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Variability of particulate matter (PM_{10}) in Santiago, Chile by phase of the Madden–Julian Oscillation (MJO)

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HIGHLIGHTS

- Variability of surface PM_{10} by MJO phase was explored for winter months.
- During phases 4, 5 and 7, PM_{10} levels in Santiago were above normal.
- During phases 1 and 2, PM_{10} levels in Santiago were below normal.
- Supporting variability was found for multiple atmospheric parameters.

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ABSTRACT

Topographical, economical, and meteorological characteristics of Santiago, Chile regularly lead to dangerously high concentrations of particulate matter (PM_{10}) in the city during winter months. Although the city has suffered from poor air quality for at least the past forty years, variability of PM_{10} in Santiago on the intraseasonal time scale had not been examined prior to this study. The Madden–Julian Oscillation (MJO), the leading mode of atmospheric intraseasonal variability, modulates precipitation and circulation on a regional and global scale, including in central Chile. In this study, surface PM_{10} concentrations were found to vary by phase of the MJO. High PM_{10} concentrations occurred during phases 4, 5 and 7, and low concentrations of PM_{10} occurred during phases 1 and 2. Precipitation, low-troposphere circulation, and lower-troposphere temperatures supported the observed PM_{10} variability. For example, during phases 1 and 2 (low PM_{10}), precipitation was above normal, morning and evening temperature inversions were less intense than normal, and 900 hPa winds were anomalously westerly. During phases 4, 5 and 7 (high PM_{10}), precipitation was normal to below normal, morning and evening temperature inversions were stronger than normal, and 900 hPa winds were anomalously easterly.

1. Introduction

Global industrialization and urbanization over the past four decades in the megacity of Santiago, Chile, has contributed to significant degradation in its air quality (Muñoz and Alcafuz, 2012). One of the most important and hazardous contributors to this poor air quality has been particulate matter (Grass and Cane, 2008; Pope et al., 2009), a complex mixture of fine and large particles. Particulate matter concentrations are usually categorized with respect to aerodynamic diameter, and PM_{10} corresponds to those particles with diameters greater than 10 μm (ISO, 1995). In Santiago, PM_{10} has varying origins, physical and thermodynamic characteristics, and chemical compositions. It is generally formed by mechanical processes such a fragmentation and re-suspension of high mineral concentrations (Ca, Fe, and Si) and contains aerosols, smoke, soot, combustibles, sea salt, and trace toxic elements (Rojas et al., 1990; Artaxo, 1998). A wide range of factors have been found to influence particulate matter concentrations at the surface in Santiago, including day of the week, time of day, altitude, wind conditions, and precipitation (Gramsch et al., 2006; Préndez et al., 2011). A complicating factor for Santiago is ventilation and dispersion of air pollution, which are restricted by the Andes Mountains (elevations up to 5500 m) to the east, the Coastal Range to the west (elevations up to 2000 m), the Chacabuco mountain range to the north, and the Cantillina mountain range to the south (Sax et al., 2007; Elshorbany et al., 2010; Préndez et al., 2011). Because of intense societal interest in predicting PM_{10} concentrations, neural network methods have been developed in cities around the world to understand variability

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of particulate matter on short (daily) time scales, including Athens (Chaloulakou et al., 2003), Helsinki (Kukkonen et al., 2003), and Shanghai (Jiang et al., 2004), as well as Santiago (Perez et al., 2000; Perez and Reyes, 2002, 2006). However, very few studies have examined the variability of PM_{10} on the intraseasonal time scale (Tian et al., 2008, 2011; Tian and Waliser, 2012), and none for metropolitan Santiago.

Santiago experiences its highest concentrations of PM_{10} during the autumn-winter months of March through August (Préndez et al., 2011), and with hourly concentrations regularly exceeding 150 μg m^{-3}, it ranks as one of the most polluted cities in South America (Koutrakis et al., 2005). The Chilean government has long considered high levels of particulate matter to be a major concern (Préndez et al., 2011), and as a result of early studies on particulate matter in the region (e.g., Préndez et al., 1984; Trier, 1984; Trier and Silva, 1987; De La Vega et al., 1987; Rojas et al., 1990; Préndez et al., 1991), the Chilean government implemented a variety of measures to try to reduce PM_{10} levels. For example, in the late 1980s, car-use bans were imposed based on license plate number, and mandatory vehicle inspections were implemented. In the early 1990s, new cars were required to have catalytic converters, and beginning in the 2000s, efforts were made to replace the old bus fleet, clean and pave roads, and line roads with trees to reduce dust (Koutrakis et al., 2005). Despite these improvements, serious health problems persist, including associated daily morality and medical visits for respiratory illnesses associated with high PM_{10} levels in Santiago (Sanhueza et al., 1999; Ostro et al., 1999; Ilbaca et al., 1999; Cifuentes et al., 2000; Lee et al., 2000; Pino et al., 2004; Cakmak et al., 2007; Grass and Cane, 2008). Given that much emphasis has been placed on understanding short-term (daily) PM_{10} variability in Santiago (Alvarado et al., 2012), understanding the variability of PM_{10} on longer time scales (e.g., Silva et al., 2001), including the intraseasonal time scale, would allow for effective government-based planning measures and bring significant community health benefits.

