Does dust from Patagonia reach the sub-Antarctic Atlantic Ocean?

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[1] Although emission of dust from the Patagonia desert is shown by global aerosol models, there is conflicting observational evidence of dust activity in the region. Because dust from Patagonia into the Southern Ocean (SO) may play a role in regulating phytoplankton activity, it is necessary to confirm whether there is dust activity and if so, how far the dust travels into the SO. We used a combination of surface visibility, satellite measurements (MODIS and OMI) and transport model (HYSPLIT) to track and report for the first time a dust event originating in Patagonia. We show that the dust reached the free troposphere in the Sub-Antarctic Atlantic Ocean. Although the dust emission was significant, cloudiness and dilution of the plume resulted in difficult conditions to track dust in the SW Atlantic. We show that the use of any single tool (i.e., MODIS or OMI) is not enough to track the dust and only an integrated approach of satellite and modeling tools can achieve a consistent description. As a result, current platforms used for dust detection are probably underestimating aerosol loading in the area. **Citation:** Gassó, S., and A. F. Stein (2007), Does dust from Patagonia reach the sub-Antarctic Atlantic Ocean?, *Geophys. Res. Lett.*, *34*, L01801, doi:10.1029/2006GL027693.

1. Introduction

[2] The role of the Southern Ocean (SO) in regulating and storing atmospheric CO_2 has been emphasized in several studies [*Sarmiento and Toggweiler*, 1984; *Marinov et al.*, 2006]. Ice-cores studies in Antarctica show that fluctuations in atmospheric CO_2 correlate with dust deposited in the Antarctic ice sheet [*Gaspari et al.*, 2006]. Because dust layers were deposited right before an observed decrease in atmospheric CO_2, one current theory hypothesizes that iron-rich dust blown from Patagonia during the drier glacial times deposited over the SO and promoted removal of atmospheric CO_2 due to the iron-fertilization effect in primary productivity [*Martin*, 1990; *Wolff et al.*, 2006]. Although controversial [*Kohfeld et al.*, 2005], this theory has received a boost in recent years due to the results of dedicated field experiments which showed an increase in phytoplankton mass due to an artificial increase of iron [e.g., *Coale et al.*, 2004].

[3] The extent of the iron-fertilization effect and the possibility that it may be occurring in present times downwind of important dust sources has been the object of many modeling studies [e.g., *Jickells et al.*, 2005]. In particular, *Erickson et al.* [2003] showed a strong correlation between modeled dust deposition from Patagonia and observed chlorophyll anomalies in the Sub-Antarctic region of the South Atlantic Ocean. However, there is conflicting observational evidence of recent dust activity in Patagonia. Although some surface studies indicate that dust emission in Patagonia follows a seasonal pattern [*Gaiero et al.*, 2003], satellite observations offer a mixed picture. For example, studies with the TOMS detector indicate that Patagonia is an active source of dust [*Prospero et al.*, 2002] but observations with the MODIS detector do not show important dust activity [*Kaufman et al.*, 2002]. Thus, our knowledge of dust activity in the area is limited to modeling studies and it is uncertain whether Patagonian dust can reach the high-nutrient low-chlorophyll waters of the Sub-Antarctic Ocean or even Antarctica.

[4] This study reports for the first time observational evidence of dust emitted in the Patagonia region and its long range transport to the Sub-Antarctic Ocean in the vicinity of the South Georgia Island (54–55°S, 36–38°W). This case study illustrates the main features of a Patagonian dust event by tracking a dust plume through the South Atlantic ocean with the observations made by two satellite detectors (MODIS and OMI) and an aerosol transport model (HYSPLIT).

