Morphological evolution in the migrating dune of Valdevaqueros (SW Spain) during an eleven-year period.

M. Navarro[1], J. J. Muñoz Pérez[1], J. Román[1], B. Tejedor[1], I. Rodríguez[2] and G. Gómez Pina[3].

[1]Applied Physics Dept. Sea Sciences Faculty. University of Cadiz. CASEM. Puerto Real (Cádiz) SPAIN.

[2]Rey Juan Carlos University. ESCET. Madrid, Spain.

[3]Demarcación de Costas Andalucía-Atlántico. Cádiz, Spain.

ABSTRACT

Located in Tarifa, near the Strait of Gibraltar, the migration of Valdevaqueros dune was controlled by sand extractions for building purpose. As the Spanish Shore Act was approved in 1988, the sale of sand was forbidden and the dune started to move forward, burying the leeward pine wood and the only road to Maspalomas village.
Consequently, six topographic levellings have been taken during the last eleven years. Sedimentary granulometries and meteorological features were taken into account. D_{50} values have been calculated for dune foot, windward and dune top. Wind speed threshold is estimated above 15 km/h. East winds are responsible for dune movement, whose advance rate has reached very high values (over 18 m/year). Slope and volumetric changes have been determined, providing a clearer explanation of the dune evolution.

KEY WORDS: Dune; evolution; advance rates; aeolic sand transport; meteorological conditions; Valdevaqueros; Spain.

INTRODUCTION

Many researches have been performed in the last decades about dunes' behaviour (Gares, 1966; Sharp et al, 1977; Avis, 1989; Siljestrom et al, 1990; Mountney et al, 2006; Levin et al, 2007) in order to reach its stabilization. This is the first step to manage a sustainable development in the dune ecosystem.
Despite that, there are some kinds of dunes characterized by their remarkable behaviour, as they make more difficult the monitoring process, having the particularity of being non-stabilizated dunes.
A vulnerability index (VI) was applied by Martinez et al, 2006, based on variables that described geomorphological condition, marine and aeolian influence, vegetation condition and human effects.
These sand mobile surfaces, that have an important extension and a constant windward slope, invade other ecosystems as brushwood, pinewood, wetlands, etc. (Cooper and Mclaughlin, 1998).
Valdevaqueros dune, does not follow the typical cyclic seasonal behaviour of this kind of ecosystems, whose function is to provide sand to the beach in stormy events (Gómez Pina et al, 2002). In this sense, it is considered to be a free migrating dune, with a special aeolic conditions that favour its growth and advance.
These special aeolic conditions could be the main reason why the evolution of this kind of dunes, as Valdevaqueros, has not been deeply studied until nowadays.
In the process of dune growing, wind plays a very important role, as aeolic sand transport begins once the wind exceeds the threshold velocity (Dingler et al, 1992). It is known that the development of these aeolian forms relies on sediment type, the nature of the sediment supply, the presence of winds above the sediment entrainment threshold and vegetation capable of initial stabilization (Carter, 1995).
In the Doñana Nacional Park there are several parallel dunes, with similar orographic and dynamic characteristics to Valdevaqueros (Ramírez Díaz and Torres Martínez., 1977). In this case, dunes are separated by pine rows that have been buried by the dune advance. Despite that, they return to grow in an approximated cycle of several years.
Nevertheless, in Valdevaqueros dune, the cyclic advance is been stopped by the presence of foothills.
The aim of this paper is, therefore, to determine a joint of parameters that allow to know the behaviour of this sort of dunes.

STUDY AREA

Valdevaqueros dune has 1500 m of extension and it is located in Tarifa (36ºN 5ºW), in the Province of Cadiz, near the Strait of Gibraltar, facing the Atlantic Ocean, on the SW coast of Spain (Fig. 1).
The littoral of Cadiz (SW of Spain) is characterized to have a dominant swell that comes from the west and south-west towards the coast. Therefore, the net submerged sediment transport is generally driven towards the SE.
The littoral fringe has a meso-microtidal environment, with mean tidal levels from 0.05 m in low tide to 1.5 m

elevation respect the datum lowest low waterlevel.

