GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L03708, doi:10.1029/2008GL036035, 2009

Impact of aerosol on sea surface temperature over the subtropical Atlantic Ocean: A potential trigger factor of the NAO phase conversion?

Gan Luo,[1,2] Fangqun Yu,[1] and Zifa Wang[2]

Received 18 September 2008; accepted 6 January 2009; published 14 February 2009.

[1] The North Atlantic Oscillation (NAO) is one of the most prominent patterns of atmospheric circulation variability over the Northern hemisphere, yet little is known about its underlying mechanism of phase conversion. Our analysis reveals that the recent decline of Aerosol Optical Depth (AOD) over the Subtropical Atlantic Ocean (SAO) contributes significantly to the enhancement of SAO Sea Surface Temperature (SST). We further show that the aerosol variations over SAO appear to be a trigger factor of NAO phase conversion. A new conceptual model, which details for the first time the atmospheric thermodynamic and dynamic anomaly structures during positive and negative NAO phase, has been presented here to illustrate the impact of aerosol on the SST over the SAO and the atmospheric response of the NAO. **Citation:** Luo, G., F. Yu, and Z. Wang (2009), Impact of aerosol on sea surface temperature over the subtropical Atlantic Ocean: A potential trigger factor of the NAO phase conversion?, *Geophys. Res. Lett.*, *36*, L03708, doi:10.1029/2008GL036035.

1. Introduction

[2] The NAO is the dominant dynamic mode of atmospheric variability over the Euro-Atlantic sector [*Hurrell*, 1995; *Jones et al.*, 1997; *Rogers*, 1984]. The possible contributions or responses of NAO to Atlantic and Arctic climate change [*Bengtsson et al.*, 2004; *Johannessen et al.*, 2004] are still under discussing. It has long been recognized that the fluctuations in SST and the climate change over the North Atlantic are related [*Bjerknes*, 1964]. However, the evidences from theoretical and modeling studies suggest that mid-latitude SST anomalies have only a weak impact on the NAO [*Kushnir et al.*, 2002], and some studies conclude that the basic structure of the NAO mainly arises from the internal and nonlinear dynamics of the atmosphere [*Thompson et al.*, 2000]. While the theory based on atmospheric internal dynamics successfully explained the high-frequency variability of the NAO, it has difficulty to explain the inter-annual change and the decadal trend of the NAO structure. A number of researches show that the ocean forcing, as a dominant external factor, is very important to the variation of the NAO [*Hoerling et al.*, 2001; *Hurrell et al.*, 2004; *Sutton and Hodson*, 2003; *Terray and Cassou*, 2002]. *Hoerling et al.* [2001] found that the North Atlantic climate change since 1950 is linked to the progressive warming of tropical SST, especially over Indian and Pacific Ocean. *Sutton and Hodson* [2003] also found evidence of tropical Indian Ocean forcing of the NAO on long time scales, but they concluded that this effect was likely secondary to the forcing from the North Atlantic itself. These arguments indicate that the mechanism of the NAO phase conversion is still an open question, and the ambiguities mainly arise from: (1) what is the primary direct trigger factor of the NAO phase conversion; (2) how does local and remote oceanic forcing impact the phase and amplitude of the NAO; (3) what is the physical nature of the NAO phase structures? Lack of consensus on the process or processes responsible for its inter-annual variability is the major obstacle to understand the decadal variation of the NAO. To reveal the underlying process of the NAO phase conversion, identification of the contributions from other external factors and solid evidences from observations are essential.

