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Key Points:
- This is the multidecadal characterization of modern dust activity of the largest and most active source in the Patagonia desert (South America)
- Several multiyear periods of enhanced dust activity are found
- Data set is useful for constraining the modeling of dust over the Southern Ocean and interpretation of provenance of dust found in *E. Antarctica*

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Temporal Characterization of Dust Activity in the Central Patagonia Desert (Years 1964–2017)

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Abstract Dust emitted from the southern end of South America (SSA) is transported long distances over the Southern Ocean and deposited over this marine ecosystem. Whether the nutrients released through dissolution have a biogeochemical impact is a question with biological as well as climate implications, yet there is no clear answer. Additionally, the provenance of dust recently found in accumulated snow in East Antarctica is still a matter of debate. The Patagonia desert in SSA is the likely source, but there are no detailed records documenting dust activity in this area, thereby preventing any definite assessments. Here we provide a survey of modern dust activity of the largest dust source in SSA, the lake Colhué Huapi in central Patagonia. We analyzed five decades (1964–2017) of surface synoptic observations (World Meteorological Weather Present weather codes) and concurrent satellite aerosol detection (UV Aerosol Index from the Total Ozone Monitoring Sensor and Ozone Monitoring Instrument detectors, 1978–2017). We assessed the seasonal, year-to-year variability and periods of major dust activity. Several periods of enhanced activity were found with roughly 2- to 10-year duration each (1970–1976, 1989–1994, 1996–1997, and 1999–2017). While dust activity peaks during summer months, wintertime activity during the most active years can well exceed the summer average of nonactive years. For a period of coincident satellite observations, the occurrence of at least three periods of high activity is confirmed. Since satellite detection is more sensitive to mesoscale dust events, the large events that occurred during these periods brought abundant dust into the SW South Atlantic. Satellites with polar orbits tend to under detect dust events in this region. Significant cloudiness obstructs the direct view of dust, and dust activity tends to occur late in the afternoon after the overpass of polar satellites. These observations have a time span adequate for comparison with transport models and modern records of dust samples collected in East Antarctica. The results contribute to a better understanding of the dynamic of modern dust transport in the Southern Hemisphere, the provenance of dust found in Antarctica, and the provenance of eolian nutrients into the Southern Ocean.

Plain Language Summary Like a peninsula into the Southern Ocean, the vast Patagonia desert in the southern tip of South America is the largest landmass present in the high southern latitudes (40–60S). It is exposed to constant high winds, and dust blown from this region has important impacts thousands of kilometers away, yet these impacts are very difficult to assess. Questions such as the sources of dust found in snow in East Antarctica as well as the provenance of nutrients in the Southern Ocean marine ecosystem remain unanswered. While the Patagonia desert is the likely source there is a dearth of observational records of dust activity from this desert. This study fills the gap in observations by providing a record of 50 years of surface and satellite observations of the largest and most active dust source in Patagonia: lake Colhué Huapi. The seasonality, frequency, and periods of major dust activity are identified from meteorological records at a station located 100-km downwind from the lake. Collocated satellite observations confirmed the major periods of dust activity in the last 30 years. This data set provides information on how to interpret records of recent dust found in East Antarctica snow as well as help to understand the CO_2 cycle in the Southern Ocean.

1. Introduction

The removal of carbon dioxide (CO_2) from the atmosphere is an essential component in the evolution of Earth's climate. There is considerable interest in understanding the mechanisms by which this greenhouse gas is captured, stored, and later returned to the atmosphere at different time scales (Jaccard et al., 2016; Sigman et al., 2010; Wang et al., 2017). The largest reservoir of CO_2 is in the depths of the Southern

Ocean, and in this context, the biogeochemical cycle that modulates its marine ecosystem has received considerable attention (Kohfeld & Ridgwell, 2009; Sigman et al., 2010). Among the processes involved, an important and active area of research is how marine microorganisms respond to the nutrients available in their environment. There is considerable diversity in the type and sources of these nutrients (such as coastal sediments, ocean upwelling and eolian deposition). Also, their availability to the biota and their influence can vary depending on the source region and the marine ecosystem (Jickells, 2005). Further, how much and how often eolian nutrients are deposited over ecosystems known to be deficient of those nutrients is one of the main unanswered questions in marine biogeochemical studies (Mahowald, 2011; Schulz et al., 2012). During glacial periods in the Pleistocene epoch (2.5 Ma to 11 Ka B.P.) (Lamy et al., 2014; Martínez-Garcia et al., 2011), the Southern Ocean received massive amounts of dust, and it is thought that this dust played an essential role in modulating the observed variability of ambient temperature and CO_2 concentrations (Fischer et al., 2007).

Important gaps in understanding the dust impacts on marine ecosystems remain (Albani et al., 2016; Lambert et al., 2013, 2015; Shaffer & Lambert, 2018), and the study of modern dust transport and deposition at high latitudes may provide clues on how the dust-climate hypothesis operated in the past (Maher et al., 2010). Among those high-latitude environments (Bullard et al., 2016), the Patagonia desert is a current active source of dust. Patagonia, the desert located south of the Colorado River (~39S) in southern South America (SSA), has been singled out as the largest source of dust found in ice cores in East Antarctica through the Pleistocene (Albani et al., 2016; Basile et al., 1997; Delmonte et al., 2004; Delmonte et al., 2017; Gili et al., 2016, 2017; Grousset et al., 1992). While Patagonia remains currently an active source, there have been very few studies dedicated to understanding the transport of dust and its impacts.

Much of what it is known about dust transport in this sector of the South Atlantic is provided by model studies (Li et al., 2010; Li et al., 2010; Mahowald et al., 2007; Neff & Bertler, 2015) that provide an idealized but at the same time comprehensive view. In contrast, there have been very few studies specifically dedicated to measure dust at the source, in transit or at its destination. In addition to a few satellite case studies (Gassó et al., 2010; Gassó & Stein, 2007; Johnson et al., 2011), there have been a handful of surface observations. Gaiero et al. (2003), Ramsperger et al. (1998), and Crespi-Abril et al. (2017) reported observations measured with sampling stations in Central and Northern Patagonia. Evangelista et al. (2010) and Kanitz et al. (2013) made observations of dust during cruises in transit over the SW Atlantic. Evidence of long range transport is suggested by the observations of recent (spanning last decades) findings of dust in snow of the Antarctica Peninsula (McConnell et al., 2007; Pereira et al., 2004) and East Antarctica (Bory et al., 2010; Laluraj et al., 2014). Recently, Hooper et al. (2019) reported the presence of recent (last decade) deposition of dust in the east flank of a glacier in South Georgia Island directly downwind of Patagonia.

While the big picture of dust transport as it relates to synoptic systems was provided by Iriondo (2000), the mechanisms on how dust reaches East Antarctica is not well understood. One of the reasons is the sporadic dust activity in SSA with a handful of intense events per year with the potential for long-range transport. Thus, it is not surprising that dedicated surveys of geochemical oceanic tracers (Geotraces Programme, Morton et al., 2013; Rijkenberg et al., 2014) in the Atlantic Ocean often fail to capture such activity and report background concentrations of SSA dust in the South Atlantic (e.g., Chance et al., 2015). While surveys at the Neumayer site (located in the Atlantic sector of East Antarctica) do report evidence of long-range transport of smoke (Weller et al., 2013), they only report evidence of background levels of aerosols of crustal origin in their observations (Weller et al., 2008). Also, the Legrand et al. (2017) study in Dome C (East Antarctica) did not report any significant presence of dust, while one study reported a case where Patagonian dust may have reached this site (Gassó et al., 2010). Recently, more examples of ephemeral yet strong dust activity was suggested by two studies (Hooper et al., 2019; Kavan et al., 2018) where dust was found in suspension in Antarctica Peninsula and in firns in South Georgia Island. In both cases, long-range transport from Patagonia could not be ruled out. The contradicting nature of these reports highlights the rather episodic nature of the long-range transport of dust.