Synoptic-scale meteorological conditions in Central Chile have been linked to particulate matter level variability. For example, amount of rainfall in the Santiago area has been found to inversely relate to PM_{10} concentration (Gramsch et al., 2006), because in addition to wet scouring of suspended particles, the wet ground after rainfall events leads to less re-suspended particles in the atmosphere (Barmpadimos et al., 2011). In addition to rainfall, temperature inversions in the lower troposphere above Santiago have been linked to PM_{10} variability (Garreaud and Rutllant, 2004). For example, in the winter months, inversions can be as low as 300 m at night and early in the morning, and they average between 600 and 900 m above the city throughout the day. The presence of an inversion decreases ventilation and dispersion of pollutants (already reduced due to the topography), leading to high PM_{10} (Préndez et al., 1991; Gramsch et al., 2000). Wind direction and magnitude has also been connected to PM_{10} variability. For example, katabatic nocturnal winds, which often flow down the narrow Andean valleys, are episodically enhanced with an easterly component, a phenomenon locally known as *Raco* winds. These *Raco* winds are associated with high PM_{10} levels because they reduce flushing out of the morning air, enhancing the static stability of the lower troposphere (Rutllant and Garreaud, 1995; Gallardo et al., 2002; Rutllant and Garreaud, 2004). Finally, large-scale circulation, particularly anticyclonic conditions with low wind speeds and reduced rainfall, has also been found to lead to increased levels of PM_{10} (Préndez et al., 2011).

While these regional- and local-scale factors control PM_{10} variability, it is important to note that they themselves respond to variability on the global scale, including variability associated with the Madden–Julian Oscillation (MJO). The MJO is the leading mode of atmospheric intraseasonal variability, a 40–50 day cycle of planetary-scale, eastward-moving regions of deep convective clouds and heavy precipitation, bounded on both west and east by regions of suppressed convection and minimal precipitation (Madden and Julian, 1972). Zonal circulation cells connect the east and west boundaries, with lower troposphere (near 850 hPa) anomalous westerly (easterly) winds to the west (east) of the deep convection. The circulation anomalies are reversed in the upper troposphere (near 200 hPa) (Nogues-Paegle et al., 1989; Chau and Salstein, 2005; Kiladis et al., 2005; Zhang, 2005; Mo et al., 2012). The atmosphere responds to deep convection in the Maritime Continent with longwave Rossby trains that propagate eastward and poleward (Hoskins and Karoly, 1981). These Rossby waves propagate throughout the atmosphere and modulate global and regional circulation and precipitation (Donald et al., 2006; Jeong et al., 2008; Wheeler et al., 2009; Jones et al., 2011; Martin and Schumacher, 2011), including in Chile (Barrett et al., 2012a,b). Given the MJO's global influence, it is natural to expect it to have some effect on local-scale phenomena, including PM_{10} concentrations in Santiago, and the MJO has been found to modulate aerosols in other parts of the world (Tian et al., 2008, 2011). However, as yet, no studies exist that examine the effects of the large-scale MJO on local-scale PM_{10} in Santiago. Here, we focus on Santiago because of its unique combination of meteorology and topography leading to persistent, PM_{10}-driven poor air quality. Therefore, the objectives of this study are: (1) to determine the relationship between the MJO and levels of surface PM_{10} in Santiago, Chile during winter months; and (2) to connect observed variability in levels of PM_{10} to variability of meteorological conditions known to affect PM_{10} concentrations. The reminder of this paper is organized as follows: data and methodology are described in Section 2; intraseasonal variability of PM_{10} and meteorological factors affecting PM_{10} variability are described in Section 3; and discussions and conclusions are described in Section 4.