2. Analysis of AOD and Its Impact on SST Over the SAO

[3] Satellite retrievals and ground-based measurements have shown tremendous changes in global concentrations and distributions of aerosol [*Mishchenko et al.*, 2007; *Torres et al.*, 2002; *Wild et al.*, 2005]. The global mean direct aerosol radiative effect has been estimated to be around -0.5 ± 0.33 W m^{-2} from satellite remote sensing studies [*Yu et al.*, 2006] and -0.46 ± 0.20 W m^{-2} based on model simulations [*Schulz et al.*, 2006]. The historical AOD data from AVHRR [*Ignatov et al.*, 2004] indicates a maximum loading of aerosols over the African continent downwind regions, which are mainly from the Saharan desert dust deflations and Congo rainforest open fire burning (Figure 1a). The AOD of dense aerosol hazes covering huge areas of the SAO is about 2 times of the global mean (0.14) and is much higher than that over other oceanic regions. More importantly, the linear trend analysis of AVHRR data (Figure 1b) suggests a significant decline of AOD over the downwind region of Africa during the period. The decreased AOD over this region is likely associated with the condition of African droughts and rainfall in the Sudan-Sahel [*Giannini et al.*, 2003; *Prospero and Lamb*, 2003].

[4] Considering the importance of aerosol radiative forcing on Earth's climate, the substantial and durative changes of aerosol over the SAO should cause a strong climate response. The change of SST and oceanic heat-content over

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[1] Atmospheric Sciences Research Center, State University of New York, Albany, New York, USA.

[2] Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.

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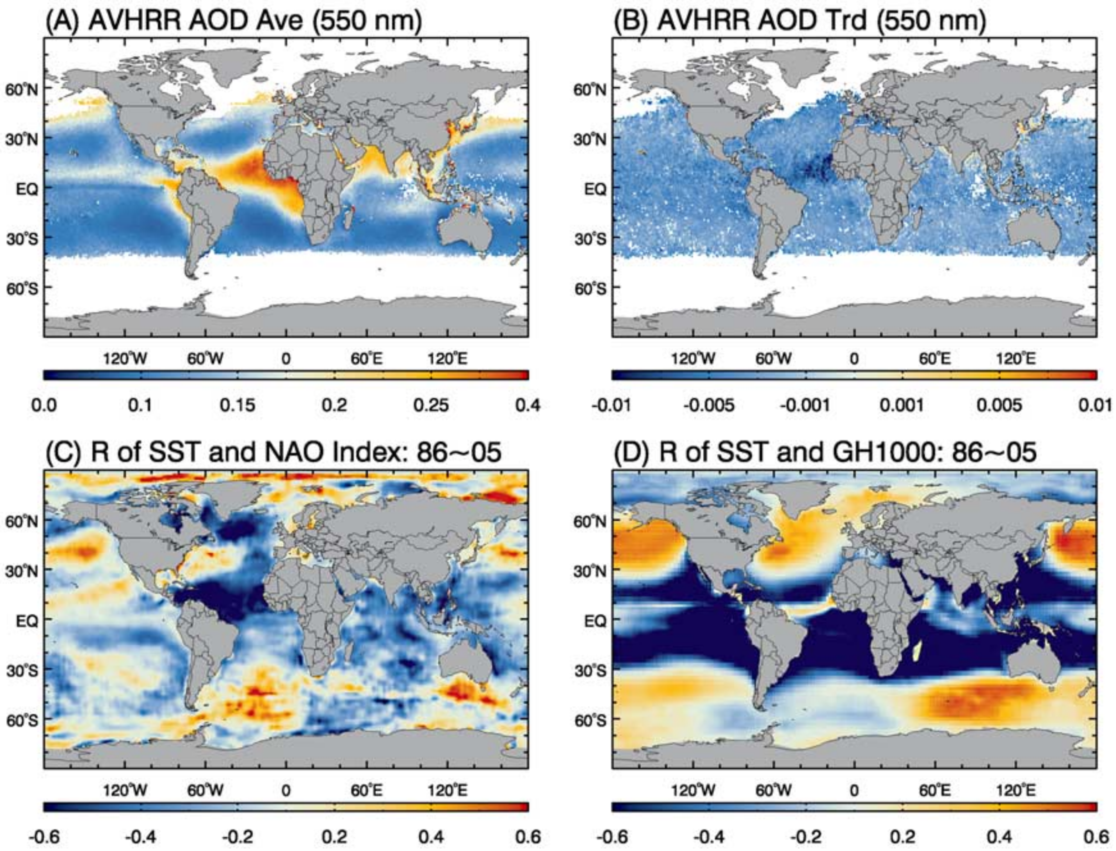

