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Seasonality and mineral, chemical and optical properties of dust storms in the Sistan region of Iran, and their influence on human health

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DECLARATION:

I declare that the thesis that I hereby submit for the PhD degree in Geoinformatics at the University of Pretoria has not previously been submitted by me for degree purposed at any other university.

SIGNATURE……DATE…….

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Summary:

Atmospheric aerosols are suspensions of solid and/or liquid particles in the air from natural and anthropogenic sources. Aerosols are ubiquitous in the air and are often observable as dust, smoke and haze. Dust is considered to be one of the major components of tropospheric aerosols over the globe. Natural and human processes contribute to aerosol emissions. Each year, several billion tons of soil-dust is entrained into the atmosphere playing a vital role in solar irradiance attenuation, and affects marine environments, atmospheric dynamics and weather. Air pollution has recently become a serious environmental problem. Over recent years in the public health domain particulate matter (PM) concentration has become a topic of considerable importance, since epidemiological studies have shown that exposure to particulates with aerodynamic diameters of < 10 µm (PM_{10}) and especially < 2.5 µm ($PM_{2.5}$) induces an increase of lung cancer, morbidity and cardiopulmonary mortality.

Mineral dust plays an important role in the optical, physical and chemical processes in the atmosphere, while dust deposition adds exogenous mineral and organic material to terrestrial surfaces, having a significant impact on the Earth's ecosystems and biogeochemical cycles.

The role of dust aerosols in atmospheric processes, i.e. Earth's radiation balance, cloud microphysics, etc, strongly depends on a variety of physico-chemical parameters, size distribution, dust sources, atmospheric lifetime and mixing processes in the atmosphere.

Analysis of the physical properties and chemical composition of dust aerosols is important to determine aerosol sources, mixing processes, transport pathways and their effects on human health.

Atmospheric aerosols affect the global climatic system in many ways, i.e. by attenuating the solar radiation reaching the ground, modifying the solar spectrum, re-distributing the earth-atmosphere energy budget and influencing cloud microphysics and the hydrological cycle. Satellite remote for sensing provides an important observational means for monitoring dust production and for improving the understanding of the effects of regional-scale atmospheric processes on dust emission and transport.

The Sistan region is located in southeastern Iran, close to the Iranian borders with Pakistan and Afghanistan. The climate is arid, with low annual average precipitation of ~55 mm occurring mainly in the winter (December to February) and evaporation exceeding ~4000 mm.year^{-1}. During summer (June – September), the area is under the influence of a low pressure system attributed to the Indian thermal low that extends further to the west as a consequence of the south Asian monsoon system. These low pressure conditions are the trigger for the development of the Levar northerly wind, commonly known as the "120-day wind", causing frequent dust and sand storms and contributing to the deterioration of air quality. Therefore, one of the main factors affecting the weather conditions over the region is the strong winds rendering Sistan as one of the windiest deserts in the world. Severe droughts during the past decades, especially after 1999, have caused desiccation of the Hamoun lakes which is located in the northern part of Sistan, leaving a fine layer of sediment that is easily lifted by the wind, thus modifying the basin to one of the most active sources of dust in southwest Asia. The strong winds blow fine sand off the exposed Hamoun lake beds and deposit it to form huge dunes that may cover a hundred or more villages along the former lakeshore. Hamoun dry lake beds are mainly composed of quaternary lacustrine silt and clay material as well as Holocene fluvial sand, silt and clay. These materials have been carried to the basin by the rivers, while along their courses neogene fluvial sand, eolian sand, silt and clay are the main constituents.

This thesis analyses the aerosol characteristics, dust loading and air quality over the Sistan region based on first time measurements conducted. The dust loading was measured using dust traps near the Hamoun basin during the period August 2009 to July 2010. Dust loading from the Hamoun basin appears to have a significant contributing influence on the

development of extreme dust storms, especially during the summer days. This influence firstly seems to depend on the intensity and duration of dust storms, and secondarily, on the distance from the source region, the wind speed and altitude. The grain-size distribution of the dust loading is strongly influenced by the distance from the dust source. Furthermore, the particle size distribution exhibited a shift towards lower values as the altitude increases, with this feature found to be more obvious amongst larger sized particles, while the frequency of particles below 2.5 μm seemed not to be affected by altitude. In general, the analysis revealed significant spatio-temporal variability of regional dust loading and characteristics. This finding necessitates more systematic observations at as many locations as possible around the Hamoun basin in order to improve the understanding of force dynamics, transport mechanisms as well as to quantify the dust amounts emitted from the Hamoun basin.

