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# Precipitation Response to the Gulf Stream in an Atmospheric GCM\*

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#### ABSTRACT

The precipitation response to sea surface temperature (SST) gradients associated with the Gulf Stream is investigated using an atmospheric general circulation model. Forced by observed SST, the model simulates a narrow band of precipitation, surface convergence, and evaporation that closely follows the Gulf Stream, much like satellite observations. Such a Gulf Stream rainband disappears in the model when the SST front is removed by horizontally smoothing SST. The analysis herein shows that it is convective precipitation that is sensitive to SST gradients. The Gulf Stream anchors a convective rainband by creating surface wind convergence and intensifying surface evaporation on the warmer flank. Deep convection develops near the Gulf Stream in summer when the atmosphere is conditionally unstable. As a result, a narrow band of upward velocity develops above the Gulf Stream throughout the troposphere in summer, while it is limited to the lower troposphere in other seasons.

### 1. Introduction

The influence of the Gulf Stream on the atmosphere has been studied for the past century (Page 1906; Strachan 1907). Carson (1950) proposed a hypothesis that the Gulf Stream causes stratus over the lower Atlantic coast through frontogenesis along the Gulf Stream with limited sounding data. Since the late 1960s, satellite observations, field campaigns, and numerical simulations enable detailed studies of atmospheric structures around the Gulf Stream. Raman and Riordan (1988) report a surface convergence zone along the Gulf Stream during the Genesis

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of Atlantic Lows Experiment (GALE) in winter. Warner et al. (1990) and Doyle and Warner (1993) suggest that sharp sea surface temperature (SST) gradient causes the surface convergence zone using mesoscale model experiments, while Sublette and Young (1996) show that the convergence can be seen in the warm season. Using satellite images, Alliss and Raman (1995a,b) show that high clouds frequently occur over the Gulf Stream associated with convection and surface convergence, although their analyses are limited to areas near the coastal region.

Gulf Stream SST and its gradient also affect synoptic cyclogenesis (Pope 1968; Cione et al. 1993; Giordani and Caniaux 2001). Strong surface fluxes from the ocean to the atmosphere occur in cold air outbreaks associated with extratropical cyclones (Zolina and Gulev 2003). Surface heat fluxes help form surface baroclinicity and a "storm track," a possible mechanism that connects the Gulf Stream to the upper troposphere (Hoskins and Valdes 1990; Nakamura et al. 2004).

The climatic effects of the Gulf Stream are still under debate in the literature. Frankignoul et al. (2001) find no evidence that interannual variability in the Gulf Stream's

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path has a direct impact on large-scale atmospheric circulation from an atmospheric reanalysis. Based on atmospheric general circulation model (GCM) experiments, Seager et al. (2002) suggest that the Gulf Stream's influence, such as that which warms Europe during winter, may be limited in the horizontal and vertical extent.

On the other hand, recent high-resolution observations from satellites show that mesoscale meandering of major ocean fronts and oceanic eddies affect the surface atmosphere in general and surface winds in particular (Nonaka and Xie 2003; Chelton et al. 2004; Chelton and Wentz 2005; Sampe and Xie 2007; Small et al. 2008). A vertical mixing mechanism is often used to explain the SST modulation of surface winds, in which warm SSTs reduce the surface atmospheric stability, bringing down high momentum to accelerate surface winds. Young and Sikora (2003) show low cloud modulations by Gulf Stream meanders.

Several sensitivity experiments to midlatitude SST fronts using atmospheric GCMs (AGCMs) have been conducted. Reason (2001) shows that the Agulhas Current affects the regional atmospheric circulation patterns around the South Indian Ocean. Nakamura et al. (2008) suggest that midlatitude oceanic frontal zones are important to maintaining the mean state and dominant variability in the tropospheric circulation by aquaplanet experiments. However, the horizontal resolutions of their AGCMs are coarse and may not be sufficient to capture the fine structure of SST fronts.

Minobe et al. (2008) show that surface wind convergence and precipitation estimated from satellites are sharply confined on the offshore, warmer flank of the SST front associated with the Gulf Stream, and the updraft anchored over the surface convergence extends to the upper troposphere based on outgoing longwave radiation (OLR) observations and an atmospheric analysis product from the European Centre for Medium-Range Weather Forecasts (ECMWF). In an AGCM with 50-km horizontal resolution, the Gulf Stream-trapped structures of surface wind convergence, precipitation, and cyclone activity disappear when the SST data are smoothed. Their linear model response to diabatic heating over the Gulf Stream indicates the possibility of a downstream influence.

The present study investigates the mechanism by which the Gulf Stream anchors a major rainband as depicted in the annual mean analysis of Minobe et al. (2008). We will use the same AGCM as in Minobe et al. (2008) and extend that study by examining the seasonal cycle and stratifying precipitation into convective and stratiform condensation. We show that it is convective rainfall that is most strongly affected by the Gulf Stream front. A companion paper in this special collection on western boundary currents discusses the seasonal variations of atmospheric structures along the Gulf Stream based on satellite datasets and atmospheric analysis datasets (Minobe et al. 2010).

The rest of the paper is organized as follows. Section 2 describes the model and experiment configuration. Section 3 discusses seasonal variations of precipitation response to the Gulf Stream front in the atmospheric model. Section 4 presents a composite analysis for cumulus precipitation in the Gulf Stream rainband. Section 5 discusses the relationship between cumulus precipitation and vertical velocity in the troposphere. Section 6 offers a summary and conclusions.

