Heat and Mass Transport Anomalies in the Gulf Stream Region

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Abstract

Strong western boundary currents in the Northern Hemisphere midlatitude oceans transport heat from the warm tropical regions to 35-40N, where much of the heat is fluxed to the atmosphere. Some of this heat continues on into the subpolar gyre to warm the high-latitude regions, as part of what is commonly termed the ocean's heat "conveyor belt". Observations of sea surface height (SSH) anomalies show large interannual-to-decadal variations in the structure of current systems such as the Gulf Stream. Changes in SSH represent changes in the strength of the geostrophic currents: an increase in the SSH difference across the boundary current represents an increase in the surface (mass) transport. On what spatial and temporal scales are current anomalies coherent in the western North Atlantic? In other words, is the conveyor belt continuous through the Gulf Stream region and into the North Atlantic Current?

It is sometimes assumed that changes in the meridional overturning circulation (MOC, of which the Gulf Stream is the upper limb) imply changes in the meridional heat transport. If much of the heat is transported in the relatively shallow (wind-driven) ocean, as suggested by some recent studies, then the circulation changes observed by the altimeter may give an estimate of changes in the meridional heat transport and those changes may be wind-driven. What is the relationship between changes in mass transport and changes in heat transport?

Using both a simple thermodynamical model (with currents specified by SSH) and an ocean general circulation model (0.1-degree resolution hindcast POP, Parallel Ocean Program) that assimilates SSH, we examine the spatial and temporal coherence of current anomalies and the relationship between changes in the strength of the Gulf Stream and changes in heat transport.

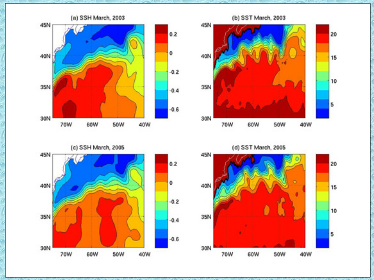


Figure 1. Two Phases of the Gulf Stream.

Sea surface height maps from Jason-1 altimeter data (left) and sea surface temperature maps from the Advanced Microwave Scanning Radiometer (AMSR-E) (right) show the large interannual variations in SSH and SST in the Gulf Stream region.

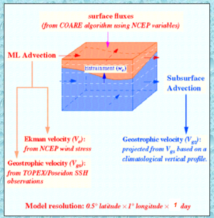


Figure 2. Schematic of thermodynamic model.

A simple three–dimensional thermodynamic model was used to analyze the heat balance in the GS region from 1992-2004 (Dong and Kelly, 2004). The model was forced by surface heat fluxes derived from NCEP2 variables as well as NCEP2 surface stress for Ekman transport. Geostrophic surface velocities were specified by sea surface height measurements.

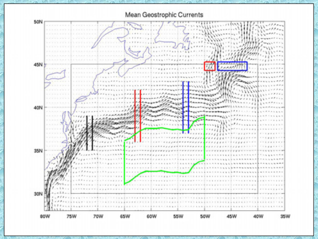


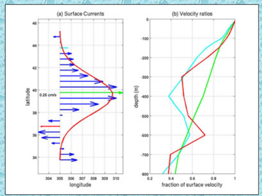
Figure 3. Gulf Stream Mean Geostrophic Currents.

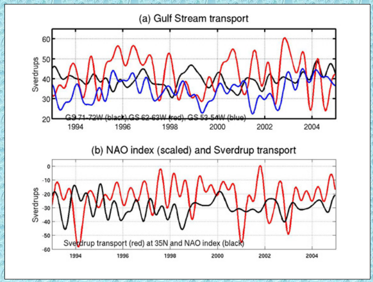
Mean geostrophic current vectors derived from the Maximenko-Niiler mean sea surface. Three sections were defined for subsequent analyses in the Gulf Stream itself: Inflow 71-72W, Recirculation gyre 62-63W, and Outflow 53-54W. Two regions were defined at the northern boundary (45N) as the southward flowing Labrador Current (LC) and the North Atlantic Current (NAC).

Figure 4. Gulf Stream Statistics in Stream Coordinates.