Figure 1. (a) 10-year (1986–2005) average of AVHRR Aerosol Optical Depth (AOD) at 550 nm, (b) AOD annual linear trend during the period 1986~2005, (c) the linear regression of SST and the NAO annual Indices, and (d) the linear regression of SST and geopotential height at 1000 hPa. The SSTs for the regression come from the NOAA Optimum Interpolation (OI) Sea Surface Temperature V2 anomaly, which is produced by the observations from buoys, ships and satellites [*Reynolds et al.*, 2002]. The NAO indices are from the CAS Data Catalog's Annual PC Based NAO Index. The geopotential height at 1000 hPa is from the NCEP reanalysis database.

the SAO have been observed and reported recently by *Lozier et al.* [2008], but the physical reasons of such change are unclear. As we will show below, the variations in aerosol radiative forcing can significantly contribute to the oceanic heat-content change over the SAO and then impact high-latitude regions through its influence on the NAO and atmospheric circulation.

[5] Figure 1c reveals a tripole pattern of SST and the NAO correlation over the North Atlantic sector. The distinct negative correlation signal can be found over the SAO with the value high up to -0.6, implicating that the atmosphere-ocean interaction over the region is very strong. The regression analysis of SST and the geopotential height at 1000 hPa (Figure 1d) shows a positive correlation located over mid-latitude Atlantic Ocean and a negative correlation located over the SAO. This suggests that the SST variations over the Azores High and the Icelandic Low are mainly a response to the fluctuation of the NAO; but at the SAO, the atmospheric pattern is changed by the SST. Therefore, the variations of SST over the SAO appear to be forced by some other factors. Our investigation of the relations between monthly SST and the NAO annual indices indicates that the negative correlation is strengthened over the SAO from March to June (shown in the auxiliary material), and the negative correlation region matched well with the African dust outflow over the continent downwind region (Figure 1a).[1] A logical and natural explanation of the phenomenon described above is that African aerosol may contribute to the NAO variation through its radiative forcing and impact on SST.

[6] Long-term variation of SST over the SAO region is given in Figure 2. The OIv2 data indicates that the SST declined during the period from 1990 to 1994 (period I), then abruptly enhanced from 1995 to 1998 (period II). This SST enhancement was interrupted by a sudden decline in 1999, then continued during the early 2000s (period III). It should be noted that absolute changes of SAO SST shown in Figure 2a (left) are average values over a relatively large area ($20° \times 10°$) and long time period (annual mean) and are statistically significant (although the changes are within $\sim$1 K). To understand the possible causes of SST variations, we compare SST variations over the SAO with those of AOD [*Ignatov et al.*, 2004; *Torres et al.*, 2002], Cloud Optical Depth (COD) [*Zhang et al.*, 2004] and Surface Wind Speed (SWS) [*Swail and Cox*, 2000] (Figures 2b (left)–2e (left)). It is clear that SST and the above mentioned external and internal factors is highly anti-correlated

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL036035.

