P1.16 MESOSCALE STRATOCUMULUS BANDS CAUSED BY GULF STREAM MEANDERS

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1. INTRODUCTION

Mesoscale patterns in surface temperature, and hence surface heat flux, have long been known to give rise to mesoscale solenoidal circulations in the atmospheric boundary layer (e.g. Holton 1992). Phenomena of this type include: sea breezes (e.g. Arritt 1993), mid-lake cloud bands (e.g. Passarelli and Braham 1981, Hjelmfelt 1982, Niziol et al. 1995), and anomalous cloud lines downwind of East Coast bays and bights (Sikora et al. 2001; Sikora and Halverson 2002). For each of these phenomena, spatially fixed surface features control the mesoscale pattern of surface temperature (Arritt 1993). Thus, the location of the resulting mesoscale solenoidal circulation depends primarily upon the synoptic-scale wind direction in the planetary boundary layer. Similarly, the existence of these phenomena depends upon the solenoidal forcing being strong enough to overcome both drag and synoptic scale advection (Sikora el al. 2001).

For intermediate values of synoptic-scale wind, a solenoidal circulation advects downwind of the original surface hot spot as a pair of counter-rotating horizontal vortices of mesoscale dimension (Hjelmfelt 1982). Thus, surface-driven solenoidal circulations can cause boundary-layer cloud bands by any of three mechanisms: encroachment deepening of the boundary layer over the heated surface, advective deepening of the boundary layer by the mesoscale circulation, and intensified microscale convection in the region of enhanced surface heat fluxes. Indeed, the physical linkage between these processes is such that the three mechanisms work in concert.

Fixed coastal features are not the only source of mesoscale hot spots for solenoidal circulation formation. Meanders and rings arising from the Gulf Stream can also create mesoscale regions of elevated surface temperature (e.g. Halliwell and Mooers 1983, Robinson et al 1988, Lee and Cornillon 1996). The Gulf Stream is the western boundary current of the North Atlantic. As such, it sweeps a band of high-temperature water northeastward from the southeast coast of the United States to the region well south of Nova Scotia. The sea surface temperature (SST) gradient along the northwest side of the Gulf Stream is particularly intense, earning it the name North Wall (Warnecke et al. 1971). With typical temperature differences of 5 to 10 *C across a few kilometers, the Gulf Stream North Wall is as thermodynamically significant as most of the surface features known to drive mesoscale solenoidal circulations (Sublette and Young 1996).

The mesoscale pattern of surface forcing becomes more complicated when the Gulf Stream's northeastward progress breaks down into a series of meanders such as those in Figure 1. The typical meander has a wavelength of 330-350 km and amplitude of 200 km (Halliwell and Mooers 1983, Lee and Cornillon 1996). Thus, the typical Gulf Stream meander is similar in spatial scale and baroclinicity to one of the Great Lakes and is markedly larger than the Chesapeake and Delaware Bays, but evolves on a scale from days to weeks (Halliwell and Mooers 1983, Robinson et al. 1988, Lee and Cornillon 1996). These characteristics suggest that Gulf Stream meanders, and quite possibly rings, could provide sufficient forcing for mesoscale solenoidal circulations during cold-air outbreaks. These meander-forced soleniodal circulations are the focus of our study.

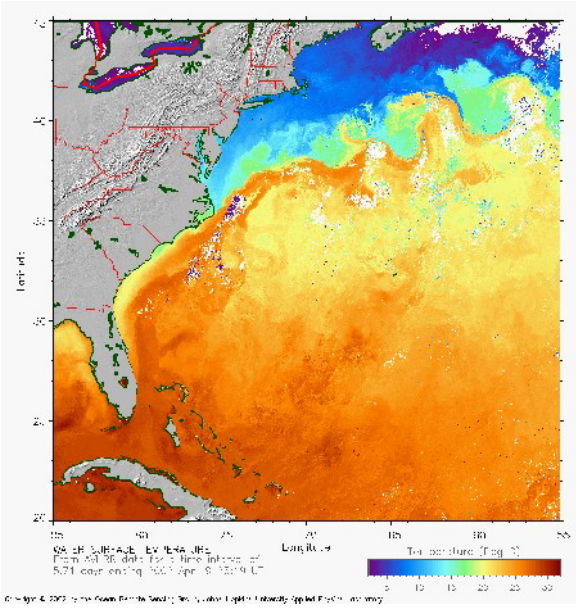

Figure 1. Sea surface temperature analysis for the Gulf Stream region valid April 9, 2002. Based on an average of the JHU/APL composite of AVHRR channels 3B, 4, and 5 for the 5.71 days prior to 23:19 UTC.