2. Data and methods

Hourly PM_{10} concentrations were examined at seven observing stations in the Santiago metropolitan region (Cerrillos, El Bosque, Independencia, La Florida, Las Condes, Parque O'Higgins, and Pudahuel) for the winter months of May–August from 2002 to 2012 (Fig. 1). Despite MJO activity tending to be weaker during Boreal summer (Madden and Julian, 1994; Salby and Hendon, 1994), this study only examined the months of May–August because surface PM_{10} concentrations in Santiago are much higher during local winter months than during the rest of the year. Although observations were available from 1997 to 2012, the data in this study were restricted to 2002–2012 to reduce the impact of the long-term decrease of PM_{10} that occurred from 1997 to 2001. Between 2002 and 2012, 98.4%–99.5% of hourly PM_{10} observations were available at each of the seven stations (Table 1). These data were available publically from the National Air Quality Administration System (SINCA by its Spanish acronym, http://sinca.conama.cl), operated by the Ministry of the Environment. Basin topography and the locations of each observing station are shown in Fig. 1, and a summary of each station's characteristics are presented in Table 1. MJO phase was determined by the Real-time Multivariate MJO Index (RMM; Wheeler and Hendon, 2004; hereafter WH04). The WH04 RMM is based off a pair of empirical orthogonal functions of near-equatorially averaged longwave radiation, 200 hPa zonal wind, and 850 hPa zonal wind, from which a principle component time series is derived. The projections of daily data onto the empirical orthogonal functions act as an effective time filter index useful in real-time settings (WH04). A through description of RMM Index and several examples showing how it can be used to

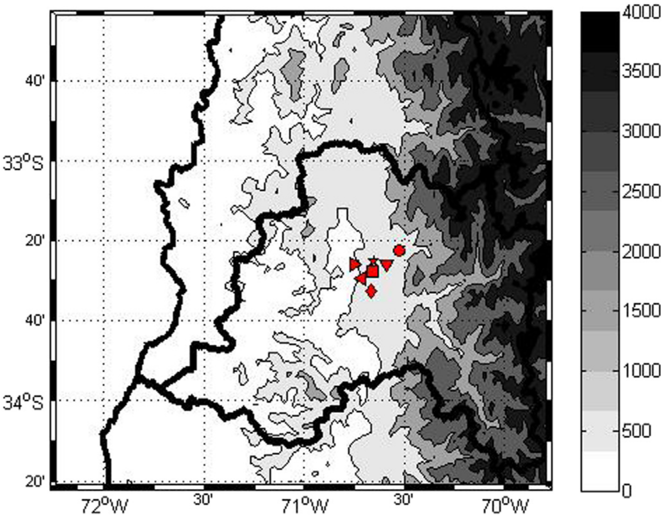

Fig. 1. Topography (shading, in m) and the SINCA PM_{10} observing stations (red symbols) for the Santiago metropolitan region. Political boundaries indicated by heavy black lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

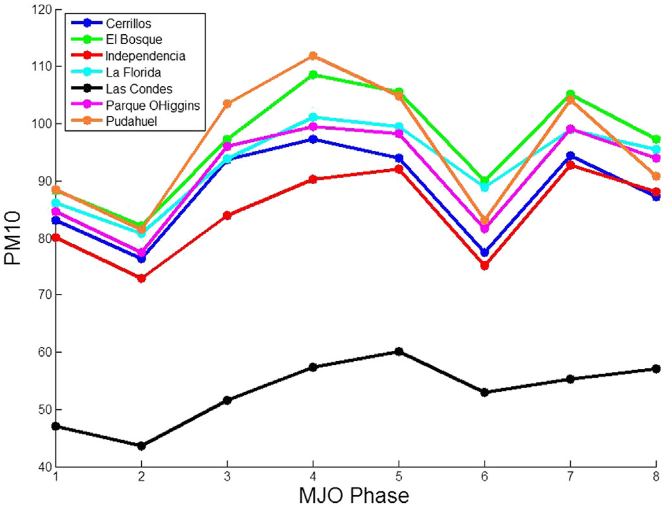

Fig. 2. Daily PM_{10} averages (μg m^{-3}), May–August 2002–2012 by MJO Phase.

diagnose MJO modulation of the atmosphere can be found in WH04, and the most current RMM Index can be found at (http://cawcr.gov.au/staff/mwheeler/maproom/RMM/). The MJO is divided into 8 phases, each corresponding to a broad location of the enhanced convection signal. An active MJO for this study was defined as one where the root sum of the two squared principles components, RMM1 and RMM2, were greater than one. After determining MJO phase from the RMM index, daily PM_{10} concentrations were then binned by phase. Hourly PM_{10} data were averaged to create daily PM_{10} concentrations, similar to the methodology of Gramsch et al. (2006).