Overall, the infrequent campaigns leave an incomplete picture of the patterns of dust activity of the Patagonia desert. Only two studies addressing some basic questions (frequency and seasonality) have been published. Gaiero et al. (2003) reported geochemical characteristics of dust collected at three sites along the coast of Patagonia and reported a short time series (1 year) of dust deposition. The latter reported observations downwind from Colhué Huapi lake, located in central Patagonia (46S), the largest and most active dust source (Montes et al., 2017). Crespi-Abril et al. (2017) studied the variability of particulate matter (mostly dust) at a site in northern Patagonia (outside of the city of Puerto Madryn). While providing a 10-yearlong data set, this study is representative of only one sector in this immense region.

Major dust activity in lake Colhué Huapi has been increasing with dense dust clouds reaching the city of Comodoro Rivadavia, located approximately 90 km east. Local newspapers have pointed out a decline of the air quality in the city during these events. The Colhué Huapi lake is shallow, and its water levels have been highly variable in the last decades with a steady decline in the last 10 years (Llanos et al., 2016; Montes et al., 2017). Sediments exposed at its shores are frequently entrained and dune displacement has caused a severe impact on the local economy surrounding the lake. A recent survey of sediments found in San Jorge Gulf (200 km east of lake CH) confirmed the presence of eolian dust in the surface waters making up to 10% of the sediment found (Desiage et al., 2018). In addition, dust clouds from Colhué Huapi lake have been observed over the SW Atlantic. However, because of cloudiness, it is not possible to directly observe and track the dust clouds and presumably, much of the dust is deposited over the Patagonian sea shelf and beyond. This is relevant for the marine ecosystem in the Patagonian sea shelf because this sector has high levels of primary productivity (Garcia et al., 2008) and it is an important contributor to the global ocean CO_2 uptake from the atmosphere (Bianchi et al., 2009). Recent studies highlighted the sensitivity of this ecosystem to the deposition of nutrients contained in Patagonian dust (Cabrerizo et al., 2017; Paparazzo et al., 2017).

This study focuses on the characterization of dust activity of the Colhué Huapi lake. The objective is to provide a general view of dust activity with a data set of surface and satellite observations collected daily and spanning almost 50 years. Results are aggregated at monthly and yearly resolutions so future studies can compare these observations with dust records found in snow in Antarctica that have similar time resolutions (Pereira et al., 2004; McConnell et al., 2007; Laluraj et al., 2014; Hooper et al., 2019). Section 2 provides a description of the area of interest, section 3 details the databases utilized, section 4 provides an analysis and interpretation of the surface observation, and section 5 incorporates the satellite data into the surface observation analysis. Section 6 provides a summary of results and recommendations of this study.

2. The Patagonia Region and the Lake Colhué Huapi

The geographical setting of the Patagonia desert is confined by the Andes mountain range to the west, the Colorado River in the north, and the SW Atlantic Ocean to the east (Coronato et al., 2008, 2017). With its approximately 700,000 km^2 of total area (roughly the size of France, England, and Scotland combined), it is the only continental mass in the latitude ranges 39–56 south. Steady and strong westerly winds with daily mean wind speeds of the order of 40 km/hr are a common feature. There are no major changes in surface elevation, only interrupted by the east-west valleys of eight major rivers. With the exception of a narrow swath of alpine forests along the lee side of the Andes, the remaining landscape is a tableland devoid of trees with patches of shrub. The annual precipitation is less than 200 mm and concentrated in the fall and winter seasons (Coronato et al., 2008; Montes et al., 2017). The Patagonia desert extends approximately 1,600 km north–south with examples of dust activity recorded at both ends: in Tierra del Fuego (54S; Gassó et al., 2010), its northern end at Bahia Blanca (39S; Abraham et al., 2016) and in intermediate locations (Crespi-Abril et al., 2017; Gaiero et al., 2003; Gassó & Stein, 2007; Johnson et al., 2010). Every 2–4 days during the austral spring (September–December) and summer (December–March), polar low pressure perturbations move in from the SE Pacific generating sustained wind speeds reaching well above 70 km/hr for several hours (Labraga, 1994); gusts above 110 km/hr are frequently reported. The lack of the soil moisture, sparse vegetation covers, and strong surface winds provides the appropriate conditions for dust emission.

There are diverse sources of dust in the Patagonia desert associated with geomorphological features typical of environments commonly seen at low and high latitudes. South of 46°, there are old glacier washout plains still fed by glacier silt and seasonal snowmelt, for example, the Deseado and Santa Cruz Rivers (Coronato et al., 2017; Hernández et al., 2008). Occasionally and depending on the river water levels, sediments exposed at the shores are blown away by the steady and strong westerlies as well as katabatic winds that frequently occur inside the valleys. This activity is similar to what has already been reported in Northern Hemisphere

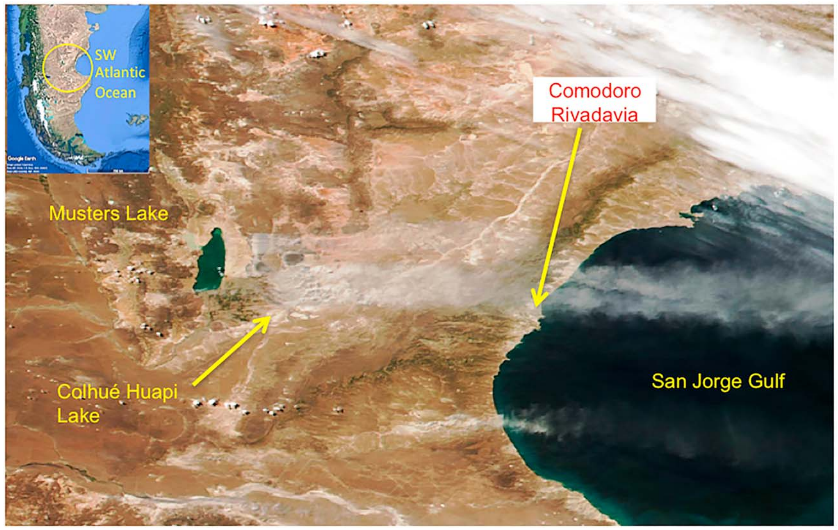

Figure 1. The Colhué Huapi lake is a shallow lake located in Central Patagonia (insert left), 90 km west of the coastal city of Comodoro Rivadavia. The constant and strong westerlies along with the coastal sediments (exposed by the frequent large swings in lake's water level) combine to generate dust blowouts and bringing abundant sediments into the SW Atlantic as this image illustrates (VIIRS image, 1 December 2016, images courtesy National Aeronautics and Space Administration and Google Earth). NDD = number of dust days.

paraglacial environments (Crusius et al., 2011; Dagsson-Waldhauserova et al., 2017). In this regard, Patagonia can be considered a high-latitude dust source area as defined by Bullard et al. (2016). In addition, depression hollows are abundant throughout the region (also known as *deflation basins*, *pans*, or *bajos sin salida*). While the major sources have been identified in the climatology derived by Ginoux et al. (2012) using the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite detector, not all sources are included due to the persistent cloudiness in the area. These *bajos* are common features in many arid areas throughout the world and are important contributors to the global dust budget (Goudie, 2008; Goudie & Wells, 1995; Prospero et al., 2002). They accumulate pluvial and fluvial sediments during the wet season and are usually totally or partially dried up by the end of the summer when these depressions become active dust sources (Mazzonia & Vazquez, 2009). Their size ranges from tens to hundreds of meters in diameter. Examples of activity from these sources were reported in Gassó and Stein (2007) and Gassó et al. (2010). Many of them are smaller than the typical satellite pixel size (MODIS detectors pixel size is 250 m), and from space, only the plumes are visible. The total number of bajos has not been quantified, but it certainly ranges in the hundreds (Clapperton, 1993). More recently, Mazzonia and Vazquez (2009) reported a high density of such hollows west of Rio Gallegos city (52S).