#### 2. Model and experiment configuration

We use the AGCM for the Earth Simulator (AFES; Ohfuchi et al. 2004) version 2 (Enomoto et al. 2008) developed at the Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology (JAMSTEC). It is based on the Center for Climate System Research (CCSR)/National Institute of Environment System (NIES) AGCM (Numaguti et al. 1997), replaced with Emanuel's convection scheme (Emanuel 1991; Emanuel and Živković-Rothman 1999; Peng et al. 2004), and a new radiation scheme "MstrnX" (Nakajima et al. 2000; Sekiguchi et al. 2003; Sekiguchi 2004; Sekiguchi and Nakajima 2008). The horizontal resolution is T239, about 50 km in grid spacing, with 48 sigma levels in the vertical. For the bottom boundary condition, the real-time global SST (RTG SST; Thiébaux et al. 2003) dataset of the National Centers of Environmental Prediction (NCEP) on a 0.5° grid and at daily intervals is used.

Two experiments are conducted: the control experiment (CNTL) uses the original RTG SST data, while the other experiment (SMTH) smoothes the SST data over the Gulf Stream region by applying a 1-2-1 running mean filter in both the zonal and meridional directions 100 times on a 0.5° grid over 25°–55°N, 100°–30°W. Figure 1 shows the annual and seasonal mean SST for the CNTL and SMTH runs and the differences between CNTL and SMTH. Initial conditions are taken from the 40-yr ECMWF Re-Analysis (ERA-40) data at 0000 UTC 11 February 2001, and both experiments are integrated for 5 yr, until 0000 UTC 1 March 2006. The simulations are the same as in Minobe et al. (2008), except for the analysis period. The present study uses the 6-h output for 5 yr from 0000 UTC 1 March 2001 to 1800 UTC 28 February 2006, while Minobe et al. (2008) use the output from January 2002 to February 2006.

To make a comparison with the model simulations, we use precipitation observations from the Tropical Rain Measuring Mission (TRMM) provided by the Goddard Earth Science Data and Information Services Center from March 2001 to February 2006. The TRMM 3A25 product features monthly accumulation of convective



FIG. 1. Annual and seasonal mean of precipitation (shaded, mm day<sup>-1</sup>) for (left) TRMM 3B43, (middle) CNTL, and (right) SMTH: (a)–(c) annual mean, (d)–(f) MAM, (g)–(i) JJA, (j)–(l) SON, and (m)–(o) DJF. (left) The original RTG SST used in CNTL run (K, contour) and (right) the smoothed SST used in SMTH run are shown. (middle) The difference between CNTL and SMTH SSTs (CNTL – SMTH).

and stratiform rain at  $0.5^{\circ} \times 0.5^{\circ}$  horizontal resolution estimated by spaceborne precipitation radar measurements between 38°S and 38°N. The TRMM 3B43 data are for monthly mean rainfall at  $0.25^{\circ} \times 0.25^{\circ}$  between 50°S and 50°N derived from TRMM, other satellite observations, and rain gauge data.

Surface evaporation is evaluated using the Japanese Ocean Flux datasets with Use of Remote sensing Observations, version 2.1 (J-OFURO2.1; Kubota and Tomita 2007). The data provide daily sea surface flux from January 1988 to December 2006 at  $1^{\circ} \times 1^{\circ}$  horizontal resolution. The fluxes are estimated by the Coupled Ocean–Atmosphere Response Experiment, version 3.0 (COARE3.0) flux algorithm (Fairall et al. 2003) using SST and surface wind from several spaceborne microwave radiometers and scatterometers, surface air specific humidity estimated from the Special Sensor Microwave Imager (SSM/I), and surface air temperature from the NCEP–Department of Energy (DOE) reanalysis 2 (Kanamitsu et al. 2002).

# 3. Seasonal variations

Figure 1 shows annual and seasonal means of precipitation for TRMM 3B43 observations, CNTL, and SMTH. The precipitation band over the Gulf Stream, described by Minobe et al. (2008) for the annual mean, appears in all seasons in observations with seasonal changes in strength and shape. The precipitation band is located on the warmer flank of the SST front, which corresponds to the Gulf Stream axis and features warm SST anomalies compared to SMTH. The rainband is strongest and broadest in December-February (DJF), weakest in March-May (MAM), and narrowest in June-August (JJA). These features are almost reproduced by the AGCM in CNTL, though precipitation is underestimated near the coastal region and overestimated over the subtropics and east of 50°W. Therefore, the precipitation magnitude in JJA is comparable to that in MAM, and the precipitation band is discontinuous in September–November (SON) in CNTL. In SMTH, the precipitation band almost disappears in JJA and SON, while a broader and weaker band can be seen in MAM and DJF. Broad atmospheric storm tracks help maintain the rainband in cold seasons. In the seasonal cycle, precipitation magnitude does not depend solely on the magnitude of the SST gradient (e.g., the SST gradient in JJA is weaker than that in MAM), but the width of the precipitation band depends on the SST gradient as in the comparison between CNTL and SMTH.

Precipitation forms are a useful characteristic to infer mechanisms and the atmospheric environment for precipitation occurrence. The TRMM 3A25 product distinguishes convective and stratiform precipitation from the vertical structure of precipitation radar echo (Iguchi et al. 2000). Precipitation in AFES can also be classified as being either convective (generated from the subgrid-scale cumulus convection scheme) or stratiform (from the resolved grid-scale condensation scheme). The former follows the Emanuel cumulus parameterization (Peng et al. 2004), depending on vertical thermodynamic profiles in a column, and the latter large-scale condensation parameterization, depending mainly on relative humidity at each grid point (Le Treut and Li 1991). Although these classifications are not strictly equivalent and TRMM data coverage is limited to the south of 38°N, it is meaningful to compare them because convective precipitation from the AFES cumulus convection scheme and in TRMM can be considered as resulting from convectively unstable situations. Vertical stratification of an atmospheric column is important for convective precipitation, while large-scale upward motion is important stratiform precipitation. Figure 2 shows annual mean convective and stratiform precipitation in TRMM 3A25, CNTL, and SMTH. Convective precipitation concentrates more sharply over the Gulf Stream than stratiform precipitation in TRMM 3A25, consistent with coastal radar measurements (Trunk and Bosart 1990) and lightning observations from space (Christian et al. 2003). Similarly, in CNTL, the rainband trapped by the Gulf Stream is largely due to cumulus convection, while stratiform precipitation is much broader and does not seem to be strongly affected by the SST front. In SMTH, the narrow cumulus precipitation band along the Gulf Stream disappears, while stratiform precipitation is not much different from that of CNTL. The cumulus precipitation difference over the Gulf Stream between CNTL and SMTH is quite significant above the 99% level of the Student's t test. The degree of freedom for the Student's t test in the present paper is based on the number of monthly mean data in CNTL and SMTH.