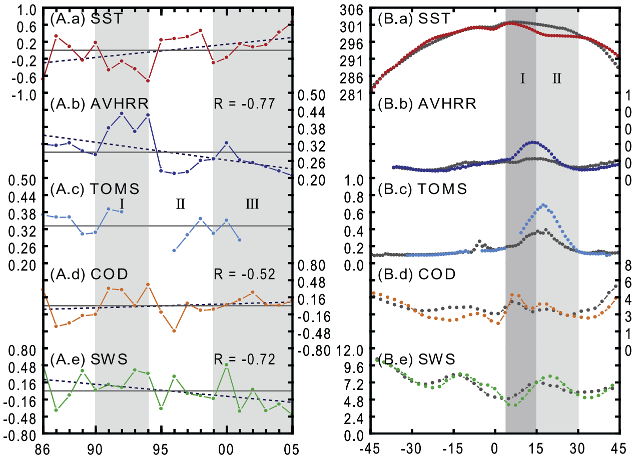

Figure 2. (left) Time series of annual OIv2 SST anomaly (red, K), AOD (blue for AVHRR and cyan for TOMS, 550 nm wavelength, unitless), ISCCP D2 Cloud Optical Depth (COD) anomaly (orange, 600 nm, unitless), NCEP Reanalysis Surface Wind Speed anomaly (green, $m \cdot s^{-1}$) at the sensitive region (20∼40°W, 10∼20°N). The dashed lines represent the 20-year linear trend. (right) 20-year mean values of summer time (JJA) SST (red), AOD (blue for AVHRR and cyan for TOMS), COD (orange), and Surface Wind Speed (green) averaged over the 20∼40°W zonal region. The corresponding values averaged zonally over the global oceans are also given in each panel (grey lines) for comparison.

and the correlation coefficients reach up to −0.77, −0.52 and −0.72, respectively. Solar radiation, wind stress and vertical mixing are known to be the three major factors impacting the SST seasonal variations and abrupt changes [*Chen et al.*, 1994]. Solar radiation is the primary heating term in the surface layer heat budget, and wind stress influences SST by driving oceanic advective processes that redistribute heat in the upper ocean. Both terms also impact the SST through their influences on oceanic vertical mixing. It is well recognized that atmospheric aerosols affect solar radiation. Even in the absence of volcanic eruptions, high concentrations of tropospheric aerosols such as dust carried from African deserts have been shown to reduce solar radiation by up to 2.2 W m^{-2} and cause cooling of subtropical Atlantic SST [*Sokolik and Toon*, 1996]. In addition, aerosol can also affect cloud droplet radius [*Breon et al.*, 2002] and shallow water clouds over the Atlantic Ocean [*Kaufman et al.*, 2005]. *Kaufman et al.* [2005] found that the coverage of shallow clouds increases in all of the cases by 0.2–0.4 from clean to polluted, smoky, or dusty conditions. Our investigation shows that the declining SST during period I is probably caused by the Mount Pinatubo (June 1991) eruptions and the increasing SST during period II is associated with the reduced dust aerosol over the SAO. We find that AOD is the primary factor which does not have direct interactions with the SST over the sensitive region. It should be noted that the changes of the above-mentioned three factors are not able to fully explain the abrupt SST changes from 1998 to 1999, which may also involve the change in ocean currents associated with the significant El Niño/La Niña event during this period [*Elliott et al.*, 2001].

[7] Another evidence supporting the aerosol's long-term solar radiation impact on the SST over the SAO is the 20-year mean summer time (JJA) differences between zonally averaged values along the region within 20~40°W and global zonal means. The largest SST differences mainly locate over regions I and II (Figure 2a (right)) with a maximum difference of 2.5 K around 18°N. It is clear that the SST over the SAO is much lower than the global mean temperature over the tropic regions form 5°N to 30°N. Figure 2e (right) suggests that the low SST over region II may partially be explained by the high wind speed. However, the surface wind speed over region I is much lower than that of the global mean, indicating that the abnormity of SST (at least over region I) is mainly caused by the cooling effects of enhanced AOD and COD over there.