The area of interest for this study is located approximately at 45.5S and 68W, at the Musters and Colhué Huapi (to be referred as CH) lakes (Figure 1). Both lakes are part of an endorheic basin in the Sarmiento depression, and they are the remnants of the late Holocene paleo lake Sarmiento (González Díaz & Di Tommaso, 2014). Although currently inactive, the Chico River on the eastern shore of the lake CH provided a discharge to the ocean and it has been intermittently active since at least the early twentieth century (Montes et al., 2017). Both lakes are fed by the Senguer River with sources at the snowmelt-fed lakes (Fontana and La Plata) on the east side of the Andes. The lake CH is shallow with abundant sediments in suspension, whereas the lake Musters is much deeper and much less rich in sediments.

The causes of lake CH variability will not be explored here, but it should be pointed out that the intense evotranspiration as well as the variable incoming flow from the Senguer River are major factors. The variability in river flow is not only due to snowfall variability at the sources but also possibly due to extraction of water for irrigation, human consumption, and oil prospecting activities that have increased steadily since the early 2000s (Hernández et al., 2008; Mazzonia & Vazquez, 2009). In addition, overgrazing has been recognized as one of the main causes of desertification in the region (Del Valle et al., 1998; Gaitán et al., 2009).

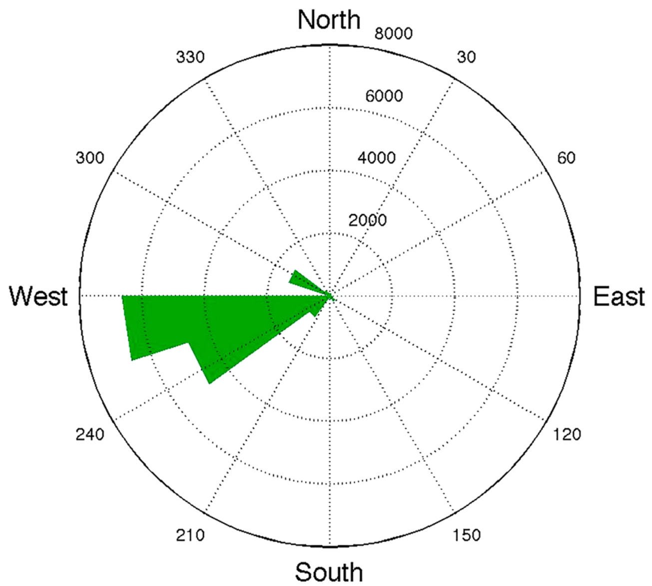

Figure 2. Direction of the wind when a dust event was reported at the Comodoro Rivadavia (CR) airport. The lake Colhué Huapi located west of the airport is the main and most frequent source of dust observed at this site. In this study, observations at the airport are used as proxy for dust activity at the lake.

3. Data Sets and Methodology

3.1. Surface Observations

The Comodoro Rivadavia Airport (referred as CR in this study) is located approximately 90 km east of the lake CH on the coast of central Patagonia (45.47S, 67.3W, 46 above sea level). The station is one the oldest meteorological stations in Patagonia; it started to operate in the early 1900s when oil was discovered in the region. Observations are reported hourly every day of the year (World Meteorological Organization [WMO] station ID 87860, Argentina ID: 10270). The data sets utilized in this study were obtained directly from Argentina's weather bureau office (Servicio Meteorológico Nacional or SMN) central archive. They have already been checked postobservation by SMN operators for obvious inconsistencies. These observations are part of the Surface Weather Observations (commonly known as SYNOP, World Meteorological Organization, 2014), and they include the standard meteorological variables along with a code referring to the type of weather event of notice at the time of observation (Present Weather) as well as during the period since the last observation (Past Weather). The surface observations of the WMO data set are very useful for long-term studies of specific aerosol type activity (Engelstaedter et al., 2003;Mahowald et al., 2007; O?Loingsigh et al., 2010; Dagsson-Waldhauserova et al., 2014; Founda et al., 2016; Li et al., 2016). The Present Weather code includes identifiers for different types of dust activity (Wang, 2015), ranging from widespread dust in suspension not raised by wind (code 6) to dust storms of different magnitude or accompanied with other meteorological features (codes 7–9, 30 to 35, and 98). In addition, SYNOP include codes for magnitudes of visibility (or meteorological range) and amount of cloudiness (reported in octals). The CR station began to use the SYNOP codes in 1964. The frequency of observations was 4 times per day until 31 December 1975 when the station switched to hourly reports.

In this study, all SYNOP reports at the station were evaluated. A *dust day* was defined as any day where any of the dust codes was reported at least once during the 24 period. Then the number of dust days (or NDD) per month and per year was stored for analysis. In calculating NDD, no discrimination was made on the magnitude of the event, that is, whether the event was reported as a dust storm o just as dust in suspension. The rational for this approach is based on a preliminary analysis of time series of NDDs with single codes. This revealed that there were very few days with dust storm codes reported in the full data set (53 years of observations). There were 1,4760 observations of dust in the 53 years of observations and only 76 (0.5%) were labeled as dust storm. Further findings revealed that operators tend to underreport the magnitude of the dust loading as expressed in the visual range observations (*Visibility*) but they do not omit whether dust was present or not. For example, the corresponding weather code for the dust event in Figure 1 was code 6 (*widespread dust in suspension not raised by wind*) through the duration of the event. Frequently, the densest sector of the dust cloud does not blow over or is within the observing range of the station and the event is recorded as *dust in suspension* even though the satellite image may indicate a widespread event (as in Figure 1). Observers at the airport only have a direct view dust clouds from the lake CH when the wind is due straight west. The airport is at sea level whereas the lake is located 80 km away and elevated with respect to the airport.

Figure 2 shows a polar diagram with a histogram of wind direction when a dust event was reported at the airport. It demonstrates that the vast majority of dust observations occurred when the wind direction is from the W and WSW sectors. It confirms that observations at the site are an adequate proxy of dust activity originating in the lake CH.

Certainly, the interpretation of SYNOP codes could be more sophisticated (e.g., O?Loingsigh et al., 2010, O'Loingsigh et al., 2014) than the approach used here. However, due to the lack of additional information of operator procedures, density of observation sites in Patagonia (stations with WMO data are spaced every 200–300 km), sources of local urban development data, or the reliability of the observations (beyond the application of WMO protocols), a rather conservative approach is used here where the only assessment is whether a dust code was reported without evaluation of the event's intensity. The scale and magnitude of the event will be further discussed in the satellite data analysis section.

3.2. Satellite Data

3.2.1. Sensors

With its global coverage, the Total Ozone Monitoring Sensor (TOMS) on board the Nimbus 7 satellite deployed in 1978 and provided a daily view of the Patagonia region until 1993. Successors of this instrument (TOMS and Ozone Monitoring Instrument [OMI] on board the Earth Probe and Aura satellites, respectively) have provided almost continuous daily ozone observations with observing channels in the wavelength range of 200–400 nm. While these sensors were designed for ozone studies, early observations revealed that ozone retrievals were sensitive to the presence of absorbing aerosols, such as smoke and dust. Initially, the aerosol contribution to the ozone signal was removed as an atmospheric correction but it was later utilized to obtain information on the nature and amount of the aerosol present in the pixel (Torres et al., 1998). The long time series of TOMS and OMI data (+30 year) as well as its unique features to distinguish between absorbing and nonabsorbing aerosols over land make them a unique set of observations ideally suited to compare with a similar long time series of measurements such as the airport observations used here. Although the MODIS satellite detectors (King et al., 2003) are better sensors designed for aerosol remote sensing, they do not have the unique combination of features (multidecadal time span and aerosol-type detection over land) that TOMS and OMI have.

