Modification of surface winds near ocean fronts: Effects of Gulf Stream rings on scatterometer (QuikSCAT, NSCAT) wind observations

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Modifications to surface winds by currents and sea surface temperature (SST) gradients near frontal boundaries of Gulf Stream rings are analyzed using satellite SST and scatterometer (NASA’s Quick Scatterometer (QuikSCAT), NASA scatterometer (NSCAT)) wind observations. A component of scatterometer wind approximately equal and opposite to the surface current vector is observed and attributed to the fact that scatterometers detect relative motion of water and air. Warm-core ring (WCR) SSTs act to destabilize the marine atmospheric boundary layer (MABL), increasing surface wind magnitude by 10–15% and decreasing veering angle by 5–15° relative to large-scale mean winds. Cold-core ring (CCR) SSTs cause impacts of similar magnitude and opposite sense. Magnitudes and directions of modifications are accounted for by MABL dynamics of a nonlinear planetary boundary layer model forced by air-sea temperature differences. Wind modifications occur within tens of kilometers of SST fronts, implying a wind response timescale of order 1 hour. By contrast, uniformity of modified winds across the larger area within rings suggests the response time for the MABL to return to equilibrium downstream from a front exceeds 10 hours. Over WCRs, strong divergence (convergence) occurs on the upwind (downwind) side; curl is strongly negative (positive) to the right (left) side facing downwind. Opposite patterns are generally seen over CCRs. Divergence (curl) peaks where winds blow perpendicular (parallel) to SST fronts. SST image analysis indicates enhanced cloudiness occurs with downwind convergence over WCRs. Wind stress curl due to ring modifications causes dipolar Ekman pumping sufficient to influence ring translation and decay processes.


1. Introduction

Ocean fronts are recognized as important sites for air-sea interaction. Well-known persistent large-scale frontal regions, such as the equatorial zone of the eastern Pacific or the north wall of the Gulf Stream, have been the target of most observational analyses. Here the focus is on fronts that bound Gulf Stream rings. We exploit the ability of satellite measurements of sea surface temperature (SST) and scatterometer surface winds to follow moving rings. This work builds on recent studies [Cornillon and Park, 2001; Park and Cornillon, 2002] that demonstrate how ocean currents and changes in marine atmospheric boundary layer (MABL) stability associated with rings affect the surface wind stress observed by scatterometers.

[3] Previous studies have explored relationships between SST and surface winds at numerous locations. Eastern equatorial Pacific winds blowing northward across a front, from cold SST to warm, cause a pronounced horizontal divergence [Wallace et al., 1989]. FASINEX (Frontal Air-Sea Interaction Experiment) examined effects on MABL turbulent fluxes in a frontal region southwest of Bermuda [Rogers, 1989] and found that larger sea-air temperature and humidity differences give rise to larger sensible, latent, and buoyancy fluxes on the warm side of the front [Khalsa and Greenhut, 1989]; Friehe et al. [1991] found that for across-front winds blowing toward warmer (colder) SST, on the downstream side the MABL stability decreased (increased), while the downstream backscattering and wave heights were reduced significantly [Song et al., 2004] for winds blowing toward the cold side. In an analysis spanning the major oceans, Wentz et al. [2000] found that surface winds and weekly SST from TMI (TRMM, Tropical Rainfall Measuring Mission, Microwave Imager) were strongly correlated. In the Arabian Sea, Vecchi et al. [2004] noted higher (lower) wind speeds over regions of higher (lower) SST. Over cold ocean regions Xie [2004] demonstrated a
positive SST-wind speed correlation. In the Southern Ocean, O'Neill et al. [2003] observed relationships between SST gradients and wind curl and divergence. The dependence of air-sea momentum transport (wind stress) on the wind relative to surface current has a long history of investigations related to the bulk parameterization of drag coefficient [e.g., Liu et al., 1979]. Aspects of the influence ocean currents have on wind parameters are examined in global-scale analyses by Chelton et al. [2004], who describe persistent patterns in scatterometer wind stress curl associated with major currents, and Kelly et al. [2001], who find a strong relationship between ocean currents and the difference between winds measured by scatterometer and by moored instruments. The analysis of tropical instability waves by Polito et al. [2001] includes an example of the bias introduced in scatterometer winds by ocean currents.

[4] Gulf Stream rings can be considered in many ways to be ideal experimental laboratories for observing frontal air-sea interaction processes. They exist as warm-core rings (WCRs) and cold-core rings (CCRs) with inner regions of opposing anomaly sense and therefore differing influences on MABL stability. They are bounded by fronts having strong gradients, comparable to the important persistent fronts found globally. All angles between wind and front are present for each ring because the horizontal scale of winds exceeds typical ring sizes. Satellite measurements of SST and surface winds resolve ring spatial and temporal scales well. Furthermore, there is an advanced level of understanding of many other ring characteristics based on extensive previous observational and modeling studies [e.g., Joyce, 1984; Evans et al., 1985; Joyce and Kennelly, 1985; Lai and Richardson, 1977; Schmitt and Olson, 1985; Nof, 1983; Dewar and Flierl, 1987; Olson et al., 1985]. For example, ring translation has been analyzed using satellite-tracked drifting buoys [Richardson, 1980] and by tracing the ring centers time-consecutively from infrared images [Cornillon et al., 1989; Hooker and Brown, 1994].

[5] In this study, two main effects of rings on winds are considered and interpreted using scatterometer (NASCAT, QuikSCAT) winds. The first main effect is due to water velocities associated with rings, and underscores that scatterometer winds should be interpreted as wind relative to ocean surface currents, not as absolute wind. The second main effect results from modifications to the MABL by SST fronts at ring boundaries. For neither effect is the emphasis here on analyzing errors or artifacts in scatterometer winds, although it is true that if scatterometer winds are interpreted as absolute winds then the present analysis can be viewed as identifying and quantifying a component of their error which is due to ocean currents. In addition, it is recognized that the scatterometer wind products used are equivalent-neutral, so denoted because they have been determined using a cross-section function developed for a neutrally stable MABL; the analysis supports the view adopted, that errors in the scatterometer wind retrieval algorithm associated with deviations from MABL neutrality are less important than changes to true winds associated with different MABL conditions. Wind modifications associated with the influence of SST fronts on the MABL are investigated through comparison with an updated version of a representative planetary boundary layer (PBL) model from University of Washington [Brown, 1982]. Spatial distributions of the divergence and curl of wind stress near rings are also examined, given their known dynamical importance, and a relationship between observed surface wind divergence and cloudiness is demonstrated.