To connect PM_{10} variability to the larger atmosphere, several meteorological data sets were examined. Sounding data for central Chile were taken from the NCEP Integrated Global Radiosonde Archive (IGRA); gridded upper-air data were taken from the ERA-Interim dataset (Berrisford et al., 2009); and daily precipitation was taken from the NCEP Global Summary of the Day (GSOD). Composite 0000 UTC and 1200 UTC vertical temperature profiles were created using the following methodology. First, data from both Quintero (1990–1998) and Santo Domingo (1998-present) (both radiosonde stations were approximately 150 km west of Santiago) were combined into one complete record from 1980 to 2011, as the move of the upper-air station in 1998 had minimal effect on the atmospheric profile (Falvey and Garreaud, 2007). Second, to capture the lowest part of the troposphere representative of Santiago itself, surface temperature observations from Pudahuel (station SCEL) were appended to the bottom of the coastal sounding profile. The Pudahuel observations were placed at 961 hPa, which was the mean station pressure at the Pudahuel site. Third, the irregularly vertically spaced observations from each radiosonde were linearly interpolated to every 1 hPa, from 961 hPa to 100 hPa (with the lowest few hundred hPa examined most closely for effects on inversion strength). Finally, the interpolated profiles were binned by phase of the MJO. Reanalysis geopotential height, temperature, and wind observations for central Chile and the adjacent Southeast Pacific were examined from 1980 to 2012. Anomalies of 0000 UTC geopotential heights at 500 hPa were calculated for each MJO Phase, and anomalies of 0600 UTC temperature and component u- and v- wind were calculated at 900 hPa for each MJO Phase. Winds above Santiago were interpolated from the nearby ERA-interim grid boxes, and winds were examined at 0600 UTC to capture any variability resembling the *Raco* wind phenomenon (Rutllant and Garreaud, 2004).

3. Results

3.1. PM_{10} variability

Winter PM_{10} concentrations at seven SINCA observing stations in Santiago were found to vary by phase of the MJO. Low daily average PM_{10} occurred during phases 1 and 2. High daily average PM_{10} occurred during phases 4, 5 and 7 (Fig. 2). This variability by MJO phase was found to project onto the well-known spatial distribution of PM_{10} in Santiago, whereby stations in the western and lower parts of the city (Pudahuel and El Bosque) had the highest

Table 1
SINCA measuring station characteristics. Symbol corresponding to Fig. 1 map, location of station, percentage of useful data from May–August 2002–2012, Latitude and Longitude and elevation.

Symbol (in Fig. 1)	Station name	Percentage of data available (%)	Latitude (decimal degree)	Longitude (decimal degree)	Elevation (m)
Triangle (left)	Cerrillos	98.4	−33.49	−70.71	511
Diamond	El Bosque	99.3	−33.54	−70.66	580
Pentagram	Independencia	99.1	−33.42	−70.65	560
Triangle (down)	La Flordia	99.5	−33.51	−70.59	599
Circle	Las Condes	99.2	−33.37	−70.52	799
Square	Parque O'Higgins	99.0	−33.46	−70.66	542
Triangle (right)	Pudahuel	99.1	−33.43	−70.75	495

mean PM_{10} levels that ranged from near 80 μg m^{-3} to near 110 μg m^{-3}, and the station in the eastern and upper part (Las Condes) had mean lower PM_{10} levels that ranged between about 40 and 60 μg m^{-3}. Despite these differences in concentration levels, daily mean concentrations at all seven stations were found to vary between 20 and 30% from lowest to highest MJO phases. In addition to daily variability, the diurnal cycle of PM_{10} was also found to vary by MJO phase (Fig. 3). Hourly PM_{10} was highest in phases 4, 5, and 7, and lowest in phases 2 and 6, in good agreement with daily variability (Fig. 2). At Cerrillos, the morning peak in concentrations ranged from 115 to 145 μg m^{-3}, and afternoon concentrations ranged from near 50–70 μg m^{-3}. Slightly higher values, but similar ranges, were found at Parque O'Higgins, consistent with its location in the center of Santiago, and lower values and ranges were found for Las Condes, consistent with its location in the elevated eastern part of Santiago (Fig. 3). In all phases at Cerrillos and Parque O'Higgins, the influences of daily rush hours were apparent: two peaks were visible, a morning and a late afternoon peak, with MJO modulating the severity of those peaks. At Las Condes, the morning peak was muted, in agreement with Gramsch et al. (2006), but the influence of the MJO was evident in the afternoon peak. Similar to mean daily variability (Fig. 2), hourly PM_{10} concentrations varied 20–30% between the minimum and maximum MJO phase, with the exception of Las Condes, where concentrations decreased as much as 50% between the highest and lowest MJO phase.