(a) A "stream-coordinate" estimate of the strength of the Gulf Stream was computed by fitting an error function to the SSH, or, equivalently, a Gaussian profile to the geostrophic velocity, using weekly SSH maps from AVISO, plus the Maximenko-Niiler mean sea surface. These time series of profiles were used to compute statistics of the path and the height difference across the GS (delta h). In addition, using the Gaussian profile as a guide to the GS location, both volume and temperature transports for the GS itself were computed from the 3-dimensional velocity and temperature fields.

(b) Profiles of velocity ratios relative to the surface current strength, calculated from thermal wind balance. Profiles in the GS jet (green) are monotonic, whereas the profiles to the north (cyan) and south (red) of the jet show more structure.





(not shown) Sea surface height differences across the jet are a measure of the Gulf stream transport in the high resolution ocean model, POP (performed by Julie McClean). The correlations are not significant between the upstream and down stream sections, and the correlations are small with the indices in (b).

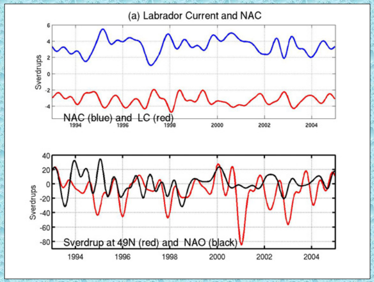
Figure 5. Volume Transport Estimates for the three sections in the Gulf Stream Jet (Figure 3).

(a) Transport in the recirculation region (red) is considerably larger than in the other regions, but smaller than in situ estimates. The recirculation and outflow time series are correlated, with the center region leading the outflow region by 50 days. The recirculation region transport leads the inflow by about 75 days, suggestive of westward propagation. Inflow and outflow are not correlated, suggesting that inflow transport fluctuations are not transmitted far downstream.

(b) Gulf Stream transport estimates were compared with both the Sverdrup transport at 35N and the North Atlantic Oscillation (NAO) index. Correlations are all small, although some are marginally significant, and the signs and lags vary. The largest correlation is between the recirculation region transport and the NAO (positive with lag of 18 months). For comparison, Baringer and Larsen (2001) found an 18-month lag between the Florida Current and the NAO, but with a negative correlation. Thus, there is *no robust statistical relationship* between the transports and these indices.

Figure 6. Northern Boundary Transports.

Along 45N, the southward flowing Labrador Current (LC) meets the Gulf Stream outflow and feeds the North Atlantic Current. The correlation between the LC and the NAC (-0.6) at zero lag is significant, but the NAC is not correlated with the Gulf Stream outflow, suggesting that LC fluctuations dominate in the NAC. Both the NAC and the LC are correlated with the Sverdrup transport at 49N and with the NAO, in the sense that stronger westerlies give a stronger subpolar gyre at a lag of about 1 year. In situ measurements give LC transports of 4-7 Sv (Gyory et al) with the lower numbers from geostrophic estimates and the higher values including a substantial barotropic component.



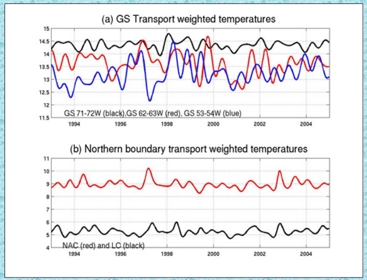
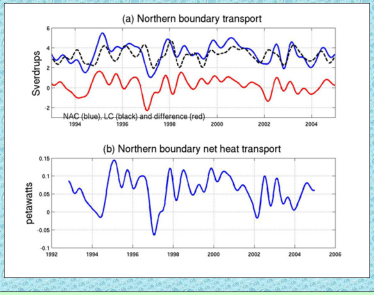


Figure 7. Transport-Weighted Temperature.

Although interannual volume transport fluctuations are not transmitted coherently through the Gulf Stream system to the subpolar gyre, it is possible that temperature anomalies are transmitted. Therefore, for each of the sections in Figure 3, transport-weighted temperature time series were computed. The temperature anomalies showed a similar lack of coherence, except that the recirculation gyre temperatures are clearly correlated with inflow temperatures at a lag of about 2.5 months. Again, the NAC and LC are positively correlated at zero lag: a warmer LC corresponds to a warmer NAC.