2. The Patagonian Desert

[5] Patagonia is a high latitude desert located in the southern end of South America. It is dominated by steady and strong westerly winds (with daily mean wind speeds of the order of 40 km/h). The geography is defined by the presence of the Andes mountain range to the west and the South Atlantic Ocean to the east. The Patagonian plateau extends to the Atlantic Ocean without any major elevations, only interrupted by the east-west valleys of eight major rivers. As a result, the landscape north of 50°S is a tableland devoid of trees with patches of shrubs. The annual precipitation is less than 200 mm and concentrated in the fall and winter seasons [*Warner*, 2004]. Every 2 to 4 days during spring and summer, low pressure perturbations move north into the land mass generating storms with sustained wind speeds reaching above 70 km/h for several hours [*Lassig et al.*, 1999; *Labraga*, 1994]. Gusts above 110 km/h are frequently reported. The lack of the soil moisture, sparse vegetation cover and strong surface winds provide the appropriate conditions for dust emission [*Ginoux et al.*, 2001]. In general, dust activity is highest during the summer months, but winter and fall dust events have also been reported [*Gaiero et al.*, 2003].

3. Data

[6] The data employed in this analysis come from four sources. First, satellite observations were obtained from the MODIS detector onboard of the satellites Terra (AM pass) and Aqua (PM pass). The MODIS detector is a moderate resolution spectrometer with a high number of narrow spectral bands with

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a daily global coverage. A number of aerosol parameters are retrieved by MODIS [*Remer et al.*, 2005]. Relevant to this study is the aerosol optical depth (AOD) which can be related to aerosol concentration [*Gassó and Hegg*, 2003]. A typical value of background oceanic AOD in this area is $\leq$0.1. The MODIS aerosol products are reported at a 10 $\times$ 10 km ground resolution and only under clear sky conditions. Version (or collection) 5 of the aerosol algorithm is used in this study. In addition, a second source of data is the Ozone Monitoring Instrument (OMI) onboard of the satellite Aura which flies in formation of a few minutes behind the Aqua satellite. Although OMI is primarily used as an ozone instrument, it is also sensitive to aerosol absorption in the ultra-violet region (a spectral region not measured by MODIS) and it provides independent information of the aerosol present in the scene under observation. Specifically, because dust absorbs in the UV-bands and sea-salt does not, the aerosol index (AI) measured by OMI provides a tool to differentiate the main two aerosol types commonly found in this area. Unlike MODIS, the AI is sensitive to aerosol absorption even when the particles are above a cloud. Thus, AI is derived in both cloudless and cloudy conditions. OMI has a ground resolution of the order of 13 $\times$ 24 km (nadir). OMI is the heritage instrument of TOMS and uses a retrieval algorithm of AI similar to the one used by TOMS [*Torres et al.*, 1998]. An AI > 1 is considered typical of absorbing aerosols such as smoke or dust. The combination of aerosol measurements of MODIS and OMI is unique in that it is possible to locate the presence and the type of aerosol at high spatial resolution. A third source of data used in this study was provided by the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) [*Draxler and Hess*, 1998]. HYSPLIT utilizes a Lagrangian approach to estimate the emission, advection, dispersion, and deposition of dust. For this application, HYSPLIT assumes a top hat (2D disc) mass distribution in the horizontal and a Lagrangian particle in the vertical to describe the air parcels. Finally, surface observations of standard meteorological variables (including visibility and cloud cover) at several airports along the coast of Patagonia were obtained directly from the Argentine National Weather Service. The surface observations were reported every hour and provided a ground truth of the state of the atmosphere before and after the satellite passes.

4. Observations

4.1. Detection of a Dust Event in Patagonia

[7] On April 5 2006, the passage of a low pressure system south of Cape Horn at approximately 11UTC (7 Local Time) brought high westerly winds with abundant cloudiness to the Central and South sections of Patagonia (40 to 53S). Sustained winds between 40 to 65 km/h were recorded starting at 13UTC at several stations and remained above 40 km/h until 1UTC (day after). Gusts above 90 km/h were reported at the San Julián station (49S) around 18UTC. All surface stations reported the presence of clouds covering at least 1/8 to 7/8 of the sky throughout the region during the event. Dust was reported at the stations Comodoro Rivadavia (46S), Gobernador Gregores (48.5S), Puerto Deseado (48S) and San Julián (49S) between 16 and 22 UTC.