2. DATA

In order to undertake this study it is necessary to observe the open ocean cloud bands—and the meteorological and oceanographic environment in which they form. This study relies primarily on satellite imagery for cloud band detection and mapping as well as analysis of the SST pattern. Operational analyses

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from the National Weather Service (NWS) and individual buoy observations from the National Data Buoy Center (NDBC) are used to document the synoptic setting. Overland climatological records from the National Oceanographic and Atmospheric Administration supplement the Coupled Ocean/Atmosphere Data Set (COADS) in describing the climatological conditions necessary for cloud band formation.

Geostationary Orbiting Environmental Satellite (GOES)-8 infrared imagery (channel 4, 10.20 to 11.20 µm), archived by Unisys Weather Information Services (http://weather.unisys.com/), were examined for the Fall 2000 through Spring 2002 time period in order to detect open ocean cloud band cases. These 4 km resolution images proved sufficient to distinguish our phenomenon of interest from the cloud streets caused by the more common wide-mode boundary-layer rolls (Young et al. 2002). Once illustrative cases and counter-cases were selected, a more robust selection of GOES-8 and National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) images were obtained for subsequent analysis.

The GOES-8 images were provided by the Cooperative Institute for Research in the Atmosphere (CIRA) of Colorado State University (http://www.cira.colostate.edu/). Of the five channels available, channels 1 (0.55 to 0.75 µm, 1 km resolution), 2 (3.80 to 4.00 µm, 4 km resolution), 4, and 5 (11.50 to 12.50 µm, 4 km resolution) proved the most useful. The cloud bands could be seen on the channel 1 during the day, and on the other three channels day or night. They were typically most apparent on channel 5, as were the other boundary-layer cloud features such as wide-mode rolls.

AVHRR images were provided by the Applied Physics Laboratory of Johns Hopkins University (JHU/APL) (http://fermi.jhuapl.edu/). Channel 1 (0.58 to 0.68 µm), 2, (0.725 to 1.10 µm), 3B (3.55 to 3.93 µm), 4 (10.30 to 11.30 µm), and 5 (11.50 to 12.50 µm) data were obtained. The resolution of the AVHRR imagery is 1.1 km. The infrared imagery was particularly useful as it captured both the cloud bands and the sea surface temperature pattern in the surrounding clear-sky areas.

AVHRR-derived SST analyses of the Gulf Stream region were also obtained from JHU/APL. Channels 3B, 4, and 5 are used by JHU/APL to generate their SST images. Because of the persistent cloudiness associated with cold-air outbreaks, it was necessary to use their multi-day composites despite the loss of temporal resolution. The meanders in the Gulf Stream evolved slowly enough that this did not present a problem.

Synoptic conditions were documented using the NWS operational Northern Hemisphere charts for 850 hPa and the surface. These FAX charts were downloaded from the National Climatic Data Center (NCDC) (http://lwf.ncdc.noaa.gov/oa/ncdc.html). Boundary-layer winds were determined from these charts and from moored buoy observations downloaded from NDBC (http://www.ndbc.noaa.gov /index.html). Climatological SST values were obtained from the Columbia University online catalog of COADS monthly averages (http://ingrid.ldgo.columbia.edu/SOURCES/OBERHUBER/) while the overland air temperature climatology was obtained from NOAA's 30-year means. Small-scale variability was reduced by using the averages for climatological divisions within a state rather than those for individual stations.

3. RESULTS AND DISCUSSION

This section will document the occurrence and origin of open ocean cloud bands using one banded case and two counter cases in which bands failed to occur despite synoptically similar conditions. Each of the counter cases was selected to highlight the importance of a particular oceanographic feature in the formation of open ocean cloud bands.

