). These dates were chosen based on the occurrence of a cyclone over the North Atlantic preceding the initial block detected in the North Atlantic or Europe region, as observed from ERA5 data. The forecast was initiated approximately 4 days before the observed block was initially detected to allow the contributing cyclone to sufficiently interact with the GS. These events were chosen randomly with priority given to more recent dates due to higher-quality data assimilation (de Rosnay et al., 2022). All results shown are for resolution Tco639 unless otherwise specified.

To assess the impact of GS SLHF on atmospheric blocking, a sensitivity experiment was conducted. It compared the full physics control run to a corresponding simulation with GS SLHF suppressed (here-after referred to as NO_GS_SLHF). GS SLHF is turned off by applying a mask to the moisture transfer scheme (ECMWF, 2021), preventing moisture transfer where the mask is applied. This mask linearly relaxed, allowing complete moisture transfer after a distance of 5° from the original mask, as illustrated by the gray contours in Figure 1. The mask roughly corresponds to the region of 200Wm⁻² SLHF from wintertime ERA5 climatology in the North Atlantic and was applied throughout the entire run.

2.2. Diagnostic Methods

Following Schwierz et al. (2004), blocking is identified as an upper-level negative PV anomaly that surpasses defined thresholds for overlap, amplitude, spatial scale, and duration. Initially, the PV field is averaged between 500 and 150 hPa, and a two-day running average is applied. To calculate the anomaly, a 2-day smoothed daily ERA5 climatology is subtracted from the averaged PV field. The upper PV anomaly field is then analyzed using the Steinfeld (2020) algorithm, with thresholds for overlap, duration, amplitude, and size being 40%, 5 days, -1.2PVU and 10⁶ km² respectively. The relatively low overlap threshold is chosen due to the 12-hourly temporal output from the model and to maximize the difference between the NO_GS_SLHF and control runs. Various threshold values were tested, and most results were comparable across different overlap and amplitude thresholds, as discussed in Section 3.3. Each detected block is labeled, and its characteristics, including duration, size, and intensity (total PV per area), are calculated for each time step. These characteristics are related to the overall blocking frequency in the NH, as seen in Table 1, through the equations:

$$\text{Frequency}(x, y) = \frac{1}{TDM} \sum_{t=1}^T \sum_{d=1}^D \sum_{m=1}^M f(x, y, t, d, m), \quad (1)$$

$$f(x, y, t, d, m) = \begin{cases} 1, & \text{if blocking is detected at grid point} \\ 0, & \text{otherwise} \end{cases}, \quad (2)$$