3. A New Mechanism for the NAO Phase Conversion

[8] We have shown above that the declining AOD over the SAO region is the most remarkable change of aerosol optical properties around the globe in the last 20 years, and the resulted radiative forcing can significantly contribute to the progressive change of SST over the SAO. It will be interesting to understand how these changes may relate to the NAO phase conversion. Based on a comprehensive analysis of the spatial structure and temporal variation of the NAO, we present a conceptual model (Figure 3) illustrating the thermodynamic and dynamic consequence of aerosol radiative influence on subtropical Atlantic SST and the implications to the NAO/AO. The conceptual model is supported by zonally averaged geopotential height, temperature and wind anomaly profiles (Figure 4) derived from the NCEP-2 reanalysis data for the positive phase (A) and negative phase (B) of the NAO (the details are described in the auxiliary material).

[9] Our investigation shows that the SST anomaly over the SAO, which has been underestimated in many previous studies, is a direct source of the NAO variations. SST over the SAO can be considered as the heat engine of North Atlantic climate system as it drives the atmospheric and oceanic changes over tropical and extratropical regions. The possible role of tropical part of the SST tripole over North Atlantic in inducing the atmospheric response of the NAO has been demonstrated by some numerical experiments

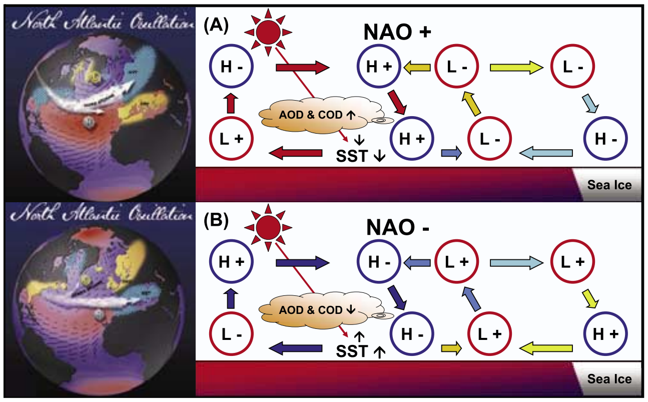

Figure 3. A conceptual model of the aerosol radiative impact on subtropical Atlantic SST and its influences on the NAO/AO (the positive and negative NAO index phases at the left side are from http://www.ldeo.columbia.edu/NAO by Martin Visbeck). The H and L represent the High Pressure System and Low Pressure System, respectively. The positive and negative signs represent the enhancement and decline of pressure, respectively. The arrows represent atmospheric circulation of air mass, and the warm color means the enhancing circulation, while the cold color indicates the declining circulation.

[*Terray and Cassou*, 2002]. Our diagnostic analysis of the NCEP-2 reanalysis data, showing clearly the NAO phase structure for the first time (Figure 4), provides solid evidence of such a role. Figures 3 and 4 demonstrate the physical processes on how SST over the SAO influences the NAO phase conversion through tropical convection and Hadley circulation. When AOD and COD are enhanced over the subtropics of Atlantic Ocean, the downward solar radiation is reduced by the absorbing and scattering processes of aerosols and clouds. According to the new conceptual model (Figures 3 and 4), the declined SST over the SAO associated with the reduced solar radiation triggers a stronger tropical Hadley cell than normal years. Then in the upper layer (500~100 hPa), more air mass transports northward to downwind regions, which results in a decreased subtropical upper layer High. The relative wind convergence at middle-low latitude and divergence at middle-high latitude could enhance the Azores High and deepen the Icelandic Low. The increased pressure gradient between the two pressure systems strengthens the Ferrel cell, and then causes the westerlies stronger than normal years. The enhanced western wind usually could also deepen the Polar vortex and reduce the pressure over high latitude regions. It is clear from Figure 4 that the south-warm and north-cool temperature anomaly structure over middle latitude regions is formed by the impact from the changed atmospheric stability. In the stratosphere, because of the strengthened western wind, more warm polar air can transport southward to the tropic and subpolar regions to enhance the temperature over there, while the stratospheric temperature in subtropics and polar is reduced by the enhanced wind speed due to their close association. When AOD and COD decline over the SAO, the opposite occurs. The above physical interpretations agree well with the NAO phase structure rebuilt from the NCEP-2 reanalysis data.