1.1. Influence of Ring Currents

[6] A conceptual model for idealized ring and wind interaction (Figure 1) demonstrates the effect of currents on scatterometer winds. This subsection considers a neutral MABL, in order to isolate effects of currents for the sake of discussion; for nonneutral conditions fundamental aspects of the effects of currents are expected to be similar. The horizontally uniform wind blows unmodified from south to north over a circular Gulf Stream ring. Currents of the WCR (Figure 1a) are clockwise, and those of the CCR (Figure 1b) counterclockwise. They are assumed purely azimuthal, increasing in magnitude linearly from zero at the center to 1 m s⁻¹ at the outer radius, and absent at larger radii. Because scatterometers measure the relative stress between moving air and moving water, different patterns in scatterometer winds occur over a WCR (Figure 1c) and a CCR (Figure 1d). Where the wind is roughly aligned in the same direction as the current (to the left side of a WCR, for example) reduced values will be observed, and vice versa. A generally cyclonic (anticyclonic) curvature in the scatterometer wind is seen over a WCR (CCR), though the absolute wind is horizontally uniform.

[7] Wind stress at the sea surface is conventionally parameterized,

\[ \tau = \rho_0 C_D \mathbf{U}_{10} \cdot \mathbf{n} \quad \text{or} \quad \tau = \rho_0 C_D \mathbf{U}_{10} \cdot \mathbf{U}_{10}, \]  

(1)

where \( \rho_0 \) is air density, \( C_D \) a drag coefficient, and \( \mathbf{U}_{10} \) is the absolute wind vector with respect to fixed earth coordinates, the subscript indicating 10-m height above the sea surface as is commonly used. The normalized radar backscatter cross-section \( \sigma_0 \) measured is treated [Jet Propulsion Laboratory, 1998] using known empirical relationships of the form

\[ \sigma_0 = F(U_{10}, \chi, ..., f, p, \theta), \]

(2)

where \( \chi \) is the azimuth angle between wind and incident radar, \( f \) is the radar frequency, \( p \) is the polarization, \( \theta \) is the incidence altitude angle, and dependence on various other geophysical parameters is also included. In practice, the wind vector \( \mathbf{U}_{10} \) is calculated using measured \( \sigma_0 \) and inversion of the empirical cross-section function, with no knowledge of the surface current.

[8] It is reasonable to expect that a more faithful representation of the stress between moving air and moving sea surface is provided by substitution of the relative vector between wind and sea-surface current \( \mathbf{U} \) into the expression for stress,

\[ \tau' = \rho_0 C_D \left( \mathbf{U}_{10} - \mathbf{U} \right) \cdot \left( \mathbf{U}_{10} - \mathbf{U} \right), \]

(3)

In fact, it is the momentum flux effectively imparted by \( \tau' \) that gives rise to the capillary and short gravity waves from which radar backscatter is measured by scatterometers. It
follows that there is some justification to consider the known cross-section relationship to apply as

\[ \sigma_0 = F(\tilde{U}_{10} - \tilde{u}, \chi, \ldots, f, p, 0). \]  

(4)

Hence, because

\[ \sigma_0(\tilde{U}_{10} - \tilde{u}) \simeq \sigma_0(\tilde{U}_{10}) - \sigma_0(\tilde{u}) \propto \tilde{U}_{10} - \tilde{u}, \]  

(5)

the \( \tilde{U}_{10} \) conventionally determined by scatterometers would better be treated as \( \tilde{U}_{10} - \tilde{u} \), the 10-m wind relative to surface currents, as opposed to the absolute wind.

[9] In summary, over strong ocean currents such as Gulf Stream rings, to the extent that other processes are less important, scatterometer winds (as presently calculated without use of surface current information) are expected to include a component approximately equal and opposite to the surface current. Hence an improved estimate of the absolute wind can be found as the sum of the conventionally determined scatterometer wind vector and the surface ocean current vector. In this paper direct quantitative evidence for this effect is presented based on statistics of multiple Gulf Stream ring realizations.

1.2. Influence of SST Differences

[10] The second main effect considered is the influence of SST differences across ring boundaries have on surface winds by modifying the MABL. High SST within WCRs is a destabilizing influence on the MABL, enhances vertical latent and sensible heat fluxes, and promotes more active vertical turbulence. This will more effectively transmit the higher momentum of aloft winds downward, therefore amplifying surface winds. Over CCRs the opposite influence is felt, hence tending to reduce surface winds.

[11] A key parameter is the difference between SST and surface air temperature, \( T_s - T_a \), for which increasingly positive values reduce MABL stability. Because direct measurements of \( T_a \) that resolve Gulf Stream rings are unavailable, the proxy used here for \( T_s - T_a \) over the interior of a ring is \( T_{Inner} - T_{Outer} \), the difference between SST within and outside the ring. It is recognized that magnitudes will likely differ, but the two quantities are expected to be strongly correlated. The proxy is supported by the reasonable expectation that outside the ring the MABL is more nearly in equilibrium than inside the ring hence the large-scale average air temperature and SST are more nearly the same than within the ring.

[12] The focus of the present analysis is effects due to SST variations, which act through their modifications to the MABL, on actual winds. Effects of parameters related to atmospheric stability, SST, viscosity, and sea state on scatterometer retrieval methods, including errors and artifacts, have been examined extensively elsewhere [e.g., Liu, 1984; Keller et al., 1989; Wu, 1991; Quilfen et al., 2001]. For a fixed absolute wind speed, viscosity increases (decreases) associated with SST decreases (increases) act to dampen capillary waves more (less) strongly and can contribute to weaker (stronger) scatterometer wind. The viscosity effect is similar in sense to the MABL dynamics of interest here, and therefore could potentially partially...
account for some of our results. However, dependence on viscosity is generally thought to be less important than MABL influences (see, e.g., Long [1996] and references cited therein for further discussion).

[13] Methods applied for data processing, and for comparisons between observations and modeling, are explained in section 2. Section 3 is a description of baseline observations. Section 4 presents results: observed modifications of winds over rings, comparisons to PBL model output, and attributes of wind stress divergence and curl with a discussion of their impacts including relations to cloudiness data. A summary and conclusions follow in section 5.

