Secondary Circulations at the Air-Sea Interface in the Presence of High Winds and Strong SST Gradients

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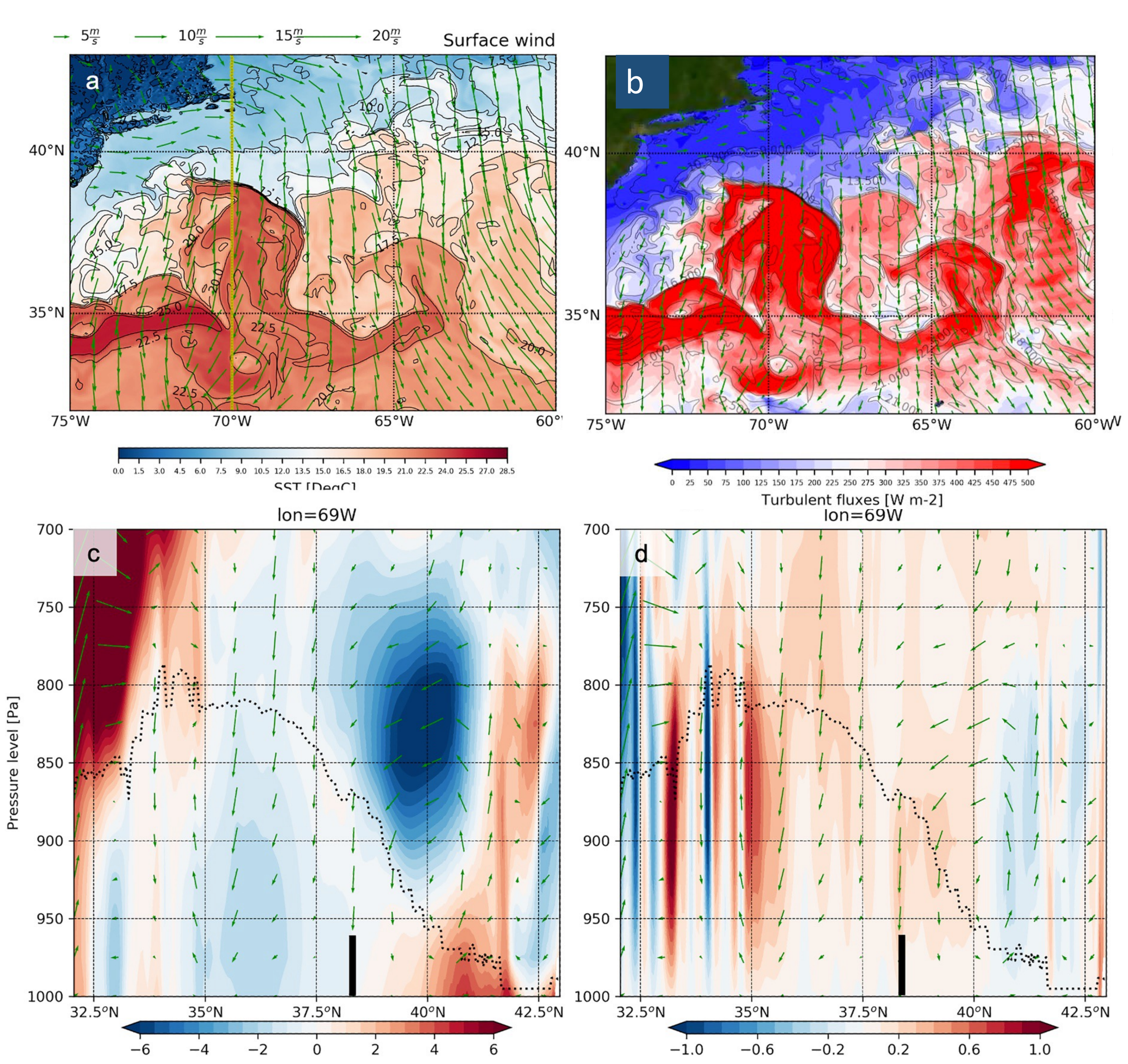
Introduction

The earth's climate state is fundamentally linked to the mechanisms that transport heat between the ocean interior and the upper troposphere across the air-sea interface. One important vehicle for this transport is the action of mesoscale Sea Surface Temperature (SST) anomalies with typical spatial scales of 50–500 km, reaching magnitudes of 2.5–3 ^{o}C. These anomalies are typically bordered by sharp SST fronts at the submesoscale (<50 km), driven in part by baroclinic instability in the ocean interior that produces mesoscale eddies. In regions such as Western Boundary Currents (WBCs), mesoscale eddies and submesoscale structures are thought to explain most of the upward vertical heat transport in the global ocean, up to 7PW close to the surface, leading to a cooling of the ocean interior and a warming of surface layers.