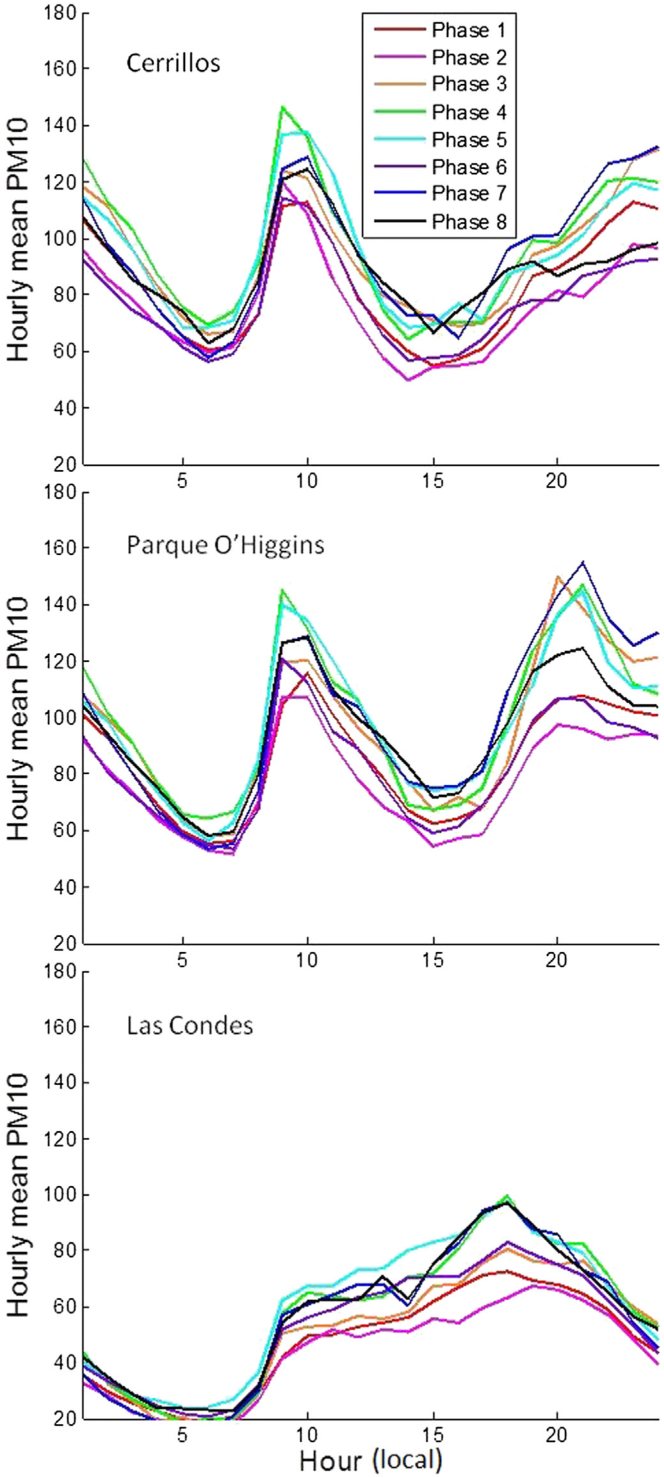

Fig. 3. Diurnal cycle of PM_{10} concentration (μg m^{-3}) by hour (local) at Cerrillos, Parque O'Higgins and Las Condes, May–August 2002–2012, by MJO Phase.

3.2. *Temperature, precipitation, and circulation variability*

To explain PM_{10} variability by phase of the MJO, first, profiles of temperature were examined. Strength of the morning temperature inversion (1200 UTC; 0800 local) was found to vary by phase of the MJO (Fig. 4), and the resulting variability agreed well with observed