[8] Figure 1 shows a true color image from Aqua taken at 18:35 UTC. The sources are identified as seasonal lakes, also known as "deflation basins" (or "bajos sin salida") located W and NW of the city of San Julián. Their size ranges from a few tens to hundreds of meters in diameter. Examples of the plumes generated in these bajos can be seen in Figure 1 approximately located between the 49S and 49.75S. Many of these sources are smaller than the pixel size of MODIS (250 m) and only the plumes are visible. A large single source of several hundred meters in diameter can be identified at 48.65S, 69.10W. The total number of bajos has not been quantified but it certainly ranges in the hundreds if not thousands [*Clapperton*, 1993]. *Prospero et al.* [2002] indicated that bajos such as these are common features in many arid areas throughout the world and important contributors to the global dust budget. These bajos accumulate pluvial and fluvial sediments during the wet season and are usually totally or partially dried up by the end of the summer. In addition, dust emission initiated earlier as indicated by surface visibility observations at the city of coastal city of Río Gallegos ($\sim$52S). The true color image from Terra pass at 14:35UTC (not displayed here) confirmed the dust emission by small lakebeds west of the city. However, at the time of the Aqua pass, these sources were not active. Figure 2 (left and right) displays the AODs from Aqua and AIs from OMI (South Pole crossing at 18:19 UTC) for non-cloudy pixels. To facilitate the comparison with MODIS data, only OMI clear sky pixels (defined as pixels with reflectance (331 nm) < 0.1 O. Torres, personal communication, 2006) are displayed. It clearly shows a dust plume advecting from the same source seen in the true color picture. The surface stations Pt. Deseado and Comodoro Rivadavia, reported dust and cloudy conditions at same time suggesting that additional sources may have been active during this event but were not observed by either of the two satellite detectors.

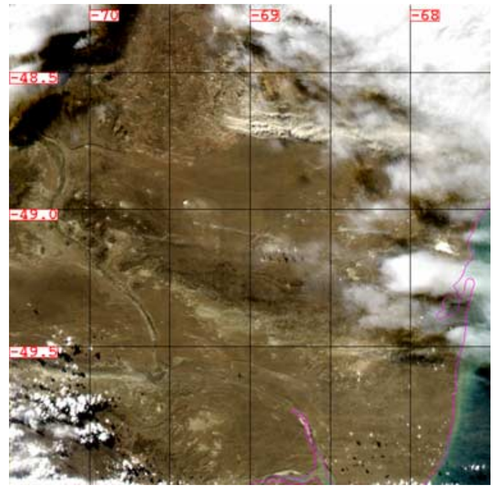

Figure 1. Dust emission on April 5, 2006 as seen in MODIS True color image (Aqua, 18:35). Region displayed ranges from 48.25S to 50S and 67.5W to 70.5W. A large number of sources at pixel size (250m) or smaller are located between the 49S to 49.75S.

4.2. Observation of Long Distance Transport

[9] On April 6, NCEP reanalysis maps show that the low pressure system displaced eastward to south of South Georgia island. In addition, surface and 850 mb winds were consistently from the west in most of the SW South Atlantic region. Around

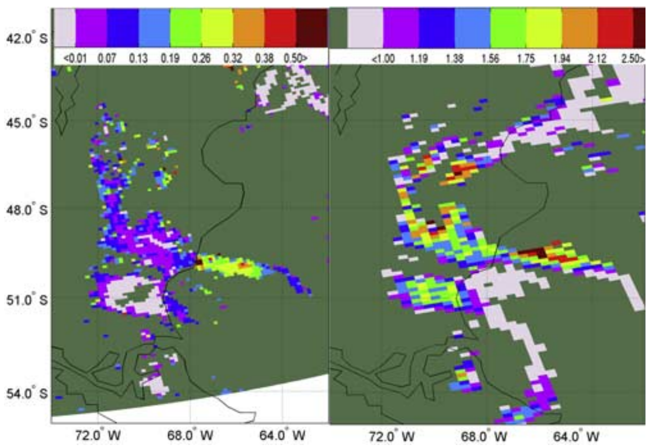

Figure 2. Dust emission on April 5, 2006 as seen in MODIS-Aqua (18:35), MODIS AODs (left) and OMI (polar pass 18:19, right). Pixels with AI > 1 are associated with absorbing aerosols (only clear sky pixels are shown).