The Ultra-Violet Absorption Aerosol Index (UVAI) is a parameter computed from the ratio of two observed near-UV radiances (one very sensitive to aerosol absorption and the other less sensitive). This ratio is compared with the same ratio of modeled radiances for a hypothetical atmosphere with no aerosols and no clouds. The difference of the logarithms of both ratios (and multiplied by −100) constitutes the UVAI. Several studies have demonstrated the effectiveness of using the positive values of UVAI to detect the presence of absorbing aerosols (Buchard et al., 2015; Colarco et al., 2017; Herman & Celarier, 1997; Hsu et al., 1999; Zhang et al., 2005). One particular feature of the UVAI is its sensitivity to absorbing aerosols over bright backgrounds, such as semiarid and arid regions and clouds. Thus, the UVAI is an effective tool for detecting the presence of dust, and in this study, the magnitude of the UVAI was used to test for dust originating in the lake CH.

The three satellite probes considered here are the Nimbus7-TOMS (years 1978–1993), EarthProbe-TOMS (1996–2004), and Aura-OMI (2004–2017 and still operating) detectors. Each sensor has channels suitable for computing the UVAI, although individual features in each require customized considerations. For example, each sensor has different spatial resolutions and slightly different pair of near UV channels used in the UVAI computation. In addition, there were hardware failures in each of those sensors. For example, starting in 2007, the OMI sensor lost sensitivity in almost half of the detector units and it degraded the global coverage to every 2 days instead of once a day (Torres et al., 2018). While the OMI instrument had remarkable stable calibration throughout its lifetime, both TOMS sensors exhibited calibration drifts that became apparent over time. Corrections were applied to the observed radiances by the respective calibration teams; however, in the case of the EP-TOMS sensor, clear trends remained in the UVAI (Kiss et al., 2007), even after the application of corrections, and the science team does not recommend using any data after June 2001. In the case of N7-TOMS, while the calibration seemed to remain fairly stable through the mission, small biases appeared at the edges of the swath. The following versions of the respective UVAI algorithms were used in this study: version 1.8.9.1 for OMI, version 0.4.3 for N7, and version 0.1.3 for EP.

3.2.2. Selection of the Threshold UVAI and Evaluation Approach

The UVAI is sensitive to the presence of three types of absorbing aerosols: smoke, volcanic ash, and dust. In the region of interest, forest fires are very infrequent and volcanic activity (and associated ash resuspension) is occasional, which can be constrained in time. Dust in concentrations ranging from background to high concentration levels is the most predominant aerosol type present. Thus, a positive value of UVAI can be interpreted as dust present in the pixel.

A sector in the plateau between the lake CH and the CR airport was selected for evaluation of the UVAI. A swath spanning 180 km north–south and 60 km west–east was approximately centered by an imaginary line joining the lake and the airport. The sector in the west–east direction approximately covers the region of

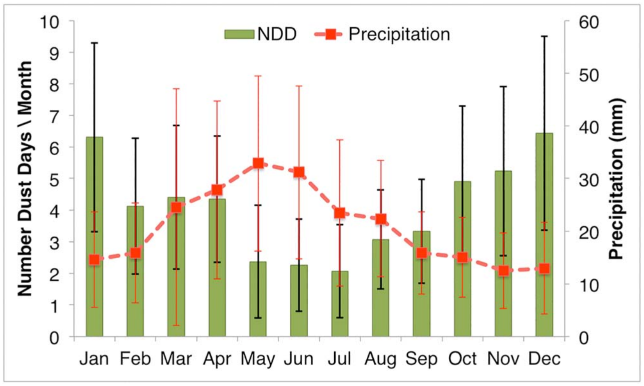

Figure 3. Average number of days per month with at least one dust observation (NDD) during the day and average monthly precipitation at the Comodoro Rivadavia airport averaged over the years 1964 to 2017. Respective standard deviations are displayed. Highest dust activity occurs during the summer months (December–March), while the precipitation is the lowest.

Pampa del Castillo and Cerro Dragón; it does not include the airport and the surrounding urban development. The UVAI of pixels with centers inside this sector was evaluated. The size of the selected region was large enough to capture dust events generated by W, SW, and NW winds. Also, the selected area is big enough to include inside several OMI pixels (size 20 × 13 km at nadir) and a handful of TOMS pixels (~40 × 50-km nadir).

However, there are some considerations when working with UVAI derived from each of these sensors. The bands used to compute the UVAI are very similar in the N7-TOMS and OMI sensors (the pair near 350 and 380 nm) and different in the case of EP-TOMS (331 and 360 nm). In practical terms, this means that the UVAI from EP-TOMS tends to be larger than the UVAI from N7-TOMS (or OMI) for the same aerosol loading and height. Thus, when creating the time series, different thresholds were used to count the number of days with high UVAI. The magnitude of this threshold was determined by testing different thresholds. The threshold used for N7-TOMS and OMI was UVAI equal to 1.25 and for EP-TOMS was 1.50. When the area of interest is located at the edges of the swath of the sensor, pixels can stretch for more than a hundred kilometers, particularly in the case of TOMS. A stretched pixel can include a mixture of surfaces such as the lake CH and oceanic sediments and blooms in the San Jorge Gulf, all of which are known to have a high UVAI even with no dust present; therefore, pixels at the edges of the swaths were not considered in the analysis. In the case of TOMS, three pixels on each side of the swath were ignored (this also took care of the calibration biases noted for N7-TOMS). With the development of the row anomaly in 2007, OMI changed from an instrument with daily overpasses in any given part of the world into an instrument with a revisit every 2 days. Since the objective is to observe changes in dust activity through time, only OMI pixels that were operational through the 13 years were selected (Torres et al., 2018). These are the pixels from the east side of the swath from rows 1–24. However, in order to avoid misclassification due to pixel stretching, only pixels in the rows 4–24 were used.

4. Surface Observations Analysis

4.1. Climatology of Dust Activity in Central Patagonia

Before analyzing the variability of dust activity through the time series of observations, a general climatological description is provided.

Figure 3 displays monthly averages of NDD and precipitation for the full database (years 1964 to 2017) of surface observations at the airport. Dust activity peaks during the summer months; typically, dust is observed for about 5 days per month during December and January, and the activity is minimal during the winter (July–September) with lower values (less than 2 days/month). A similar pattern was reported by Crespi-Abril et al. (2017) for a site located 400 km north of the CR airport. Correspondingly, average monthly precipitation peaks during the late (local) spring/early winter and is minimal in the (local_ summer coinciding with the highest dust activity. The overall monthly mean is 20.8 mm (±27.6 standard deviation (STD)) and the annual mean is 249.2 mm (±93.54) in agreement with the values reported by Montes et al. (2017) for the same site. The correlation coefficient between NDD and precipitation is 0.51, but if applying a 1 month lag in precipitation, the coefficient rises to 0.81.

Table 1
Summary of Number of Dust Days and Total Precipitation Per Year Averaged (AVE) Over Different Periods at the Comodoro Rivadavia Airport

Period (years)	NDD per year			Total precipitation per year		
	AVE	STD	CV	AVE	STD	CV
1965–1970	7.0	3.4	0.49	177.7	50.5	0.28
1971–1980	25.2	6.7	0.27	300.4	64.8	0.22
1981–1990	21.0	5.9	0.28	227.1	62.8	0.28
1991–2000	54.2	13.9	0.26	288.5	119.7	0.41
2001–2010	54.7	12.3	0.23	230.1	87.3	0.38
2011–2017	126.5	14.9	0.12	291.0	131.2	0.45
1965–2017	48.1	14.8	0.31	249.2	95.4	0.38

Note. Standard deviation (STD) and coefficient of variation (CV = STD/AVE) are included. Bottom row is the average for the whole time period. NDD = number of dust days.