To assess air quality characteristics in two cities of Zabol and Zahedan affected by the Sistan dust storms , systematic airborne PM concentrations were measured during the period September 2010 to September 2011 and July 2008 to March 2010, respectively. The results showed that the PM_{10} concentrations were considerably higher than the corresponding European Union air quality annual standard and the mean $PM_{2.5}$ concentration (32 μgm^{-3}) also overcame the Air Quality Index (AQI) annual $PM_{2.5}$ standards. This poor air quality is affected by dust storms from the Sistan desert. The drainage of the Hamoun wetlands, in association with the intense Levar winds in summer, is the main factor responsible for the frequent and massive dust storms over the Sistan region. Hamoun, as an intense dust source region, caused a dramatic increase in PM_{10} concentrations and a deterioration of air quality (65% of the days were considered unhealthy for sensitive people and 34.9% as hazardous) in Zabol city. The maximum PM_{10} concentrations occurred between 8:00 to 11:00 Local Sidereal Time (LST) in Zabol and between 12:00 and 20:00 LST in Zahedan, indicating that Sistan dust storms reach Zahedan after six to nine hours. The strong correlation between daily $PM_{2.5}$ and PM_{10} concentrations indicated that they have similar sources and an increase of PM_{10} significantly affects $PM_{2.5}$. Considering the air pollution standards defined by the United state Environmental Protection Agency (USEPA), determining that only on one day per year may the AQI be higher than 100 $\mu g.m^{-3}$, it was found that the values of AQI in Zahedan overcame this level for 86 days out of 399, expressing a fraction of 21.5%. It should be noted that on 25 days (6.3%) the atmospheric conditions were very unhealthy or hazardous for the whole population and this requires more attention by officials, managers and urban planners.

Windblown transport and deposition of dust is widely recognized as an important physical and chemical concern to climate, human health and ecosystems. To mitigate the impact of these phenomena, this thesis examines for the first time, the mineralogical and chemical properties of dust over Sistan by collecting aerosol and soil samples. These data were analyzed to investigate the chemical and mineralogical characteristics of dust, relevance of inferred sources and contributions to air pollution. Dust aerosol characterization included chemical analysis of major and trace elements by X-Ray Fluorescence (XRF) and mineral analysis by X-Ray Diffraction (XRD). The results showed that quartz, calcite, muscovite, plagioclase and chlorite are the main mineralogical components of the dust, in descending order, over Sistan, and were present in all the selected airborne dust samples. In contrast, significantly lower percentages for enstatite, halite, dolomite, microcline, gypsum, diopside, orthoclase and hornblende were found, since these elements occurred only in some of the samples. On the other hand, silicone dioxide (SiO_2), Calcium oxide (CaO), Aluminum oxide (Al_2O_3), Sodium oxide (Na_2O), Magnesium Oxide (MgO) and Iron (III) Oxide (Fe_2O_3) were the major elements characterising the dust, while large amounts of Fluorine (F), Chlorine (Cl) and Sulfur (S) were also found as trace elements. The mineralogy and chemical composition of airborne dust at both stations were nearly the same and quite similar to the soil samples collected at several locations downwind. This suggests that the dust over Sistan is locally emitted, i.e. from the Hamoun basin, and in a few cases can also be long-range transported to distant regions. On the other hand, individual dust storms showed significant differences between either evaporite-dominated aerosols or those characterized by deflation from alluvial silts. These possibly reflect either localized climatic cyclicity or desiccation cycles. However, in some cases the soil samples showed poor comparisons with aerosol compositions, suggesting that dynamic sorting, soil-forming processes and climatic influences, such as rainfall, altered the mineralogy and chemistry in these partially eolian deposits. Estimates of Enrichment Factors (EF) for all studied elements show that all of them have very low EF values, suggesting natural origin from local materials. The results suggest that a common dust source region can be inferred, which is the eroded sedimentary environment in the extensive Hamoun dry lakes. Scanning Electronic Microscope (SEM) analyses of the samples indicated that airborne dust has rounded irregular, prismatic and rhombic shapes, with only the finer particles and a few cases of the coarser dust being spherical.