3.1 April 8, 2002

Both visible (not shown) and infrared (Figure 2) satellite imagery show bands of enhanced cloudiness extending from the northwest to southeast. Because the atmosphere upwind of the bands is cloud-free, it is possible to see the sharp SST contrast at the Gulf Stream North Wall in Figure 2. Each band can be seen to originate within one of a series of Gulf Stream meanders. These bands are at least as long as the more common cloud streets associated with wide-mode boundary-layer rolls (Miura 1986, Young et al. 2002). They are however much wider than wide-mode rolls would be given any reasonable boundary layer depth (Young et al. 2002, Miura 1986). This relationship between horizontal scale of the cloud features and boundary layer depth is quite robust for wide-mode rolls, so the extreme width of the current bands suggests that they represent a different phenomenon.

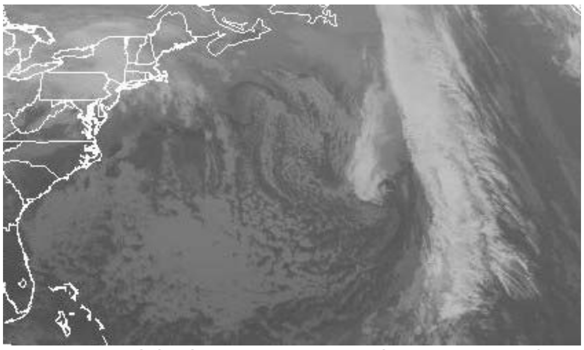

Figure 2. GOES-8 channel 5 infrared image from 13:45 UTC on April 8, 2002.

The Gulf Stream and its meanders are more evident in the corresponding AVHRR-derived SST analysis (Figure 1). The Gulf Stream appears as a mesoscale band of higher SST separating cool water to the northwest from warm waters to the southeast. As is typical (Robinson et al. 1988, Lee and Gornillon 1996), these meanders grow in amplitude but decrease in intensity in the downstream (northeast) direction. A high-resolution AVHRR channel-4 image from this same period (Figure 3) reveals more detail of the SST field in and around these meanders. The

North Wall can be seen as a sharp boundary looping across the image occasionally breaking down in the presence of smaller oceanographic eddies. The boundary-layer cloud field is similar to that seen in cold-air outbreaks over the Great Lakes, small clouds form just downwind (southeast) of the North Wall and grow into larger and more complex structures to the southeast. The mesoscale atmospheric structure seen in Figure 2 is clearly modulating microscale convective elements in Figure 3. This pattern and its relationship to the mesoscale meanders of warm, Gulf Stream water are strongly reminiscent of the mid-lake convective bands observed during along-lake cold-air outbreaks (Hjelmfelt 1982, Niziol et al. 1995).

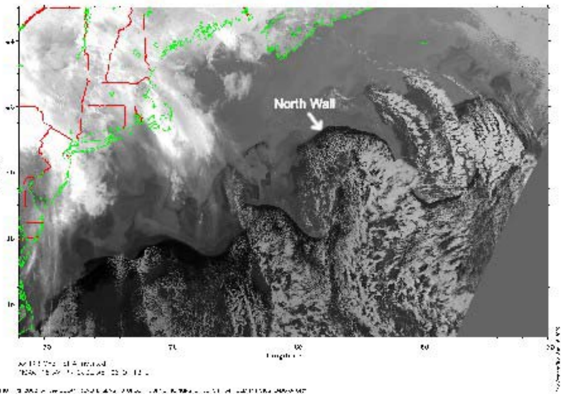

Figure 3. AVHRR channel 4 infrared image from 07:13 UTC on April 8, 2002.

The atmospheric synoptic setting is also similar to that for lake-effect cloud bands. The NWS 850 hPa analysis for 12 UTC on April 8 (not shown) depicts a cold front extending south-southwest from a low near Greenland, with northerly winds extending behind the front to about 70˚ west longitude. Cold advection is occurring throughout this region. The cloud bands described above are confined to the region of northerlies and cold advection between the cold front and the trailing high. The surface analysis (not shown) is similar although the high is displaced further to the east and the geostrophic winds in the cold-air outbreak are from the north-northeast instead of north. Frictional backing would however cause the true surface winds to more nearly parallel those at 850 hPa. Thus, the boundary-layer wind in the region of the bands was approximately northerly, matching the alignment of the cloud bands.