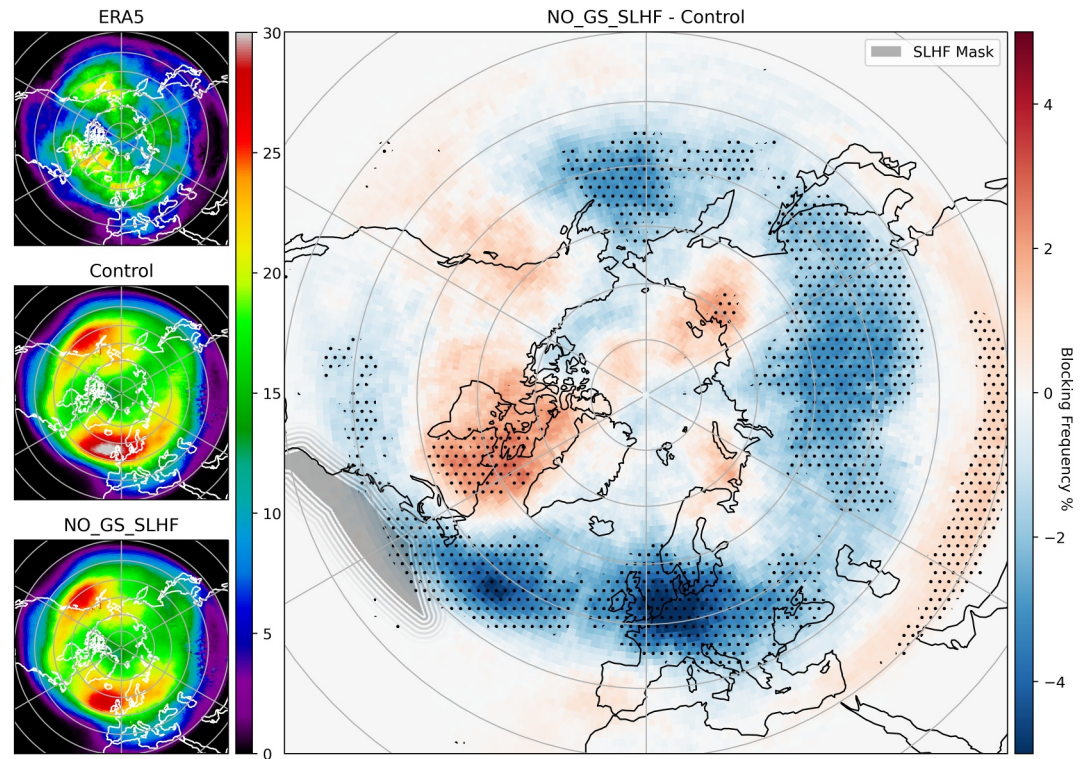


Figure 1. Mean blocking frequency for ERA5 (top left), the control run (middle left), the NO_GS_SLHF run (bottom left), and the difference between the NO_GS_SLHF and control runs (right). The gray contours indicate the surface latent heat flux mask applied, with the darkest (lightest) contour indicating complete suppression (permission). Stippling indicates areas that exceed the 95% confidence interval.

$$\iint_{NH} \text{Frequency}(x, y), dx dy = \frac{\sum_{n=1}^N \text{Duration} \times \overline{\text{Size}}}{\text{Forecast Length}}, \quad (3)$$

where T , D , M , and N represent the number of time steps, initial dates (as seen in Table S1 of Supporting Information S1), ensemble members, and blocks detected, respectively. The over-bar denotes the average over the life cycle of the block.

The phase speed-wavenumber analysis follows the approach outlined in Jiménez-Estevé et al. (2022a). First, a fast Fourier transform is applied in both the longitudinal and temporal directions. Then, the phase speed of the Rossby waves is calculated according to Randel and Held (1991), weighting this spectrum along latitudinal directions. Finally, the spectrum is averaged along the latitudinal direction.

Statistical significance at the 95% confidence interval is determined using a two-tailed t -test between the ensemble members of the NO_GS_SLHF and control runs.

3. Results

3.1. The Effect on Atmospheric Blocking

Figure 1 compares average blocking frequencies from ERA5 data covering the same dates as the IFS experiment, control, and NO_GS_SLHF simulations over a 46-day forecast. Both simulations show a more extensive frequency of atmospheric blocking across the NH than observed in ERA5, with a smoother signal attributed to ensemble averaging. The overestimation of blocking frequency in our experiments is in contrast to the underestimation

Table 1
Percentage Change in Blocking Frequency Over the Northern Hemisphere Relative to the Control Run for the Entire Reforecast Period is Presented

Resolution	All dates	Winter	Summer
Tco639	−4.34% (−4.22%)	−5.9% (−6.64%)	−2.45% (−1.33%)
Tco319	−3.88% (−2.96%)	−5.32% (−4.90%)	−2.60% (−0.18%)
Tco199	−3.35% (−3.55%)	−3.30% (−5.27%)	−3.41% (−1.51%)

Note. The first 2 weeks of the forecast are shown in brackets. Winter reforecasts correspond to NDJFMA, while Summer corresponds to MJJASO, as indicated in Table S1 of Supporting Information S1. Results significant over the 99% confidence interval are depicted in **bold**.

