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Quantifying SST errors from an OGCM in relation to atmospheric forcing variables

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ABSTRACT

The relationship between various atmospheric variables at the sea surface and climatological monthly means of sea surface temperature (SST) is investigated over the global ocean. The goal is to quantify the change in SST that results solely from variations in a particular atmospheric variable. This is accomplished using a series of numerical simulations from an atmospherically-forced ocean general circulation model (OGCM). It is first demonstrated that SST variations at all latitudes are generally strongly and positively correlated with increases in near-surface air temperature, and vapor mixing ratio and net shortwave radiation at the sea surface, while they are often moderately and negatively correlated with increases in near-surface wind speed. There is only a weak and negative relationship between variations in SST and those in net longwave radiation at the sea surface. Variations in the net shortwave radiation and vapor mixing ratio are found to have more influence in driving the seasonal cycle of SST than other atmospheric variables. Global averages of slope values from the least squares fit indicate that a 1 °C change in air temperature results in ≈0.2 °C change in SST. Similarly, a 1 g kg^{-1} change in vapor mixing ratio gives ≈0.4 °C change in SST, and 10 W m^{-2} change in shortwave (longwave) radiation results in ≈0.13 °C (≈0.07 °C) change in SST. All these values vary regionally, and are neither constant nor in the same direction everywhere. In addition, some atmospheric variables are already correlated to each other. Therefore, a fractional factorial design which involves the joint effects of all atmospheric variables on SST at the same time is further applied. Results from the factorial design are somewhat consistent with the simple linear regression analysis, in that a 2 °C increase in air temperature can typically give an increase in SST, generally ranging between 0.5 and 0.8 °C over the global ocean.

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1. Introduction and motivation

Spatial and temporal variability of sea surface temperature (SST) is closely related to the substantial heat content of the ocean mixed layer, which itself is largely influenced by atmospheric conditions near the sea surface (e.g., Chambers et al., 1997; Boccaletti et al., 2004; Willis et al., 2004; Du et al., 2005). This is due largely to the fact that the oceanic mixed layer gives rise to small scale variability with longer persistence times than the variability associated with such scales in the atmospheric boundary layer (e.g., Stull, 1988). Atmospheric variables at/near the sea surface (e.g., net solar radiation wind speed, etc.) play substantial roles in driving the seasonal variations in SST.

The major focus of this study is to quantify the relationship between atmospheric variables and SST, given the fact that mechanisms by which climatological variations in SST are tied to atmospheric forcing are poorly understood. For example, a few modeling investigations (Palmer and Sun, 1985; Barnston, 1994; Kushnir and Held, 1996) and observational studies (Cayan, 1992) examined the the influence of atmospheric variables on SST, but did not investigate the relationship between the two over the global ocean. Some other studies applied the heat flux as a forcing function (e.g., Eden and Willebrand, 2001; Gulev et al., 2003, 2007) in investigating the role of SST in ocean climate simulations but did not specifically explore impact of individual atmospheric forcing variables on seasonal variability of SST. Kara et al. (2009a) explored effects of various near-surface atmospheric variables in controlling the seasonal cycle of climatological SST over the global ocean, but they did not provide any quantitative results.

The relationship between atmospheric variables and SST is of importance to both observational researchers and climate modelers (e.g., ocean and coupled atmosphere-ocean modelers) for various applications. In particular, an ocean modeler would be interested in knowing which atmospheric variable may result in the largest deficiencies in model-simulated SST, and should therefore pay specific attention to its accuracy before using it for a model simulation. This is due to the fact that atmospheric forcing products have their unique biases over the global ocean (Rienecker et al., 1996; Trenberth and Caron, 2001).

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In this paper, the relationship between a given atmospheric variable and SST is addressed by answering the question, "how much variation in a given atmospheric variable (e.g., net shortwave radiation) results in a quantitative change in SST (e.g., 1 °C). Regions where large/small SST changes resulted from a particular atmospheric variable are mapped over the global ocean. This is done using an OGCM. Our hypothesis is that variations in climatological monthly mean SSTs are largely determined by atmospheric variables in ocean model simulations that are performed with no assimilation of or relaxation to any SST data.

Accordingly, the paper is organized as follows. A brief description of the OGCM and simulations from the model are given in Section 2. The procedure for analyzing the relationship between atmospheric variables and SST is introduced in Section 3. Results are demonstrated at selected individual locations in Section 4 and over the global ocean in Section 5. A fractional factorial design study for the model SST errors is presented in Section 6. Conclusions of the paper are given in Section 7.

2. Ocean model

2.1. HYCOM description

The HYbrid Coordinate Ocean Model (HYCOM) includes a large suite of physical processes and incorporates numerical techniques that are optimal for dynamically different regions of the ocean. It contains five prognostic equations: two for the horizontal velocity components, a mass continuity or layer thickness tendency equation and two conservation equations for a pair of thermodynamic variables, such as salt and potential temperature or salt and potential density (Bleck, 2002).

