Contributions to Large-scale Sea Level Changes in the North Atlantic Ocean

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Abstract

Large-scale sea level in the North Atlantic region is studied using sea surface height (SSH) from the TOPEX/Poseidon/Jason altimeters, wind stress curl from the European Center for Medium-Range Weather Forecasting (ECMWF) and Smith and Sandwell gridded bathymetry. We model SSH changes owing to heating and wind forcing. On interannual time scales surface heating is an important contributor to SSH anomalies, modifying the low-frequency changes of SSH. The constant-depth thermocline baroclinic Sverdrup model with motionless abyss captures large-scale spatial patterns of nonsteric SSH observations but with a larger amplitude and more zonal structure. Adding the effects of the full topography on the spatial structure of the wind-driven SSH signal improves the spatial comparisons in the subpolar region. In the subtropics, using the mean depth of the ocean of 1000 m but still including topographic effects also improves the spatial structure. Both of the topographic Sverdrup balance solutions improve the representation of the (NAC) North Atlantic Current.

Models

Model 1 Thermosteric Height

[*Cabanes et al.*, 2006; *Vivier et al.*, 1999]:

$$\eta(x,y,t)=\int_{t_0}^{t}\frac{\alpha Q_{net}}{\rho_0 c_p}+\eta_0(x,y,t_0)$$

Then remove the linear trend.

Q_{net} - Surface heat flux (J/m^2);
ρ_0 - Density (kg/m^3);
α - Thermal expansion coefficient$(/K)$;
c_p - Specific heat$(J/(K\cdot kg))$.

Model 2 Baroclinic Sverdrup Balance(flat bottom):

$$\eta(x,y,t)=\eta_E(y,t)+\int_{x_E}^{x}\frac{f}{\rho_0\beta g H_{const}}\vec{k}\cdot\nabla\times\vec{\tau}(x,y,t)dx$$

η_E - Eastern boundary observation (m);
$\nabla\times\vec{\tau}$ - Wind stress curl (N/m^2);
H_{const} - 500m;
x_E - Eastern boundary(m);
f - Coriolis parameter (s^{-1});
β - $\partial f/\partial y(Units: s^{-1}m^{-1})$;

Model 3 Topographic Sverdrup Balance [*Vivier et al.*, 1999]:

$$\eta=\eta_E(y,t)+\int_s\frac{f}{\rho_0\beta g H(x,y)J(s,q)}\vec{k}\cdot\nabla\times\left(\frac{\vec{\tau}(x,y,t)}{H(x,y)}\right)ds$$

H is the real topography varying with x and y
$q=f/H(Units: s^{-1}m^{-1})$
s is the curvilinear abscissa $(ds^2=dx^2+dy^2)$ along constant q contours
$J(s,q)=\pm\|\nabla q\|$ is the determinant of the Jacobian matrix

Model 4 Modified Topographic Sverdrup Balance

$$\eta=\eta_E(y,t)+\int_s\frac{f}{\rho_0\beta g H_m(x,y)J(s,q)}\vec{k}\cdot\nabla\times\left(\frac{\tau(x,y,t)}{H_m(x,y)}\right)ds$$

Same equation with Model 3, but with

$$H_m=-1000m+0.1*(H-mean(H))$$

Data

Time: 1993-2007; Resolution: 0.5 degree;
Area: North Atlantic Ocean (10°N-65°N, 0-80°W);
Heat fluxes: Oaflux; Wind stress: ECMWF
SSH: AVISO (http://www.aviso.oceanobs.com/)