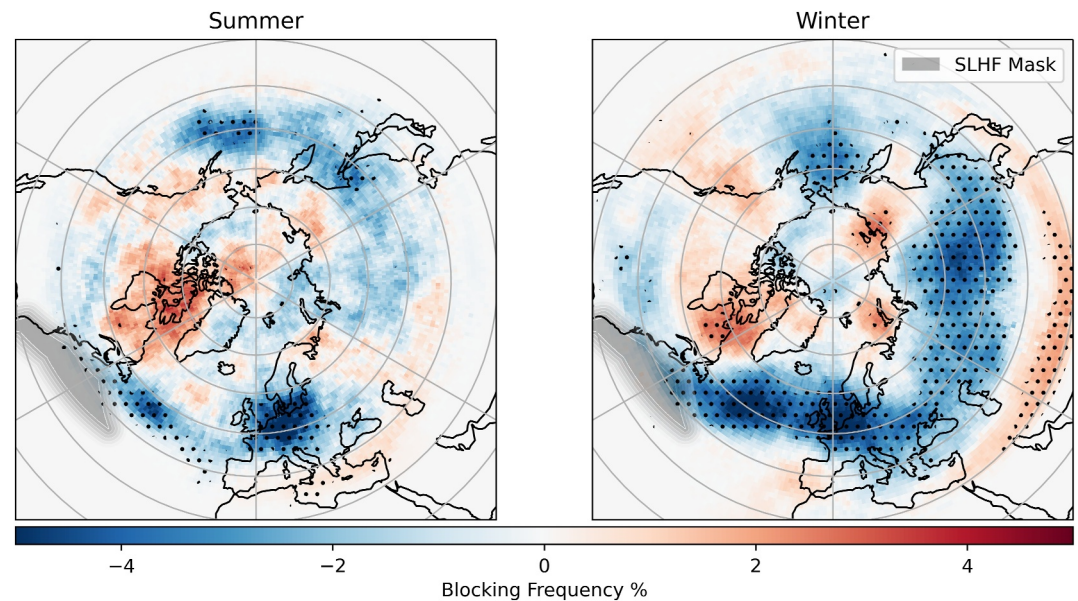


Figure 2. The difference in mean blocking frequency between the NO_GS_SLHF and control runs for the extended summer (left) and extended winter (right). The gray contours indicate the surface latent heat flux mask applied, with the darkest (lightest) contour indicating complete suppression (permission). Stippling indicates areas that exceeded the 95% confidence interval.

identified in previous IFS versions (e.g., Davini et al., 2021), but is consistent with a positive NH blocking frequency bias in ECMWF operational reforecasts for the same IFS cycle when calculated over a longer period (not shown). The situation is clearly more complicated than the commonly held view that models underestimate blocking frequency due to finite resolution. The NO_GS_SLHF simulation reveals a significant decrease in blocking frequency, by up to 30%, over the North Atlantic storm track, Western Europe, Russia, and the North Pacific compared to the control, as highlighted in the right panel of Figure 1. Conversely, NO_GS_SLHF shows an increase in blocking over northeastern Canada and central Asia, though with a smaller spatial footprint and intensity, suggesting a complex shift in blocking patterns.

We evaluated the sensitivity of blocking to GS moisture fluxes using a geopotential height reversal index (Davini et al., 2012) and a geopotential height anomaly index (Woollings et al., 2018). Interestingly, the diagnosed biases are sensitive to the choice of blocking index, with IFS forecasts under-representing blocking frequency compared to ERA5 with the reversal index (Figure S1 in Supporting Information S1) but slightly over-representing blocking frequency with the anomaly index (Figure S2 in Supporting Information S1). Nevertheless, both geopotential indices are consistent with the PV blocking metric and show a decrease in blocking frequency over the North Atlantic storm track and Europe when moisture flux is suppressed, with a similar relative magnitude. However, only the anomaly indexes shows a strong signal propagating to the North Pacific basin, as depicted in Figure 1.

Results from the first 2 weeks of reforecasts align more closely with ERA5 (Figure S3 in Supporting Information S1), indicate a significant decrease in blocking over the North Atlantic and Western Europe in the NO_GS_SLHF run compared to the control run. This suggests that the signal has not had sufficient time to propagate from the North Atlantic to the North Pacific. A reduction in blocking frequency across the entire NH during this period was observed, as outlined in Table 1.

Turning to the seasonal strength of this signal, the same analysis was conducted for dates within the extended winter (NDJFMA) and extended summer (MJJASO) periods, comprising of 9 and 6 initial dates respectively, as indicated in Table S1 of Supporting Information S1. The results of this seasonal analysis are presented in Figure 2. The summer composite reveals a significant decrease in blocking over the North Atlantic storm track, Western Europe, Northern Japan, and the North Pacific. Additionally, during winter, a more prominent area of reduced blocking spans from the Western North Atlantic to East Asia, accompanied by a signal in the North Pacific. Expanding this perspective to encompass the overall change in blocking frequency across the NH, once more, the

