Low-frequency variability of the global sea surface height revealed by satellite altimetry

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Decade-long observations of the sea surface height made by the TOPEX/Poseidon (T/P) altimetry mission were analyzed for studying the low-frequency variability of the global oceans. Spatial Gaussian smoothing was performed to retain wavelengths larger than 500 km. Complex-valued empirical orthogonal function (CEOF) analysis was performed to describe the spatial and temporal characteristics of the large-scale low-frequency (periods between 18 months and 10 years) variability. In the Pacific and Indian Oceans, the first mode represents the ENSO and the Indian Ocean Dipole variabilities, respectively. In the North Atlantic Ocean, the first mode reveals an oscillation of the Gulf Stream gyre with a period about 5 years. In the South Atlantic Ocean, the first mode is characterized by interannual Rossby waves along 30°S with a period of 5 years. In all the three ocean basins, the second mode represents variability with quasi-biennial periods.

The focus of the paper is the variability of the North Atlantic Ocean. Large-scale low-frequency variability of the North Atlantic has recently been studied based on model simulations (e.g. Hakkinen, 1999, 2001), as well as analysis of altimetry data in conjunction with in-situ data (e.g., Verbrugge and Reverdin, 2003). These studies have suggested significant interannual to decadal changes in the North Atlantic in the 1990s.

Because sea surface height is a strong constraint for estimating the circulation and density field at ocean depths, assimilation of altimetry data into numerical ocean circulation models is an effective approach to estimating the circulation and water properties of the entire water column. A global data assimilation effort has been carried out at JPL to produce estimates of the physical state of the ocean from satellite altimetry data with supplementing XBT observations (Fukumori et al., 1999). This is a collaborative effort with MIT and the Scripps Institution of Oceanography, and the University of Hamburg. The project is called the Estimation of the Circulation and Climate of the Ocean (ECCO). These estimates include temperature, salinity and velocity vector at 46 vertical levels with a spatial resolution of 1 degree in latitude and longitude at latitudes higher than 20 degrees, with the latitudinal resolution decreasing gradually to 1/3 degrees within 10 degrees from the equator. An approximate Kalman filter is used to propagate the information of the sea surface height observations into the other variables. The ECCO products are used to study the circulation and thermal field associated with the variability observed from the altimetry data.

Shown in Figure 1 are the various components of the leading CEOF (accounting for 30% of the variance) of the variability of the North Atlantic as observed by T/P. The temporal function (Figure 1c) reveals a time scale of 5 years. The spatial patterns are quite complex. The maximum amplitude at 43°N and 320°E is about 10 cm. The areas of high variability are roughly along the path of the Gulf Stream and its extension. This mode clearly involves the circulation and heat transport of the Gulf Stream gyre. The phase

pattern shows the details of the temporal evolution of the mode. A line of demarcation between positive and negative phase is approximately along 30° N. The variability of the mode can be characterized as an oscillation that begins in the subtropical North Atlantic along the zero-phase line between 10°-20°N. The signal then propagates northward along the path of the Gulf Stream. A prominent feature of the phase map is a small enclosed region centered at 37°N and 318° E in which the phase differs from that of the surrounding areas by 180°. This sharp gradient in phase implies enhanced change in the surface geostrophic velocity. The change of the surface geostrophic currents associated with the mode is thus around this region either clockwise or counter-clockwise. Such change in surface circulation must involve subsurface change in current and temperature, resulting in change of the heat transport of the ocean.