SSHa and Thermosteric Height at 24.5N

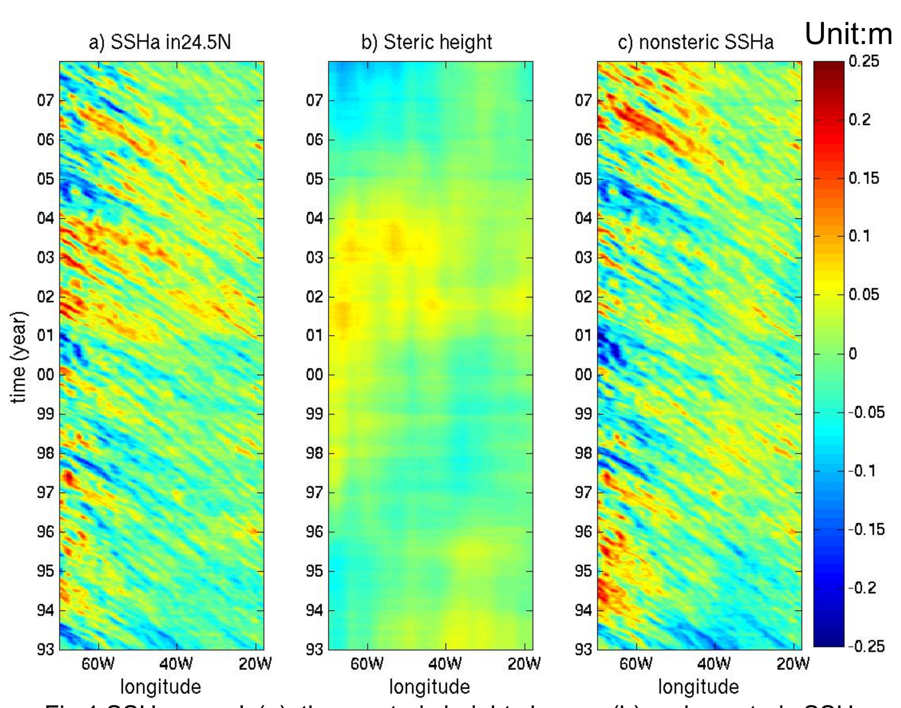


Fig.1 SSH anomaly(a), thermosteric height changes(b) and nonsteric SSH anomaly(c) at 24.5°N. Seasonal cycle is removed for all of them. Units:m.

- Fig.1 shows westward propogation of SSH anomaly (Fig.1(a) and (c)) and interannual thermal steric height changes (Fig.1(b)).

EOFs of SSHa, thermosteric Height and nonsteric SSHa

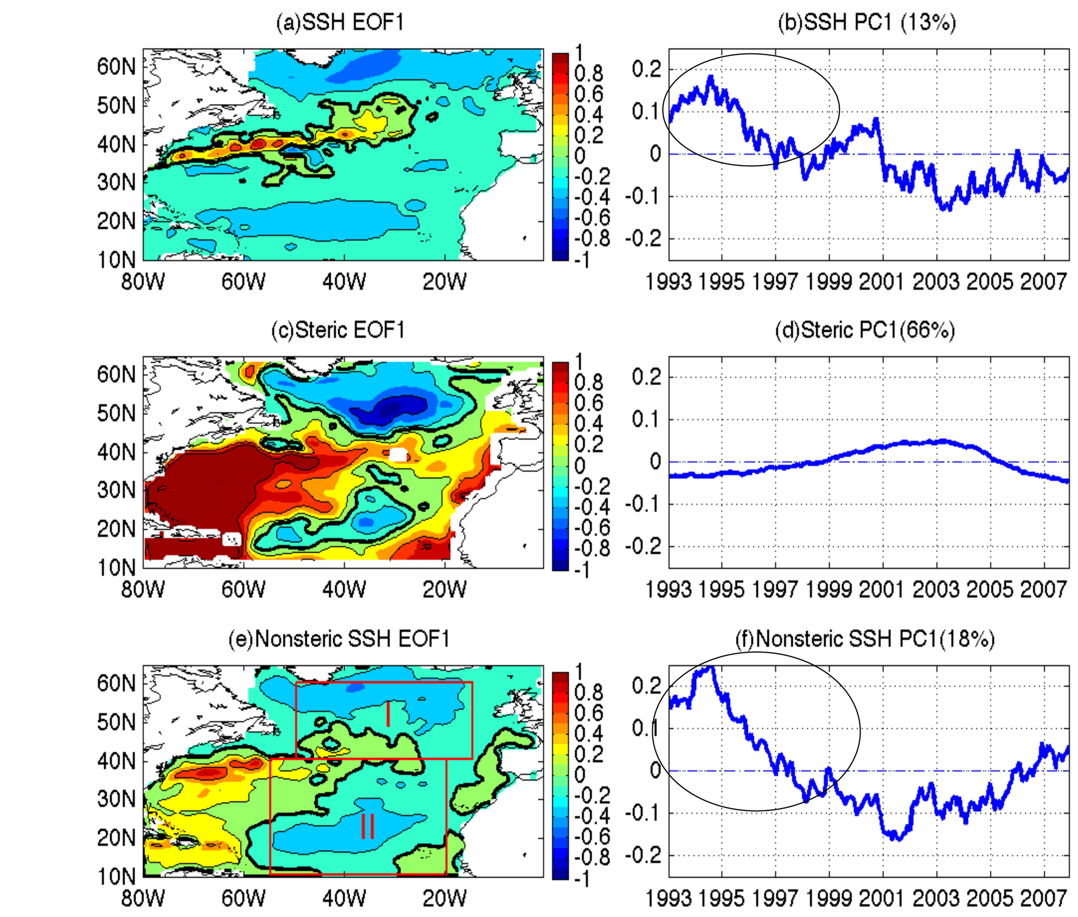


Fig.2 EOF1 and PC1 of SSH anomaly ((a) and (b)), thermal steric height((c) and (d)) and nonsteric SSH anomaly((e) and (f)) in the whole North Atlantic Ocean. Solid bold black lines are the zero contours. EOF1 is nondimensional and unit for PC1 is meter. Box I is subpolar box (40°N-60°N, 15°W-50°W) and box II is subtropical box (10°N-40°N, 20°W-55°W).