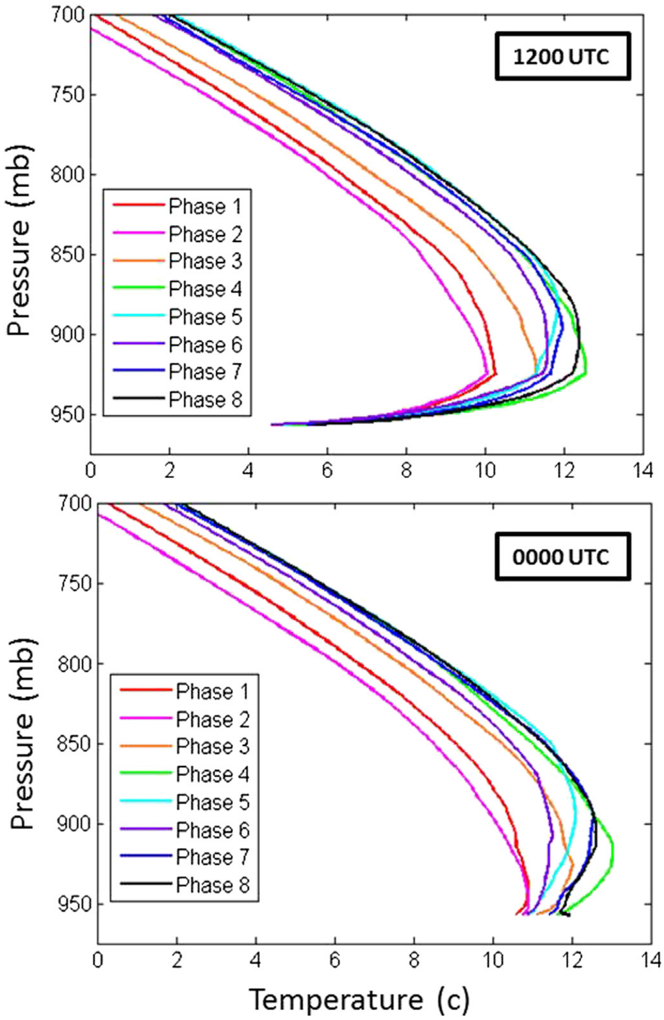

Fig. 4. Temperature (C) above Santiago at 1200 UTC (0800 local; top panel) and 0000 UTC (2000 local; bottom panel), May–August 1990–2011, by MJO Phase.

variability in PM_{10}. Surface inversions were strongest during phases 4, 6, 7 and 8, when PM_{10} concentrations were neutral to high. Weaker surface inversions occurred during phases 1 and 2, when PM_{10} concentrations were low. Temperature inversions were not as well developed at 0000 UTC (2000 local), but differences between MJO phases were still apparent: inversions were most pronounced during phases 4, 6, 7 and 8, and weak inversions were found during phases 1 and 2. These results, both in the morning and the afternoon, agreed well with the variability of both daily and hourly average PM_{10} concentrations by MJO phase. Physically, this agreed well with Préndez et al. (1991), who noted that stronger temperature inversions in Santiago resulted in enhanced static stability, which hampered the subsequent development of the mixed layer and led to higher surface PM_{10} levels.

Related to inversion strength, the MJO was also found to affect low-troposphere (900 hPa) temperature over a broader part of southern South America, including central Chile (Fig. 5). Below average 900-hPa temperatures were found during phases 1, 2, and 6, while above-normal temperatures were found during phase 4, 5, 7, and 8. Phase 3 was found to have neutral 900-hPa temperature anomalies. Phases with above-normal temperatures corresponded to those with above-normal levels of daily PM_{10} and higher spikes in the morning and evening levels of hourly PM_{10}, while phases with below-normal temperatures corresponded to those with below-normal levels of PM_{10}. Temperature anomalies in the reanalysis data at 900 hPa agreed well with temperature anomalies found in the observed upper-air profiles, whereby phases with above-normal 900-hPa temperatures had stronger morning temperature inversions, and phases with below-normal 900-hPa temperatures had weaker morning temperature inversions.

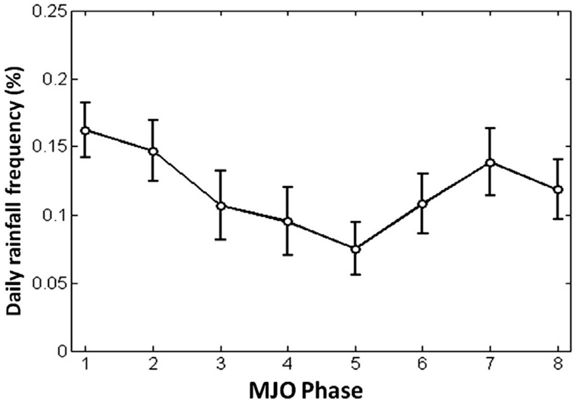

Fig. 6. Frequency of at least 1 mm of daily rainfall in Santiago, Chile by MJO Phase, May–August 1990–2012. Confidence intervals correspond to the 95% level.