2. Methods

2.1. Data and Data Processing

[14] Rings were located and characterized using satellite-derived SST fields [Cornillon et al., 1987]. In addition to processing using the standard Pathfinder SST algorithm (http://www.rsmas.miami.edu/groups/rsl/ pathfinder/Processing/proc_index.html), the University of Rhode Island decladding algorithm [Cayula and Cornillon, 1996] was applied and the resulting cloud masks used to calculate fractional cloudiness.

[15] The region from 30°N–45°N and 75°W–50°W was treated, during two time intervals based on the corresponding scatterometer wind data: the entire NSCAT period (September 1996 to June 1997) and a portion of the QuikSCAT period (July 1999 to April 2000). During the NSCAT (QuikSCAT) period the spatial resolution of SST data was 5.5 km (1.1 km); both are sufficient to determine frontal locations, frontal temperature gradients, and temperature differences between inside and outside of rings for purposes of this analysis. Images were subsampled to a 300 by 300 km region around each ring, to include both the ring and a sufficiently large surrounding area. A total of 439 WCR observations and 260 CCR observations are analyzed, with 835 and 430 wind passes, respectively, from both the QuikSCAT and NSCAT periods; data are predominantly from the QuikSCAT period (403 WCR observations and 218 CCR observations, with 561 and 283 wind passes, respectively).

[16] Frontal boundaries of rings were digitized and fit to ellipses [Hooker and Olson, 1984] in a least squares sense, to determine the ring center, major and minor axis lengths, eccentricity, and orientation angle. For WCRs, frontal boundaries are defined as the local maxima in the SST gradient bounding the SST anomaly; this approach suffices because maximum gradients tend to be at the outer ring edge and the water surrounding the ring is relatively homogenous on all sides. In contrast, CCRs often have a tongue of relatively warm water that has been advected partially around the ring following an interaction with the Gulf Stream. This results in SST gradients both within and partially around the ring following an interaction with the Gulf Stream. This results in SST gradients both within and partially around the ring following an interaction with the Gulf Stream. This results in SST gradients both within and partially around the ring following an interaction with the Gulf Stream.

[17] NSCAT and QuikSCAT 10-m equivalent-neutral winds were obtained from the Jet Propulsion Laboratory (JPL) Physical Oceanography–Distributed Active Archive Center (PO-DAAC). Spatial resolution of wind vector cells is 25 km, and temporal sampling is nominally once per day though irregular depending on latitude and satellite orbit. These scatterometers are designed to measure wind speed accurate to 2 m s⁻¹ and direction accurate to 20 degrees for winds between 3 and 20 m s⁻¹ [Jet Propulsion Laboratory, 1998]. Wind speeds of NSCAT were reported to have a small bias of −0.3 m s⁻¹ and residual RMS errors of 1.3 m s⁻¹ and have standard deviations of 1.3 m s⁻¹ over the wind speed range from 1 to 18 m s⁻¹ [Freilich and Dunbar, 1999]. On the basis of skew in histogram distributions (not shown), winds greater than 15 m s⁻¹ and less than 3 m s⁻¹ are omitted from the analysis.

[18] For each ring observation, NSCAT (QuikSCAT) passes which sample the ring location with time difference of less than 3 days (2 days) relative to the SST image time were included in the analysis. The larger time difference for NSCAT winds was chosen to increase sample size; ring translational velocities of WCRs average 6.4 km d⁻¹, for which misalignment of the ring center due to the time difference is 19.2 km or less, smaller than the spatial resolution of the wind vector cells. Wind vectors were used from a roughly square region, either 11-by-11 or 13-by-13 wind vector cells depending on ring size, chosen to cover the entire ring and an adequate surrounding area as for SST images. Each group of wind samples was assigned to bin 3–6, 6–9, 9–12, or 12–15 m s⁻¹ on the basis of its mean wind speed.

[19] Wind stress was calculated as defined in (1), where $U_{10}$ is the scatterometer wind vector uncorrected for the ring current effect, $p_e = 1.25$ kg m⁻³, and the drag coefficient is as determined by Anderson [1993],

$$C_D = 7.55 \times 10^{-4} \left| \frac{U_{10}}{e} \right| < 4.5 \text{ m s}^{-1}$$

$$C_D = 4 \times 10^{-4} + 7.9 \times 10^{-5} \left| \frac{U_{10}}{e} \right| > 4.5 \text{ m s}^{-1}.$$  

Divergence and curl of wind stress were calculated using

$$\vec{k} \cdot \nabla \times \vec{\tau} = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \nabla \cdot \vec{\tau} = \frac{\partial \tau_x}{\partial x} + \frac{\partial \tau_y}{\partial y},$$

where $\vec{k}$ is a vertical unit vector and $\tau_x$ and $\tau_y$ are eastward and northward wind stress components.

[20] Positions of all data have been transformed to a common ring-centric circular normalized coordinate system defined using ellipse parameters from the fit to SST-based frontal boundaries (Figure 2). For a sampled location $P$ at $X_P$ east and $Y_P$ north from the ellipse origin, coordinates in a rotated system aligned along and across the major axis of the ellipse are

$$X_P = \text{Re} \left( X_P e^{iY_P} \cdot e^{-i\theta_0} \right),$$

$$Y_P = \text{Im} \left( X_P e^{iY_P} \cdot e^{-i\theta_0} \right),$$

where $\theta_0$ is the angle of rotation.
where \( \theta_p \) is the orientation angle of the major axis counterclockwise from east. In the ring-centric system the normalized or fractional radius is defined,

\[
r^* = \frac{R_p}{R_p'} = \frac{\sqrt{X_p^2 + Y_p^2}}{\sqrt{X_p'^2 + Y_p'^2}},
\]

where \( X_p, Y_p \) are rotated coordinates of the point \( P' \) located on the ring boundary where it intersects a line through the origin and \( P \), and the angle \( \theta_p \) is defined in terms of ellipse major and minor axes \( a \) and \( b \) using the relations

\[
X_p' = \frac{ab}{\sqrt{b^2 + a^2 \tan^2 \theta_p}}, \quad Y_p' = X_p' \tan \theta_p.
\]

Data are mapped to the new coordinate system and binned in normalized \( +x \) and \( +y \) distance, which will hereafter be used to refer to the orthogonal axes of the rotated ring-centric frame. When treating wind and cloudiness data, coordinates are rotated such that the \( +x \) axis is aligned with the direction of the mean wind. For example, for wind vector \( \vec{W}_j \) the along-wind component \( V_j \) and the cross-wind component \( U_j \) are given at each bin location by

\[
U_j = \frac{1}{N} \sum_{k=1}^{N} \text{Re} \left( |\vec{W}_j| e^{i(\tilde{\theta}_x - \theta_{\text{wind}})} \right),
\]

\[
V_j = \frac{1}{N} \sum_{k=1}^{N} \text{Im} \left( |\vec{W}_j| e^{i(\tilde{\theta}_x - \theta_{\text{wind}})} \right),
\]

where \( N \) is the number of samples contributing to bin \( j \) and \( \theta_{\text{wind}} \) is the direction angle of the mean wind vector for the wind pass containing the particular wind vector point of interest.

