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LETTERS

Influence of the Gulf Stream on the troposphere

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The Gulf Stream transports large amounts of heat from the tropics to middle and high latitudes, and thereby affects weather phenomena such as cyclogenesis[1,2] and low cloud formation[3]. But its climatic influence, on monthly and longer timescales, remains poorly understood. In particular, it is unclear how the warm current affects the free atmosphere above the marine atmospheric boundary layer. Here we consider the Gulf Stream's influence on the troposphere, using a combination of operational weather analyses, satellite observations and an atmospheric general circulation model[4]. Our results reveal that the Gulf Stream affects the entire troposphere. In the marine boundary layer, atmospheric pressure adjustments to sharp sea surface temperature gradients lead to surface wind convergence, which anchors a narrow band of precipitation along the Gulf Stream. In this rain band, upward motion and cloud formation extend into the upper troposphere, as corroborated by the frequent occurrence of very low cloud-top temperatures. These mechanisms provide a pathway by which the Gulf Stream can affect the atmosphere locally, and possibly also in remote regions by forcing planetary waves[5,6]. The identification of this pathway may have implications for our understanding of the processes involved in climate change, because the Gulf Stream is the upper limb of the Atlantic meridional overturning circulation, which has varied in strength in the past[7] and is predicted to weaken in response to human-induced global warming in the future[8].

It is a challenging task to isolate the climatic influence of the Gulf Stream from energetic weather variability using conventional observations, which are spatially and temporally sporadic. Recently, high-resolution satellite observations of surface winds made it possible to map the influence of the Gulf Stream[9,10] and other major sea surface temperature (SST) fronts[11–14] on the near-surface atmosphere. The Gulf Stream affects the 10-m wind climatology as observed by the QuikSCAT satellite[15], with wind divergence and convergence on the cold and warm flanks, respectively, of the Gulf Stream front[9,10] (Fig. 1a). However, the mechanism by which the SST fronts influence surface winds is still under much debate[9,10]

The identification of the mechanism responsible has been hampered by the need to know parameters not available from satellite observations, for which we turn to high-resolution atmospheric operational analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF). The operational analysis successfully captures the observed pattern of wind divergence (Fig. 1b). Interestingly, the wind convergence closely resembles the pattern of the laplacian of sea-level pressure (∇^2SLP) (Fig. 1c). This correspondence is consistent with an immediate consequence of a marine atmospheric boundary layer (MABL) model[16] (see Methods Summary). Note that it is virtually impossible to see the correspondence between the wind convergence and SLP itself without taking the laplacian. The laplacian operator acts as a high-pass filter, unveiling the SST frontal effect that is masked by large-scale atmospheric circulations.

In contrast to the free atmosphere where wind velocities are nearly non-divergent, substantial divergence occurs in the MABL in the presence of strong friction and is proportional to the SLP laplacian in the MABL model described in the Methods Summary. Such a linear relation approximately holds in observations (Fig. 1f), with a correlation coefficient as high as 0.70 for a region where wind