The geographic correspondence of each of the cloud bands to a warm meander in the Gulf Stream is striking as can be seen from a comparison of Figures 1, 2, and 3. Unlike traditional cold-air outbreak cloud-streets, these bands begin near the Gulf Stream North Wall rather than the coast. The upwind end of each band lies near the tip of a warm meander. The lack of clouds northwest of the Gulf Stream North Wall can be understood in terms of the change in air-sea temperature difference across this oceanographic feature. The farthest southeast moored buoy, 44011 lying well south of Nova Scotia but still to the north of the Gulf Stream's April 8th position, reported an air-sea temperature difference of only -3 ˚C at the time. In contrast, situating the same air over the Gulf Stream would result in an air-sea temperature difference of -15 to -20 ˚C, values similar to those seen in intense lake-effect convection (e.g. Hjelmfelt 1982, Niziol at al. 1995).

From the discussion above, it is apparent that the open ocean cloud bands observed on April 8, 2002 bear a striking resemblance, in both form and environment, to mid-lake convective bands in lake-effect snowstorms (e.g. Passarelli and Braham 1981, Hjelmfelt 1982, Niziol et al. 1995) and to the dynamically similar bay-effect cloud bands (Sikora et al. 2001, Sikora and Halverson 2002). The open ocean cloud bands form only where a mesoscale region of large negative air-sea temperature difference is surrounded on the upwind and lateral sides by regions of modest air-sea temperature difference. From this point of origin, they trail downwind for hundreds of kilometers over the more nearly uniform SST field southeast of the Gulf Stream North Wall. Thus, while the existence of a mesoscale region of enhanced boundary-layer instability gives rise to a band of convective cloudiness, the band can persist far downwind of its parent surface feature. Similar downwind persistence has been observed in lake-effect cloud bands (e.g. Niziol et al. 1995) and bay-effect cloud bands (Sikora et al. 2001), and is attributed to the existence of a mesoscale solenoidal circulation. The initial circulation forms in response to the localized surface heating as described in the introduction. The circulation then persists downwind for as long as sufficient warmth, and thus buoyancy, remains in its updraft plume to counteract drag. The several hundred kilometer persistence seen in this case is not unusual for phenomena of this ilk.

3.2 December 10, 2000

The air-sea temperature difference and static stability associated with cold-air outbreaks are very different in mid Autumn to early Winter than in late Winter to early Spring. This change occurs because, during the former period, the land (source of cold air) is much cooler than either the Gulf Stream or the inshore waters. During the cold-air outbreak of December 10, 2000, for example, the air-sea temperature difference northwest of the Gulf Stream (buoys 44004, 44008, and 44011) was approximately -8 ˚C, a sharp contrast to the weak inshore instability seen in the mesoscale cloud band case described above. Because of this much greater inshore instability, convective cloud cover began near the coast instead of near the Gulf Stream North Wall, as can be seen in the infrared GOES-8 image from (Figure 4) 12:15 UTC. Unlike the band case discussed above, December 10 exhibits a typical cold-air outbreak cloud pattern with wide-mode rolls beginning a uniform distance off the coast as the thermal internal boundary layer grows to the lifting condensation level (Chang and Braham 1991). Because of the bight between Massachusetts and Nova Scotia, the upwind ends of the cloud streets are farther upwind (northwest) in that region. There is also some indication of mesoscale banding in Figure 4. These bands begin well to the northwest of the Gulf Stream and have no spatial correspondence to the Gulf Stream meanders seen in Figure 5. The difference in cloud pattern between this and the previous case cannot be tied to corresponding differences in the synoptic pattern (not shown). Indeed, the setting is similar to those of the Gulf Stream meander cloud band case. That is, there was a cold-air outbreak occurring in the northwesterly flow west of a cold front and east of a polar high. Thus, for this cold-air outbreak with large inshore air-sea temperature difference, it is the coastal features rather than those of the Gulf Stream that control the mesoscale structure of the cloud field. Moreover, this difference in source feature was due to seasonal changes in the surface temperatures of land and sea rather than differences in the atmospheric synoptic setting or oceanographic mesoscale setting.