The cloudiness fraction \( C_{ij} \) at the \((i, j)\) pixel is defined by

\[
C_{ij} = \frac{\sum_k I_j(x_k | x_k = 1)}{N_{ij}},
\]

where \( I_j \) is a flag set to 1 or 0 based on whether the declouding algorithm identifies the pixel as cloud-contaminated, and \( N_{ij} \) is the total number of SST images. Owing to the limited number of samples at larger radii, only cloudiness data at \( r^* < 1.5 \) are treated.

### 2.2. PBL Model Description and Comparisons to Observations

[22] Models for PBL processes are well established on the basis of extensive research parameterizing effects such as heat flux and ocean surface roughness. Here an updated version of one such model that has seen operational use (from University of Washington [e.g., Brown and Liu, 1982; Liu et al., 1979; Brown, 1982; Foster and Brown, 1994] is applied to investigate the extent to which observed scatterometer wind characteristics over Gulf Stream rings can be accounted for by PBL behavior associated with SST changes.

[23] The model is one-dimensional in the vertical and incorporates parameterized effects of turbulent fluxes and stratification on similarity solutions for a logarithmic vertical profile in a near-boundary layer within the spiral wind structure of an Ekman layer. A fundamental dynamic the model quantifies is the greater (lesser) extent to which the near-surface wind vector will match the geostrophic wind vector of the upper atmosphere as a result of enhanced (reduced) near-surface turbulence associated with an unstable (stable) MABL. The observed increase (decrease) of wind speed over WCRs (CCRs) shown in Figure 11 in section 4.1 is consistent with these physics and motivates the more detailed examination pursued here. For context, Brown and Liu [1982] and Businger and Shaw [1984] report that in a typical midlatitude Northern Hemisphere situation with neutral stability, relative to the geostrophic wind the 10-m wind decreases in magnitude by as much as 40% and veers to the left by up to 15°; for an unstable (stable) MABL the magnitude decrease weakens to about 20% (strengthens to about 50%) and the veering angle decreases to about 5° (increases to about 30°).
A series of model simulations explores dependence on two parameters: the upper-atmosphere geostrophic wind magnitude $G$ and the air-sea temperature difference $T_s - T_a$. Both are held constant throughout each simulation, with atmospheric humidity and $T_r$ fixed at annual-mean climatological values based on COADS data (see Figure 6 in section 3), and results are presented from the steady state achieved. Model output is in terms of (1) the ratio $U_\infty/U_*$, where $U_\infty$ is the surface friction velocity, and (2) the difference angle $\alpha$ between surface friction velocity and the geostrophic wind (positive counterclockwise by convention). For proper comparison, scatterometer wind components are thus converted to friction velocities using the standard log relationships

$$U(Z) = \frac{1}{K} \log \left[ \frac{Z}{Z_o} \right]$$

$$Z_o = 0.011 \frac{U_*^2}{g} + 0.11 \frac{\nu}{U_*}$$

where $Z$ is a height of 10 m, $K = 0.4$ is von Karman’s constant, $Z_o$ is the roughness parameter, $g$ is the gravitational acceleration constant, and $\nu$ is the kinematic viscosity of air, following the formulations and parameter values of Smith [1988] and Fairall et al. [1996]. Post-storms, the formulation assumes neutral stability, which may or may not be the case but is appropriate in the sense that scatterometer winds are equivalent-neutral and there are no independent measurements to support an alternative. Observed difference angles were calculated as the average orientation angle of all friction velocities within the ring less that determined for those outside the ring. Contributions to the difference angle associated with the ring current effect (described above) are symmetric on opposite sides of a ring and will tend to cancel such that the net effect is not considered important.

The observational analysis focuses on the ratio of vector mean winds inside Gulf Stream rings to those outside rings. For WCRs the boundary between inner and outer regions is $r^* = 1.0$ and the outer region extended to the limits of the square area subsected from the scatterometer pass, nominally 300 km on a side. For CCRs two calculations are performed, for boundaries of $r^* = 0.5$ and 1.0, the former deemed more appropriate as justified on the basis of the SST structure described in section 3 below. To facilitate comparison with the observations, the ratio between model $U_\infty/G$ for conditions inside and outside rings is calculated. Given the absence of direct measurements of atmospheric conditions, conditions outside the ring are presumed to include a neutrally stable MABL with friction velocity denoted $U_\infty$. Hence dependence of modeled $U_\infty/U_\ast$ as a function of $T_s - T_a$ is investigated for given values of $G$. These curves are compared to observed $U_{\text{Inner}}/U_{\text{Outer}}$ as a function of $T_{\text{Inner}} - T_{\text{Outer}}$ based on SST, the latter difference used (as explained above) as a proxy because there are no measurements for $T_r - T_a$. The model curves are characterized by monotonous increase with an inflection point, and they are shifted such that their inflection point lies at the origin as is appropriate in order to account for the fact that the SST-based $T_{\text{Inner}} - T_{\text{Outer}}$ is known to differ from $T_s - T_a$.

3. Statistical Summary of Baseline Observations

Multiple observations were made for at least 11 individual WCRs during the 10-month QuikSCAT period used for this study (Figure 3; for clarity they are shown with identifying symbols and colors). All of the WCRs were detected near the continental shelf edge and translated to the south and west (Figure 3). Semimajor and semiminor axis lengths of best-fit ellipses range from 40 to 110 km with mean 74 km, and eccentricities $(\sqrt{a^2 + b^2}/a)$ range from 0.2 to 0.8 with mean value 0.55. In contrast, CCRs are distributed across the Sargasso Sea (Figure 4) to the south, and propagate with a more variable range of speeds and directions than WCRs. Semimajor and semiminor axis lengths of CCRs range from 60 to 140 km with mean 90 km, somewhat larger than WCRs, and their mean eccentricity is 0.58. Ellipse characteristics during the NSCAT period (not shown) are similar.