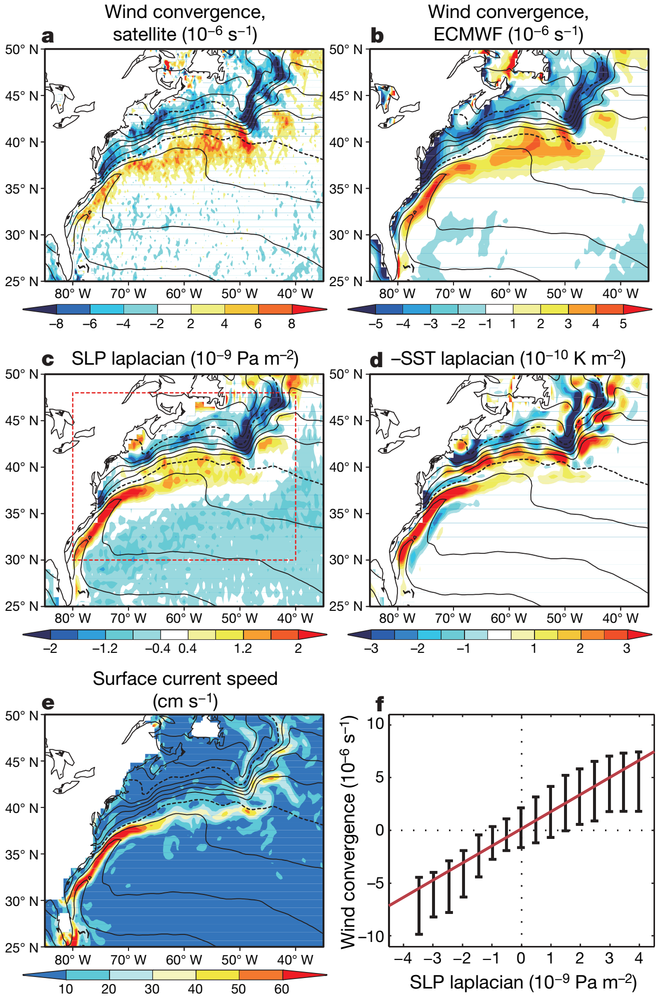

Figure 1 | Annual climatology of surface parameters. a, b, 10-m wind convergence (colour) in QuikSCAT satellite observations (**a**) and in the ECMWF analysis (**b**). **c, d,** SLP laplacian (**c**) and sign-reversed SST laplacian (**d**) in the ECMWF analysis. **e,** Surface geostrophic current speed. In **a–e**, SST contours (2 °C interval and dashed contours for 10 °C and 20 °C) are shown. **f,** Relationship between the SLP laplacian and wind convergence based on monthly climatology in the red-dashed box in **c**; the regression line is shown red. Error bars, ±1 s.d. of wind convergence for each bin of SLP.

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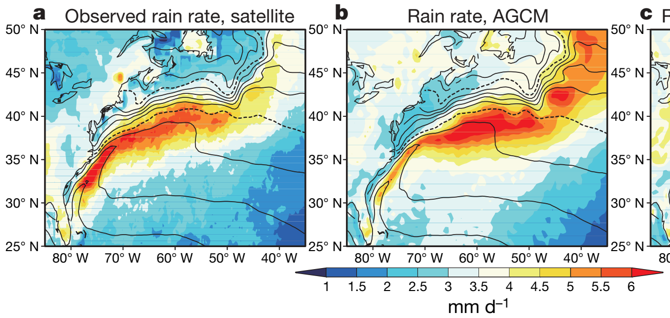

Figure 2 | Annual climatology of rain rate. **a**, Observed by satellites. **b**, **c**, In the AGCM with observed (**b**) and smoothed (**c**) SSTs. Contours are for SST, as in Fig. 1.

convergence and divergence are strong (80°–40° W, 30°–48° N, red-dashed box in Fig. 1c). Furthermore, consistent with the MABL model[16] where SST variations force pressure adjustments, the pattern of laplacian SST with sign reversed ($-\nabla^2$SST) exhibits some similarities to laplacian SLP and wind convergences (Fig. 1d). These results indicate that MABL pressure adjustments to SST gradients near the Gulf Stream are important for surface wind divergence. Relatively high pressures on the colder flank and relatively low pressures on the warmer flank induce cross-frontal components of near-surface winds, leading to divergence and convergence (Supplementary Fig. 1).

Previous studies suggested that warmer SSTs induce stronger vertical momentum mixing, and the enhanced mixing is responsible for mesoscale features in the surface wind convergence field[9,10], consistent with a numerical model experiment focusing on near-surface adjustments[17]. Our observational result indicates the importance of the overlooked pressure adjustment mechanism, consistent with both a recent short (a few days) regional model experiment for the Gulf Stream[18] and a numerical study of tropical instability waves[19]. Note that the observed surface wind convergence is roughly collocated with the axis of the Gulf Stream (Fig. 1e, Supplementary Fig. 1).

Satellite observations further reveal that the Gulf Stream anchors a narrow rain band roughly collocated with the surface wind convergence (Fig. 2a). Although there was evidence that the Gulf Stream affects precipitation[20], our high-resolution analysis reveals that the narrow rain band meanders with the Gulf Stream front and is confined to its warmer flank with SSTs greater than 16 °C. This close co-variation in space is strongly indicative of an active role of the Gulf Stream. The precipitation pattern is well reproduced in the operational analysis (Supplementary Fig. 2), with a bias of excessive rain rates compared to satellite observations.