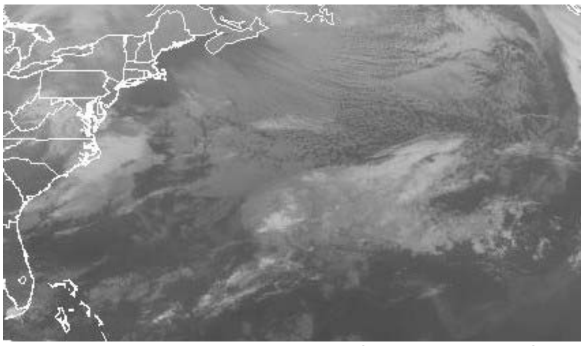

Figure 4. As in Figure 2 but from 12:15 UTC on December 10, 2000.

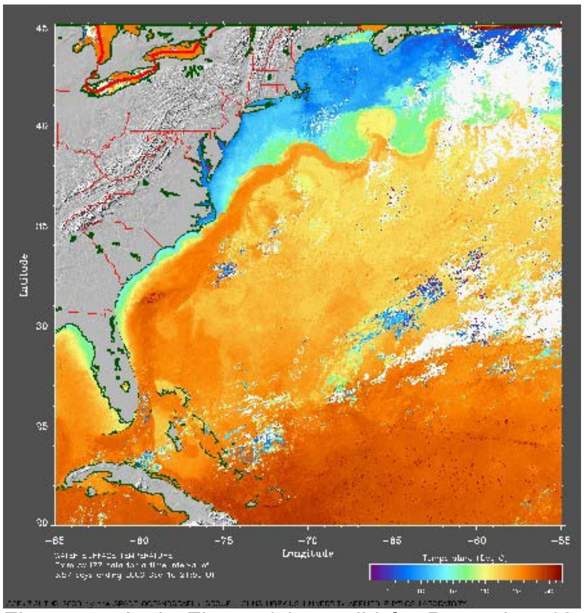

Figure 5. As in Figure 1 but valid for December 10, 2000 based on a composite from the 5.57 days prior to 21:59 UTC.

3.3 March 20, 2001

Even when the pattern of air-sea temperature differences across the Gulf Stream North Wall is conducive for meander-generated cloud bands, it is possible to have cold-air outbreak cases in which the bands do not form. The GOES visible (not shown) and infrared imagery (Figure 6) for 00:15 UTC March 20, illustrate one such case. Only wide-mode rolls are present in the cold-air outbreak cloud field, a feature also illustrated in the AVHRR imagery from 20:19 UTC (Figure 7). These rolls do however begin at the Gulf Stream North Wall (Figure 8) instead of the coast. This positioning reflects the lack of air-sea temperature difference over inshore waters during this case. Buoys 44004 and 44008 northwest of the Gulf Stream North Wall had air-sea temperature differences of 1 ˚C or less while buoy 44011 in the warmer water reported an unstable air-sea temperature difference of more than -6 ˚C. Thus, the thermodynamic forcing was similar to that in the mesoscale band case. Moreover, the surface winds were similar to those in the band case. Thus, the bulk surface heat fluxes should have been similar as well, with small values inshore and larger values over the Gulf Stream. The synoptic setting was likewise similar with cold advection occurring in the northerly and northwesterly flow west of a cold front (not shown). Yet, despite these similarities, the March 20 case exhibited wide-mode rolls parallel to the boundary-layer wind instead of mesoscale cloud bands.

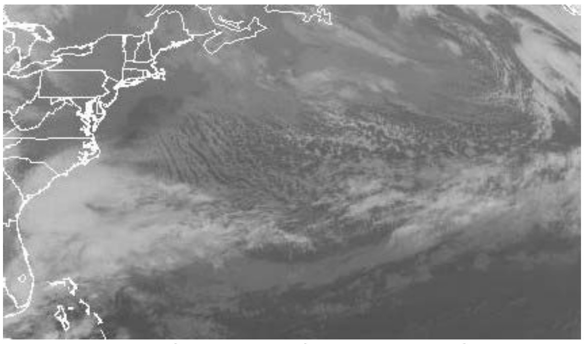

Figure 6 As in figure 2 but from 00:15 UTC on March 20, 2001.