Figure 8. Meridional Heat Transport.

The NAC and LC volume transport residual is relatively small, but the transport-weighted temperature difference is about 4C, suggesting a substantial heat transport in this region. Meridional heat transport across 45N for the upper 800m of the water columns (panel (b)) was estimated by combining the temperature transports from the NAC and the LC with a residual. The residual consists of the difference between the NAC and LC (panel (a), red line) multiplied by the mean LC temperature. The mean heat transport is about 0.1 petawatt, compared to estimates of about 0.5 petawatt for the entire North Atlantic (Trenberth and Caron, 2001).



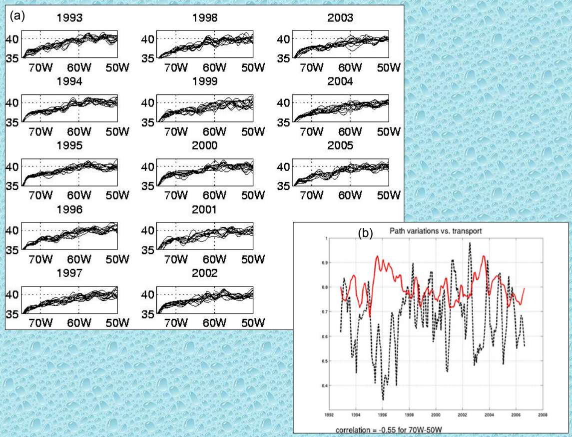


Figure 9. Gulf Stream Paths and Surface Transport.

(a) Monthly Gulf Stream paths show quiescent ("stable") periods (e.g., 1996, 2003) and periods of intense meanders ("unstable", e.g., 1998-1999), as observed by Qiu and Chen (2005) for the Kuroshio Extension. (b) A comparison of the height difference across the GS and the seasonal standard deviation of path latitude shows that the stable paths correspond to periods when the GS is strong (large delta-h), as observed in the Kuroshio Extension by Kelly et al (2007).

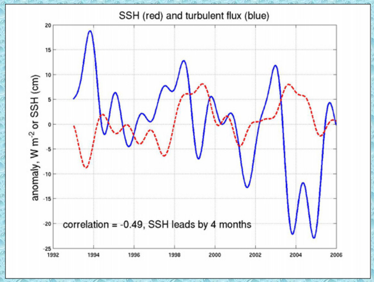


Figure 10. Heat Content and Heat Fluxes.

South of the Gulf Stream, heat storage anomalies in the recirculation gyre region are reflected in the SSH anomalies. When the heat storage is large, there is a corresponding increase in the heat fluxed to the atmosphere. Taking a region 2-7 degrees latitude south of the Gulf Stream (to exclude GS meanders) and from 65-50W (green box Figure 3), turbulent heat flux anomalies are lag-correlated with SSH, with fluxes lagging by about 4 months. This suggests that interannual variations of up to 25 W/m^2 are caused by changes in the heat storage.

Summary

Discontinuity in the Ocean Heat Conveyor Belt:

Interannual variations (1992-2004) in volume transport and in temperature are not spatially coherent in the Gulf Stream system and are not consistently related to either the NAO or to the Sverdrup transport.

Interannual variations in transport and in temperature in the North Atlantic Current at 45N are not significantly correlated with the Gulf Stream, but are clearly correlated with the Labrador Current. Further, they are correlated with the NAO and Sverdrup transport in the subpolar gyre.

Meridional heat transport at 45N is estimated to be about 0.1 PW in the upper 800 meters, compared to an estimate of 0.5 PW based on closing the global heat budget.

Gulf Stream Dynamics and Thermodynamics:

The Gulf Stream has periods of low volume transport, which correlate with periods of large meanders, a relationship also found in the Kuroshio Extension.

High heat storage south of the Gulf Stream (in the recirculation gyre/mode water region) forces larger heat loss to the atmosphere (up to 25 W/m^2 interannually).

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Acknowledgments

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Advanced Microwave Scanning Radiometer sea surface temperature data courtesy of Remote Sensing Systems (www.ssmi.com)