The model behaves like a conventional σ (terrain-following) coordinate model in very shallow oceanic regions, like a z-level (fixed-depth) coordinate model in the mixed layer or other unstratified regions, and like an isopycnic-coordinate model in stratified regions. The optimal coordinate is chosen every time step using a hybrid coordinate generator. The ability to adjust the vertical spacing of the coordinate surfaces in HYCOM simplifies the numerical implementation of several physical processes, such as mixed layer detrainment, convective adjustment, etc, making it a candidate to investigate SST variations over the global ocean.

The HYCOM domain used in this paper spans the global ocean from 78°S to 90°N. It has a 0.72° equatorial Mercator grid between 78°S and 47°N, with an Arctic bi-polar grid north of 47°N, but with latitudinal resolution doubled near the equator. The model has $0.72° \times 0.72° \cos(\text{lat})$ (longitude $\times$ latitude) resolution on a Mercator grid. There are 26 hybrid layers in the vertical. The atmospheric forcing is discussed in Section 2.2. Monthly mean temperature and salinity from the Generalized Digital Environmental Model, version 3 (GDEM3) climatology (Carnes, 2009) are used to initialize the model. The simulations use realistic bottom topography with the model boundary at the 50 m isobath. The K-Profile Parameterization (KPP) mixed layer submodel of Large et al. (1997) is used in the simulations.

The model includes computationally efficient bulk heat flux parameterizations for latent and sensible heat fluxes which include stability-dependent exchange coefficients (Kara et al., 2005a). Because there is no relaxation to any SST climatology, most effects of atmospheric variables are taken into account through net surface energy balance in the model (Kara et al., 2005b). This further confirms the appropriate use of an atmospherically-forced model (i.e., with no oceanic data assimilation) in exploring the relationship between atmospheric variables and SST. Note that the SST seasonal cycle is also influenced by various dynamical processes, such as atmospheric advection and oceanic upwelling (Sutton and Allen, 1997; Scott, 2003; Wang and Chang, 2004). However, our hypothesis is that these processes are also related to the atmospheric variables, i.e., the ocean model (i.e., HYCOM) takes these effects into account in the upper ocean with the mixed layer submodel, finally resulting in a SST.

2.2. Atmospheric forcing and model simulations

The model was first run for 5 years until statistical equilibrium was reached and then extended for another four years. Our experience is that four model years is enough to equilibrate SST, primarily because this is a direct response to the atmospheric forcing. For example, there is almost no difference between the monthly mean SST from year 5 and year 9 of the standard forcing case. As an example, we ran the model for about 25 years, demonstrating almost no changes in the mean of basin-averaged net heat fluxes and SST over the global ocean (Fig. 1).

Climatological monthly means of atmospheric forcing variables were formed from the $1.125° \times 1.125°$ European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year re-analysis over the years 1979–2002 (Uppala et al., 2005). For example, the January mean is the average of all Januaries from ERA-40 from 1979 to 2002. A climatological mean correction is applied to some fields obtained from ERA-40 to improve their accuracy. Winds are improved by using the satellite winds (QuikSCAT) as described in Kara et al. (2009b). Zonal and meridional components of wind stress are then computed following Kara et al. (2007). A high frequency component is added to the climatological winds, i.e., the wind forcing includes 6-h variability added to the monthly means (e.g., Kara et al., 2005c). This variability is added because the mixed layer is sensitive to sub-monthly changes in surface forcing down to time scales of a day or less. A correction for shortwave and long-

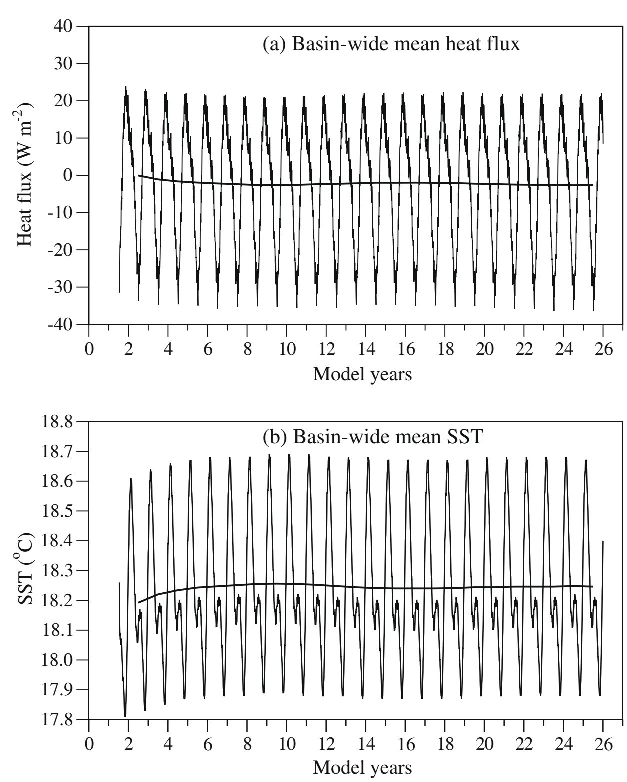

Fig. 1. Basin-wide variations of (a) mean heat flux and (b) mean SST as obtained from the 0.72° global HYCOM for the seasonal cycle and long-term mean.