Figure 3 shows seasonal variations of cumulus and stratiform precipitations in CNTL over the Gulf Stream. In this study, the Gulf Stream precipitation band is defined as the area where annual mean precipitation in CNTL is larger than 5 mm day<sup>-1</sup> within 30°-48°N, 80°-40°W (the area bounded by the thick solid contour and outer dashed square in Fig. 2c). The maximum precipitation is collocated with the Gulf Stream current axis estimated from the satellite-derived surface currents (see Fig. 1 in Minobe et al. 2008) and with that defined by 15°C temperature at 200-m depth (Joyce et al. 2009). In this region, cumulus precipitation is dominant throughout the year, especially in summer, while stratiform precipitation is comparable in spring and winter. In SMTH, the amount and seasonal cycle of stratiform precipitation are almost the same, but cumulus precipitation is significantly weaker (not shown). Thus, cumulus convection is a key aspect of the atmospheric response to the Gulf Stream.

Minobe et al. (2008) show that a band of enhanced evaporation forms over the Gulf Stream. Figure 4 shows seasonal mean surface evaporation based on J-OFURO2.1, CNTL, and SMTH. An evaporation band is found over the Gulf Stream in all seasons. The evaporation band is largest in winter and weakest in summer both in J-OFURO2.1 and CNTL. In SMTH, the evaporation band disappears in JJA, while a broader and weaker band is displaced south in other seasons.

The difference between precipitation and evaporation suggests how much evaporation from the Gulf Stream contributes to the precipitation band formation. Figure 5 shows monthly precipitation and evaporation averaged within 30°–48°N, 80°–40°W. Evaporation is larger than precipitation in cold seasons, while evaporation is



FIG. 2. (left) Annual mean cumulus precipitation (PRCPC) and (right) stratiform–grid-scale precipitation (PRCPL) for (a),(b) TRMM 3A25, (c),(d) CNTL, (e),(f) SMTH, and (g),(h) CNTL – SMTH. (a)–(f) Precipitation (mm day<sup>-1</sup>) is shaded and SST (K) is indicated by contours, while (g)–(h) the precipitation difference is shown by contours and the 99% significant area of the Student's *t* test is shaded. The outer dashed-line square in (c) shows the target area for the precipitation and evaporation average in Fig. 5; the thick, solid contour is the annual mean precipitation of 5 mm day<sup>-1</sup> in CNTL, and the area it encloses is defined as the Gulf Stream rainband. The area bounded by the inner square and the thick solid contour is the target area for the cumulus composite. The white area north of 38°N in TRMM 3A25 is beyond TRMM observation domain.

comparable to or less than precipitation in summer both in observations and AFES experiments. Consequently, the amplitude of the evaporation seasonal cycle is larger than that of precipitation. Although the seasonal cycle of evaporation in CNTL is weaker than that in the observations, precipitation is similar to the observations. Regionally averaged precipitation varies little between CNTL and SMTH, suggesting that the narrow rainband in CNTL is due to enhanced evaporation over the Gulf Stream.



FIG. 3. Monthly variations of cumulus precipitation (PRCPC, solid line) and stratiform precipitation (PRCPL, broken line) for CNTL averaged over the Gulf Stream rainband within 30°–48°N, 80°–40°W.

Surface convergence is locally enhanced over the Gulf Stream (Chelton et al. 2004; Minobe et al. 2008). Figure 6 shows the seasonal mean differences of 10-m wind and its convergence between CNTL and SMTH.

The convergence shows a large difference, especially in MAM and DJF. The highly significant wind difference tends to be confined near the Gulf Stream, while the 5-yr integrations are too short to filter out atmospheric internal variability on the planetary scale. Indeed, Reason (2001) conducts 11-member simulations to get a 95% significance level for the Agulhas Current influence on hemispherical-scale circulation, while Rodwell et al. (2004) suggest that 20 yr are necessary to identify significant responses to SST anomalies in the North Atlantic region.

Minobe et al. (2008) show a high correlation between the surface wind convergence and  $\nabla^2$ SLP in the ECMWF operational analysis data, suggesting the importance of a pressure adjustment mechanism (Lindzen and Nigam 1987) under SST forcing over the Gulf Stream. The annual and seasonal variations of the correlation coefficients among surface wind convergence,  $\nabla^2$ SLP, and  $-\nabla^2$ SST in



FIG. 4. Seasonal mean surface evaporation from (left) J-OFURO2.1, (middle) CNTL, and (right) SMTH for (a)–(c) MAM, (d)–(f) JJA, (g)–(i) SON, and (j)–(l) DJF. The contours are for SST (K).



FIG. 5. Monthly mean precipitation (thick lines) and evaporation (thin lines) averaged within 30°–48°N, 80°–40°W: TRMM 3B43 and J-OFURO2.1 (solid lines), CNTL (broken lines), and SMTH (dotted lines).

CNTL and SMTH are shown in Table 1. These are based on the monthly data over the North Atlantic Ocean within 30°–48°N, 80°–40°W, following Minobe et al. (2008). The annual correlation coefficient between the surface wind convergence and  $\nabla^2$ SLP in CNTL of 0.69 is almost same as the 0.7 discussed in Minobe et al. (2008), and the seasonal variation is small. Surface convergence and  $\nabla^2$ SLP are both correlated with  $-\nabla^2$ SST, while the correlation is smaller than that between them. It is interesting that even in SMTH, a high positive correlation between surface wind convergence and  $\nabla^2$ SLP can be seen, but neither shows a correlation with  $-\nabla^2$ SST. Thus, the  $-\nabla^2$ SST associated with the Gulf Stream SST front influences surface wind convergence through the  $\nabla^2$ SLP modification in CNTL suggested by Minobe et al. (2008). The reduced correlation between surface wind convergence and  $-\nabla^2$ SST may be due to advection that causes time and space lags in the SLP and wind responses to the SST forcing. This is consistent with the result that the correlation between the surface wind convergence and  $-\nabla^2$ SST in JJA is larger than that in DJF when horizontal wind is stronger than in JJA.