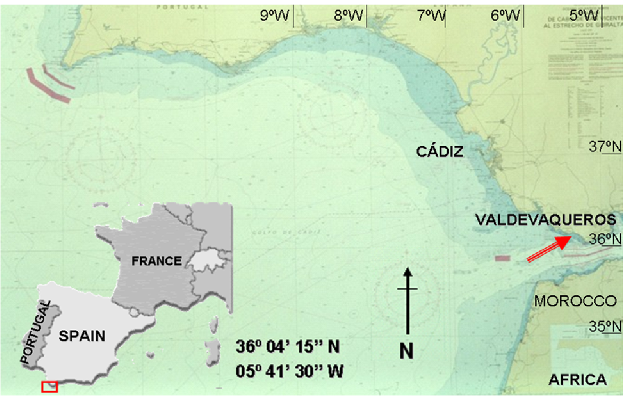

Fig 1. Location of Valdevaqueros dune, Cadiz, Spain.

All the study area is affected by West winds, associated to Atlantic Ocean cold fronts and strong East winds. Wind mean speed is 3.42 m/s (12.3 km/h), despite some gusts can reach more than 100 km/h (Gómez Pina et al, 2002).
Along this coast, several important tectonic processes throughout the history, as transversal faults have also taken place. These structures have changed the littoral morphology, giving to the coast a stepping shape in all the Atlantic Ocean side. This feature combined with the strong eastern winds in this part of the littoral, creates sand accumulative zones in several points of the coast, as the beaches and dunes of Valdevaqueros, Bolonia and Caños de Meca, in the SW Spain. A view of Valdevaqueros dune and beach can be seen in Fig. 2.


Fig 2. Panorama of Valdevaqueros dune and beach.

Beach sand comes from the net addition of the different littoral transports originated by the western and southern storms.
Nevertheless, only eastern winds are the responsible of aeolian sand transport from the beach towards the dune top, creating a free migrating dune. It must be highlighted that each beach has a different aeolian sand transport potential, depending on local beach/dune morphology, wind patterns and surface characteristics (Gomes, 2002).
The origin of Valdevaqueros dune was, at first, natural, of the quaternary period, but historic uses and activities on the dune provoked an unbalanced profile. Until 1988, sand extractions were carried out for housing building use, but since Spanish Shore Act approbation, this practice has been prohibited and the dune has increased its advance, covering the adjacent pine groves, telephonic cables and even the only road that drives to a little village (Mas Palomas). Throughout the history, Mas Palomas road has had to be moved landwards in several occasions.
In Fig. 3 a perspective of the dune invading the road is shown. This situation is mainly due to the lack of vegetation cover, as local supply of sand available for dune migration is reduced at a rate inversely proportional to the rate of vegetation encroachment (Hugenholtz and Wolfe, 2004). Although Coastal Department is carrying out sand by-passes and several soft techniques as wooden fences, *Ammophila arenaria* sowing and avoiding human trampling, dune stabilization has not been reached. Ruz et al (2005) emphatised the importance of human intervention in dune rehabilitation.

Fig 3. Perspective of Valdevaqueros dune invading the road.

In the 30's, there was already a significant sand accumulation on the back-shore of Valdevaqueros beach. Due to the building of military cannon batteries in Punta Paloma, several obstacles were placed over the dune, which began to show a gradually growth. The aim of this action was to stop the sand movement towards those military batteries, cutting the sand supply that fed a mobile dune field located in San Bartolomé hillside, which was not covered by vegetation at that time.
Since the 40's, Valdevaqueros dune has experienced different activities, as the settle of pentagonal concrete structures of 1 m of height (Román et al., 2004).
Later, on the 60's these systems were replaced by stem