Patterns of mean SST, and mean SST gradient magnitudes, emerge when mapped to the normalized ring-centric coordinate system binned by 0.1 in fractional distances (Figure 5). In WCRs the interior temperature is 19°–20°C and nearly spatially uniform within normalized radius $r^* = 1.0$. This is 3–4 higher than the surrounding water that lies within about $r^* < 2.0$. The degree to which the SST contours in these plots are circular, especially those in the vicinity of a normalized radial distance of 1, attests to the suitability of the normalized coordinate system. Frontal gradients magnitudes are highest at $r^* = 0.8 – 1.2$, reach 0.25°C km⁻¹, and are somewhat stronger (weaker) to the northwest (southeast) side. In contrast, for CCRs the mean temperature reaches a minimum of 20.5–21°C in a small central region $r^* < 0.5$, where temperatures are about 1 colder than in the rest of the ring and about 1–2°C colder than the water surrounding the ring. Corresponding gradient magnitudes are weaker than in WCRs and concentrated in two regions: the strongest at $r^* = 0.3 – 0.7$ aligned with the edge of the central temperature minimum, and a second along the main outer ring boundary. Differences between rings during the QuikSCAT and NSCAT periods are relatively minor in relation to these general patterns.

Climatological seasonal variations in relative humidity, sea surface temperature, and surface air temperature provide context for large-scale average MABL conditions within which the two types of rings are found (Figure 6). COADS (Comprehensive Ocean-Atmosphere Data Set) values from 1989 to 1994 have been averaged across two large regions, one to the north of the mean Gulf Stream path containing all WCR observations, and a second to the south containing all CCR observations. Relative humidity is generally higher over the WCR region (mean 80%) than over the CCR region (mean 77%), while SST over the WCR region (mean 16.52°C) is 4–8°C colder than that over the CCR region (mean 22.52°C). This apparent reversal, from an expected pattern of increased relative humidity over higher SST, arises because the WCR region lies at the southern edge of a subpolar low pressure zone where air generally ascends while the CCR region lies in a subtropical high pressure zone where air generally descends. Air
temperatures over the two regions differ by at most a few degrees, typically less than 2°C throughout a seasonal cycle with 11–12°C minimum in March and 24°C maximum in August. An important quantity for MABL behavior is the difference $T_s - T_a$ between SST and air temperature, which when positive (negative) generally has a destabilizing (stabilizing) influence on the MABL. For the WCR region $T_s - T_a$ is about +1°C in fall and winter and about −2.5°C in spring and summer. For the CCR region it is positive all year and reaches a minimum (maximum) of about +2°C (+8°C) in late summer (winter). In general, over large scales the MABL conditions in the WCR region are therefore expected to be more stabilizing than over the CCR region.

4. Results

4.1. Observed Ring-Related Wind Modifications

The downwind component of scatterometer winds averaged across groups of mean wind speed, the NSCAT and QuikSCAT data sets, and WCRs and CCRs, is presented (Figure 7) in ring-centric coordinates rotated as in Figure 1 such that the upward $y$ axis is along the mean wind. The downwind component over CCRs shows...
substantial asymmetry with increased (decreased) magnitude to the left (right) side of the ring viewed in the downwind direction (Figures 7c and 7d). The same pattern is seen in both the QuikSCAT and NSCAT periods, and appears more clearly in the latter because the relatively fewer ring images from that period had particularly sharp frontal boundaries and homogeneous inner temperatures.

[30] The maximum left-right speed difference is about 2 m s⁻¹, approximately twice a typical ring current speed. The pattern has the sense associated with the expected influence of currents on scatterometer winds: increased (decreased) magnitude where the wind and underlying current are opposed (aligned), for example to the left (right) side of CCRs. The conclusion that this is direct evidence for the effects of currents is well supported given that alternative explanations, including MABL behavior as will be discussed below, cannot account for the observed pattern.

[31] In contrast to CCRs, for WCRs a relatively symmetric pattern of increased winds throughout the entire ring is clear in most speed ranges and for both data sets. Magnitudes within the ring increase by about 7.7–9.2% compared to those outside the ring within \( r^* < 1.6 \). The region of elevated magnitudes coincides closely with the unit circle, such that downwind motion appears to increase (decrease) over the relatively short horizontal scale of tens of kilometers as the wind encounters the upwind (downwind) ring boundaries. Differences between the NSCAT

Figure 4. Same as Figure 3 but for CCRs, without grouping observations by individual rings.
and QuikSCAT periods include enhanced amplitudes of changes in the former, and only a moderately detectable effect in the latter at low mean wind speed. Unlike the CCR results, the WCR pattern shows little left-right asymmetry, with magnitudes slightly exceeding those expected owing to ring currents.

\[ 32 \]
Across-wind structure of the along-wind component is made more clear by averaging the data of Figure 7 in the along-wind \((+y)\) direction (Figure 8). Measurements are compared to the idealized model of Figure 1, in which the only influence is assumed to be from ring currents, using peak current strength of 1 m s\(^{-1}\) (1.2 m s\(^{-1}\)) for WCRs (CCRs) based on analysis of 6 years of direct current measurements by the MV Oleander [Rossby and Gottlieb, 1998] and other published ring velocity observations [Richardson, 1980; Joyce, 1984]. Observed scatterometer winds over CCRs show a left-right asymmetry quite similar to the idealized model. This is much less the case for winds

\[ \text{Figure 5. Temporal mean of SST and SST gradients over warm and cold-core rings during QuikSCAT and NSCAT periods.} \]
over WCRs, where it occurs partially and only for certain wind speeds. These results can be understood in terms of the different nature of the current and SST structure of WCRs and CCRs. In WCRs both the peak current and the sharp temperature gradient occur at outer radii near $r^* = 1$, hence the winds are strongly influenced by both the ring current effect and modifications to the MABL by the SST gradient (discussed below). This explains the poorer agreement for WCRs between the idealized curves in Figure 8, which are for current effect only, and the observations. In CCRs, the strongest SST gradients are limited to the inner portion of the ring, while near the outer edge of the ring where the current is strongest its influence on the wind acts essentially in isolation from the SST gradient effects. Hence there is markedly better agreement between the idealized curves and the observations for CCRs, particularly near the outer boundary of the ring.