The causality is further examined using an atmospheric general circulation model (AGCM)[4]. It successfully captures the rain band following the meandering Gulf Stream, although the rain rate near the coast is somewhat too weak compared with satellite observations (Fig. 2b). When the SST is smoothed (see Methods for details), however, the narrow precipitation band disappears in the AGCM (Fig. 2c). Compared to the smoothed SST run, rain-bearing low-pressure systems tend to develop along the Gulf Stream front in the control simulation (Supplementary Fig. 3). These results indicate that the narrow precipitation band in the western North Atlantic results from the forcing by the sharp SST front of the Gulf Stream.

Similar to precipitation, surface evaporation also exhibits a narrow banded structure on the offshore side of the SST front (Supplementary Fig. 2). This evaporation band is consistent with a short-term field observation[21]. The amount of evaporation is slightly larger than that of precipitation, indicating that local evaporation supplies much of the water vapour for precipitation. The local enhancement of evaporation on the warmer flank of the Gulf Stream is due to enhanced wind speed and the large disequilibrium of air temperature from SST[9,13].

As precipitation off the US east coast is often associated with deep weather systems, the rainfall pattern described above suggests that the Gulf Stream's influence may penetrate to the free atmosphere. Indeed, the upward motion across the Gulf Stream displays a deep structure extending to the upper troposphere (Fig. 3a). The upward motion is anchored by wind convergence in the MABL (Fig. 3a). The latter peaks at the sea surface, and is strongly affected by SST (Fig. 1). It is interesting to note that although surface convergence and divergence are similar in magnitude (Fig. 1), the upward motion over surface wind convergence is much stronger and deeper than the downward motion over the wind divergence (Fig. 3a). This is suggestive of the importance of condensational heating above the MABL in developing the asymmetry between the upward and downward motion.

The upward wind velocity is strongest just above the MABL between the 850 and 700 hPa levels (Fig. 3a). The horizontal distribution at these levels is quite similar to the distribution of the surface convergence. The structure trapped by the Gulf Stream is clearly visible at 500 hPa and remains discernible at the 300 hPa level (Supplementary Fig. 4). Remarkably, the divergence in the upper troposphere is also dominated by a meandering band following the Gulf Stream front (Fig. 3b)—such a pattern is required by mass conservation, with the tropopause acting virtually as a lid for the mean circulation.

Next we examine the occurrence of high clouds, and infer cloud-top temperature using three-hourly outgoing long-wave radiation (OLR) derived from satellite observations. Lower OLR levels indicate lower temperatures and higher altitudes of cloud tops. Figure 3c shows the occurrence rate of OLR lower than 160 W m^{-2}, which roughly corresponds to a cloud-top height of about 300 hPa. A narrow band of high occurrence hugs the SST front of the Gulf Stream in

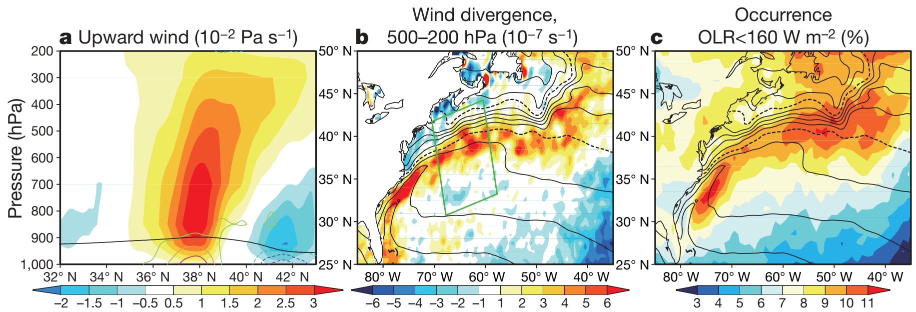

Figure 3 | Annual climatology of parameters connecting MABL and free atmosphere. **a**, Vertical wind velocity (upward positive; colour), boundary layer height (black curve) and wind convergence (contours for $\pm 1, 2, 3 \times 10^{-6}\,\mathrm{s}^{-1}$) averaged in the along-front direction in the green box in **b**, based on the ECMWF analysis. **b**, Upper-tropospheric wind divergence averaged between 200 and 500 hPa (colour). **c**, Occurrence frequency of daytime satellite-derived OLR levels lower than 160 W m^{-2} (colour). Contours in **b** and **c** are for SST, as in Fig. 1.