fences to decrease the aeolic sand transport capacity. In this case, accumulation took place on leeward. After each strong storm, fences were returned to its place, as they became practically buried by the wind action. Subsequently, weaker and wooden fences were located, with different capacity to retain sediments. It must be highlighted the continuous sand extractions performed by particulars until 1988, for building purpose, whose intervention reduced the dune volume, and therefore, the dune advance.
After 1988, several sand by-passes have been carried out by the Ministry of Environment to avoid the road cover. It must be taken into account that the road has been removed in several occasions due to the invasion of the dune along the history.
Furthermore, different "soft techniques" have been applied over the dune to control its movement. These soft techniques consist in the settle of wooden fences, *Ammophila arenaria* sowing and avoiding human trampling. The last plantations that were carried out in 2004 (Román et al, 2004) increased dune top elevation, producing a sharper slope. Despite this, the destabilization of the sand mass continues to be a problem.

METHODOLOGY

In order to study the long-term behaviour of the dune, topographic levellings were performed with a total station placed on each profile head, measuring the dune width in the cross-dune direction, from 1995 to 2006. Each campaign contains the same five profiles taken from West to East, placed on the most representative areas of the dune growth. Profile heads were emplaced on the slope foot oriented leeward (fig 4).

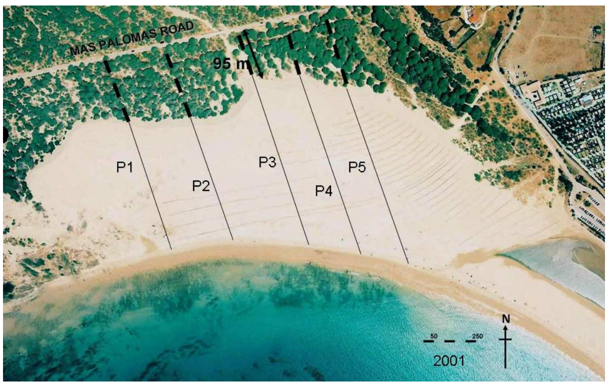

Fig 4. Schematic representation of dune collected profiles.

These profiles were taken successively in each campaign, maintaining the same head profile position. The base of the total station was always placed on the same point at the beach parking.

Aerial photographs from 1956 to 2006 have been collected to determine the distance from the dune foot to the road in a preliminary way, in order to calculate the relative dune advance rates. The slip face (front dune) can be manually identified either by the shaded areas or by the area at the foot of the dune where vegetation begins (Levin and Ben-Dor, 2003).
Meteorological data as wind direction and velocity, temperature, humidity and rainfall during the study period were requested to the nearest meteorological station, located in Tarifa.
In order to obtain a first relationship between the sediment transport and the wind celerity, a sand trap was located on the dune top. The sediment trap has got 50 cm of height and it is divided into five hollows of 20x10 cm. The structure allows determining aeolic sediment transport according to the height from the dune base. Punctual wind data were measured in situ in each height to identify wind shear velocity. Furthermore, sand sampling was carried out in different points of the beach and dune, to analyze the granulometric sediment distribution.

RESULTS AND DISCUSSION

According to Anthony et al (2006) a threshold of wind velocity above 8 m/s (28,8 km/h) is considered a reasonable limit above which significant aeolian transport may occur, given the humidity of roughness constraints in the study sites (humid upper beach, semi-vegetated hummocky dune topography). In Valdevaqueros dune, wind speed threshold is around 15 km/h during dry periods. Qiu et al (2004) demonstrated that almost 100% of the sand grains were distributed in the range of 0-10 cm, showing clearly that sand flux occurs within 10 cm of the ground surface.
The advance rate of sand dunes can be measured by locating the front of the dune at successive times (Levin and Ben-Dor, 2003). A representation of the distance from the dune to the road as well as advance rates is shown in fig 5.

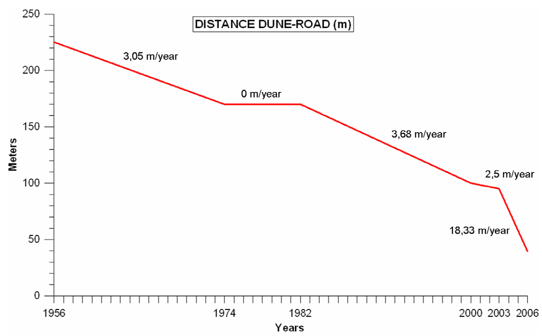

Fig 5. Representation of the distance from the dune to Mas Palomas road from 1956 to 2006.