[10] Our investigation indicates that the anomaly of Hadley cell is the essential characteristic of the NAO phase structure. The pressure anomaly over Azores High and the Icelandic Low is the atmospheric response to the change over low latitude. Through the influence of westerlies on Polar vortex, the tropical change can also impact the Polar region. In conclusion, our study indicates that the subtrop-

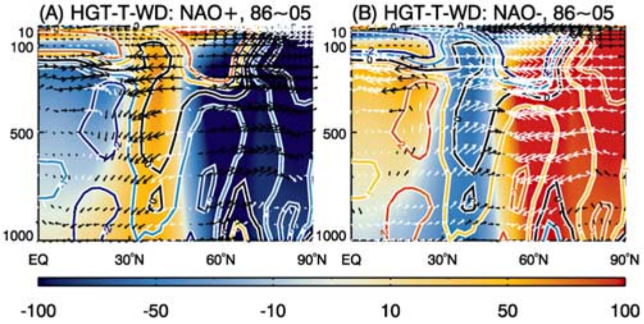

Figure 4. Overlapped zonally averaged profiles of NCEP reanalysis data anomaly for the region from Tropic (50~40°W) to Arctic (0~10°W) during the period 1986~2005: (a) NAO positive phase years; (b) NAO negative phase years. The shade represents the total geopotential height anomaly (unit: m); the lines give the total temperature anomaly (Blue: −2 K, Cyan: −1 K, Black: 0 K, Orange: 1 K, Red: 2 K); the arrows show the total latitude-direction and vertical-direction (50 times of the negative omega value) wind vector anomaly (black color means that the latitude-direction wind velocity anomaly agrees with the 20-year mean vector, and white color indicates that the latitude-direction wind velocity anomaly is opposite to the 20-year mean).

ical Atlantic SST anomaly, which is caused by the change of AOD and COD, can significantly contribute to the alternation of positive and negative phases of the NAO/AO.

4. Summary and Discussion

[11] Currently, the NAO has been suggested as a composite result of the multi-forcing from Atlantic SST anomaly, tropic origin over Indian Ocean and Pacific Ocean the stratospheric downward control [*Hurrell et al.*, 2003], and even the greenhouse gas [*Kuzmina et al.*, 2005]. Nevertheless, the key physical processes responsible for the annual/decadal fluctuation of the NAO are still unclear. Based on our comprehensive analyses of a variety of relevant data and a new conceptual model illustrating for the first time the atmospheric thermodynamic and dynamic anomaly structures during positive and negative NAO phase, we show that the two decades variation of African aerosol may partially explain the fluctuation of SST over the Subtropical Atlantic Ocean and the associated influences on the North Atlantic climate change. Since African aerosol, which is dominated by the dust defilation and transport processes, is highly anti-correlated with rainfall in the Sudan-Sahel [*Prospero and Lamb*, 2003] which in turn is quite sensitive to SST variability in all tropical basins including the remote (Pacific) and local (Atlantic and Indian) [*Giannini et al.*, 2003], the aerosol variation over the SAO and its implicated climate impact on the NAO/AO may present a bridge to link the teleconnection of the NAO and SST anomaly over tropical Pacific/Indian Ocean regions.

[12] **Acknowledgments.** This research was supported by NOAA/DOC under grant NA05OAR4310103 and NASA under grant NNX08AK48G. Work at IAP was funded by Chinese Academy of Science (KZCX2-YW-205), the National Basic Research 973 grant (2005CB422205) and NSFC grant (40775077).

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G. Luo and F. Yu, Atmospheric Sciences Research Center, State University of New York, 251 Fuller Road, Albany, NY 12203, USA. (ganluo@asrc.cestm.albany.edu)

Z. Wang, Institute of Atmospheric Physics, Chinese Academy of Sciences, Building 40, Huayanli, Beijing 100029, China.