The subsurface variability of temperature and velocity as derived from the ECCO analysis is primarily confined to the upper 1000 m of the ocean. The meridional heat transport across 45° N was computed from the temperature and current velocity from the ECCO analysis (Figure 2). In addition to the interannual variation of about 0.1 PW in heat transport, there is a decadal trend of decreasing northward heat transport of about 0.1 PW in the past 10 years. The interannual variability is consistent with the findings of Hakkinen (2001), but the magnitude is much smaller in the present study. The decreasing trend is consistent with the notion that the northward meridional heat transport of the North Atlantic is correlated with the North Atlantic Oscillation index, which has a decreasing trend in the past 10 years.
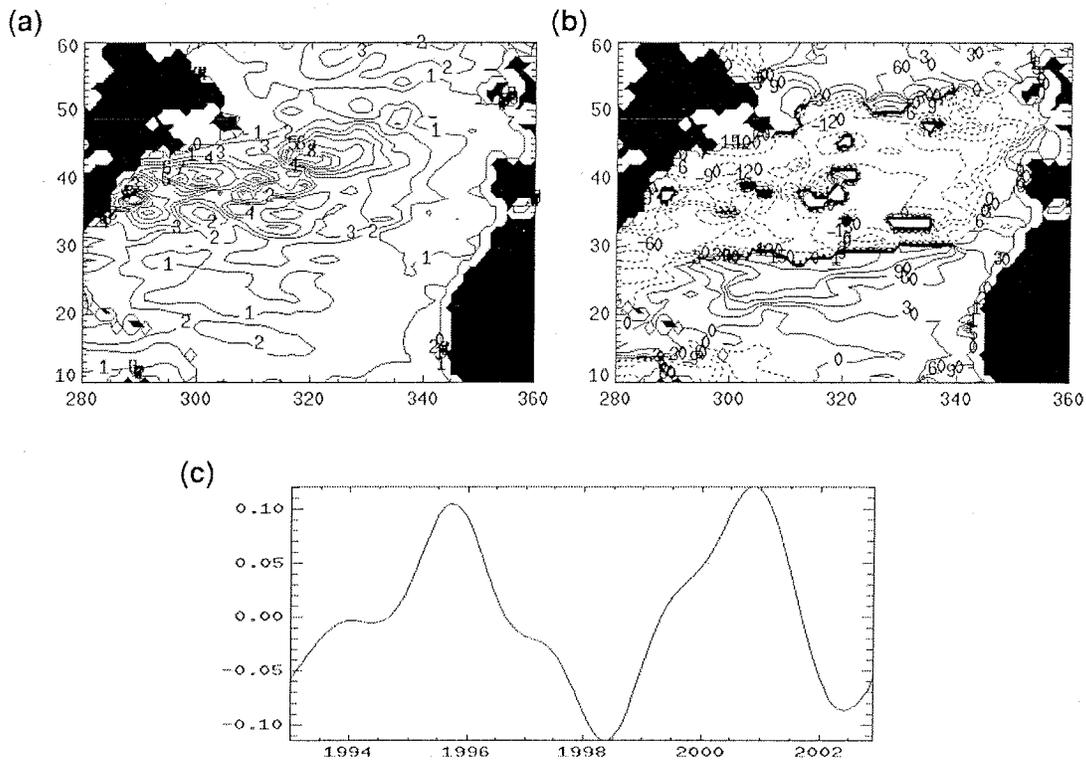

Figure 1 Leading CEOF of the low-passed T/P sea surface height; (a) spatial function in cm, (b) phase function in degrees, and (c) temporal function in arbitrary unit.
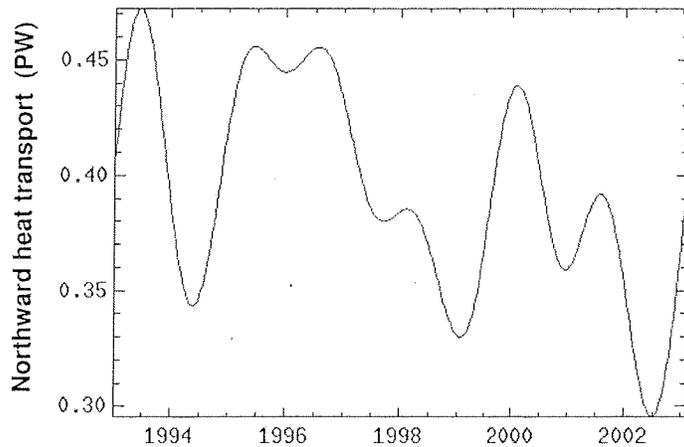
Figure 2. The meridional heat transport of the North Atlantic Ocean in petawatt.

Acknowledgements

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