daytime. This high-occurrence band is slightly shifted to the north compared with the bands of surface wind convergence and precipitation, consistent with the northward tilt of positive vertical velocity towards higher altitudes (Fig. 3a). At night time, the Gulf Stream-related signature is less prominent, suggesting a diurnal cycle of atmospheric convection. Our OLR result is consistent with fragmental evidence reported previously. Satellite observations showed a high frequency of lightning occurrence along the Gulf Stream, indicative of cold ice clouds[22]. With a limited offshore coverage, coastal radars showed an echo height distribution suggestive of deep convection over the Gulf Stream[23]. The Gulf Stream's signature in high cloud as reported here is strong evidence that the influence of the Gulf Stream on the atmosphere is not limited to the MABL, as reported previously[9,10], but penetrates deeply into the upper troposphere.

In summary, the present study shows that the Gulf Stream affects the entire troposphere, from the surface to the tropopause, in a systematic manner (Supplementary Fig. 1). In the MABL, the Gulf Stream directly influences air temperature and pressure fields. The resultant relatively low (high) pressures on the warm (cold) flank of the Gulf Stream front cause wind convergence (divergence). The Gulf Stream-induced convergence anchors the upward motion where precipitation is locally enhanced providing diabatic heating to the atmosphere. Remarkably, upper-tropospheric divergence shows a banded structure similar to the surface convergence and precipitation patterns, all meandering with the Gulf Stream. The deep influence of the Gulf Stream is further corroborated by frequent occurrence of high-level clouds along it. We thus suggest that on the warmer flank of the Gulf Stream front, roughly corresponding to the current axis, high instability of the atmosphere as manifested in enhanced latent and sensible heat flux leads to deep convection, enabling the influence of this warm ocean current to reach the entire troposphere.

Diabatic heating originating from surface heat fluxes over the North Atlantic Ocean is important for maintaining climatological circulations of the atmosphere, both over the ocean basin and in downwind regions, including Europe[5,6]. Deep condensational heating by the Gulf Stream and the resultant upper-tropospheric divergence revealed by this study may be important for generating stationary Rossby waves that produce remote responses (Supplementary Fig. 5). Indeed, several recent studies suggested that SST anomalies near the Gulf Stream induce atmospheric circulation changes[24–26], with significant feedback from changes in synoptic eddies[27].

The Gulf Stream is the upper limb of Atlantic meridional overturning circulation (AMOC). Both the AMOC and the Gulf Stream display large variability in palaeoclimate observations[28]. How the effects of AMOC changes in the middle-to-high latitudes are transmitted throughout the Northern Hemisphere has been a long-standing problem[7]. Whereas recent coarse-resolution model simulations pointed to the tropical Atlantic as an important conduit[29], our results suggest an additional, more direct pathway via the Gulf Stream's deep heating of the atmosphere. The AMOC is projected to slow down in response to increasing greenhouse-gas concentrations[8], giving rise to changes in the Gulf Stream[30]. It is conceivable that such Gulf Stream changes would cause precipitation anomalies along the warm current, and induce atmospheric circulation changes by way of adjustments in planetary waves and storm tracks.

METHODS SUMMARY

We used the following satellite products: QuikSCAT wind velocity on a 0.25° grid from Remote Sensing Systems; the TRMM 3B43 precipitation product derived from the Tropical Rainfall Measuring Mission (TRMM) and other satellite data on a 0.25° grid; three-hourly OLR data on a 1° grid from the NASA Langley Atmospheric Science Data Center; and monthly sea surface geostrophic current velocity on a 1/3° Mercator grid distributed by Aviso. The monthly operational analysis was provided by the European Centre for Medium-Range Weather Forecasts with an original model resolution of 38 km and re-gridded on a 1/2° grid. The AGCM has T239 horizontal resolution (~50 km) and 48 levels[4]. The analysis period is from January 2002 to February 2006, except for the OLR data that end in June 2005. More detailed information can be found in Methods.