51S,40W, the wind direction shifted from W to N-NNW and remained with a constant direction along the ~37W meridian. Figure 3 (left) shows the MODIS AODs as a composite of two Terra (13:30 and 13:35 UTC, left side of panel) and two Aqua granules or passes (15:55 and 16:00 UTC, right side of panel). Cloudless conditions were prevalent in the SW Atlantic and most of the AODs retrieved are well below 0.1, consistent with very low aerosol loadings. We note two regions with higher than background AODs. One located east of the Malvinas (Falklands) Is. The presence of patches of aerosols and the abrupt change in AOD in contiguous pixels suggest the presence of a field of scattered clouds. As a result, it is possible that many clear sky pixels are cloud contaminated east of the Malvinas islands. A second area of interest is the streak of higher than background AODs. It follows an arc from approximately 46S,53W and bends south following the 39W meridian it reaches the NW tip of S. Georgia island. The location of the streak follows the wind direction suggested by the NCEP synoptic charts. The texture of the streak is smooth and continuous and it is surrounded by clear sky pixels. All these factors strongly suggest that the high AODs pixels have minimal cloud contamination and that MODIS detects non-background aerosol concentrations. However, at these moderately high AODs (0.1–0.4), the spectral signature of dust and sea-salt aerosols (or the mixture of both) is approximately the same in the MODIS bands. Thus it is not possible to determine the aerosol type from MODIS measurements alone. Figure 3 (right) shows OMI AIs (South Pole crossing at 17:24 UTC) for clear sky pixels and it provides some insights on the nature of the aerosol detected by MODIS. OMI shows that the high AODs east of Malvinas islands are not consistent with dust. Inspection of the respective MODIS true color picture (not shown) confirms the presence of abundant mid level clouds and high level cirrus. With respect to the arc of high AODs reaching S. Georgia Island, the AIs are below 1 in the section of the arc with highest AODs. When the arc bends south, the AI increases to reach the highest values south-west of S. Georgia. We note that the OMI AIs are more sensitive to absorbing aerosols above the boundary layer [*Torres et al.*, 1998] and the sensitivity decreases towards the surface particularly if the aerosol concentrations are low. This is not the case for April 05 where OMI was clearly sensitive to the sources at the surface when concentrations were the highest (Figure 1). However the day after, dilution and removal processes in the boundary decrease aerosol concentrations resulting in a weak absorbing signal seen by OMI. As a result, we cannot confirm by using only satellite measurements that the high AODs seen by MODIS in the 46S, 51W region can be attributed to dust. This also applies to the high AODs east of Malvinas Is. However, the higher than 1 AIs along 39W (from 48S to 58S) are consistent with the high AODs along the same meridian. We note that MODIS detects high AODs only north and west of S Georgia island whereas OMI shows absorbing aerosols SW of the island. We attribute the discrepancy to the time difference between MODIS-Aqua and OMI observations. The Aqua granules in Figure 3 (left) were captured ~1.5 hrs before the OMI pass.

5. Modeling Study Setup

[10] We used the HYSPLIT model to simulate the event of April 05, 2006. The objective is to establish whether the model is able to place dust in the same areas suggested by both MODIS and OMI. The model was initialized with the sources identified in Figure 1. The first and main source was located at 48.65 S and 69W and the second and smaller at 50.6S and 70W. Because no information of source intensity was available, the