## 4. Cumulus convection analysis

Analyses in the previous section suggest that cumulus convection, instead of stratiform precipitation, is sensitive to the Gulf Stream SST front and aids in narrow rainband formation. This section investigates the mechanisms by which the Gulf Stream SST front anchors cumulus precipitation. We consider the following three factors for time-averaged precipitation amount: 1) precipitation intensity, 2) duration, and 3) frequency of precipitation events. Multiplication of mean precipitation intensity and duration gives the precipitation amount per event, and additional multiplication of the frequency gives the climatological mean precipitation rate. Figure 7 shows annual mean differences in these factors for cumulus precipitation between CNTL and SMTH, based on 6-h output. For a precipitation event to be analyzed at a



FIG. 6. The differences between CNTL and SMTH of seasonal mean surface wind (vectors, m s<sup>-1</sup>) and its convergence (colors,  $10^{-6}$  s<sup>-1</sup>) in (a) MAM, (b) JJA (c) SON, and (d) DJF. The thin contour shows SST (K) for CNTL and the thick contour shows 95% significant level of Student's *t* test.

TABLE 1. Annual and seasonal correlation coefficients for 10-m wind convergence  $(-\nabla \cdot \nabla_{SFC}), \nabla^2 SLP$ , and  $-\nabla^2 SST$  based on the monthly data of CNTL (SMTH) over the North Atlantic Ocean within 30°–48°N, 80°–40°W.

Season	$- \mathbf{\nabla} \cdot \mathbf{V}_{SFC}$ and $\nabla^2 SLP$	$\nabla^2$ SLP and $-\nabla^2$ SST	$-\mathbf{\nabla} \cdot \mathbf{V}_{SFC}$ and $-\nabla^2 SST$
MAM	0.71 (0.55)	0.44 (-0.05)	0.25 (-0.05)
JJA	0.66 (0.62)	0.42(-0.02)	0.31 (0.06)
SON	0.67 (0.62)	0.41 (0.03)	0.28 (0.08)
DJF	0.68 (0.49)	0.46 (-0.13)	0.22(-0.05)
ANN	0.69 (0.55)	0.44 (-0.07)	0.25 (-0.01)

given grid point, cumulus precipitation must occur continuously for at least 6 h. The mean cumulus precipitation intensity substantially increases in CNTL compared to SMTH over the Gulf Stream rainband (Fig. 7a). This factor accounts for most of the difference in total cumulus precipitation. The duration of cumulus events in CNTL is about 1 day longer than that in SMTH (Fig. 7b). Cumulus events, however, are less frequent in CNTL than SMTH over the precipitation band (Fig. 7c). The frequency increases, however, in CNTL outside the precipitation band. The Gulf Stream strengthens the intensity and duration of cumulus events, and their effect on mean precipitation



FIG. 7. CNTL – SMTH differences in annual mean cumulus precipitation statistics: (a) intensity (mm day<sup>-1</sup>), (b) duration (day event<sup>-1</sup>), and (c) frequency (event month<sup>-1</sup>) of continuous precipitation events. Positive areas are shaded. (right) Zonal averages between  $80^{\circ}$  and  $40^{\circ}$ W with CNTL (solid lines) and SMTH (broken lines).



FIG. 8. Composites (see text for details) for cumulus precipitation [shaded, mm (6 h)<sup>-1</sup>], CAPE (solid contour, J kg<sup>-1</sup>), and SST (broken contour, K) in (left) CNTL and (right) SMTH, at 12-hourly intervals from T - 12 h to T + 48 h in JJA. Horizontal (degrees longitude) and vertical (degrees latitude) axes are relative distances from the reference point where cumulus precipitation starts at T = 0 h.



FIG. 9. Time series of (a),(b) CAPE (J kg<sup>-1</sup>), (c),(d)  $\partial$ CAPE/ $\partial t$  [J kg<sup>-1</sup> (6 h)<sup>-1</sup>], (e),(f) vertically integrated moisture budget terms [mm (6 h)<sup>-1</sup>;  $\partial q/\partial t$  (black), evaporation (red),  $-q\nabla \cdot \mathbf{V}$  (purple),  $-\mathbf{V} \cdot \nabla q$  (orange), cumulus precipitation (blue), stratiform precipitation (aqua), and  $-\partial q_l/\partial t$  (green)] in JJA at the center of the Fig. 8 panels in (left) CNTL and (right) SMTH.

amount dominates over that of frequency change. This conclusion holds for all seasons.

To examine why cumulus convection intensifies and lasts longer over the Gulf Stream, composite analyses are conducted for cumulus events that continue for at least 24 h. The target area is where the annual mean precipitation rate exceeds 5 mm day<sup>-1</sup> over the Gulf Stream within 65°-47°W (the area bounded by the thick solid contours within the inner square in Fig. 2c). There the precipitation band is zonally oriented and far from land, enabling us to extract the Gulf Stream influence. The start time of a convective event is defined as T = 0 h. The analyses are conducted for JJA and DJF separately, because the relative contributions of cumulus and stratiform precipitation are different between them (Fig. 3). The analyzed events account for the majority of total cumulus precipitation (96% in CNTL JJA, 91% in SMTH JJA, 66% in CNTL DJF, and 46% in SMTH DJF).