[33] The wind component perpendicular to the mean wind (Figure 9) reveals additional patterns. Over WCRs the general tendency is for this component to be mostly negative (positive), that is, directed to the left (right), in the downwind (upwind) half of the ring, while the opposite is true for CCRs. These features are considered further evidence for the ring current effect. Across-wind averaging is applied to facilitate direct comparisons (Figure 10) to the idealized model for the current effect in a uniform unmodified absolute wind (Figure 1). Agreement between the observations and the idealized model is quite good for some wind speeds while poor for others, an indication of the importance of processes other than ring currents. In contrast to the along-wind component, agreement occurs in about the same number of wind speed bins for WCRs as it does for CCRs. This is not surprising in that changes in the stability of the MABL have little effect on the across-wind component while the ring current effect is as strong in the across-wind direction as in the downwind direction.

[34] To help investigate increase/decrease in wind strength over rings as a function of MABL conditions, the ratio of QuikSCAT wind magnitudes inside and outside of rings has been plotted (Figure 11) as a function of the SST difference inside and outside of rings, a proxy (see introduction) for the air-sea temperature difference $T_s - T_a$.
within the ring and hence MABL stability. Similar results (not shown) are seen during the NSCAT period. As motivated by their differing SST structures (described above; Figure 5), for WCRs (CCRs) the inner and outer regions were defined by $r^* = 1.0$ ($r^* = 0.5$). The result (solid curve, Figure 11) indicates a systematic increase of wind speed, for positive SST differences representative of unstable MABL conditions, by up to 8–10% for SST differences up to about $4^\circ$C. Wind speed decreases of similar magnitude occur, for negative SST differences representative of stable MABL conditions, for comparable SST differences. For inner boundary of $r^* = 1.0$ in CCRs (dashed curve, Figure 11) the deceleration is less marked as a result of inclusion of regions outside the central SST minimum (see Figure 5), with uncertainties reduced owing to the larger number of wind cells used.

There is a weak spatial phase lag of the wind speed to the change in SST, in the sense that boundaries of regions exhibiting modified observed winds align with SST gradients to within tens of kilometers (Figure 7). The interpretation of observed patterns as the response to air movement across ocean fronts therefore implies that the timescale of the modifications is less than an hour, based on an advective scale set by the mean wind speed. By contrast, the time required for the MABL to come back into equilibrium with the sea surface after crossing an SST front, i.e., for the air temperature to adjust to the sea surface temperature, is substantially longer. This is most clearly seen for WCRs (Figure 7). Specifically, the wind speed increases as the wind crosses the upwind boundary of the ring, remains quite constant across the entire ring and then decreases back to the value that it had upwind of the ring as it crosses the downwind boundary. The initial adjustment is due to a change in MABL stability. The fact that the wind speed remains constant as it crosses the ring suggests that the instability of the MABL remains about the same across the entire ring. The return to pre-ring wind speed downstream of the ring is further evidence that the air temperature has not adjusted to the SST and an indication of the MABL returning to pre-ring stability levels. For a mean diameter of 150 km for WCRs, winds of 5 m s$^{-1}$ would take on the order of 8 hours to cross the ring. Given the relatively small change in wind speed across the ring, this suggests that the e-folding time for a response of the MABL stability to an SST front is, at a minimum, several times higher. This is not inconsistent with previous results suggesting MABL

![Figure 7](image-url)
response time on the order of a day [Rogers, 1989; Giordani et al., 1998].

4.2. Comparison to PBL Model

[36] Dependence of modeled friction velocity ratio on temperature difference (continuous curves, Figure 12) shows the expected increase (decrease) in wind speed over positive (negative) temperature differences that correspond to a destabilizing (stabilizing) influence on the MABL. For a given temperature difference, changes to the velocity ratio are much more pronounced at low wind speeds than at high. Furthermore, at low wind speeds the change from decreased to increased speed ratio occurs over a narrower range of temperature differences centered on zero. Finally, some asymmetry is clear, particularly at the lowest wind speed for which the velocity ratio is reduced (enhanced) by about 50% (30%), for 6-degree negative (positive) temperature difference.

[37] Corresponding observed friction velocity ratios using NSCAT winds (symbols with error bars, Figure 12) agree with the sense of increase (decrease) over positive (negative) temperature differences. They also show enhanced changes at higher wind speed magnitudes. Magnitudes of observed decreases are substantially less than the model curves, while magnitudes of observed increases are slightly less than model results. Results for QuikSCAT winds (Figure 13) show slightly reduced increases but are otherwise similar.

[38] Observed differences between veering angles inside and outside rings, $\alpha_{\text{inner}} - \alpha_{\text{outer}}$, decrease (increase) for positive (negative) temperature difference inside and outside rings (symbols, Figure 14). This is in agreement with the sense of the model result (smooth curve, Figure 14) for $\alpha(T_s - T_a) - \alpha_N$, where $\alpha(T_s - T_a)$ is the veering angle for a given air-sea temperature difference and $\alpha_N$ is that for a neutrally stable MABL. While uncertainties are large, and there is a suggestion that observed magnitudes are smaller (larger) than modeled at temperature differences smaller (larger) than about 2–3 deg, the observed and modeled magnitudes are of similar order. The agreement between the observations and model is strongest for WCRs, while modifications over CCRs are more modest than in the model. This is consistent with the fact that over large spatial scales the WCR (CCR) region has a smaller (larger) $T_s - T_a$ (Figure 6), is therefore likely to be nearer to (farther from) neutral stability, and provides conditions under which the SST effect will be more (less) prominent.

[39] Many assumptions have been required to facilitate this comparison between model and observations, for example the presumption that a neutral MABL is representative of conditions outside of rings. These assumptions do not hold perfectly and provide numerous reasons for which discrepancies between model and observation should be expected. However, the comparison strongly supports the conclusion that characteristics of observed winds inside and outside Gulf Stream rings can to a large extent be accounted for by behavior of the MABL under the influence of SST differences as captured by the dynamics of the PBL model used. Agreement of the model with these observations is thought to be associated with its nonlinear nature, which explicitly includes effects of organized large eddies and their ability to facilitate rapid vertical advective effects;
Figure 9. As in Figure 7, but for component of scatterometer winds across the mean wind direction, positive rightward, in ring-centric coordinates.