Figure 3 and respective averages for the whole data set show large standard deviations indicating high variability within the data set. When the data are segregated by decades (Table 1), the first period had a notable small number of NDD and low accumulated precipitation per year. This seems counterintuitive, but unfortunately, there are no independent

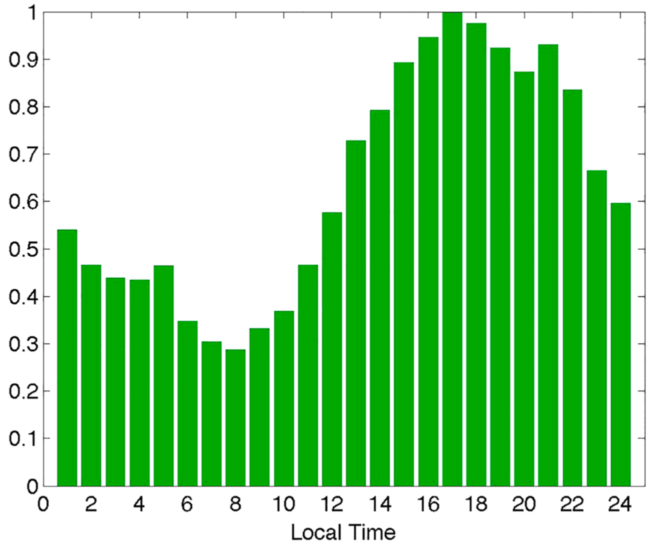

Figure 4. Normalized histogram of time of the day when a dust observation is recorded at the Comodoro Rivadavia airport. Dust activity is recorded at any time during the day with a nonnegligible proportion of activity during nighttime. Peak activity occurs late in the day.

records to confirm if indeed these were periods of low dust activity with low precipitation. Human observation bias cannot be ruled out. For the following decades, the yearly mean values of NDD steadily increase. The dust activity during second and third decade was steady and both decades had similar year to year variability. The end of the century decade and its first also have similar levels of activity and variability but a significant higher number of dust events (by a factor of 2) than the previous two decades. The last decade (2011–2017) also has notable increases by a factor of more than 2 compared to the previous two decades. For the whole data series, dust was observed in 13% of days of the year at the site (~48 days/year). When this average is partitioned by decade, the percentage of days with dust exhibits a clear increasing trend as 2%, 7%, 6%, 15%, 15%, and 35% for each of the decades listed in Table 1.

The average accumulated precipitation segregated by decade does not exhibit a clear trend as in the dust observations. In particular, the pattern of high rain-low dust activity is not apparent when data are grouped by decade in contrast to the seasonal variability between dust and precipitation noted in the discussion for Figure 2. This may suggest that the simple rain-dust correlation operates at time scales that may not be captured at decadal averages and/or additional drives of dust activity are at play. Additional discussion related to this trend and correlation rain-dust is included in section 4.3

Since observations are carried out at every hour of the day, the time of the day when dust is most frequent can be evaluated. Figure 4 shows a histogram of dust activity during the day normalized to the maximum. Dust activity peaks in the late afternoon (17 local time = UTC-3 hr). Dust activity is also reported during the nighttime. This fact may signal that not only afternoon heating is a driver of dust entrainment but also the intense winds associated with the passage of polar lows, which transit at any hour of the day in the region. The fact that dust activity also occurs during nighttime poses an observational challenge from the viewpoint of satellite surveillance since satellite detection is carried out mostly during daytime.

4.2. Cloudiness during Dust Events

Low-pressure systems entering from the Pacific Ocean bring high wind speeds as well as abundant cloudiness. While most of the moisture is discharged in the west side, the Andes range at these latitudes is not high enough to fully prevent the passage of clouds. This is one of the main reasons why it has been so difficult to survey dust activity in Patagonia with satellite observations: dust in suspension is frequently accompanied by clouds. In addition to reporting whether dust is present, the surface observations at CR are accompanied with observations of cloud coverage (or cloud fraction). This is reported by the number of *oktals* (or fractions of eight) ranging from 0 (clear sky) to 8 (overcast). As an example, cloud coverage at the time when dust was observed at the CR airport is shown in Figures 5 for the year 2016. The left figure shows a histogram of cloud coverage for observations at any time of the day, whereas the plot on the right is for observations reported during the time window of the typical OMI sensor overpass. The left histogram shows that clear skies during dust events do happen but they are not the most frequent occurrence. While observer bias cannot be ruled out (it is easier to report either *clear* or *cloudy* conditions than assessing the intermediate ranges), it is evident that fully and partially cloudy conditions are more frequent than clear sky conditions. This is also apparent when restricting the data to the satellite overpass time frame (early local afternoon), when clouds covering more than 50% of the sky are most frequent (Figure 5, right). In this case, when a dust event was reported during the time frame of satellite overpass, 78% of the observations were carried out when more than half of the sky was covered by clouds.

These observations provide a rationale for the lack of dust budget assessments in the region using satellites: cloudiness prevents a full characterization of dust activity. With one or two satellite overpasses per day, polar satellites may miss a dust event because cloudiness is high. Even when an event is detected, a significant portion of the dust remains under cloud, making the assessment of the full extent of the dust cloud very difficult.

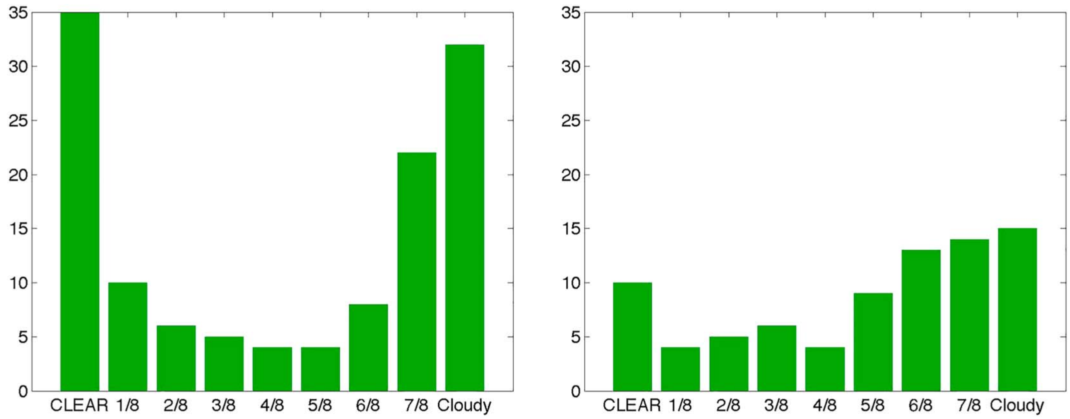

Figure 5. Histogram of cloud coverage at the Comodoro Rivadavia airport when a dust observation was reported at the station (year 2016). Units are in oktals. (left) Events reported at any hour of the day. (right) only for observations between 12 and 18 hr. Local time (15 and 19 UTC), the approximate window of time of the OMI sensor overpass.

The combination of cloudiness and dust activity peaking during the late afternoon (Figure 4) results in a poor representation of dust activity in global surveys of dust from this region, since the detectors commonly used for aerosol detection (e.g., MODIS TOMS/OMI) have polar orbits with1 day time overpasses typically in the midmorning/early afternoon. Thus, the lack of timing results in an underrepresentation of dust activity in these satellite surveys. It is expected that the new generation of geostationary satellites (such as GOES-East and GEOS-West) with higher spatial and temporal coverage will be able to better capture dust activity in Patagonia.

4.3. Time Series of Dust Activity in the Last 50 Years

By accumulating the number of dust days (or NDD) per month, it is possible to obtain a picture of how dust activity has varied in the region since 1964. This variability is apparent in Figure 6 where NDD is displayed for the full data set (the black line is a 3-month running average).