In addition to temperature, variability in precipitation and circulation were also examined. At each phase of the MJO, PM_{10} concentrations were found to vary inversely with rainfall. Above-normal rainfall occurred during phases 1, 2 and 7, when PM_{10} was low, and below normal rainfall occurred during phases 3, 4, 5 and 6, when PM_{10} was normal to high (Fig. 6). Physically, this agreed with Gramsch et al. (2006), who noted that rainfall acted to remove PM_{10} from the atmosphere in Santiago, similar to the findings of Tian et al. (2008) and Tian et al. (2011) for MJO relationships between global rainfall and aerosols. Mid-tropospheric geopotential heights were also found to vary by phase of the MJO (Fig. 5), offering support to the variability in rainfall, as much of the

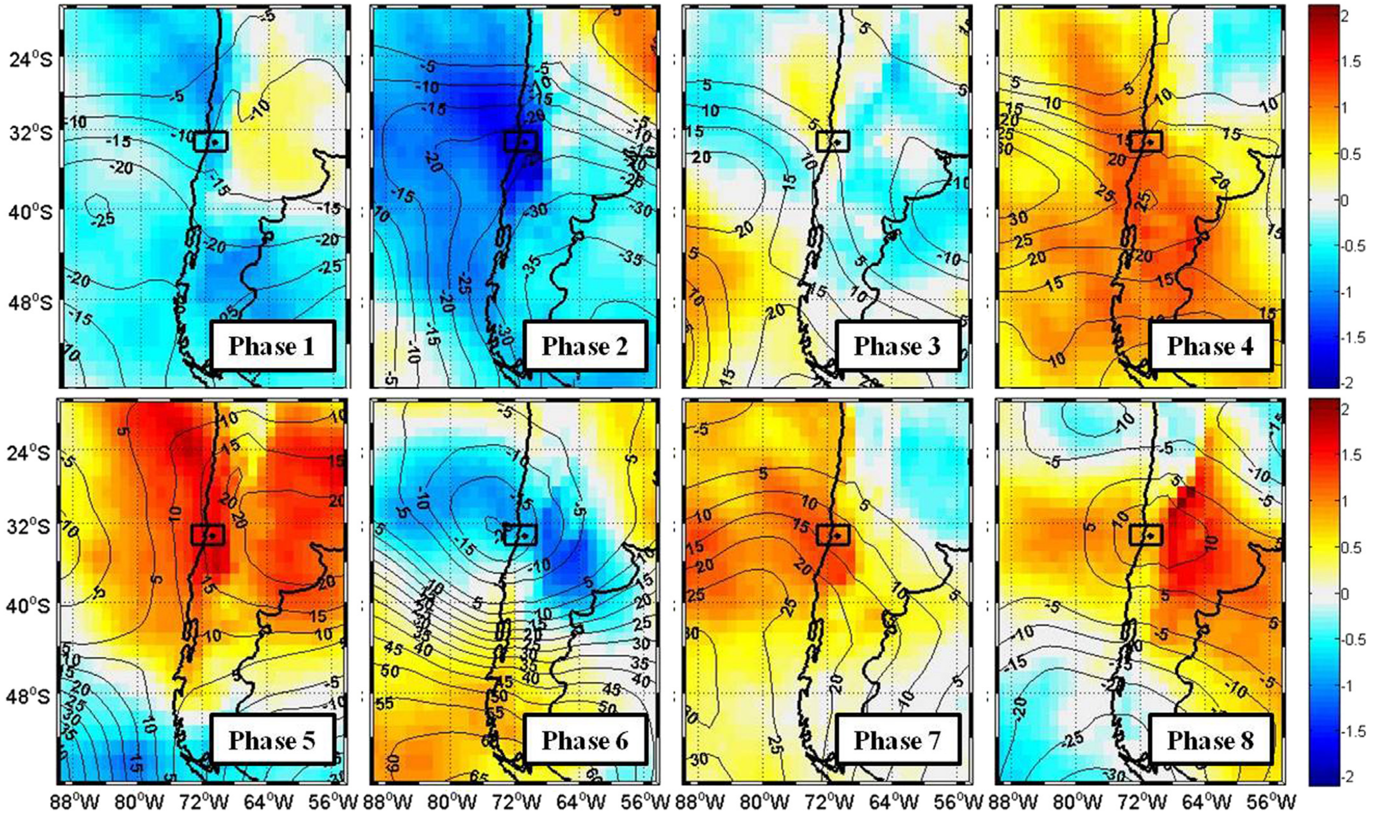

Fig. 5. Temperature anomalies (in C; color shading) at 900 hPa at 0600 UTC, and height anomalies (in m; solid contours) at 500 hPa at 0000 UTC, from May–August 1997–2012. Phase number is noted in the lower right, and the small box indicates the location of the Santiago metropolitan region (and corresponds to the area shown in Fig. 1).