Tis thesis analyses the aerosol patterns over the arid environment of Sistan region by means of multiple satellite platforms aiming to reveal the spatio-temporal and vertical

distribution of dust aerosols. The dataset used includes records of Aerosol Index (AI) from the Total Ozone Mapping Spectrometer (TOMS) on board the Nimbus-7 (1979–92) and the Earth Probe (mid-1996 to 2001) satellites and six-year AI records from OMI aboard Aura. Moreover, the Aerosol Optical Depth (AOD) is analyzed through 11-year records from Multi-angle Imaging SpectroRadiometer (MISR) aboard Terra (2000-2010) and from seven-year Deep Blue records from MODIS aboard Aqua (2002-2011). The main focus is to determine similarities and differences in dust climatology provided by these sensors over the Sistan region and surroundings. The results showed a marked seasonal cycle with high aerosol loading during summer and lower in winter, while MISR, MODIS Deep Blue and OMI climatologies agree in both terms of monthly and seasonally mean spatial and temporal aerosol patterns revealing similar seasonal behavior over the region. After prolonged drought conditions in 1999 at Hamoun lakes (northern of Sistan) the dust-aerosol load over the area has increased. The higher aerosol concentrations during summer are interpreted as a result of the Levar northerly winds and the drying of Hamoun lakes. The satellite monitoring highlights Sistan and Hamoun basin as major dust source regions in south Asia, spreading dust aerosols over Afghanistan, Pakistan and Arabian Sea.

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AERONET	Aerosol Robotic Network
AI	Aerosol Index
AIRS	Atmospheric Infrared Sounder
Al	Aluminum
Al_2O_3	Aluminum oxide
AOD	Aerosol Optical Depth
AQI	Air Quality Index
ARF	Aerosol Radiative Forcing
As	Arsenic
Ba	Barium
BSNE	Big Spring Number Eight
CALIPSO	Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observation
CaO	Calcium oxide
CCN	Cloud Condensation Nuclei
Cl	Chlorine
Co	Cobalt
COPD	Chronic Obstructive Pulmonary Diseases
Cr	Chrome
Cr_2O_3	Dichromium trioxide
Cs	Cesium
Cu	Copper
dp	Particle Size
d0.5	Median grain size
d0.9	90% of the grain size of particles is below this value
EARLINET	European Aerosol Research Lidar Network
EFs	Enrichment Factors
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency
EPMSP	Enhanced Particulate Matter Surveillance Program
EU	European Union
F	Fluorine
Fe	Iron
Fe_2O_3	Iron III Oxide
g	Asymmetry parameter
GDP	Gross domestic product
HAVA	Helmand-Arghandab Valley Authority
HIRDLS	High Resolution Dynamic Limb Sounder
HNLC	High-Nutrient, Low-Chlorophyll
ICZ	Intertropical Convergence Zone
IDDI	Infrared Difference Dust Index
K_2O	Potassium oxide
LST	Local Sidereal Time
LULC	Land Use Land Cover
MgO	Magnesium Oxide
MISR	Multi-angle Imaging Spectro-Radiometer
MnO	Manganese oxide

MODIS	Moderate Resolution Imaging Spectroradiometer
MWAC	Modified Wilson and Cooke
N7T	Nimbus 7
Na_2O	Sodium oxide
Na_3PO_412H2O	Tri-sodium orthophosphate
NaOH	sodium hydroxide
NASA	National Aeronautics and Space Administration
Ni	Nickel
NiO	Nickel Oxide
OMI	Ozone Monitoring Instrument
P_2O_5	Phosphorus pentoxide
Pb	lead
PM	Particulate matter
PM_{10}	Particulates with aerodynamic diameters of < 10 µm
ppm	Parts per million
r	Correlation coefficient
R^2	Determine coefficient
RH	Relative Humidity,
S	Sulfur
SEM	Scanning Electron Microscopy
Si	silicon
SiO_2	silicone dioxide
SSA	Single scattering albedo
SSDS	Siphon Sand and Dust Sampler
SUSTRA	SUspended Sediment TRAp
Tg	Million tons (Teragram)
TiO_2	Titanium dioxide
TOA	Top-Of-Atmosphere
TOMS	Total Ozone Mapping Spectrometer
U.S	United state
USEPA	United state Environmental Protection Agency
UV	UltraViolet
V_2O_5	vanadium pentoxide
WDFG	Wedge Dust Flux Gauge
WMO	World Meteorological Organization
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
Zn	Zinc
ZrO_2	Zirconium oxide