Seasonal variations are apparent in the monthly averages with maximum activity during the summer months and minimum during the winter months. There is a remarkable difference in activity between the early years of the data series (1964–1989) and the period after. At the beginning of the time series, there are very few reports of dust before 1970, some years with less than 10 events per year. Dust activity started to increase in the early 1990s (most notably during summers) and additional increases after 2000 with more activity recorded during winter in addition to the summer peak levels. Overall, four periods of enhanced activity are noted: 1970–1977, 1989–1994, 1996–1997, and 1999–2017. These four periods are selected just based on increases of activity with respect to a summer background threshold of NDD. For example for the period 1970–1977, there is a clear increase with respect to the years before and after and in this case

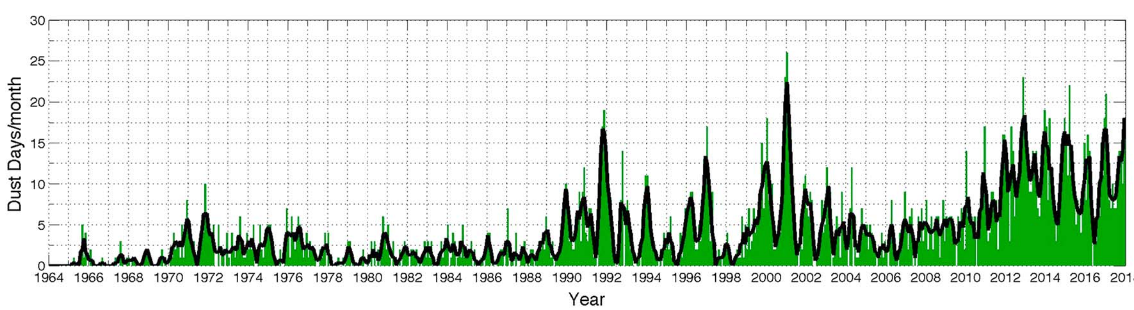

Figure 6. Time series of dust days accumulated per month at the Comodoro Rivadavia airport. The solid black line is a 3-month running average. Seasonal variability as well as consecutive years of enhanced and decreased activity is apparent. Frequency of observations was every 6 hr until January 1976 after which observations were carried out every hour. Vertical dashed lines are spaced every year (January).

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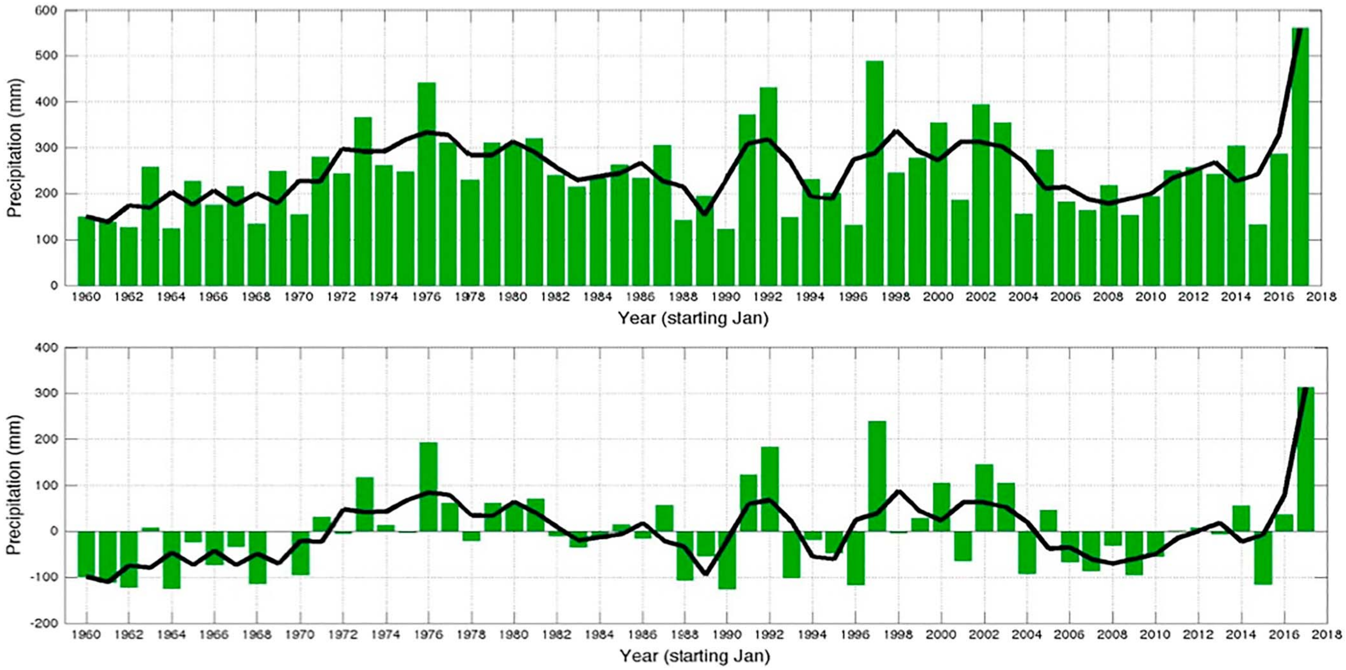

Figure 7. Time series of total annual precipitation (top) and deviation from the series mean (bottom) at the Comodoro Rivadavia airport, period 1960–2017. Black line is the 3 year running average. Precipitation is accumulated from June to May to highlight moisture available prior to the dry season. Year 2017 includes a single rain long event with 287 mm (29–30 April 2017).

the threshold is around 2–3 NDD/month. For the other periods, a threshold value of 5 NDD/month seems more appropriate.

Changes in observation protocols and observer bias are worth considering but difficult to determine. To the extent of our research, we know the frequency of daily observations changed in 1 January 1976 when 24-hr hourly observations started. Prior observations were carried out every 6 hr. However, no particular change is noted after that date in the monthly data.

Precipitation observations during the same period at the airport did show departures from the historical means (Figures 7, top and bottom). However, the correlation between dry spells at the airport and dust activity is not clear-cut. While the anticorrelation precipitation-NDD is apparent (Figures 3), it should be noted that the main source of water of the lake CH is meltwater brought by the Senguer River, which originates at the lakes located on the leeside of the Andes mountain range about 400 km west. Thus, snowpack and precipitation at the source is what largely determines the CH water levels and exposure of dust sources.

Precipitation at the CR airport is also influenced by occasional marine air incursions (Mazzonia & Vazquez, 2009;Agosta et al., 2015), and the corresponding weather systems do not necessarily reach inland to the lake CH. For example, Montes et al. (2017) reported a significantly lower annual precipitation at the city of Sarmiento (located between the Musters and CH lakes) than the CR airport. Thus, precipitation at the CR airport is a general indicator and not necessarily representative of the precipitation at the lake CH. For a more appropriate evaluation of the relationship between lake water levels' variability and precipitation, snow accumulation at the Andean lakes should be considered. Nevertheless, precipitation at CR is an indicator as it is correlated with rain brought by the Pacific cyclones. Also, given the shallowness of the lake, water loss through evaporation is an equally important natural factor. Water extraction for human consumption, agriculture and oil production has increased steadily in the last 20 years; thus, it is reasonable to expect that water levels at the lake CH are not likely related to variability in precipitation at the airport. While Figure 3 suggests a correlation between the two, Figures 6 and 7 highlight that this is not always the case. For example, a maximum of dust activity occurred in 1991–1992 with a steady decrease in precipitation in the six prior years, whereas the years 1960–1969 had consistently lower precipitation but no obvious corresponding increase in dust activity.

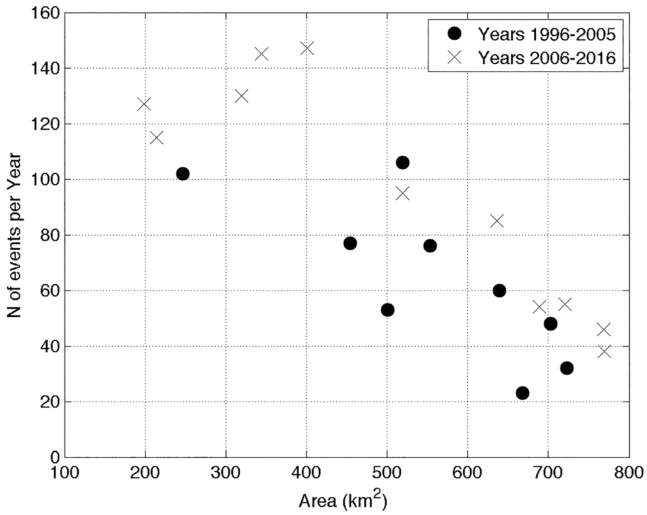

Figure 8. Area of the Colhué Huapi lake (from Llanos et al., 2016) versus number of days with dust at the Comodoro Rivadavia airport segregated by periods where anthropogenic signals (2006–2016) probably contributed to the dust observed at the airport. The correlation coefficient for all points is 0.69.