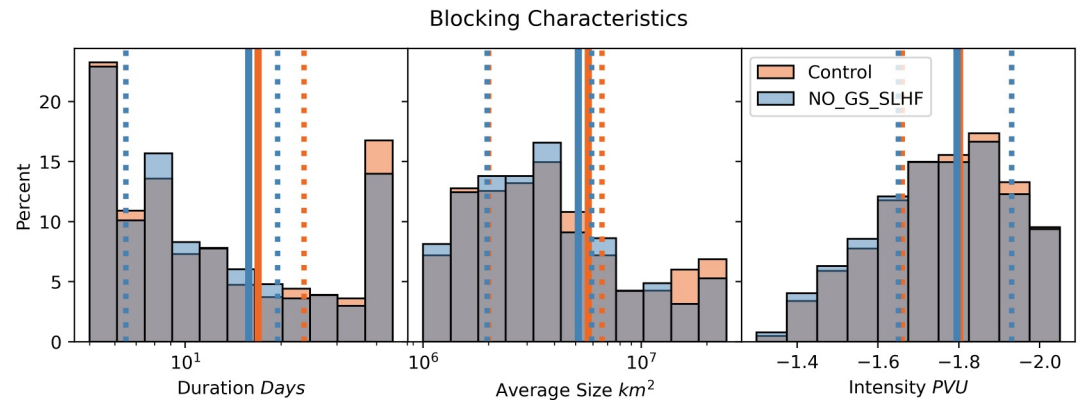


Figure 3. The distributions of the block characteristics for the control (light red) and NO_GS_SLHF (light blue) runs. From left to right the block's duration, average size, and intensity (total potential vorticity per area) are shown. Solid lines represent the mean values, while dotted lines represent the upper and lower quartiles.

dominance of the signal in extended winter becomes evident, as displayed in Table 1. This finding remains robust to changes to initial date sample size.

Examining the changes in the atmospheric block's characteristics reveals the impact of air-sea interactions on individual blocks. Figure 3 shows the probability distributions of these characteristics. The solid line, representing the mean value, illustrates that in the NO_GS_SLHF run, the blocks have shorter life cycles (−6.4%), a more compact spatial signature (−10.1%), and exhibit weaker intensity (−0.35%), indicating a weaker negative PV anomaly inside the blocks. Interestingly, the NO_GS_SLHF run detects more individual blocks compared to the control run (+16.5%). However, due to their decreased duration and size, this discrepancy is not substantial enough to result in an overall increase in blocking frequency, as indicated in Table 1 and seen in Figures 1 and 2. The dotted lines in Figure 3 illustrate the upper and lower quartiles of the distribution. This demonstrates that in the NO_GS_SLHF run, there is a narrower range of block durations and sizes, indicating reduced variability. Conversely, the NO_GS_SLHF run exhibits wider variability in the intensities of blocks.

3.2. Changes in the Jet Stream and Rossby Wave Characteristics

Examining the overall impact of suppressed GS SLHF on the jet stream across the NH, Figure 4a displays the difference in zonal wind at 250 hPa between the NO_GS_SLHF and control runs. The red contours represent the average zonal wind for the control run. In the North Atlantic, a shift toward the equator is observed in the polar jet, while a poleward shift is noted in the subtropical jet, suggesting a merged jet. Downstream over central Asia and the North Pacific, indications of a poleward shift in the jet are observed. Moreover, a general increase in jet speed over the North Pacific correlates with the decrease in atmospheric blocking seen in Figures 1 and 2. This finding agrees with Riboldi et al. (2020), who observed decreased blocking with increased zonal wind. Although there is a small but significant 0.9% increase in zonal wind across the entire NH in the NO_GS_SLHF run, there is no dipole signal when averaging above and below the jet stream maximum, suggesting no overall meridional shift in the jet stream. This result is further supported by meridional cross-sectional composites (Figure S4 in Supporting Information S1).

Figure 4b shows the power spectrum of the anomalous PV field from 500 to 150 hPa, between latitudes 40° and 60°N. It compares the spectral density of the NO_GS_SLHF (blue) and control runs (red), with shading indicating differences. Both runs exhibit slower eastward propagation with decreasing zonal wave number. The NO_GS_SLHF runs show more energy with higher wavenumbers, promoting faster eastward propagation. Conversely, the control run favors westward and stationary zonal waves with lower wavenumbers. With a negligible change in zonal wind speed (0.03 m/s) between 40 and 60°N, the signal isn't due to changes in the jet speed but suppressed Rossby wave forcing. This aligns with smaller blocking sizes in the NO_GS_SLHF run, implying larger zonal wave numbers. This is consistent with the findings of Riboldi et al. (2020), who associated low phase speed with atmospheric blocking.

