Effects of along-shore wind stress and surface cooling on the formation of shelf sea fronts in a simple air–sea interaction model

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This paper presents numerical simulation results from a set of control and sensitivity experiments on the effects of winter-time air–sea interaction on the variability of sea surface temperature (SST) on a two-dimensional continental shelf which is uniform in the along-shore direction and is bounded to the west by a straight coast and to the east by a prescribed Gulf Stream front. In the control experiment, the model ocean circulation is driven by a time-dependent wind forcing which is parameterically coupled to the cross-shelf SST gradient. In the sensitivity experiments, wind stress, diabatic cooling and air–sea coupling are turned on separately to estimate the individual contribution of each effect to the cross-shelf SST variation. Experiments have also been carried out for different coupling strengths and diabatic cooling rates to examine the model sensitivity to these parameters. The model results indicate that air–sea interaction could induce a secondary SST front on the shelf. Comparisons of model results with observations obtained during the Genesis of Atlantic Lows Experiment conducted off the east coasts of the Carolinas during January and February 1986 qualitatively confirm our finding.

1 Introduction

Sea surface temperature (SST) fronts or discontinuities of cross-shelf SST gradient often occur in coastal waters on the continental shelf margin off the southeast coast of the United States (known as the South Atlantic Bight, or SAB) during autumn and winter. These oceanic frontal structures can strongly influence both oceanographic and atmospheric processes in the SAB’s environment. For example, SST fronts affect the coastal marine system by modifying cross-shelf transport of water masses [17], and influence coastal atmospheric frontogenesis [3,10,21], cyclogenesis [7,12], and low-level jetogenesis [8,23] by modifying the marine atmospheric boundary layer (MABL). Thus, modeling the formation and maintenance of SST fronts on the SAB shelf is extremely important for understanding coastal oceanic and atmospheric processes in that region.

SST frontogenesis on the SAB shelf has been simulated previously by Oey [16] using a two-dimensional, southeast coast ocean model uniform in the along-shore, meridional direction. He concluded that persistent northerly winds may promote SST frontogenesis on the SAB shelf in winter by driving upper Gulf Stream water onto the shelf. The mechanism is that the cross-shelf SST contrast is accentuated in the SAB region because the Gulf Stream provides a continual supply of warm water. Thus, even if offshore shelf and Gulf Stream waters were cooled by a loss of latent and sensible heat to the atmosphere, this loss is compensated for, in the stream proper, by more warm water advected from upstream. The result is that while shelf waters may cool to 5°C to 10°C, waters just a few kilometers offshore in the Gulf Stream frontal region cool to only about 20°C. This differential cooling combined with onshore transport of upper Gulf Stream waters due to several days of southward winds would cause SST fronts on the middle shelf.

In the study of Oey [16], the interaction between the atmospheric flow and the SST front was not considered. However, observations and numerical simulations indicate that SST fronts on the shelf are conducive to the development of coastal mesoscale weather systems including fronts, cyclones and low-level jets [8,10,21]. Thus, when properly specifying the wind forcing for the ocean model, changes of wind conditions induced by SST should not be neglected.

In this study, we will apply a simple numerical model to investigate the impact of a time-dependent surface wind stress, which is parameterically coupled to the cross-shelf SST gradient, on the evolution of the cross-shelf SST distribution, over an idealized two-dimensional shelf. The text is organized as follows. In section 2, a simple two-dimensional model for SST frontogenesis on an idealized shelf will be described. Then, in section 3, we will present the results from a series of numerical simulations using the simple model. Qualitative comparisons of model results with observations are discussed in section 4 followed by a summary of conclusions in section 5.

2 Development of a simple two-dimensional model

We consider an initially uniform, motionless shelf water which is bounded to the west by a straight north–south coast and to the east by a sharp SST front (figure 1). The
entire shelf is assumed to be 75 km wide. For convenience of discussion, the shelf is divided into three cross-shelf zones according to the distance from the coast: the inner (0–20 km), middle (20–45 km) and outer (> 45 km) shelves. The equations governing the changes of SST and surface currents will be presented below.