In some years when volcanic eruptions occurred, ash and in particular resuspended ash may have been reported as dust and contribute the NDD. This is the case for the year 1991 when the volcano Hudson (located in the Andes at 45.9S) erupted in August 1991 (Global Volcanism Program, 2013). Reports of ash from the activity and later from resuspension indicate that hazes were visible until at least March 1992. Other volcanoes were active in Patagonia during the period of interest (Hudson in 1971, Chaitén (43S) in 2008, Puyehue (41.5S) in 2011, and Calbuco (40.55S) in 2015), but they did not seem to have a clear impact in the record of observations.

There are no adequate surface observations for verifying the trends noted here. Gaiero et al. (2003) collected dust downwind of lake CH for a period less than a year (1996). While NDD at the airport compared favorably with the Gaiero et al. (2003) data, the length of the data series is not enough for a definite confirmation of activity at the airport. The Crespi-Abril et al. (2017) study has a longer time span (12 years), but it was carried out in area not representative of the dust source studied here.

4.4. Change in Lake Area and Dust Activity

A recent report by the Argentine National Technological Agriculture Institute (Instituto Nacional de Tecnología Agropecuaria) analyzed the variability of the area of the lake CH with the Landsat images from 1998 to 2016 (Llanos et al., 2016). It reports two periods where lake area was minimal: the year 2000 then followed by a maximum in 2006 and a steady decrease until the last year of observations (2016). The changes in the lake area are consistent with the variability noted in Figure 6. When comparing the NDD accumulated per year at the CR airport with the changes in the lake area, the correlation is notable. Figure 8 displays the comparison between the area of the lake as measured by Llanos et al. (2016) and NDD per year from this study. The correlation coefficient is 0.69 for all points in the series. The data in Figure 8 are displayed, grouped into two time periods, and highlights the fact that the period 2006–2016 had higher NDDs than the previous period. This increase of NDD from 2006 to 2016 may be due to a combination of dust originating not only at the lake CH but also in the area in between the lake and the airport. As noted by Mazzonia and Vazques (2009), the period after the year 2000 was characterized by an increase in oil prospecting in the hills (Sierra de Dragon) and plateau (Pampa del Castillo) between lake CH and the airport. In addition, building construction immediately west of the airport (Usach & Freddo, 2016) may have contributed. Increases in the number of wells and in construction activity are apparent in Landsat images available through public geobrowsers such as Google Earth (https://www.google.com/earth/) or United States Geological Survey's EarthExplorer (https://earthexplorer.usgs.gov/) starting in 2009. In addition, this period coincided with lower than average precipitation at the airport (Figure 7), conditions that made local dust resuspension more likely with a possible contribution to the visibility observations at the airport. However, the contribution of these anthropogenic sources in the NDD record are probably not a major percentage of the total number as Figure 8 suggests.

5. Analysis of the UVAI along with Surface Observations

The analysis of observations at the airport provides a temporal albeit local perspective of dust activity in the area. The surface NDD index derived in this study does not contain information of the intensity or scale of a dust event. Thus, this information does not provide enough information to ascertain the spatial scale of a dust event or if the event was large enough to entrain abundant material that could travel long distances. As noted earlier, dust detection at the site is a combination of a few major and mostly minor events (including nonlake-sourced dust) going over the airport and it is difficult to assess the magnitude of a large event happening at distances beyond the standard meteorological range of the airport (Figure 1). Certainly, large events are included but how many of those occurred? Did the number of events increase in time as Figure 6 suggests? Satellite observations with their large regional views and sensitivity to dust such as those from the TOMS and OMI detectors can help to address these questions.

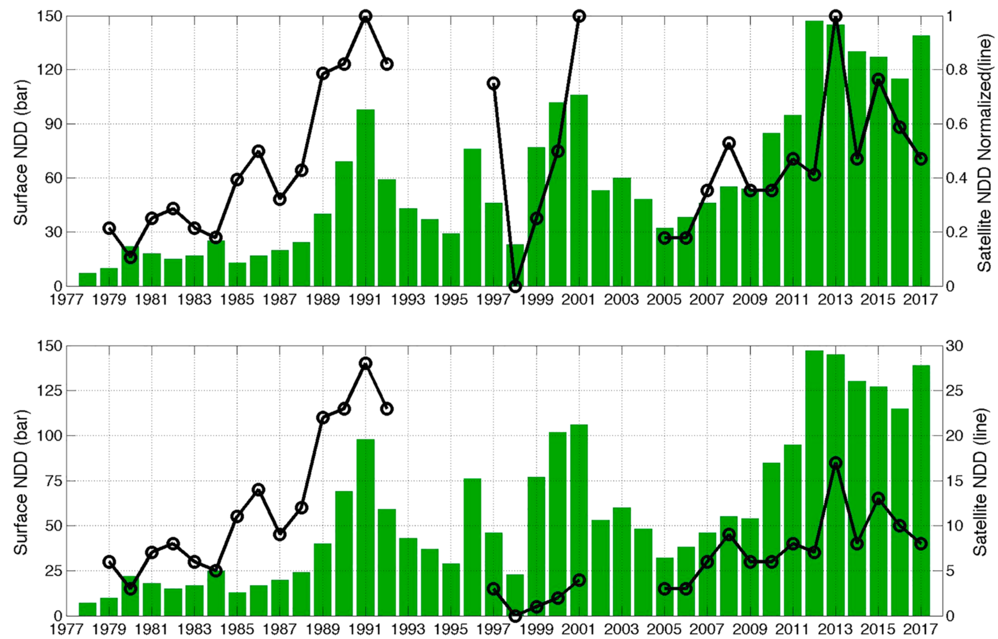

Figure 9. Time series of number of dust days (NDD) per year as observed at the Comodoro Rivadavia airport (bars) and by three satellite sensors (N7-TOMS [1979–1992], EP-TOMS [1997–2001], and OMI [2005–2017]). (top) Satellite NDD are normalized to the maximum in each satellite series. (bottom) Actual satellite NDD. Satellite data agree with surface observations in showing similar trends in the respective periods. UVAI thresholds to count as satellite NDD are for EP and OMI > 1.25 and for N7 > 1.50. TOMS = Total Ozone Monitoring Sensor; UVAI = Ultra-Violet Absorption Aerosol Index.

The analysis of the UVAI (section 3.2) provides information that complements the surface NDD time series. The UVAI is positive in the presence of dust. In addition to aerosol absorption, the UVAI magnitude is very sensitive to the height of the dust layer and concentration, where high values of either of them (or both) result in large positive values of the UVAI. Experience in analyzing this parameter shows that small-scale dust activity, such as the dust resuspension from construction building or dust devils, does not register a high UVAI value because of the small scale of these events with respect to the large pixel of a sensor such as TOMS and OMI (~20 × 10 km or higher). However, such activity might be recorded as local dust by the operators at the CR airport. A satellite time series is created by counting the number of times per year when the UVAI exceeded a predetermined threshold value in the area downwind from the lake CH. This number is the satellite equivalent to the NDD index defined earlier for the ground observations. Considerations regarding the satellite data preparation were discussed in section 3.2.2.

Figure 9 (top) displays the surface and satellite (black line, right y axis) NDD accumulated in each year. Satellite data are normalized to the maximum of each satellite series. The same plot with the absolute magnitudes of satellite NDD is shown in Figure 9 (bottom).

The surface yearly accumulated data show periods of enhanced dust activity lasting from 2 to 11 years such as 1989–1994, 1996–1997, 1999–2004, and 2006–2017 if using 30 NDD/year as threshold. The three satellite series agree with the surface observation in showing increasing trends and peaking almost at the same time. Both N7-TOMS and surface data have maximums in 1991, the year of the Hudson volcano eruption (August 1991 to March 1992).