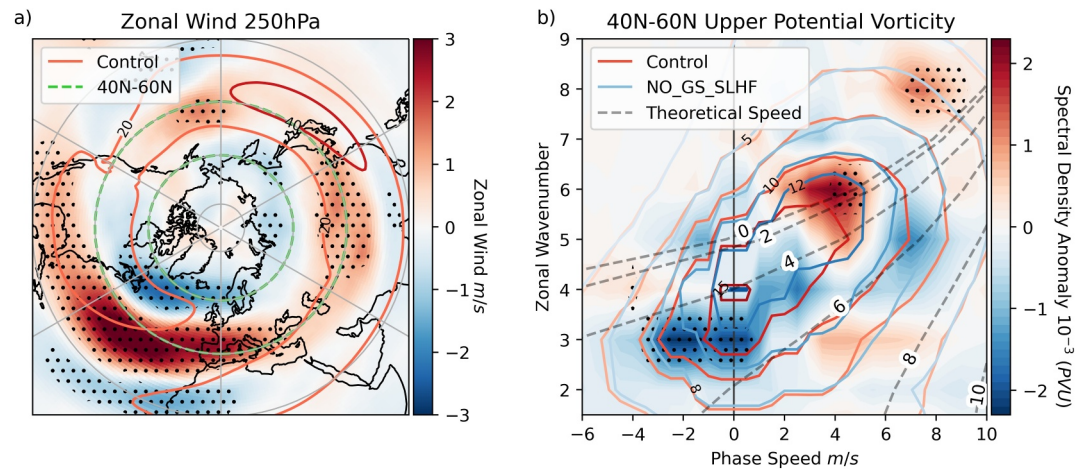


Figure 4. The zonal wind at 250 hPa (a) and the power spectrum of the vertically averaged anomalous potential vorticity field from 500 to 150 hPa within the latitudinal range of 40°–60°N (b) are presented. In both figures, the shading illustrates the difference between the NO_GS_SLHF and control runs, with the blue and red contours representing their respective reforecast means. The region between 40° and 60°N is indicated by green dashed lines. The theoretical phase speed for different meridional wavenumbers at 40°N, applying a background flow of 16.4 m/s as observed, is depicted with gray dashed lines. Areas that exceed the 95% confidence interval are highlighted with stippling.

Examining the seasonal change in this signal (Figure S5 in Supporting Information S1), the power spectrum shifts, with the most pronounced stationary wave changing from zonal wavenumber 4 in summer to 3 in winter, consistent with the increased zonal wind observed during winter. Furthermore, the difference between the NO_GS_SLHF and control runs shifts from the dipole signature seen in Figure 4b in summer to an overall reduction of wavenumbers 3–5 in winter. This again underscores the comparatively strong signal exerted by air-sea interactions in winter compared to summer. We now compare the difference between model resolutions.

3.3. Dependence on Model Resolution

First, Table 1 demonstrates a significant decrease in blocking frequency across all resolutions and initial dates for the entire NH when comparing the NO_GS_SLHF and control runs. The strength of this signal diminishes with decreased resolution, although this trend is primarily seen in winter, while the opposite trend is observed in summer. However, this pattern is less consistent within the first two weeks of the forecast, although Tco639 consistently exhibits the most substantial change.

Analyzing the change in blocking frequency for lower resolutions (Figures S6 and S7 in Supporting Information S1), we observe a smaller spatial signature in both lower resolution runs, with no propagation to the North Pacific. While the Tco199 run shows the largest spatial signature among the lower resolution runs, it has a considerably weaker magnitude. All resolutions show increased blocking over Northeastern Canada, shifting westward with lower resolution.

Figure 5 depicts the percentage change in atmospheric blocking characteristics across resolutions, with saturated color bars indicating significant results. This figure confirms that when GS SLHF is suppressed, blocks exhibit shorter duration, smaller size, and weaker intensity, though more individual blocks are detected. Notably, this signal is significant for all characteristics only at the highest resolution, Tco639.

Testing sensitivity to suppressed moisture fluxes between Tco639 and the two lower resolutions reveals no significant results, except for the block's average size, which is significant for both resolutions. Tco199 exhibits a larger difference between the two runs compared to Tco319 in all characteristics, consistent with Table 1.

To assess the robustness of this result, different overlap and PV anomaly thresholds were tested. For Tco639, blocking intensity and average size were significant for all overlap values below 0.7 and 0.6 at PV thresholds of -1.2 PVU and -1.3 PVU, respectively. However, blocking duration and the number of blocks detected showed strongest significance between 0.4 and 0.5 overlap for both PV anomaly thresholds. This sensitivity likely arises from merging and splitting events, altering the block's life-cycle and the number of individual blocks detected.