## a. JJA

Figure 8 shows the 12-hourly composites for cumulus precipitation, convective available potential energy

(CAPE), and SST from T - 12 h to T + 48 h in JJA in CNTL and SMTH. CAPE is calculated using 6-h outputs supposing that a parcel at 950 hPa is adiabatically lifted up to the condensation level, and moist adiabatically rises up to the level of neutral buoyancy. The center of each panel is where a cumulus event starts at T = 0 h. When a cumulus event starts in CNTL, a cumulus precipitation maximum approaches from the west along the warmer flank of the SST front. The precipitation maximum is associated with a high CAPE tongue that slants from the southwest to the northeast. Both the precipitation maximum and the high CAPE tongue are nearly parallel with the SST front. After T + 12 h, precipitation persists and forms a band on the warmer flank of the Gulf Stream front through T + 48 h. In SMTH, both the intensity of cumulus precipitation and CAPE values are much weaker than in that in CNTL. The precipitation maximum and CAPE tongue quickly move away from the analysis domain by T + 36 h. These results suggest a mechanism by which a convective precipitation band forms along the SST front in CNTL.



FIG. 10. Time-height sections for JJA of horizontal moisture convergence: (a),(b)  $-q\nabla \cdot \mathbf{V} - \mathbf{V} \cdot \nabla q$ , (c),(d)  $-q\nabla \cdot \mathbf{V}$ , and (e),(f)  $-\mathbf{V} \cdot \nabla q$  at the reference point of Fig. 8 in (left) CNTL and (right) SMTH.

Cumulus precipitation intensity depends on convective instability and moisture content. CAPE is larger in the CNTL than SMTH composites in Fig. 8. We now examine the evolution of the moisture budget for an air column from the surface to 10 hPa,

$$\int_{10hPa}^{SLP} \frac{\partial q}{\partial t} \, dp = \int_{10hPa}^{SLP} \left( -q \nabla \cdot \nabla - \nabla \cdot \nabla q - \frac{\partial q_l}{\partial t} \right) dp + E - P_C - P_L, \tag{1}$$

where q is the specific humidity, t the time, p the pressure, V the horizontal velocity,  $q_l$  the cloud water content, E the surface evaporation,  $P_C$  the cumulus precipitation, and  $P_L$  the stratiform precipitation. The analysis is carried out at the composite reference point where cumulus precipitation commences at T = 0 h.

Figure 9 shows the time series of CAPE,  $\partial$ CAPE/ $\partial$ t, and the terms of the moisture budget Eq. (1) for JJA in CNTL and SMTH. CAPE starts to increase at T = 0 h, and  $\partial$ CAPE/ $\partial$ t increases from T - 6 h both in CNTL and SMTH (Figs. 9a–d). Although CAPE in CNTL is smaller than SMTH at T = 0 h, in CNTL it is larger than SMTH

from T = 24 h to the end of the analysis period (T = 72 h). Around the time of convection occurrence,  $\partial CAPE/\partial t$  is also larger and lasts longer in CNTL. CAPE evolution is in phase with cumulus precipitation (Fig. 8), while  $\partial CAPE/\partial t$  is in phase with the time derivative of the column-integrated vapor content both in CNTL and SMTH (Figs. 9e,f).

Moisture advection  $(-\mathbf{V} \cdot \nabla q)$  accounts for much of the moisture convergence at T - 6 h, and then turns negative afterward, consistent with the passage of the warm sector of an extratropical cyclone. The mass convergence term  $-q\mathbf{V} \cdot \mathbf{V}$  becomes dominant from T = 0 h both in CNTL



FIG. 11. As in Fig. 8, but for  $-q\mathbf{V} \cdot \mathbf{V}$  at the surface (solid contour,  $10^{-8}$  kg kg<sup>-1</sup> s<sup>-1</sup>), evaporation [broken contour, mm (6 h)<sup>-1</sup>], and  $-\nabla^2$ SST (shaded,  $10^{-10}$  K m<sup>-2</sup>) in JJA.



FIG. 12. Time evolution of correlation coefficient between the surface wind convergence  $(-\nabla \cdot \mathbf{V}_{SFC})$  and  $\nabla^2 SLP$  (solid line),  $-\nabla \cdot \mathbf{V}_{SFC}$  and  $-\nabla^2 SST$  (broken line), and  $-\nabla^2 SST$  and  $\nabla^2 SLP$  (dotted line) within the composite area in Fig. 8 for (a) CNTL and (b) SMTH in JJA.

and SMTH. The convergence term  $-q\mathbf{V}\cdot\mathbf{V}$  is much larger in CNTL than in SMTH after cumulus precipitation starts, and remains about 0.8 mm (6 h)<sup>-1</sup> until T + 72 h. The amount of  $-q\mathbf{V}\cdot\mathbf{V}$  in SMTH rapidly decreases from T =12 h to T + 24 h, and then maintains a constant value of about 0.2 mm (6 h)<sup>-1</sup>. Surface evaporation is also larger in CNTL than in SMTH. It is interesting that stratiform precipitation is comparable to convective precipitation in SMTH, while convective precipitation is much stronger in CNTL. These results suggest that wind convergence is very important in determining cumulus precipitation evolution.

Figure 10 shows composites of total moisture convergence and its components in time-height sections at the reference point. This composite method is referred to as the cumulus composite. Major moisture convergences occur at T - 6 h at 850 hPa, mainly resulting from  $-\mathbf{V} \cdot \nabla q$ (Figs. 10e,f). When cumulus precipitation starts (T =0 h),  $-q\nabla \cdot \mathbf{V}$  in the surface layer becomes dominant. The subsequent development of moisture convergence resulting from  $-q\nabla \cdot \mathbf{V}$  is quite different between CNTL and SMTH. In CNTL,  $-q\nabla \cdot \mathbf{V}$  maintains positive total moisture convergence from T + 0 h through T + 72 h. The large surface moisture convergence is consistent with the CAPE increase in Fig. 9. In SMTH, large total moisture convergence persists only until T + 18 h because  $-q\nabla \cdot \mathbf{V}$  rapidly decreases and becomes overpowered by negative advection  $(-\mathbf{V} \cdot \nabla q)$ . These results indicate that surface wind convergence in CNTL is what sustains cumulus precipitation for a longer time than in SMTH. A natural question is how surface wind convergence is related to SSTs.