However, the magnitudes of the satellite NDD are different from the surface observations (Figure 9, bottom). There can be several factors to cause the differences between satellite and surface NDDs. For example, the satellite data are highly sensitive to the strength of the signal observed, whereas the surface observations are based on a qualitative identification of aerosol type and no intensity of event is considered in the computation of surface NDD. Also, satellite data were sampled over a sparsely populated area immediately downwind from the dust source. Because of this proximity, freshly entrained dust remains close to the surface in the pixels used for evaluation. Such dust cloud would have a lower UVAI compared to the same dust concentration but more elevated (UVAI is sensitive to aerosol concentration, height, and composition). Thus, low-altitude dust that will be visible at the airport may not have a UVAI high enough to exceed the threshold values. In addition, satellite data were evaluated northwest and southwest of the airport beyond the standard observer distance, so in cases where dust is entrained by wind direction other than straight west, both satellite and surface data may report differently. Another reason for the discrepancy is the influence of local lifting of dust due to construction and road activity, which may be recorded in the surface data but is not recorded in the satellite observation.

However, it is apparent that the satellite time series agree with the surface observations in showing an increase in dust activity during the periods 1978–1990, 1997–2001 and 2004–2016. The year 1991 is difficult to assess whether it was a particularly dusty year since the Hudson eruption occurred in the same year. The first and last periods coincide with periods of steadily below-average precipitation (Figure 6, bottom). Also, newspaper records do report drought and dusty conditions for these years (La Nación, 1996, 2011). The increase of dust activity reported at the airport also coincides with a period of severe reduction of the lake total surface (Llanos et al., 2016) as well as local records of dust activity reported (e.g., see http://www.elchenque.com.ar/geo/temrelgeo/colhuesec.htm).

While the trends in NDD in both satellite and surface observations inform the variability of dust activity in time, their magnitudes also provide some information (Figure 9, bottom). For example, surface NDD values exceed 100 in some years; given that this is an airport near a city, it indicates that air quality was degraded in many of those days. Given that satellite NDD is sensitive to larger scale events and not to the minor and local dust activity observed at the surface, Figure 9 bottom shows years with satellite NDD higher than 12, suggesting a major event at least once or twice a month during those years.

Overall, N7-TOMS and OMI data confirm two of the major periods (1978–1993 and 2004–2016) of dust activity noted by the surface data. EP-TOMS satellite partially confirms a third period (1995–2001) that agrees with the period of lower lake area (Llanos et al., 2016).

6. Summary of Main Findings and Implications

Compared to the northern Atlantic, there is a far less body of knowledge about dust production and transport into the southwest sector of this ocean. This work is an attempt to fill this gap by providing a characterization of the frequency, seasonality, and periods of major dust activity at an airport located downwind from the most active dust source in central Patagonia (Colhué Huapi lake) in Southern South America using surface weather and satellites observations. The observation period was from the year 1964–2017 for surface observations and 1978–2017 for the satellite observations. The following facts were established:

1. From the surface observation data (Figure 6), four periods of enhanced activity are identified: 1970–1977, 1989–1994, 1996–1997, and 1999–2017.
2. Independent observations of the UVAI (Figure 9) from satellite imagery (available almost continuously since 1978) confirm increasing dust activity for the periods 1989–1994 and 2006–2017.
3. At any given month, there is a report of dust activity (at least twice per month) at the CR airport. Dust originating at the Colhué Huapi lake is an important contributor to the dust observed at this site (Figures 2 and 3).
4. Landsat images (Llanos et al., 2016) confirm significant fluctuations in lake area that correlates with observations of dust at the Comodoro Rivadavia airport in the period 1996–2016 (Figure 8).
5. There are between 15 to 30 major or moderate large dust events per year in years of enhanced activity according to satellite UVAI analysis (Figure 9).
6. Dust activity peaks during the summer months (December–March) when local precipitation is the lowest (Figure 3).
7. Dust activity can occur at any time during the day and night with higher frequency of events reported in midafternoon to early evening period (Figure 4).
8. Most of the activity occurs in the presence of clouds; in fact, days with dust in suspension and no clouds can happen in less than half of the events (Figure 5).
9. Because dust activity occurs late in the day and is accompanied by cloudiness, polar satellite surveys miss this activity (overpasses are once/twice per day in the local late morning/early afternoon), resulting in a poor characterization of dust in global satellite assessments of these aerosols.

While the work presented here is representative of the most active source in Patagonia, it does not necessarily provide a full picture of dust activity of the whole region. Other sectors in Patagonia have active dust sources (Crespi-Abril et al., 2017; Gassó et al., 2010; Gassó & Stein, 2007) but not with the same frequency and consistency year to year as in the Colhué Huapi lake. A more comprehensive assessment needs to be carried out to provide a full picture of activity in the whole region. The task undertaken here focused on the lake CH because of the coincidence of the presence of a meteorological station immediately downwind with a long record of observations and corresponding long-term set of satellite observations. In particular, analysis that is more detailed is needed to understand the controlling factors that modulate dust activity in lake CH and more generally the rest of Patagonia. In the case shown here, the connection climate variability-dust activity was not explored and probably one starting point is the exploration of the connection of precipitation at Andes (snow fall at sources) and in Patagonia and dust activity with dust activity recorded at all airports.

It is expected that there will be an improvement in the characterization of dust activity in the Patagonia area. Local groups are carrying out more dedicated studies of dust and its impacts downwind (Cabrerizo et al., 2017; Crespi-Abril et al., 2017; Montes et al., 2017; Paparazzo et al., 2017). Also, the availability of better remote sensing tools, such the TropOMI sensor, a similar sensor to OMI with improved spatial resolution and the geostationary GOES-E sensor with a high temporal (at least every 30 min) and spatial resolution than previous sensors, will all help to better characterize dust activity and transport from this area.

The synergies of satellite and surface observations are useful and they complement each other. For example, O'Loingsigh et al. (2014) shows how MODIS observations can be complemented by SYNOP observations and used to detect activity not seen by the satellite. This methodology works both ways to provide a more complete picture of dust activity.

This analysis is a first assessment of the main temporal features of dust activity of the largest and most active dust source in the Patagonia desert spanning several decades. This information is useful for assessing the provenance of dust found in firns dating the last 100 years from East Antarctica and Antarctica peninsula (McConnell et al., 2007;Laluraj et al., 2014; Kavan et al., 2018) as well as in the SW Atlantic islands (Hooper et al., 2019). While dust originating from Patagonia appears to be the main candidate, the related studies have been based mostly on isotopical finger printing (e.g., Gaiero, 2007; Gili et al., 2016), study of particular cases (e.g., Gassó & Stein, 2007), and modeling (e.g., Neff & Bertler, 2015). The lack of data sets of dust observations with time spans (decades) and resolutions (monthly to yearly activity) suitable for comparisons with ice cores and large grid transport models was one of the impediments to make such assessments. The comparison of the timing of dust emission of this data set with time series of modern dust deposition (Laluraj et al., 2014; McConnell et al., 2007) will help to constrain and improve the understanding of the provenance of dust found in Antarctica. Also, this study provides observational constraints for the modeling of the biogeochemical cycle in the Southern Ocean sector (Jickells, 2005; Mahowald et al., 2010; Myriokefalitakis et al., 2018). Biogeochemical climate simulations involve temporal cycles of the order from decades to centuries with dust production highly parameterized, and there are very few with no observational data sets at time resolutions adequate to the model time steps (Moore et al., 2013; Tagliabue et al., 2009, 2016).

This work is a first step toward filling the knowledge gap in understanding the provenance of modern dust found in Antarctica. Additionally, it provides insights of major periods of dust activity in an area upwind of one of the largest high-nutrient low-chlorophyll marine ecosystems: the Southern Ocean. The information supplied in this report provides observational evidence useful to compare with the variability of biology activity observed in the area and establish possible sources of key nutrients.

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