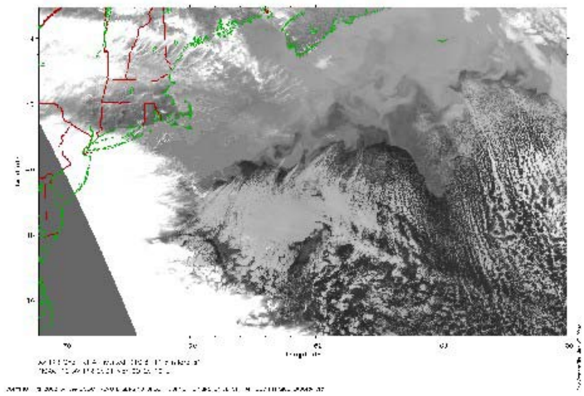

Figure 7 As in figure 3 but from 20:19 UTC March 20.

The structure of the Gulf Stream depicted in Figures 7 and 8 provides an explanation for this difference in cloud structure. Whereas the meander-induced cloud band cases of this study had clearly defined high-amplitude, high-intensity meanders in the Gulf Stream, the period around March 20 featured ill-defined, low-intensity meanders that were both convoluted and diffuse. While the upstream ends of some of the wide-mode rolls do appear to be linked to small-scale warm features along the Gulf Stream North Wall, these meanders are neither large enough nor intense enough to drive mesoscale cloud bands of the intensity seen in the first case study. Thus, the scale of the atmospheric response appears to be related to the horizontal scale of the meander, with smaller meanders resulting in narrower cloud bands.

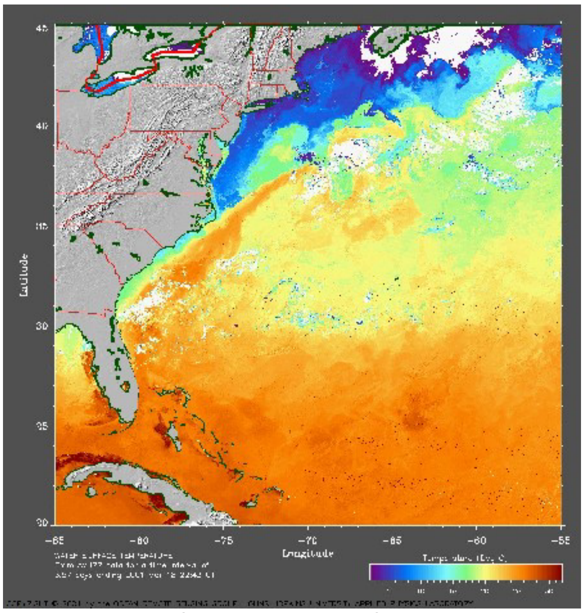

Figure 8 As in figure 1 but valid for 20 March, 2001 based on a composite from the 5.57 days prior to 22:43 UTC March 18.

3.4 Climatological considerations

Because the annual cycle of surface air temperature is different for the Gulf Stream, the inshore waters, and the upwind landmass, there is a distinct seasonality to the temperature contrast between these three regions, and thus in the possibility of a cold-air outbreak creating unstable conditions over the inshore waters. While air over the Gulf Stream is warmer than that in coastal Maine during all months of the year, the air over the coastal waters becomes cooler than that over the adjacent landmass during the months of April through August. Thus, the odds of cold-air outbreak clouds initiating at the Gulf Stream instead of the coast increase as Spring progresses. In contrast, cold-air outbreaks themselves become less common as Spring progresses. Thus, from roughly March through April, a polar airmass may penetrate southeast to the Gulf Stream before encountering water warm enough to drive convective development in the boundary layer. The season is bounded on one side by Winter's large land-sea temperature contrast and on the other by Summer's lack of significant cold-air outbreaks. This window exists only because there is a lag between the Spring warm-up of land and ocean.

Based on the two years of observations examined, it appears that this phenomenon is less common than are the cloud streets caused by wide-mode boundary-layer rolls. All of the cases observed by the authors occurred in two calendar months (March and April). Thus, the phenomenon may not be particularly rare "in season".

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