The relation between the surface wind convergence and the SST front during cumulus precipitation events is examined by the cumulus composite. Figure 11 shows 12-hourly cumulus composites for  $-q\nabla \cdot \mathbf{V}$  at 10 m, surface evaporation, and  $-\nabla^2 SST$  in JJA. A maximum of  $-q\nabla \cdot \mathbf{V}$  approaches the reference grid point from the west in CNTL, preceding CAPE and cumulus precipitation maximum in Fig. 8. Minobe et al. (2008) show a good correlation in space between surface wind convergence and  $-\nabla^2 SST$ , a relationship that is expected from atmospheric pressure adjustments to SST in the boundary layer. Indeed, the maximum of  $-q\nabla \cdot \mathbf{V}$  overlaps that of  $-\nabla^2$ SST along the sharp SST front, persisting until T + 48 h in a similar manner to persistent cumulus precipitation in Fig. 8. A tongue of larger evaporation extends over the warm flank of the SST front from the west, persisting through T + 48 h in CNTL. In SMTH, by contrast, there is no maximum of  $-\nabla^2 SST$  beneath cumulus precipitation at any time with smoothed SST. Although a maximum of  $-q\nabla \cdot \mathbf{V}$  propagates from the west before T = 0 h, it has a more circular shape than that in CNTL, and quickly moves out of the analysis domain by *T* + 48 h.

The evolution of the correlation coefficients among surface wind convergence,  $\nabla^2$ SLP, and  $-\nabla^2$ SST over the composite area shows clear evidence of the SST influence on surface convergence (Fig. 12). Surface convergence is highly correlated with  $\nabla^2$ SLP from the onset of convective precipitation through the composite period in CNTL. The correlations of  $-\nabla^2 SST$  with surface convergence and  $\nabla^2$ SLP quickly strengthen and exceed 0.6 after cumulus precipitation occurs. In SMTH, however, the correlation between surface convergence and  $\nabla^2$ SLP decreases around cumulus precipitation occurrence. After cumulus precipitation, it recovers to a high correlation. The correlations with  $-\nabla^2$ SST are weak during the analysis period. Convective precipitation and surface convergence in SMTH are still caused by the pressure adjustment mechanism within the atmospheric boundary layer, but the SST effects are weak.

These results suggest that the sharp SST front associated with the Gulf Stream induces surface wind convergence through the pressure adjustment mechanism proposed by Minobe et al. (2008). The wind convergence



FIG. 13. As in Fig. 8, but for DJF.



FIG. 14. As in Fig. 9, but for DJF.

maintains high CAPE and high moisture on the warm flank of the SST front, leading to the spatially confined, long-lasting cumulus precipitation there. In addition, locally enhanced surface evaporation also helps the Gulf Stream anchor the narrow rainband. The local enhancement of evaporation is due to disequilibrium between surface air temperature and SST across the SST front (e.g., Xie 2004; Tokinaga et al. 2009). Without an SST front in SMTH, surface wind convergence and surface evaporation lose their geostationary anchor. Consequently, cumulus precipitation in SMTH occurs only in moving atmospheric disturbances, being weaker in strength and shorter in duration without the help of SST forcing.

In addition to the stationary surface wind convergence, a strong SST front may intensify transient surface convergence by energizing synoptic disturbances (Kuo et al. 1991; Gyakum and Roebber 2001; Xie et al. 2002). Indeed, Minobe et al. (2008) report that surface cyclones tend to be more concentrated along the Gulf Stream in CNTL than in SMTH. We have decomposed the cumuluscomposite evolution of moisture convergence into synoptic (2–8 days) and longer components. However, there is little difference between CNTL and SMTH in JJA (not shown).

# b. DJF

In winter, cumulus precipitation is comparable to stratiform precipitation, and the total amount of precipitation is more than that in summer (Fig. 3). Figures 13-17 show the results from the composite analysis for DJF. The intensity of cumulus precipitation in DJF composites is stronger, and the tongue of the high CAPE is wider in DJF than in JJA, while the absolute value of CAPE is much smaller than that in JJA (Fig. 13) because of a lower temperature and moisture at the surface. As in JJA, persistent cumulus precipitation forms a band over the Gulf Stream through T + 48 h in CNTL. In SMTH, the high CAPE tongue is weaker than that in CNTL, with weak precipitation. Furthermore, the precipitation maximum in SMTH exhibits a circular shape rather than a zonal band, and it is weaker in intensity throughout the composite period, quickly moving out in an eastward direction by T + 36 h.

Figure 14 shows the moisture budget analysis for DJF. As a major difference from JJA, the CAPE is about onequarter in JJA both in CNTL and SMTH (Figs. 14a,b). The contribution of stratiform precipitation is comparable to cumulus precipitation in CNTL, consistent with Fig. 3. However, the rate of change in column moisture is larger



FIG. 15. As in Fig. 10, but for DJF.

than that in JJA. In particular,  $-q\mathbf{V} \cdot \mathbf{V}$  and surface evaporation are about twice of those in JJA. Evaporation decreases from T - 18 h and recovers at T + 24 h in CNTL and SMTH, while it is almost constant in JJA. This is due to the higher wind speed and its change in DJF (not shown). The persistence of cumulus precipitation mainly depends on  $-q\mathbf{\nabla} \cdot \mathbf{V}$  and surface evaporation, which is qualitatively similar to that in JJA. Interestingly, the evolution of  $-q\mathbf{\nabla} \cdot \mathbf{V}$  is in phase with stratiform precipitation rather than cumulus precipitation in DJF, although the difference in stratiform precipitation between CNTL and SMTH is much less than that in cumulus precipitation (cloud water changes hardly affect the moisture budget).