Figure 10. Across-wind structure of component across the mean wind: data of Figure 9 averaged in the direction across the mean wind (solid line) superposed on idealized case (dashed line) with ring current effect only (see Figure 1).
evidence in support of this view was provided by Brown [2000] in the context of comparisons between the model and other measurements.

4.3. Curl, Divergence, and Cloudiness

Wind stress divergence and curl averaged across NSCAT and QuikSCAT periods are presented in ring-centric coordinates as a mean over all WCRs and CCRs (Figure 15). Magnitudes range from 0 to $1 \times 10^{-6}$ N m$^{-3}$.

Divergence over WCRs is most positive (negative) on the upwind (downwind) side of the ring. Maximum amplitudes occur at the ring edges; averaged between $r^*$ of 0.8 and 1.2 and within a $45^\circ$ azimuth range, they are $3.85 \times 10^{-7}$ N m$^{-3}$ ($-6.27 \times 10^{-7}$ N m$^{-3}$) on the upwind (downwind) side. The downwind convergence is about 63% stronger than the upwind divergence. Divergence over CCRs shows a pattern opposite in sense to that over WCRs. Maximum amplitudes are found within the ring, not along its boundaries as for WCR. This is consistent with strongest divergences being associated with the sharpest SST gradients, which for CCRs occur in the ring interior (see Figure 5). Values averaged over the upwind (down-
wind) half of the unit circle are slightly negative, $-0.59 \times 10^{-7}$ N m$^{-3}$ (positive, $1.39 \times 10^{-7}$ N m$^{-3}$).

[42] Curl over WCRs shows an asymmetry in the direction across the mean wind, with mean value $3.64 \times 10^{-7}$ N m$^{-3}$ ($-5.28 \times 10^{-7}$ N m$^{-3}$) averaged over the left (right) half of the unit circle. As in the case of the divergence there is asymmetry in the magnitudes, with the peak negative value about 45% larger than the peak positive value. The maxima are found near the ring boundary. Curl over CCRs shows signs reversed with respect to those over WCRs, with mean values $1.99 \times 10^{-7}$ N m$^{-3}$ ($1.34 \times 10^{-7}$ N m$^{-3}$) over the left (right) half of the unit circle. Maxima are reached at about $r^* = 0.5–0.7$ well inside the ring edge, again consistent with the similar location of maximum SST gradients for CCRs.

[43] The pattern is that divergence (curl) is maximal where the mean wind is oriented perpendicular (parallel) to the frontal boundary of the ring and hence parallel (perpendicular) to the SST gradient. Thus the divergence (curl) should vary with the $y$-component ($x$-component), or component along (across) the direction of the mean wind, of the SST gradient. To quantify these trends, divergence and curl along the boundary of the ring, averaged over the region $r^* = 0.8–1.2$, are plotted as a function of these respective components of the SST gradient (Figure 16). Each component of SST gradient varies from $-0.08$ to $0.08^\circ C$ km$^{-1}$ over WCRs, but over a smaller range from $-0.01$ to $0.01^\circ C$ km$^{-1}$ over the CCRs (see Figure 5). Divergence over WCRs is positive (negative) where the $y$-component of SST gradient is positive (negative), corresponding to the upwind (downwind) ring edge. For divergence over CCRs the dependence on SST gradient is less clear because the SST gradients are smaller, but values downwind are more positive than those upwind, opposite to the WCR case.

[44] Curl over WCRs (Figure 16b) shows a clear trend with positive (negative) values to the left (right) of the mean wind direction, and between these endpoints there is a smooth variation with the $x$-component of SST gradient. On the basis of the sine fit, the maximal positive and negative values occur at similar magnitudes of SST gradient, about $0.06^\circ C$ km$^{-1}$. In contrast, over CCRs the curl is negative (positive) to the left (right) of the mean wind, and negative values substantially exceed the positive.

[45] These results are strong observational support for the conjectures of Businger and Shaw [1984] regarding how divergence and curl would be modified by the SST field associated with a warm ocean eddy. A corollary to their discussion was that the associated convergence and divergence of atmospheric winds would cause local vertical

Figure 13. As in Figure 12, but for QuikSCAT period.

Figure 14. Smooth curve shows PBL model difference between veering angle and neutrally stable veering angle, as a function of air-sea temperature difference $T_a - T_s$. Symbols show scatterometer wind difference between veering angle inside and outside of ring, as a function of SST inside and outside of ring. Inner section of WCRs defined as $r^* = 1.0$; solid (dashed) line indicates inner section of CCRs defined as $r^* = 0.5$ (1.0).
motion and hence affect cloudiness. On the downwind (upwind) side of a ring the convergence (divergence) is expected to cause local uplift (subsidence) and hence enhance (decrease) cloudiness.

To test this idea the cloudiness fraction, based on analysis of SST images, is plotted in ring-centric coordinates (Figure 17). Over WCRs, cloudiness is higher overall on the downwind side, and lower on the upwind side preferentially to the left when facing downwind, with maximum (minimum) of about 0.24 (0.18). The general pattern supports that cloudiness over WCR is enhanced on the downstream side. Viewed in more detail, differences between the spatial pattern of cloudiness and that of divergence (Figure 15) are clear, particularly the fact that cloudiness continues to be high at larger distances downwind in contrast to the localization of the maximum convergence near $r^* = 1.0$. This could be associated with the fact that the wind data applies near the sea surface while the clouds in SST images occur through a range of altitudes in the lower atmosphere, so in effect the clouds associated with a localized convergence extend for some distance farther downwind. In regions with $r^* < 1.1$, 1.2, and 1.5, the two-dimensional correlation coefficient between divergence and cloudiness is $-0.75$, $-0.66$, and $-0.31$, respectively, relatively high values considering that no spatial lag was included.

Over CCRs the cloudiness fraction is generally much higher, with the lowest values $C_{25} < 0.28$ in a core region having radius about half as large as the ring itself and located slightly to the right of the ring center. This is not strongly consistent with the divergence pattern observed over CCRs, a discrepancy for which two explanations seem reasonable. The MABL over the CCR region is generally stable on a large-scale average sense (see Figure 6 and discussion) and will more effectively restrain air parcels from moving vertically. Near-surface divergence may therefore be expected to have less influence on the upper atmosphere. In addition, divergence over CCRs differs from that over WCRs in its relatively weak magnitudes and in deriving from the relatively smaller region of SST anomaly.