An important decrease of the distance is especially identified during the last twenty-four years. The advance rate between 1956 and 1974 was around 3 m/year, becoming much more pronounced during the last 3 years of the study period (18,33 m/year).
Pluviometry data, celerity and wind direction data have been collected as well as relative air humidity and granulometry. All these features also condition the different shape of the dune.
Wind data have been represented per year through a wind rose. In fig 6 representative windy conditions of a study year are shown. It can be observed how aeolic directions appear only in the second and third quadrant. According to Hugenholtz and Wolfe (2004), aeolian activity is likely to be most pronounced in winter and spring, and generally at a minimum during July and August. However, in the proximities of the Strait of Gibraltar, East and South-East winds, responsible for the dune movement, are generally stronger than West and South-West winds.

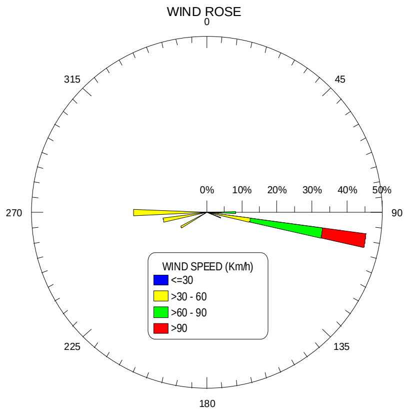

Fig 6. Wind rose during a representative whole year at the study area.

Relative humidity has been analyzed per year and per month. From 1995 to 2000, relative average humidity was around 73% in nearly all cases, except in 1996, that was a special wet year. From 1995 to 2003 several years have been especially rainy, as 1996, 1997, 2002 and 2003.
In the study area, summer months are typically dry, while November, December and January are usually wetter. Humidity conditions together with rainfall are also responsible for dune movement decrease, due to grains cohesion. Nevertheless, rainfall or the rain efficiency is not as decisive a factor in dune stabilization and mobilization as it is customary to believe (Tsoar, 2005).
These cyclic meteorological conditions have a great influence on the dune movement. During dry periods, when average humidity is around 72% together with a lack of precipitation events, dune advance is increased. In spring months this situation is combined with the fact that East winds are generally stronger.
A preliminary appreciation of the dune profiles changes has been determined. Profiles 1 and 2 show a stronger migrating behaviour, while profiles 4 and 5 are decreasing their relative volume. The main reason is the presence of a twist in the orientation of the dune advance, increasing advance rates in profile 1 and 2 and reducing this behaviour in profile 4 and 5. It must be taken into account that an aeolic erosion process is produced in the southern part of the dune. This feature and the estuarine effect of a little river (Valle River), generates a littoral lagoon that invades part of the beach surface.
On the other side, profile 3 is maintaining its relative volume as it is the central profile. For that reason, it is considered to be the most representative of all the levellings. Therefore, profile 3 will be analyzed in particular in this paper. A representation of profile 3 changes during the study period is shown in Fig. 7.

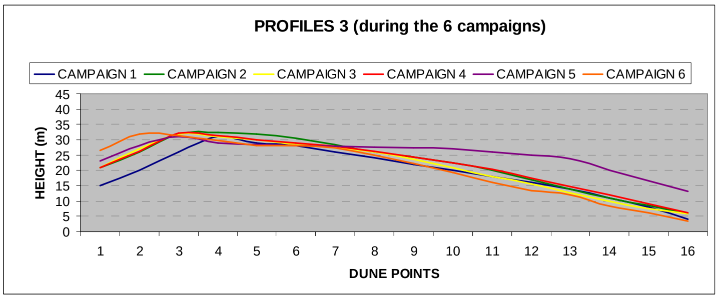

Fig 7. Representation of profile 3 changes during the study period.