The study here focuses on the Gulf Stream region, which is a region that hosts energetic mesoscale eddies.

Figure 1 Simulated Fluxes and Secondary Circulation

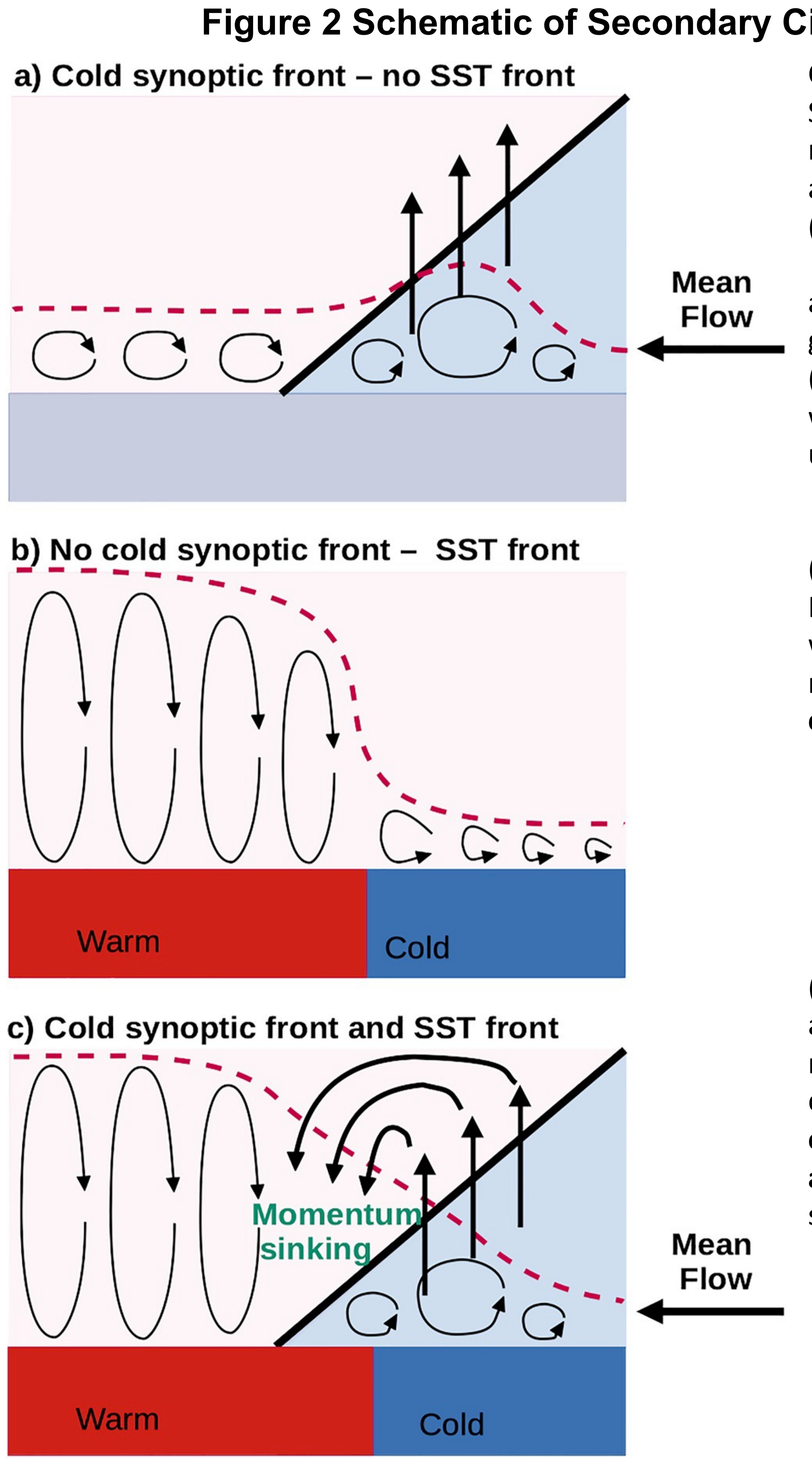


a-b) Surface wind vectors overlaid on (a) Sea Surface Temperature in deg K and (b) turbulent fluxes in W/m^2.

c-d) Vertical cross sections (at yellow line in panel a) of (c) meridional wind anomaly with respect to the mean flow in m/sec, (d) omega anomaly in hPa/sec.