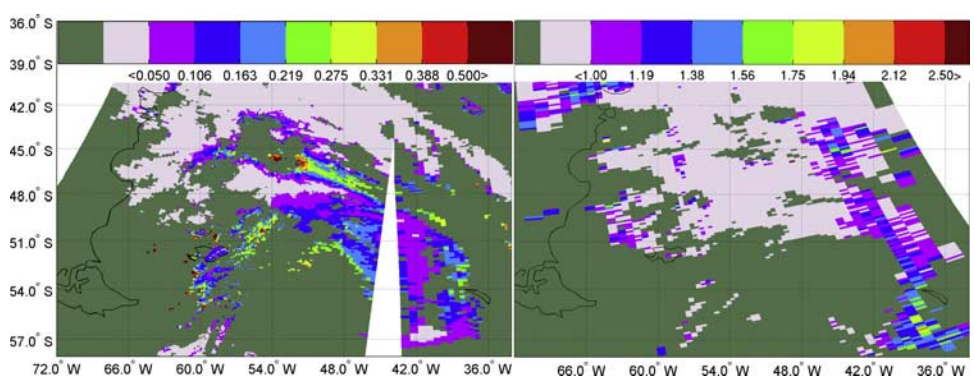

Figure 3. MODIS AODs (left panel) and OMI AI (right panel, polar pass 17:24) for April 6, 2006. The MODIS figure is a composite of two Terra granules (left side) and two Aqua granules (right side). MODIS shows a streak of high AODs around 47S,50W continuing to NW of S. Georgia Is. OMI agrees with MODIS in the streak from 47S,45W to 57S,38W with increasing aerosol absorption from N to S.

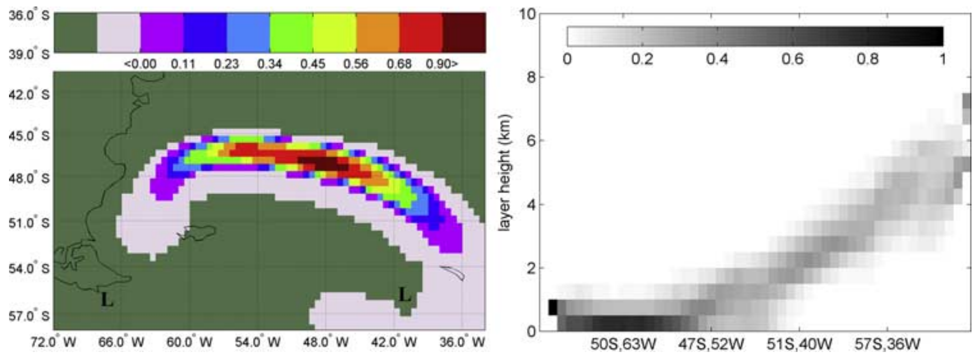

Figure 4. Output from the HYSPLIT model at 16UTC, April 06, 2006. (right) Distribution of normalized mass concentrations. (left) Profile of aerosol concentrations (normalized to the maximum in each column) along the main axis of arc in left panel. The highest dust concentrations are located in the boundary layer whereas the east part of the plume (east of ~40W) is above the BL. The leading edge in the S Georgia region is clearly located in the free troposphere. The location of two low pressure centers is indicated by an L.

source strength was normalized to 1 unit per hour for the main source and 0.1 for the secondary source. HYSPLIT released a total of 50000 Lagrangian air parcels to simulate the emission of dust. No sea-salt production was included in the simulation. The duration of emission was based on the visibility report from the closest surface meteorological station (San Julián Station) and it was set to begin at 1600 UTC and end at 20UTC. The total duration of the run was 48 hours. Transport was driven by the NCEP meteorological fields derived from the Global Data Assimilation System (GDAS) model output (http://www.arl.noaa.gov/ss/transport/gdas1.html). Runs were performed with and without removal processes (wet and dry deposition) and it was verified that the location and distribution of particles did not change significantly. The left panel in Figure 4 shows the geographical distribution of the normalized dust mass concentration and the right panel shows the vertical distribution of aerosol concentration (normalized to each column maximum) along the axis of highest concentrations for April 06 at 16UTC.