- EOF1 and PC1(Fig.2(a) and (b)) jointly show an increasing SSH over subtropical region during 1990s [*Häkkinen and Rhines*,2004] and 2001-2003 [*Häkkinen and Rhines*,2009].
- Surface heating (Fig.2(d)) contributes to the slow changes of sea level, especially during 1999-2003.
- Nonsteric SSH(Fig.2(f)) increases more rapidly in the subpolar region and drops faster over the Gulf Stream during the 1990s, compared with SSH(Fig.2(b)).

Schematic framework

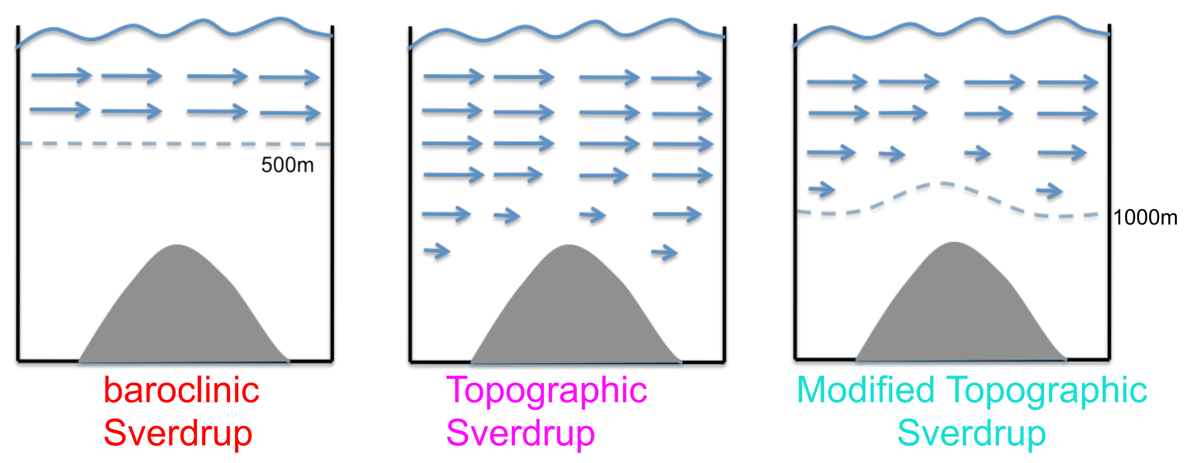
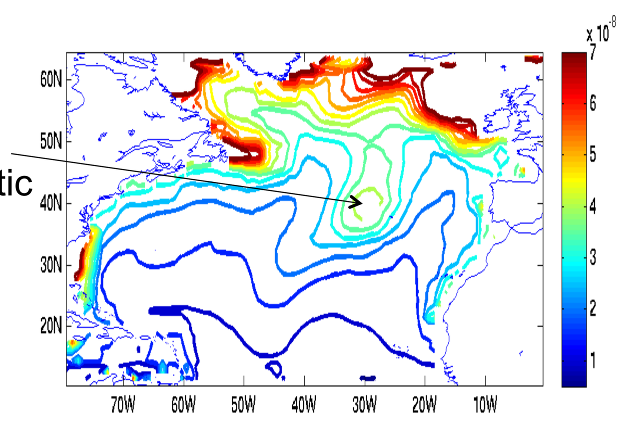


Fig.3 Schematic maps of models. (a) Constant-depth baroclinic Sverdrup model with 500-meter thermocline depth and motionless lower layer; (b) topographic Sverdrup model with full depth of water column and vertically self-similar EB mode and (c) modified topographic Sverdrup with 1000 meter line slightly deflected by bottom topography.

- Classic Baroclinic Sverdrup balance connects the wind stress curl and large-scale meridional volume transport.
- Topographic Sverdrup model is under assumption that barotropic flow is constrained by f/H contours [*Pedlosky*,1979] and vertically self-similar with a rapid decay with depth [*Killworth*, 1992].
- Here, we also construct a new model: modified topographic Sverdrup model, which combines the baroclinic and topographic Sverdrup.