In panels c-d, the dashed black lines depict the pressure level of the atmospheric planetary boundary layer, the black bars denote the location of the SST front, and the green arrows represent the wind vector normalized to the panel aspect ratio.

Figure 2 Schematic of Secondary Circulation Conditions



Cold air blows from the right over an SST change from cold to warm. The red dotted line represents the atmospheric boundary layer height (PBL).

a) A cold synoptic front approaches a gradual Sea Surface Temperature (SST) gradient (from right to left), the warmer air at the surface is pushed upward. **No secondary circulation**

(b) Cold air blows over an SST front. Higher atmospheric PBL forms above warmer SST due to higher mixing at no front conditions. **No secondary circulation.**

(c) A cold synoptic front approaches an SST front and produces momentum sinking above the front due to mixing. **Secondary circulation enhances the turbulent fluxes and atmospheric gradients.** This is the scenario shown in Figure 1.

Methods & Experiments

The coupled model used in this study is the Goddard Earth Observing System infrastructure and atmospheric model coupled to the the Massachusetts Institute of Technology general circulation ocean model (GEOS-MITgcm). The atmospheric model was configured to run with nominal horizontal grid spacing of 7 km and 72 vertical levels and the ocean and sea ice were configured to run with nominal horizontal grid spacing of 2-4 km and 90 vertical levels. The model simulation was initialized on 21 March. The results shown in this study are based a 75-day segment of the simulation from 22 April to 6 June.

Results: SST, Fluxes and Secondary Circulation

An example of the impact of mesoscale SST anomalies on the local atmosphere is shown in Figure 1.

Panels a and b emphasize the strong correspondence between the total turbulent heat flux at the sea surface (panel b) and the SST anomalies (panel a). Mesoscale SST anomalies are bordered by submesoscale SST fronts with a ~10 km width and an amplitude of up to ~0.5°C per km (Figure 1a). Patterns of large turbulent heat fluxes, with magnitudes up to 500 W/m^2 (Figure 1b) display a strong discontinuity just above SST fronts, which is consistent with observation-based studies (e.g., Gula et al., 2014).

Panels c and f show latitude-height cross sections of the meridional wind (c) and the vertical velocity (d) at the location (70W) indicated by the yellow line in Panel a. The wind vectors and the shaded contours show the acceleration of the meridional wind (panel c) towards the SST front and the downwelling motion (panel d) as the air mass approaches the SST front. This is the induced secondary circulation.

Results: Schematic of Secondary Circulation

Figure 2 shows a depiction of the conditions under which the secondary circulation is induced based on examination of simulation results under many different conditions.

Energetic wind and SST anomalies are usually characterized by different time and space scales; wind anomalies are dominated by spatial scales larger than 500 km and time scales smaller than 5 days, while SST anomalies are dominated by scales smaller than 500 km and time scales larger than 5 days. When both SST and wind anomalies are present at the same time, the air-sea coupling causes SST anomalies to have an imprint on wind anomalies and vice-versa. As emphasized in Strobach et al. (2022), mesoscale SST anomalies drive a local wind response at the same scales (due to the secondary circulation), with local wind speed increased (decreased) over warm (cold) SST anomalies. Similarly, large-scale time-intermittent wind stress anomalies are known to impact SST at the same scale (strong winds mix the upper ocean layer leading to negative large-scale SST anomalies).

Summary/Conclusions:

We presented results from a new, global, high-resolution (2-4 km for ocean and 7-km for atmosphere) earth system simulation. This simulation allows us to examine aspects of small-scale air-sea interaction beyond what previous studies have reported. Our study focuses on recurring intermittent wind events in the Gulf Stream region. These events induce local air-sea heat fluxes above Sea Surface Temperature (SST) anomalies with horizontal scales smaller than 500 km. In particular, strong latent heat bursts above warm SST anomalies are observed during these wind events. We show that such wind events are associated with a secondary circulation that acts to fuel the latent heat bursts by transferring dry air and momentum down to the surface. The intensity of this secondary circulation is related to the strength of small-scale SST fronts that border SST anomalies. The study of such phenomena requires high-resolution in both the atmospheric and oceanic components of the model.

Strobach, E., Klein, P., Molod, A., Fahad, A. A., Trayanov, A., Menemenlis, D., & Torres, H. (2022). Local air-sea interactions at ocean mesoscale and submesoscale in a Western Boundary Current. Geophysical Research Letters, 49, e2021GL097003. https://doi. org/10.1029/2021GL097003

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