To understand the relation between wind convergence and SLP laplacian, we use an MABL model[16]. Its momentum equations may be cast as $\varepsilon u - fv = -p_x/\rho_0$, $\varepsilon v + fu = -p_y/\rho_0$, where x and y are the eastward and northward coordinates, respectively, u and v are the surface wind velocities in the respective directions, ρ_0 is the MABL density, p is the pressure, ε is the constant damping coefficient, and f is the Coriolis parameter. It can be shown that the wind speed convergence is proportional to the laplacian of pressure: $-(u_x + v_y)\rho_0 = (p_{xx} + p_{yy})\varepsilon/(\varepsilon^2 + f^2)$. In the model, SLP is forced by SST[16]: $\varepsilon p + H(u_x + v_y) = -\gamma T$, where T is the SST, γ is a constant, and H is the equivalent depth. Thus, a relation between the SST laplacian and wind convergence is also expected, albeit one weaker than that for the SLP laplacian.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.M. analysed satellite and operational data, N.K. and A.K.-Y. conducted and analysed AGCM experiments, R.J.S. conducted experiments using a linear baroclinic model and analysed the results, and S.M. and S.-P.X. wrote the paper. All authors discussed the results and commented on the manuscript.

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METHODS

ECMWF operational analysis. Wind velocity at 10-m height, SLP, precipitation amount, surface latent heat flux (evaporation), and vertical wind velocity are used from the ECMWF operational product. Among these parameters, wind velocity and SLP are taken from the analysis while precipitation and latent heat flux are taken from the forecast output. Consistency between the analysis and the forecast was confirmed by a comparison of SLPs between the analysis and forecast. The atmospheric model uses a spectral dynamical core with TL511 resolution, equivalent to a grid resolution of approximately 38 km. Combined with this high model resolution, the use of high-resolution real-time, global (RTG) SST[31] substantially improves the representation of the near-surface atmospheric response to SST variations[12].

Atmospheric GCM. We conduct numerical experiments using an AGCM, called the Atmospheric general circulation model for the Earth Simulator (AFES) version 2[4]. The horizontal resolution is T239, with 48 vertical levels. AFES employs daily RTG SST as the lower boundary condition in the control simulation. We also conduct an AGCM experiment by spatially smoothing SSTs over the central-western North Atlantic (100°–30° W, 25°–55° N). The smoothing is conducted by applying a 1-2-1 running mean filter both in the zonal and meridional directions 100 times on a 0.5° grid. This low-pass filter has the half power point at 26.8°.

Satellite data. Four satellite products are analysed. Near-surface wind velocity is measured by a sea-winds scatterometer sensor (referred to as QuikSCAT) on the QuikBird satellite. The sea-winds sensor is an active radar scatterometer using high-frequency microwave pulses. We use twice-daily QuikSCAT product from Remote Sensing Systems (http://www.remss.com).

For precipitation, we use the Tropical Rainfall Measuring Mission (TRMM) 3B43 product, derived from TRMM and other satellite observations: geosynchronous infrared radiometer, Special Sensor Microwave/Imager (SSM/I), rain gauge, and the TRMM 3B31 product based on the precipitation radar and microwave imager on the TRMM satellite. The TRMM 3B43 product is available at Goddard Earth Sciences Data and Information Services Center (http://daac.gsfc.nasa.gov). Similar results are obtained from another satellite-based precipitation estimate derived from a series of SSM/I satellites.

Global three-hourly OLR data are provided as a part of the Surface Radiation Budget data set available at the NASA Langley Atmospheric Science Data Center (http://eosweb.larc.nasa.gov). We analyse the data from January 2002 to June 2005 (the latest). We identify daytime as when Universal Time is from 12:00 to 21:00, which corresponds to local time from 7:00 to 16:00 at 75° W.

Sea surface geostrophic currents are estimated from satellite altimetry data and the mean dynamic topography. The data are obtained from Aviso (http://www.aviso.oceanobs.com/). The satellite altimetry data combine measurements from the Topex/Poseidon, ERS-1/2, Jason-1 and Envisat satellites[32] while the mean dynamic topography is estimated from geoid models, hydrograph data, and buoys[33].

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