Mid-Atlantic ridge



- Mid-Atlantic ridge plays an important role on the currents in the North Atlantic Ocean

Fig.4 the characteristics contours of constant potential vorticity f/H. Units: $m^{-1}s^{-1}$

Model Results in 2004

2004

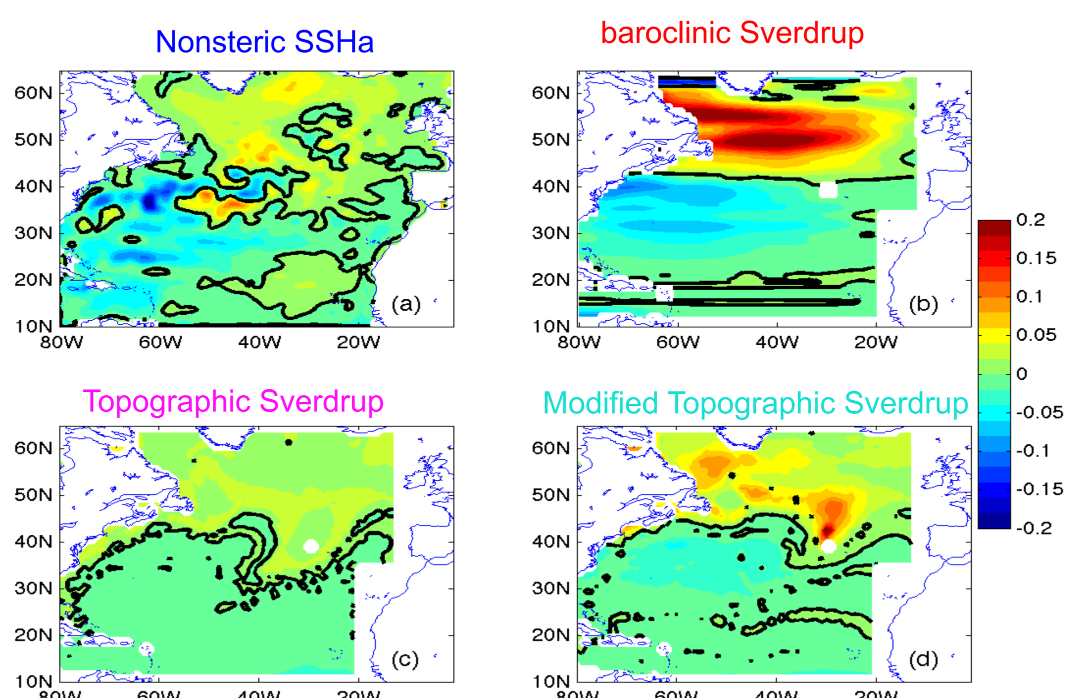


Fig.5 Nonsteric SSH anomaly (a), constant-depth Sverdrup anomaly (b) and topographic Sverdrup anomaly (c) and modified topographic Sverdrup anomaly (d) in 2004. Units:m.

- Baroclinic Sverdrup balance captures large-scale spatial patterns of observations, but maximum values are too large and contours are almost zonal.
- Both topographic Sverdrup and modified topographic Sverdrup models can reproduce the right locations of Gulf Stream (GS) and North Atlantic Current (NAC).