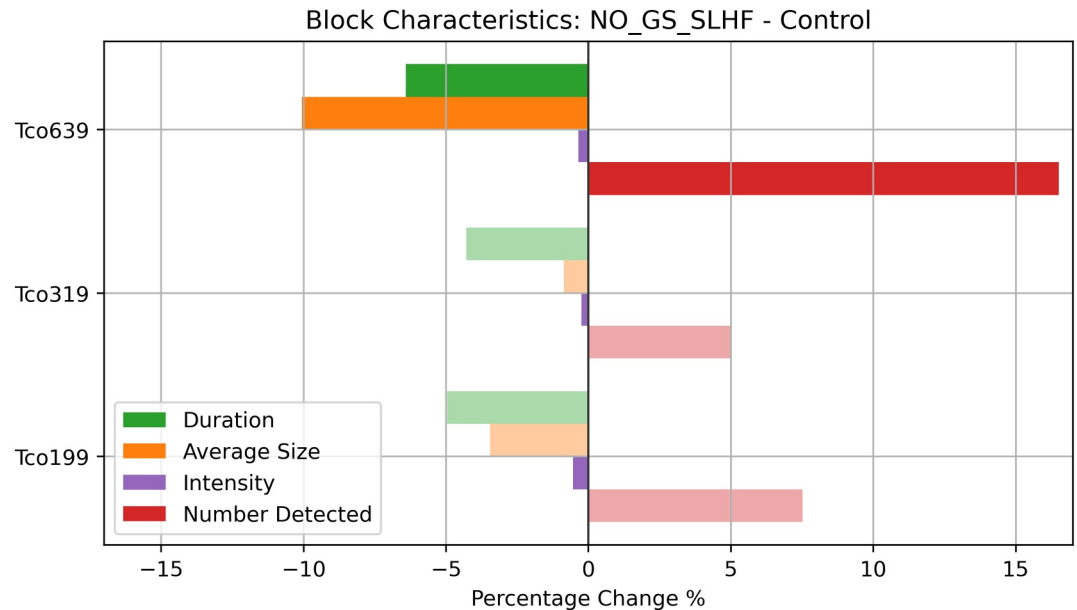


Figure 5. The percentage change in the block's characteristics for the NO_GS_SLHF run with respect to the control run versus resolution. The block's duration, average size, intensity, and the number of individual blocks detected per forecast are shown in green, orange, purple, and red, respectively. Fully saturated colors indicate changes over the 95% confidence level.

(Hauser et al., 2023). The change in sign was consistent across all threshold values. While air-sea interactions are suspected to help maintain blocks, their effect on blocking duration is less robust than on blocking size and intensity. Testing lower resolutions across threshold values shows a noisier signal, with occasional significant signals for block intensity and average size, particularly in Tco199. Neither lower resolution run exhibits significant signals for duration or the number of individual blocks detected.

4. Conclusions

In this study, the impact of suppressing GS SLHF on atmospheric blocking was analyzed using a coupled ensemble reforecast on the ECMWF IFS. When this air-sea interaction was suppressed:

1. Atmospheric blocking frequency reduced over the majority of the NH by up to 30%.
2. The duration, average size, and intensity of atmospheric blocks decreased by approximately 6.4%, 10.1%, and 0.35%, respectively. Additionally, a 16.5% increase in the number of individual blocks detected per forecast was observed.
3. Faster eastward-propagating Rossby waves with larger zonal wave numbers were evident.
4. Resolutions lower than Tco639 (~18 km) showed a weaker, non-significant change in block duration, average size, and the number of individual blocks detected. However, all resolutions exhibited a significant reduction in blocking frequency and intensity. Overall, the differences between resolutions were not statistically significant.

This experiment underscores the significant role that air-sea interactions, specifically the GS's SLHF, play in modulating atmospheric blocking and its impacts. The proposed theory by Mathews and Czaja (2024) suggests that air-sea interactions diabatically influence boundary layer air, which is then transported to the block via warm conveyor belts, altering the quality and quantity of its negative PV anomalies. Further research is needed to fully comprehend this process, including its seasonality and robustness across different models.

Data Availability Statement

The ECMWF IFS cycle 47R3 data used for the sensitivity experiment in the study are available through the ECMWF Web API via <https://apps.ecmwf.int/ifs-experiments/rd/hygz/>, where the experiment IDs are hygz, hyig, hwji, hydvd, i1ms, and i1m7 (Mathews et al., 2024a, 2024b, 2024c, 2024d, 2024e, 2024f). Spectral analysis

calculations were computed following Randel and Held (1991) using code from Jiménez-Esteve et al. (2022b) which is available at https://github.com/bernatj/paper_GRL_phase_locked_circumglobal_heat_extremes. Atmospheric blocks were detected following Schwierz et al. (2004) using the Steinfeld (2020) algorithm, which is available at <https://github.com/steidani/ConTrack>. Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview> (Hersbach et al., 2020).

