Non-seasonal fluctuations of the Arctic Ocean mass observed by GRACE

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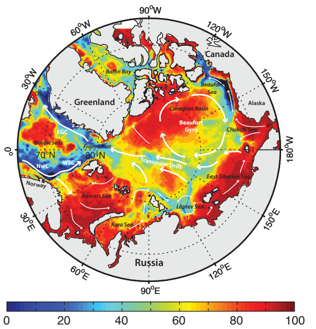

Figure 1. Portion (%) of the non-seasonal sea surface height variance explained by the non-seasonal OcM in ECCO2 model. White arrows show the general upper-ocean circulation pattern. Abbreviations: NwC – Norwegian Current, WSC – West Spitsbergen Current, EGC – East Greenland Current, BS – Bering Strait, DS – Denmark Strait.

1. Outline

The non-seasonal signals are obtained by subtracting the monthly mean climatology. As suggested by an ECCO2 ocean data synthesis product, the non-seasonal variability of the mass-related sea level (bottom pressure or **O**cean **M**ass - **OcM**) in the Arctic Ocean explains a large portion of the non-seasonal sea surface height variance (***Figure 1***). Time variable gravity observations from the GRACE satellites reveal strong non-seasonal fluctuations of bottom pressure in the Arctic Ocean with periods from 2 to 6 months and a record-high bottom pressure anomaly in February of 2011 (***Figure 2***). To examine the nature and driving forces behind those fluctuations we have **(i)** coupled GRACE measurements to concurrent wind forcing (***Figures 3 and 4***), **(ii)** revealed atmospheric and ocean circulation patterns characteristic for low and high Arctic OcM anomalies (***Figure 5***), and **(iii)** identified the sources of mass input responsible for large anomalies in 2011 (***Figures 6-8***).

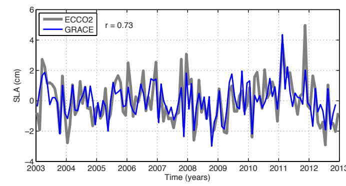

Figure 2. The basin-averaged non-seasonal OcM from GRACE (blue) and from ECCO2 model (gray). The ECCO2 model realistically simulates the Arctic OCM changes, in particular, the record high anomaly in February 2011. Correlation between the time series is 0.73. The large anomaly in November 2011 is likely real, but was not observed with GRACE due to an instrument outage between November 17 and December 12. For a monthly GRACE OcM estimate, the 1-sigma uncertainty is ~9 mm.

2. Arctic Ocean Mass Changes in Relation to Wind Forcing

- The coupled Empirical Orthogonal Functions (EOF) analysis shows that the non-seasonal variability of the Arctic Ocean mass is strongly coupled to wind forcing (Figures 3 and 4). The first coupled zonal wind stress and OcM EOF mode (***Figure 3***) explains 56% of the covariance and the correlation between the corresponding principal component (PC) time series is 0.57. The first coupled meridional wind stress and OcM EOF mode (***Figure 4***) explains 73% of the covariance and the correlation between the corresponding PC time series is 0.68.
- The zonal wind pattern is correlated with a di-pole pattern of Arctic Ocean mass changes (***Figure 3***). Consistent with Ekman dynamics, westerly wind intensification over the North Atlantic at about 60°N and over the Russian Arctic continental shelf break causes the ocean mass to decrease in the Nordic seas and in the central Arctic, and to increase over the Russian Arctic shelf. The time evolution of the zonal wind pattern is significantly correlated with the Arctic Oscillation index (r=0.52).
- Basin-wide Arctic Ocean mass fluctuations are correlated with northward wind anomalies over the northeastern North Atlantic and Nordic seas, and over the Bering Sea (***Figures 4*** and ***5a***).

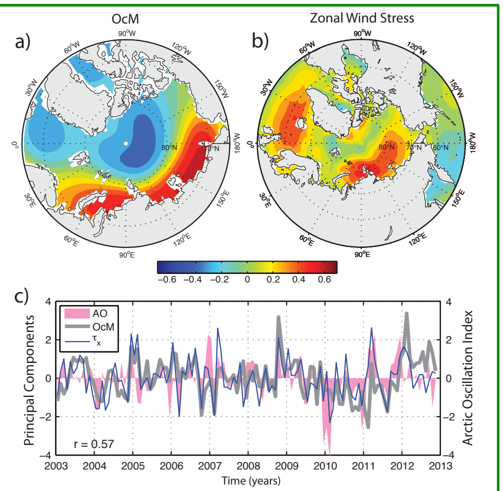

Figure 3. The spatial patterns (a, b) and the principal component (PC) time series (c) of the first coupled EOF of the Arctic OcM and zonal wind stress (τ_x). The spatial patterns are shown as heterogeneous correlation maps: (a) the correlation between the PC-1 of τ_x and OcM field and (b) the correlation between the PC-1 of OCM and τ_x field. The Arctic Oscillation index is shown by the pink-shaded area in (c) plot.