Model results in subpolar and subtropical boxes

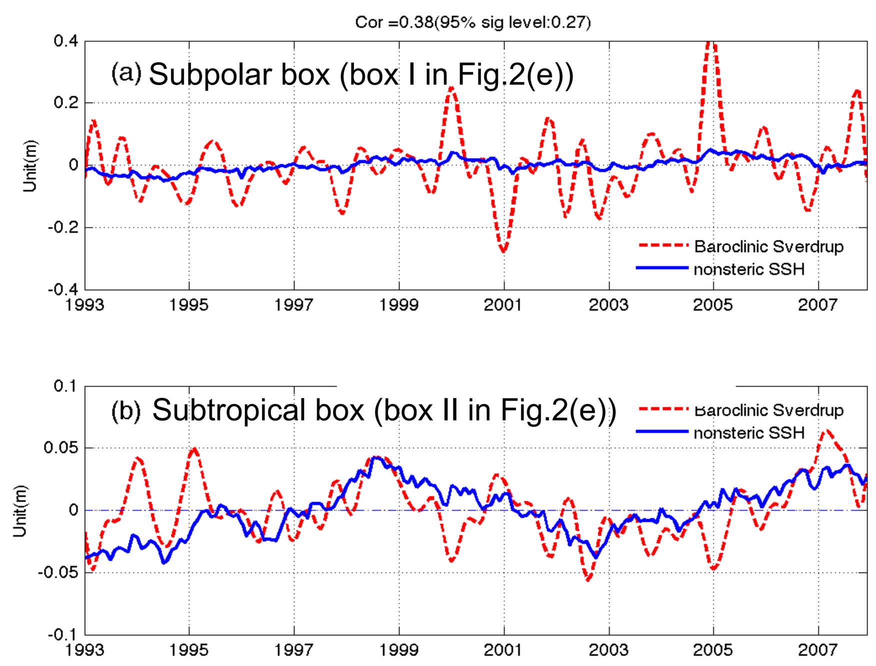


Fig.7 Baroclinic Sverdrup anomaly (dotted red) and nonsteric SSH anomaly (solid blue) in subpolar box (a) and in subtropical box (b). Units: meter.

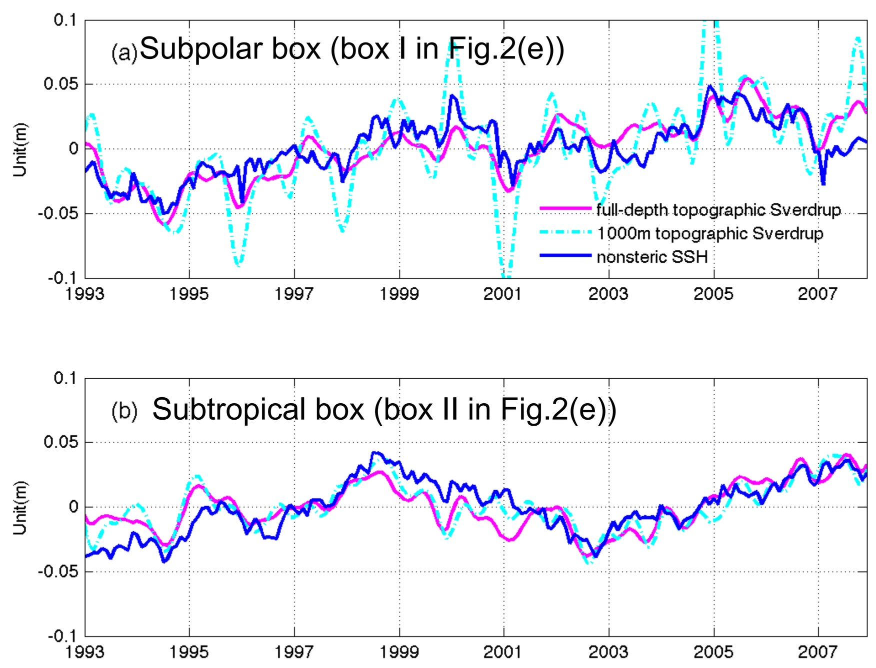


Fig.8 Topographic Sverdrup anomaly (solid magenta), modified topographic Sverdrup anomaly (dotted cyan) and nonsteric SSH anomaly (solid blue) in subpolar box (a) and in subtropical box (b). Units: meter.

		Nonsteric SSHa	Baroclinic Sverdrup	Topographic Sverdrup	Modified Topographic Sverdrup
Subpolar Box (Box I)	RMS(Unit: m)	0.021	0.103	0.024	0.04
	Correlation with nonsteric SSHa	-	0.38	0.79	0.66
	95% significance level	-	0.27	0.63	0.49
Subtropical Box (Box II)	RMS	0.021	0.025	0.018	0.019
	Correlation with nonsteric SSHa	-	0.5	0.76	0.79
	95% significance level	-	0.4	0.53	0.48

- For the subpolar gyre, the full-depth topographic Sverdrup balance has the highest correlation of 0.79 to observations and its magnitude is most consistent one with observations, which implies the barotropical structure of subpolar region;
-For the subtropical gyre, all of the three Sverdrup models show comparable magnitude with observations, but the modified topographic Sverdrup model has the highest correlation of 0.79 to observations, indicating the real structure in subtropical region might be baroclinic but with topography effects.

Conclusion

- Surface heating contributes to SSH changes in the North Atlantic by modifying and reducing the amplitude of the low-frequency anomalies forced by winds.
- Baroclinic Sverdrup balance captures large-scale spatial patterns of nonsteric SSH anomaly; however, its magnitudes are too large and contours are almost zonal.
- The right locations of GS and NAC can be predicted by both topographic models.
- For the subpolar gyre, the full-depth topographic Sverdrup balance is the only one with right amplitude and highest correlation with observations among the three Sverdrup models, which implies the barotropical structure of subpolar region.
- For the subtropical gyre, the modified topographic Sverdrup model compares as well with observations as the topographic Sverdrup model suggesting that there are topographic effects on the baroclinic flow.

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