These results add to previous reports linking changes in cloudiness to passage across ocean fronts. Using instrumented aircraft flying over the north wall of the Gulf Stream, Sweet et al. [1981] found modified low-level clouds
that persisted for up to several days, and explained them in terms of differences in atmospheric turbulence associated with changing air-sea temperature differentials on each side of the front. Deser et al. [1993] used correlations with spatial lags to demonstrate that cool low-level winds caused stratiform clouds on the warm side when blowing across a sharp SST front in the equatorial eastern Pacific. During FASINEX, Khalsa and Greenhut [1989] noted that weaker draft activity on the cold side might be responsible for reduced cloudiness in spite of saturated conditions in the upper mixed layer, in contrast to energetic updrafts and large heat fluxes on the warm side.

Finally, regarding the curls, on the basis of modeling of wind effects on rings [Dewar and Flierl, 1987], the observed dipolar pattern is expected to be of substantial consequence to ring propagation and attenuation. Using a temperature-dependent drag coefficient they showed that Ekman pumping due to the curl associated with the SST pattern of a WCR had a similar dipolar structure and is sufficient to account for a substantial fraction of observed isotherm subsidence rates and translation speeds in rings. Revisiting their modeling work with use of a nonlinear PBL such as that used in this study might yield quantitatively different results but seems unlikely to change the basic character of the dynamics. Validation of the predicted effect on translation might be possible with SST and scatterometer data, but would require substantially more observations than were available at the time of this study.

5. Summary and Conclusions

This study presents an analysis of modifications to winds, as observed by the satellite scatterometers NSCAT and QuikSCAT, over warm-core and cold-core rings of the Gulf Stream. Some associated properties of dynamical importance (divergence and curl), and fractional cloud cover, are also examined. Conventional equivalent-neutral scatterometer products are used and the emphasis is on modifications of actual winds, as opposed to errors or

Figure 16. (a) Divergence as a function of y-component of SST gradient (component along the mean wind) in a distance range of $0.8 < r^* < 1.2$. (b) Wind stress curl as a function of x-component of SST gradient (component across the mean wind) in a range of $0.8 < r^* < 1.2$. 
Figure 17. Cloudiness over (top) warm-core and (bottom) cold-core rings during the QuikSCAT period.

Artifacts in scatterometer methods. The results can be summarized in terms of four important points.

[51] The first main point is that sea surface currents result in a component of conventionally processed scatterometer winds of magnitude similar to the current and in the opposite direction. The backscattering cross section is a function of wind stress relative to sea surface currents, but the latter component of motion is ignored by standard processing. The component of the scatterometer wind due to currents has been revealed through examination of components of scatterometer wind along and across the mean wind using a ring-centric coordinate system. The component along the direction of the mean wind increases (decreases) where it is in the opposite (same) direction as the current, with differences between scatterometer winds on opposite sides of a ring approximately twice as large as the maximum current. The across-mean component showed a similar pattern, rightward (leftward) relative to the mean wind near the upwind (downwind) edge for WCRs, and vice versa for CCRs. For low wind speeds from 3 to 6 m s\(^{-1}\) the current velocity occupies a considerable fraction of the combined wind vector and the across-mean component was relatively stronger. The effect is seen more clearly in the across-mean component, and in CCRs, where a stable MABL limits the influence of SST differences (discussed below) that can otherwise strongly modify the along-mean component and dominate the influence of currents.

[52] The second main point is that near-surface wind speeds increase (decrease) by about 10–15% over WCRs (CCRs) as a result of the destabilizing (stabilizing) influence of high (low) SST on the MABL which causes a more (less) effective transfer of high-altitude wind speeds down toward the surface. The observed modifications were compared with the results of an established PBL model from University of Washington [Brown, 1982]. A number of assumptions were necessary to make the comparison, among them that the air-sea temperature difference can be approximated by the difference in SST inside and outside the ring, and that the MABL is neutrally stable outside the ring. Observed amplitudes of wind speed changes are slightly less than PBL estimates, but there is broad agreement in the sense and magnitude of their dependence on SST anomaly and wind speed, as is true also for veering angle modifications. The conclusion that ring SST patterns strongly affect near-surface winds through MABL modifications is supported.

[53] The third main point relates to bounds determined for two timescales associated with the response of the MABL to SST fronts: the time for the wind speed to respond to a front and the time for the MABL to reach neutral equilibrium after crossing a front. The former is based on the observation that on average the wind speed changes within one scatterometer pixel (25 km) of the edge of a ring, even for the wind speed bin corresponding to the largest wind speed, centered on 13.5 m s\(^{-1}\). This means that the timescale in this case is less than 1 hour (25 km/(13.5 m s\(^{-1}\)) \(\approx\) 0.5 hours). A lower bound was put on the timescale for the MABL to return to neutral equilibrium after crossing a front. This was done on the basis of the observation that the wind speed changed abruptly when a ring boundary was first encountered, remained virtually uniform as the ring was crossed, and then once again changed abruptly when the other side of the ring was encountered. Furthermore, the change on the downwind edge of the ring was approximately equal in magnitude and opposite in sign to the change on the upwind edge. This was true for all binned wind speeds including the bin corresponding to the slowest speeds centered on 4.5 m s\(^{-1}\). For a ring diameter of \(\approx\) 150 km, this results in a minimum timescale of at least 1/2 day (150 km/(4.5 m s\(^{-1}\)) \(\approx\) 10 hours).

[54] The fourth main point is that wind stress divergence and curl associated with these wind modifications are largely in agreement with previous suppositions [Businger and Shaw, 1984] and have impacts on cloudiness and ring propagation. Over WCRs there is strong divergence (convergence) on the upwind (downwind) side, while curl is strongly negative on the right edge of the ring boundary and positive on the left edge. The opposite patterns are seen over CCRs. In summary, divergence (curl) peaks where winds blow perpendicular (parallel) to SST fronts. An important impact of the enhanced convergence on the downwind side of rings is seen in cloudiness fraction data from SST images, which reveals substantially enhanced cloud probabilities on the downwind side. The wind stress curl exerts dipolar...
Ekman pumping of sense and strength which the model study of Dewar and Flierl [1987] indicated can modify ring translation and decay processes.

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