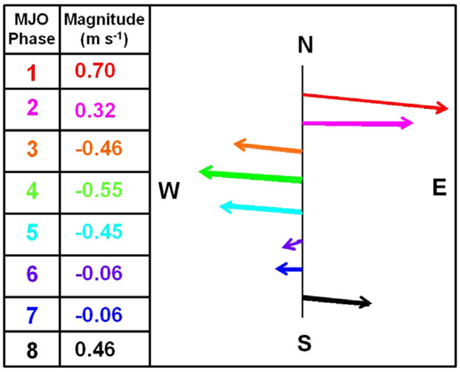

Fig. 7. Wind anomalies (in m s^{-1}) at 900 hPa at 0600 UTC in Santiago, Chile by MJO Phase, May–August 1997–2012, from ERA-interim reanalysis. Negative magnitudes correspond to easterly anomalies.

winter precipitation in Santiago is synoptically driven (Rutllant and Fuenzalida, 1991; Barrett et al., 2009; Garreaud et al., 2013). Below-normal geopotential heights in the southern cone of South America occurred during phases 1, 2 and 8, corresponding to the rainier phases, and above-normal heights above and to the west of central Chile occurred during phases 3, 4 and 5, corresponding to the drier phases. Below-normal heights to the south and southeast of the southern cone of South America occurred during phases 6 and 7, and rainfall in those phases was near-normal. This variability in 500-hPa circulation agreed very well with the larger-scale variability in atmospheric circulation associated with phases of the MJO found by Juliá et al. (2012) and Barrett et al. (2012a,b).

The final synoptically driven factor examined for relationship to MJO (and thus PM_{10}) was lower-tropospheric wind. Early morning (0600 UTC; 0200 local) horizontal winds at 900 hPa were found to vary by MJO phase. Easterly wind anomalies occurred during phases 1, 2 and 8, and westerly wind anomaly occurred during phases 3, 4, and 5 (Fig. 7). A weak easterly anomaly was also found to occur during Phases 6 and 7. The wind anomalies in phases 3, 4, 6, and 7 resembled those of *Raco* wind episodes, which, having been found to lead to elevated PM_{10} concentrations by Rutllant and Garreaud (2004), lent further support to the relationship between MJO and PM_{10}. More specifically, the wind, circulation, and temperature anomalies during phases 3, 4, and 7 resembled those of the “warm ridge” *Raco* events, where a warm ridge occurred west of the subtropical Andes (Fig. 5), preventing dispersion of accumulated particulate matter and leading to the high PM_{10} concentrations we observed (Figs. 2 and 3). Anomalies in phase 6 resembled those of the “cold trough” *Raco* event, where a surface mid-latitude low occurs to the west central Chile and a mid-troposphere cold trough occurred to the east (Fig. 5), in agreement with the near-normal levels of PM_{10} observed in this study.

4. Discussion

Here we have presented, for the first time, a statistical relationship between the planetary-scale MJO and local-scale PM_{10} concentrations for Santiago, Chile. The relationship was well supported by synoptic-scale weather conditions known to affect level of surface PM_{10}. The most significant support for the relationship was found between PM_{10} and rainfall, whereby PM_{10} was found to be above normal during phases of below-normal rainfall, and below normal during phases of above-normal rainfall. This result was not surprising, given that rain acts to cleanse the air as well as suppress potential lofted particulate matter such as dust. The relationship between rainfall and PM_{10} was further supported by large-scale circulation, whereby geopotential height at 500 hPa was below normal during rainy phases and above-normal during dry phases. Ranges in PM_{10} variability from lowest MJO phase to highest MJO phase were found to be between 20 and 30% for both daily and hourly PM_{10} at all stations except Las Condes, which had ranges up to 50%. This compared favorably to Tian et al. (2011), who found aerosol optical thickness (AOT) anomalies varied up to 20% of the AOT background mean, depending on MJO phase.

5. Conclusions

Surface PM_{10} concentrations in Santiago were found to vary by phase of the MJO. High PM_{10} concentrations occurred during phases 4, 5 and 7. Low concentrations of PM_{10} occurred during phases 1 and 2. Multiple atmospheric parameters were found supporting the observed PM_{10} variability. For example, during phases 1 and 2 (low PM_{10}), precipitation was above normal, morning and evening temperature inversions were less intense than normal, and 900 hPa winds were anomalously westerly. During phases 4, 5 and 7 (high PM_{10}), precipitation was normal to below normal, morning and evening temperature inversions were stronger than normal, and 900 hPa winds were anomalously easterly.

In conclusion, Santiago, Chile experiences dangerously high concentrations of PM_{10} during the winter months, and high concentrations of PM_{10} are a serious threat to human health. The relationships found here between PM_{10} and planetary-scale oscillations represent an important first step toward longer-range prediction of PM_{10}, particularly of poor air quality days, and especially as predictability of the MJO improves (Vitart et al., 2007). Future work to further refine these relationships will be valuable to policymakers in their efforts to predict and reduce the number of dangerous air quality days.

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