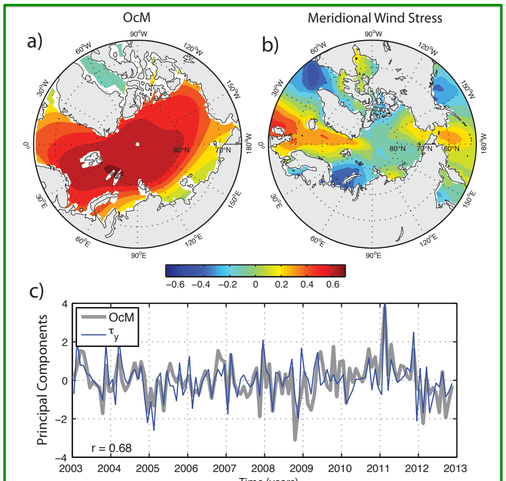

Figure 4. The spatial patterns (a, b) and the principal component (PC) time series (c) of the first coupled EOF of the Arctic OcM and meridional wind stress (τ_y). The spatial patterns are shown as heterogeneous correlation maps: (a) the correlation between the PC-1 of τ_y and OcM field and (b) the correlation between the PC-1 of OcM and τ_y field.

3. Atmospheric and Oceanic Circulation Patterns

- Positive (negative) Arctic Ocean mass anomalies are associated with anticyclonic (cyclonic) anomalies of the large-scale ocean circulation pattern (***Figure 5b***).
- Southward (northward) wind anomalies over the Nordic seas favor southward (northward) anomalies of the Ekman slope current across the region and through the Fram Strait.
- Sverdrup dynamics over the Nordic seas does not explain the Arctic OcM variability, but it can be relevant south of 65N (see wind stress curl in Figure 5a)

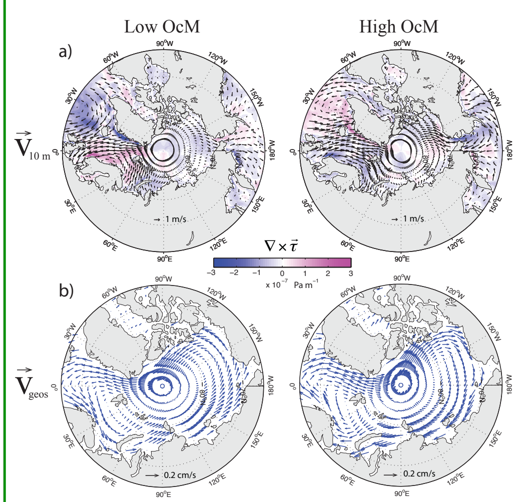

Figure 5. (a) The 10 m height wind vectors and wind stress curl (color), and (b) geostrophic velocity vectors averaged over the period of low (left) and high (right) OcM anomaly, i.e. when OcM in Figure 1 is less than -1 cm and greater than 1 cm, respectively. Abbreviations: V_{10m} – wind velocity anomaly at 10 m height, V_{geos} – geostrophic velocity anomaly of ocean currents.

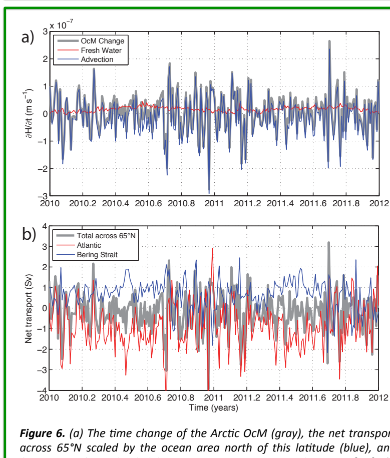

Figure 6. (a) The time change of the Arctic OcM (gray), the net transport across 65°N scaled by the ocean area north of this latitude (blue), and fresh water fluxes (red); (b) net transport in Sverdrups (1 Sv = 10^6 m^3 s^{-1}): total across 65°N (gray), across 65°N in the Atlantic Ocean (red), and through the Bering Strait (blue).

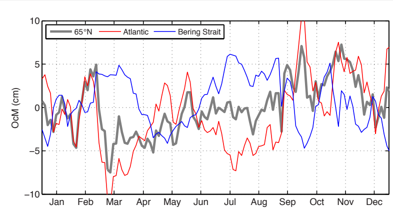

Figure 7. The de-trended cumulative sums of the net transport anomalies into the Arctic Ocean domain: total across 65°N (gray), across 65°N in the Atlantic sector (red), and through the Bering Strait (blue), scaled by the Arctic Ocean area and multiplied by the time interval to obtain equivalent sea level in centimeters.

4. Where does the water come from?

- Using the ECCO2 model, we show that the observed non-seasonal Arctic Ocean mass variability is mostly explained by the net horizontal wind-driven transports, and the contribution of fresh water fluxes is negligible (***Figure 6a***).
- The variability of the net inflow into the Arctic Ocean is mostly determined by the variability of the inflow through the Atlantic sector (***Figure 6b***). The correlation between the total inflow and the Atlantic sector inflow is 0.77., while the correlation between the total inflow and the Bering Strait transport is 0.17.
- The Atlantic sector and Bering Strait net transports partly compensate each other (***Figure 6b***). Correlation between them is -0.49.
- Transport anomalies across both the Atlantic and Pacific gateways were equally important for generating large Arctic OcM anomalies in February and November 2011 (***Figure 7***). The associated anomalies in atmospheric circulation are shown in ***Figure 8***.

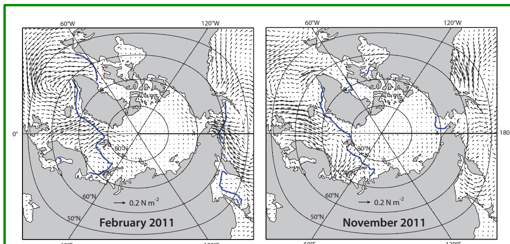

Figure 8. The ECCO2 February and November 2011 wind stress anomaly vectors, obtained by subtracting the monthly mean climatology fields. North of the blue boundary, the fractional ice covered area of grid cells exceeds 50%.

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