6. Discussion

[11] The model output shows a distribution of particles that follows an arc extending from west of Malvinas Is to south of S. Georgia Is. Due to the presence of clouds, it is not possible to verify the existence of the west end of the arc in the MODIS AODs (Figure 3). However, the east half of the arc agrees with the location of high AODs and AIs detected by MODIS and OMI respectively. Furthermore, both MODIS and HYSPLIT agree on the location of the maximum concentration. The agreement between model and observation strongly suggests the presence of dust in the streak of high AODs observed by MODIS. In addition, the vertical distribution of dust from HYSPLIT provides useful information to interpret the OMI observations. The right panel in Figure 4 shows the vertical distribution of dust along the arc. At the center of the arc where concentrations are the highest, the dust is mostly concentrated in the boundary layer. As the dust in the east end advects towards the south, it rises due the presence of a low pressure center south of S Georgia Island. As a result, the dust along ~39W is located well above the boundary layer. Therefore, the modeled vertical distribution of dust is consistent with the fact that OMI was only sensitive to absorbing aerosols above the boundary layer north and south of S. Georgia but not sensitive to the streak of high AODs within the boundary layer as reported by MODIS. The fact that MODIS shows relatively high AODs north of S. Georgia, that OMI shows high AIs south of the island and that modeling transport places dust in the same area constitutes strong evidence that Patagonian dust reaches the atmosphere above Sub-Antarctic Atlantic Ocean.

[12] We note that after its passage by South Georgia, the dust reaches the free troposphere over Antarctica 48 hours after its emission according to HYSPLIT estimations (not shown). However, because the proximity to the polar night at such high latitudes and sea-ice, there are no MODIS and OMI retrievals that can corroborate the presence of dust in the Antarctic atmosphere.

7. Summary and Final Comments

[13] This study reports first observational evidence of a dust event in Patagonia as detected by satellite. Although this analysis did not study the deposition and chemistry of dust (necessary factors to consider for fertilization of phytoplankton), it does highlight some important facts regarding emission and the long range transport of dust in Patagonia. Our observations confirm that dust advects through the SW Atlantic Ocean and it can reach the area around the biological rich sub-Antarctic Ocean within 30 hours of emission. The event here described exemplifies that the intensity of dust emission in Patagonia can be significant and very localized (Figure 1). However, the cloudy conditions that accompany the event make automatic satellite detection very difficult since satellite algorithms rely on the clear sky conditions (MODIS) and/or dust above clouds (OMI) prior to the analysis of aerosol content in the pixel. In addition, the target area of interest (high latitude southern ocean) possesses intrinsic difficulties for appropriate aerosol retrievals such as the lack of good viewing geometry or dark background (there is sea-ice present a significant part of the year). Furthermore, there is an extra degree of difficulty for automatic satellite detection of aerosols even in the presence of clear sky conditions. Patagonia dust emission appears to be short lived. As shown in this case, the dust event lasted a few hours and the natural dilution and removal processes downwind Patagonia lowered dust concentrations. This results in a weak satellite signal as expressed in this case by the moderately high optical depths and near 1 aerosol indexes measured by MODIS and OMI respectively. Therefore, the satellite

tracking of dust in the South Atlantic is a difficult task and most likely to produce an underestimation of satellite based dust concentration retrievals. The analysis here presented is the most appropriate to track the dust with existing tools. We showed that only a combined approach of different satellite detectors aided by an aerosol transport model can yield a more robust answer on the transport of Patagonian dust in the SW Atlantic. Furthermore, the use of MODIS or OMI alone will not give a definitive answer on the fate of dust transport in the area. However, an integrated approach that takes advantage of the strengths of satellite and transport model methods can yield a consistent description of dust activity in the area.

[14] **Acknowledgments.** We thank the Argentine National Weather Service (especially Lic. Silvia Nuñez and María de los Milagros Skansi) for facilitating access to the hourly data from the ground meteorological stations. We thank Steve Warren of the University of Washington for his useful comments and suggestions. P. K. Barthia and O. Torres from the OMI science team are acknowledged. This research was funded in part under the NASA Radiation Program (Hal Maring, Program Manager) (NASA grant NNG04GM36G) and by the US National Oceanic and Atmospheric Administration under contract D6-133-R06-NC0308.

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