The evolution of vertical moisture convergence is also similar to that in JJA, although the amplitudes are about twice those found in JJA (Fig. 15). Remarkably, moisture convergence develops and persists along the Gulf Stream front where  $-\nabla^2$ SST is large in CNTL in DJF (Fig. 16). As a result, high CAPE and large convective precipitation are trapped along the SST front (Fig. 13). In SMTH, moisture convergence is transient and associated with moving atmospheric disturbances.

In contrast to JJA, the synoptic component of moisture convergence is indeed larger in CNTL than SMTH (not shown), in addition to an increase in the persistent SST frontal effect. Presumably as a result, the correlations among surface convergence,  $\nabla^2$ SLP, and  $-\nabla^2$ SST are more complicated than those in JJA (Fig. 17). The correlation between surface convergence and  $\nabla^2$ SLP decreases after the cumulus precipitation starts, while retaining relatively large values in CNTL. The correlation of  $-\nabla^2$ SST with  $\nabla^2$ SLP increases after cumulus precipitation starts, and the correlation between surface convergence and  $-\nabla^2$ SST remains at about 0.6 until T + 72 h. Strong synoptic disturbances reduce the correlation in DJF compared to JJA. After T + 24 h, the surface convergence peak shifts eastward from the  $-\nabla^2$ SST peak (Fig. 16). The moving peak is likely associated with synoptic disturbances. Horizontal advection is also stronger in DJF. Surface convergence gradually spreads horizontally with time from T + 12 h in CNTL DJF (Fig. 16). In



FIG. 16. As in Fig. 11, but for DJF.



FIG. 17. As in Fig. 12, but for DJF.

SMTH, both correlations of surface convergence with  $\nabla^2$ SLP and  $-\nabla^2$ SST are negative, while the correlation between  $\nabla^2$ SLP and  $-\nabla^2$ SST is positive with a daily cycle. This means that surface convergence associated with convective precipitation in SMTH DJF is controlled by atmospheric disturbance without SST influence.

The results from the composite analyses suggest that in response to the SST front, the pressure adjustment mechanism strengthens and sustains cumulus precipitation throughout the year. Its relative importance depends on the atmospheric environment and the SST front intensity.

# 5. Vertical extension

This section examines the vertical extent of the Gulf Stream's influence on the atmosphere. Convection is an important mechanism linking sea surface conditions to the free troposphere. Minobe et al. (2008) report that strong updrafts in the Gulf Stream rainband reach the upper troposphere. Such deep updrafts could be a source of barotropic Rossby waves propagating along the uppertropospheric westerly jet.

Figure 18 shows vertical velocity in CNTL. In the annual mean, the updraft maximum follows the Gulf Stream at all levels, especially at 850 hPa, as shown in Minobe et al. (2008) using the ECMWF operational analysis. Significant seasonal variations can be seen between JJA and DJF. A narrow band of upward motion with high significant level of the Student's t test is found above the Gulf Stream over the whole troposphere in JJA, while it is restricted in the lower troposphere in DJF with a broad structure in the upper troposphere, where the difference from SMTH is insignificant. The magnitude of updraft is weaker in JJA than in DJF. These features are generally consistent with the upward motion distribution in the ECMWF operational analysis for each season (Minobe et al. 2010). Compared to ECMWF, the upward motion is too weak near the American coast in the CNTL simulation, probably associated with the underestimation of precipitation (Fig. 1). Because the seasonal variations in horizontal structure are similar between upward motion and precipitation in Fig. 1, it is suggested that updraft may be related to precipitation.

Figure 19 shows vertical meridional sections across the Gulf Stream of vertical velocity, moisture convergence, and saturation equivalent potential temperature  $(\theta_e^*)$ , averaged between 70° and 50°W for JJA and DJF. For  $\partial \theta_e^*/\partial z < 0$ , the atmosphere is conditionally unstable. Where conditionally unstable, a saturated, undiluted parcel could rise up to the altitude where  $\theta_e^*$  is the same as the surface  $\theta_e^*$  value. This altitude may be considered as the convection top.

In JJA, the updraft maximum extends from 900 to 200 hPa in CNTL, sitting just above the surface moisture convergence maximum around 38°N anchored by the Gulf Stream SST front (Fig. 19a). The warm and moist air mass extends from the south to this surface convergence zone, where  $\theta_{e}^{*}$  exceeds 340 K, a value that allows a saturated, undiluted parcel to reach 300 hPa. In contrast, there is no surface convergence zone and no updraft centered on 38°N in SMTH (Fig. 19b). The warm/moist air mass with  $\theta_e^* > 340$  K is located south of 37°N, and the updraft maximum is also displaced south. The CNTL-SMTH difference (Fig. 19c) shows an updraft over the surface moisture convergence zone reaching 300 hPa, which may be taken as the SST front effect. Thus, the updraft height agrees with the cumulus convection height set by the atmospheric thermodynamic structure, while the updraft position is strongly influenced by surface convergence and the SST front in JJA.

In DJF, the updraft maximum in CNTL appears around 850 hPa above the surface moisture convergence (Fig. 19d). As a result of the atmosphere above 850 hPa being stable, the cumulus convection height is restricted to around 700 hPa. Thus, the updraft maximum around 400 hPa is not directly related to cumulus convection. Indeed, only the lower updraft disappears in SMTH, while the upper updraft maximum remains (Fig. 19e).



FIG. 18. Vertical velocity (shaded,  $-10^{-2}$  Pa s<sup>-1</sup>) at (left) 300, (middle) 500, and (right) 850 hPa for CNTL: (a)–(c) annual mean, (d)–(f) JJA, and (g)–(i) DJF. Contours are for SST (K). Thick contour shows 95% significant level of Student's *t* test for the difference from SMTH.

The CNTL–SMTH difference in DJF, however, reaches 300 hPa, which is much higher than the height of cumulus convection. This is consistent with enhanced synoptic activity in CNTL (Minobe et al. 2008), which affects updraft at higher vertical levels.