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References

- Bouillon, S., Maqueda, M. A. M., Legat, V., & Fichefet, T. (2009). An elastic–viscous–plastic sea ice model formulated on Arakawa B and C grids. *Ocean Modelling*, 27(3–4), 174–184. <https://doi.org/10.1016/j.ocemod.2009.01.004>
- Davini, P., Cagnazzo, C., Gualdi, S., & Navarra, A. (2012). Bidimensional diagnostics, variability, and trends of Northern Hemisphere blocking. *Journal of Climate*, 25(19), 6496–6509. <https://doi.org/10.1175/jcli-d-12-00032.1>
- Davini, P., Weisheimer, A., Balmaseda, M., Johnson, S. J., Molteni, F., Roberts, C. D., et al. (2021). The representation of winter Northern Hemisphere atmospheric blocking in ECMWF seasonal prediction systems. *Quarterly Journal of the Royal Meteorological Society*, 147(735), 1344–1363. <https://doi.org/10.1002/qj.3974>
- de Rosnay, P., Browne, P., de Boissésion, E., Fairbairn, D., Hirahara, Y., Ochi, K., et al. (2022). Coupled data assimilation at ECMWF: Current status, challenges and future developments. *Quarterly Journal of the Royal Meteorological Society*, 148(747), 2672–2702. <https://doi.org/10.1002/qj.4330>
- ECMWF. (2021). *Iifs documentation CY47R3 - Part IV physical processes*. Author. <https://doi.org/10.21957/eyrpir4vj>
- ECMWF. (2023). *Iifs documentation*. ECMWF. Retrieved from <https://www.ecmwf.int/en/publications/iifs-documentation>
- Famoss Paolini, L., Athanasiadis, P. J., Ruggieri, P., & Bellucci, A. (2022). The atmospheric response to meridional shifts of the gulf stream sst front and its dependence on model resolution. *Journal of Climate*, 35(18), 6007–6030. <https://doi.org/10.1175/jcli-d-21-0530.1>
- Fichefet, T., & Maqueda, M. M. (1997). Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. *Journal of Geophysical Research*, 102(C6), 12609–12646. <https://doi.org/10.1029/97jc00480>
- Grams, C. M., Magnusson, L., & Madonna, E. (2018). An atmospheric dynamics perspective on the amplification and propagation of forecast error in numerical weather prediction models: A case study. *Quarterly Journal of the Royal Meteorological Society*, 144(717), 2577–2591. <https://doi.org/10.1002/qj.3353>
- Hauser, S., Teubler, F., Riemer, M., Knippertz, P., & Grams, C. M. (2023). Towards a holistic understanding of blocked regime dynamics through a combination of complementary diagnostic perspectives. *Weather and Climate Dynamics*, 4(2), 399–425. <https://doi.org/10.5194/wcd-4-399-2023>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hewitt, H. T., Bell, M. J., Chassignet, E. P., Czaja, A., Ferreira, D., Griffies, S. M., et al. (2017). Will high-resolution global ocean models benefit coupled predictions on short-range to climate timescales? *Ocean Modelling*, 120, 120–136. <https://doi.org/10.1016/j.ocemod.2017.11.002>
- Jiménez-Esteve, B., Kornhuber, K., & Domeisen, D. (2022a). Heat extremes driven by amplification of phase-locked circumglobal waves forced by topography in an idealized atmospheric model. *Geophysical Research Letters*, 49(21), e2021GL096337. <https://doi.org/10.1029/2021gl096337>
- Jiménez-Esteve, B., Kornhuber, K., & Domeisen, D. (2022b). Phase locked heat extremes [Software]. *GitHub*. Retrieved from https://github.com/bernatj/paper_GRL_phase_locked_circumglobal_heat_extremes
- Madec, G., Bourdallé-Badie, R., Bouttier, P.-A., Bruciaferri, D., Calvert, D., et al. (2017). NEMO ocean engine.
- Mathews, J., & Czaja, A. (2024). Oceanic maintenance of atmospheric blocking in wintertime in the North Atlantic. *Climate Dynamics*, 1–14. <https://doi.org/10.1007/s00382-024-07196-0>
- Mathews, J., Vitart, F., & Robers, C. (2024a). Tco199 control run [Dataset]. *ECMWF*. Retrieved from <https://apps.ecmwf.int/iifs-experiments/rd/i1ms/>
- Mathews, J., Vitart, F., & Robers, C. (2024b). Tco199 NO_GS_SLHF run [Dataset]. *ECMWF*. Retrieved from <https://apps.ecmwf.int/iifs-experiments/rd/i1m7/>
- Mathews, J., Vitart, F., & Robers, C. (2024c). Tco319 control run [Dataset]. *ECMWF*. Retrieved from <https://apps.ecmwf.int/iifs-experiments/rd/hwji/>
- Mathews, J., Vitart, F., & Robers, C. (2024d). Tco319 NO_GS_SLHF run [Dataset]. *ECMWF*. Retrieved from <https://apps.ecmwf.int/iifs-experiments/rd/hydv/>
- Mathews, J., Vitart, F., & Robers, C. (2024e). Tco639 control run [Dataset]. *ECMWF*. Retrieved from <https://apps.ecmwf.int/iifs-experiments/rd/hygz/>
- Mathews, J., Vitart, F., & Robers, C. (2024f). Tco639 NO_GS_SLHF run [Dataset]. *ECMWF*. Retrieved from <https://apps.ecmwf.int/iifs-experiments/rd/hyig/>
- Pfahl, S., Schwierz, C., Croci-Maspoli, M., Grams, C. M., & Wernli, H. (2015). Importance of latent heat release in ascending air streams for atmospheric blocking. *Nature Geoscience*, 8(8), 610–614. <https://doi.org/10.1038/ngeo2487>
- Pfahl, S., & Wernli, H. (2012). Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-) daily time scales. *Geophysical Research Letters*, 39(12), L12807. <https://doi.org/10.1029/2012gl052261>
- Randel, W. J., & Held, I. M. (1991). Phase speed spectra of transient eddy fluxes and critical layer absorption. *Journal of the Atmospheric Sciences*, 48(5), 688–697. [https://doi.org/10.1175/1520-0469\(1991\)048<0688:pssote>2.0.co;2](https://doi.org/10.1175/1520-0469(1991)048<0688:pssote>2.0.co;2)
- Riboldi, J., Lott, F., d'Andrea, F., & Rivière, G. (2020). On the linkage between Rossby wave phase speed, atmospheric blocking, and arctic amplification. *Geophysical Research Letters*, 47(19), e2020GL087796. <https://doi.org/10.1029/2020gl087796>
- Schwierz, C., Croci-Maspoli, M., & Davies, H. (2004). Perspicacious indicators of atmospheric blocking. *Geophysical Research Letters*, 31(6), L06125. <https://doi.org/10.1029/2003gl019341>
- Steinfeld, D. (2020). ConTrack - Contour tracking [Software]. *GitHub*. Retrieved from <https://github.com/steidani/ConTrack>
- Steinfeld, D., Boettcher, M., Forbes, R., & Pfahl, S. (2020). The sensitivity of atmospheric blocking to upstream latent heating–numerical experiments. *Weather and Climate Dynamics*, 1(2), 405–426. <https://doi.org/10.5194/wcd-1-405-2020>