2.1 SST

The change of SST ($T$) is assumed to be caused by advection and diabatic cooling according to the following equation:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = -v \frac{\partial T}{\partial y} - w \frac{\partial T}{\partial z} - Q = Q_{\text{net}},$$

(1)

where $u$, $v$, and $w$ denote, respectively, the cross-shelf $(x)$, along-shelf $(y)$ and vertical $(z)$ velocity components, $Q$ represents the rate of diabatic surface cooling and $Q_{\text{net}}$ is the rate of SST change due to the net effect of along-shore advection ($-v \frac{\partial T}{\partial y}$), upwelling ($-w \frac{\partial T}{\partial z}$) and diabatic cooling ($Q$). In a two-dimensional system uniform in the along-shelf direction, the along-shore advection is zero, i.e.,

$$v \frac{\partial T}{\partial y} = 0,$$

and if the shelf waters are also well-mixed in the vertical $(z)$, then,

$$w \frac{\partial T}{\partial z} = 0.$$  

In this case, $\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = -Q = Q_{\text{net}}$. Mathematically, this results in a very simple equation for SST,

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - Q.$$  

(1a)

The physical meaning of (1a) is that the local change of SST is caused by cross-shelf advection and diabatic cooling. These two effects are essential to frontogenesis in shelf waters as found by previous studies [2,16]. In addition, upwelling may be significant near the shelf break [11], and along-shore advection may be important near the coast and along the Gulf Stream [20]. To include the effects of upwelling and along-shore advection while still keeping a very simple equation for SST, we will use equation (1) and consider the effects of along-shore advection and upwelling as part of $Q_{\text{net}}$ which is represented by a simple analytical function to be described below.

(i) Along-shore advection ($-v \frac{\partial T}{\partial y}$): Along-shore advection is important in the vicinity of the Gulf Stream. This results in very little change of SST in the along-stream direction near the Gulf Stream velocity core.

(ii) Upwelling ($-w \frac{\partial T}{\partial z}$): This term is usually small over the inner- and mid-shelves due to weak temperature stratification [1], but it may be important near the shelf break since both vertical velocity $(w)$ and temperature stratification $(\frac{\partial T}{\partial z})$ are often significant there [11]. However, as pointed out by these authors, the magnitude of this term varies considerably depending on the location of the Gulf Stream.

(iii) Diabatic surface cooling $(Q)$: This term is proportional to the air–sea temperature differential and surface wind speed. As pointed out by Riordan [21], $Q$ is also proportional to the SST gradient in the direction of the airflow since surface air temperature is strongly influenced by SST along the upstream path of the airflow. As a result, during cold-air outbreaks when cold and dry northwesterly airflow moves offshore, maximum sea-to-air heat flux occurs near oceanic frontal features. Computations by Bane and Osgood [4] showed that during the second intensive observing period (IOP 2) of the Genesis of Atlantic Lows Experiment (GALE) conducted off the southeast U.S. coast in January 1986, the surface fluxes of both sensible and latent heat were largest over the Gulf Stream front. Their estimate showed that from January 25 to 30, 1986, the average heat loss to the atmosphere from the Gulf Stream mixed layer (where $Q$ is expected to be a maximum) could have been sufficient to cool the Gulf Stream mixed-layer water by an average of 0.62°C. This is equivalent to a mean cooling rate of 0.1°C/day for the Gulf Stream mixed layer in the GALE study area.

Since both upwelling induced surface cooling and diabatic cooling increase from the shelf toward the shelf break (where the Gulf Stream front is often located), the combined effects of upwelling and diabatic cooling result in a maximum SST reduction near the shelf break. However, this reduction of SST is largely compensated for by the along-shore advection in the Gulf Stream proper. As a result, the net effect ($Q_{\text{net}}$) of upwelling, advection and diabatic cooling is a maximum SST reduction over the outer shelf.

To represent this combined effect of along-front advection, upwelling and diabatic cooling, we assume a $Q_{\text{net}}$ of the form:

$$Q_{\text{net}} = \begin{cases} \frac{Q_0 \exp[(x - x_M)^2/(25 \text{ km})^2]}{25 \text{ km}} & \text{if } x > 25 \text{ km}, \\ \frac{Q_0 \exp[(25 \text{ km} - x_M)^2/(25 \text{ km})^2]}{25 \text{ km}} & \text{if } x < 25 \text{ km}, \end{cases}$$

(2)

where $Q_0 = 0.5^\circ \text{C/day}$, and $x_M = 50$ km representing the location of maximum SST reduction due to $Q_{\text{net}}$. 