AFES adopts a cumulus parameterization where the height of convection is defined as the level of neutral buoyancy (LNB). Figure 20 shows the frequency of the LNB occurrence for cumulus precipitation within the Gulf Stream rainband. It exhibits clear seasonal variations. Convection frequently reaches up to 200 hPa in JJA, while most convection is limited below 800 hPa in DJF. This seasonal change in convection height holds in SMTH, likely resulting from changes in atmospheric stratification and SST. Much warmer SSTs during JJA enable larger CAPE and deeper convection. These results suggest that while the vertical extent of atmospheric response to the Gulf Stream is not determined by SST gradients, the horizontal distributions of upward winds and cumulus precipitation are strongly influenced by the SST front.

#### 6. Summary

We have investigated the atmospheric response to the Gulf Stream SST front using an AGCM, with a focus on

mechanisms for the formation of a narrow precipitation band on the warmer flank of the front. The CNTL run, forced with high-resolution observed SST data, captured the structures and seasonal variations of precipitation, evaporation, and surface wind convergence over the Gulf Stream similar to satellite observations. The SMTH run with smoothed SST around the Gulf Stream, by contrast, failed to simulate several key observed features. Cumulus precipitation was sensitive to SST distribution. Cumulus precipitation increases its intensity and duration in CNTL compared to SMTH, and this sensitivity to the SST front creates a narrow band of cumulus precipitation closely following the Gulf Stream. Our composite analysis for cumulus precipitation shows that the local enhancement of surface convergence and surface evaporation by sharp SST gradients is the key to anchoring the cumulus rainband to the Gulf Stream by moistening the surface atmosphere.

Precipitation and vertical structure of upward motion display strong seasonal variations. In JJA, the precipitation and updraft are concentrated in a narrow band along the Gulf Stream, while the upward motion shows a broad structure in the upper troposphere in DJF. The seasonal variations mainly were due to changes in relative contributions from cumulus convection and synoptic



FIG. 19. Meridional–vertical sections across the Gulf Stream averaged between 70° and 50°W: vertical velocity (shaded,  $-10^{-2}$  Pa s<sup>-1</sup>), moisture convergence (thick contours, solid lines show positive and dashed lines negative,  $10^{-8}$  kg kg<sup>-1</sup> s<sup>-1</sup>), and saturation equivalent potential temperature (thin contours, K). (top) JJA and (bottom) DJF: (a),(d) CNTL, (b),(e) SMTH, and (c),(f) CNTL – SMTH. White contour in (c) and (f) shows 80% and 90% significant levels of Student's *t* test.

disturbance to updraft. In JJA, the LNB is the highest, and reaches 300 hPa because the atmosphere is conditionally unstable throughout the troposphere. LNB in DJF most frequently appeared below 800 hPa because the middle and upper troposphere is stable. The deep updraft structure in DJF is probably indirectly due to the enhancement of synoptic disturbances by the sharp SST front. Therefore, the height of atmospheric response to the surface forcing depends on atmospheric stratification, and the height of cumulus convection is important to understand the vertical extent of atmospheric response. The horizontal structure of convection is strongly influenced by the SST front through the enhancement of surface convergence, evaporation, and synoptic disturbance.

SST fronts may affect the free troposphere and largescale circulation through their effect on baroclinic eddy activity (Reason 2001; Nakamura et al. 2004, 2008). Indeed, our AGCM experiments show that surface extratropical cyclone activity is sensitive to the Gulf Stream front (Minobe et al. 2008). It is difficult to obtain conclusive evidence for the influence of the Gulf Stream SST front on large-scale circulation from our experiments that last for 5 yr. Rodwell et al. (2004) suggest that 20 yr are necessary to identify significant responses in the North Atlantic region in the presence of large atmospheric internal variations. Thus, ensemble experiments are necessary to suppress internal atmospheric variability and extract SST effects on tropospheric circulation.

Recent climatological studies report similar modulation of surface wind convergence, cloud height and lightning by the Kuroshio Extension fronts in the northwest Pacific (Joyce et al. 2009; Tokinaga et al. 2009). The atmosphere response over the Gulf Stream is much more pronounced than that over the Kuroshio Extension, because of sharper SST gradients with warmer SSTs from the Gulf Stream, larger cross-frontal changes in the surface heat flux, and surface wind convergence. The closer proximity to the North American continent may also be important, strengthening atmospheric temperature gradients in winter.

The SST frontal effect on cumulus convection should be further investigated, because our AGCM does not resolve cumulus convection explicitly. To investigate the details of the convective response, higher-resolution



FIG. 20. LNB frequency of occurrence binned every 100 hPa (10<sup>3</sup> month<sup>-1</sup>) in CNTL (white) and SMTH (gray) over the Gulf Stream rainband within 30°–48°N, 80°–40°W: (a) MAM, (b) JJA, (c) SON, and (d) DJF.

regional models are necessary. For example, Song et al. (2009) suggest that the coupling strength between the atmosphere and ocean depends on the vertical diffusion scheme of the model, even when a nonhydrostatic regional model with 15-km horizontal resolution is used. The influence of lateral boundary conditions is important, especially when the relationship between the local response and large-scale circulation is considered. In addition, the  $0.5^{\circ}$  SST product does not fully resolve sharp SST fronts of the Gulf Stream. Therefore, a newly developed, global, cloud-resolving model (Oouchi et al. 2009) is an interesting tool for studying SST frontal effects on the atmosphere.

Finally, the interaction between the ocean and atmosphere through the local atmospheric response to the SST front is an interesting topic. Xue et al. (2000) and Hogg et al. (2009) report that ocean currents can be affected by local atmosphere–ocean coupling using idealized atmospheric boundary layer–ocean coupled models. The cumulus convection response reaching the tropopause proposed in the present paper may affect the interaction with the ocean. High-resolution realistic coupled models (e.g., Komori et al. 2008) are necessary to explore this interaction.

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