- Wenta, M., Grams, C. M., Papritz, L., & Federer, M. (2024). Linking Gulf Stream air–sea interactions to the exceptional blocking episode in February 2019: A Lagrangian perspective. *Weather and Climate Dynamics*, 5(1), 181–209. <https://doi.org/10.5194/wcd-5-181-2024>
- Woollings, T., Barriopedro, D., Methven, J., Son, S.-W., Martius, O., Harvey, B., et al. (2018). Blocking and its response to climate change. *Current Climate Change Reports*, 4(3), 287–300. <https://doi.org/10.1007/s40641-018-0108-z>
- Yamamoto, A., Nonaka, M., Martineau, P., Yamazaki, A., Kwon, Y.-O., Nakamura, H., & Taguchi, B. (2021). Oceanic moisture sources contributing to wintertime Euro-Atlantic blocking. *Weather and Climate Dynamics*, 2(3), 819–840. <https://doi.org/10.5194/wcd-2-819-2021>
- Zuo, H., Balmaseda, M. A., Tietsche, S., Mogensen, K., & Mayer, M. (2019). The ECMWF operational ensemble reanalysis–analysis system for ocean and sea ice: A description of the system and assessment. *Ocean Science*, 15(3), 779–808. <https://doi.org/10.5194/os-15-779-2019>