A first appreciation confirm that this profile has experienced an important variability, as the slopes are very similar between campaigns, except in campaign 5, where sand has been distributed on windward side.
Slope and elevation data for profile 3 between all the campaigns are shown in table 1.
Windward slope is approximately 20% in all the study period, while leeward slope is near 55%. Campaign 5 changed its profile shape thanks to soft techniques, increasing the central part of the dune. In this case, leeward and windward slopes became softer (40% and 17,33% respectively).
Despite this, slopes and dune top elevation are very similar and do not show important changes during all the period.
Relative volume changes are represented between each campaign are shown in table 2.

Table 1. Slope and elevation data at different parts of the dune.

	PROFILE 3	CAMPAIGN 1 jun-95	CAMPAIGN 2 may-99	CAMPAIGN 3 nov-99	CAMPAIGN 4 jun-00	CAMPAIGN 5 feb-03	CAMPAIGN 6 may-06
SLOPE	Windward slope %	22,5	20	20	20	17,33	20,21
	Leeward slope %	53,33	55	55	56,25	40	55
	Dune top elevation (m)	31	32	32	32,25	31	31,9

Table 2. Accretion and erosion rates between the different campaigns.

		Accretion volume (m3/ml)	Erosion volume (m3/ml)	Net volume (m3/ml)	Volumetric rate (m3/ml/year)	Sand by-passes (m3)
CAMPAIGN 1-2	Jun95-May99	40	0	40	10	27.000
CAMPAIGN 2-3	May99-Nov99	1	-16	-15	-30	85.400
CAMPAIGN 3-4	Nov99-Jun00	14	-0,7	13,3	26,6	84.000
CAMPAIGN 4-5	Jun00-Feb03	56,95	-6	50,95	19,60	166.700
CAMPAIGN 5-6	Feb03-May06	8,6	-80,8	-72,2	-21,88	62.600

Notice that between second and third campaign as well as during the last three years of the study period, profile 3 has presented an important erosion rate (-30 m3/ml/year and -21,88 m^3/ml/year respectively), probably due to the horizontal sand distribution through the pine grove.

Different volumetric events are represented in Fig. 8, as sand by-passes, accretion and erosion processes and volumetric rates for profile 3 during all the study period.

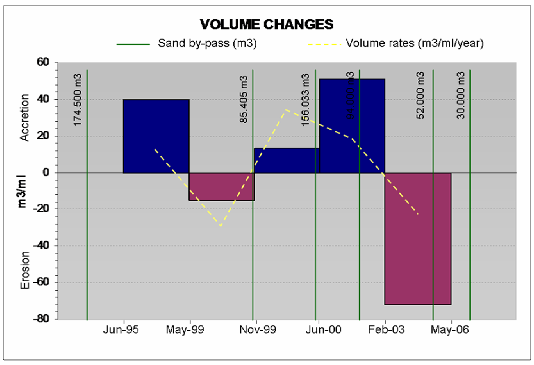

Fig 8. Volumetric processes occurred on profile 3 during the study period.

More than 455.000 m^3 of sand have been moved from the dune in the last 11 years. Between campaign 5 and 6 different slopes can be observed due to several sand by-passes carried out six months before campaign 6.

Granulometric analysis has been also carried out on different representative points of the beach and dune ecosystem.

It should be taken into account that leeward sediment comes from the dune top, therefore, granulometry is very similar in those points. On dune top and leeward side, sand size is around 0,28 mm, while on windward side and dune foot grain size is generally coarser, 0,33 mm and 0,38 mm, respectively.

CONCLUSIONS

The main purpose of dune stabilization is to manage a sustainable development, avoiding the progressive invasion of Valdevaqueros dune towards the adjacent pine grove and Mas Palomas road. The knowledge of dune behaviour during the last decade provides a useful tool to prevent future risk situations.

Field investigations determine that dune sand grains start to move once wind speed is above 15 km/h, being the mean diameter around 0,3 mm, although this process occurs mainly within the height of 10 cm from the dune surface.

In this case, East and South-East winds are responsible for the dune movement creating advance rates that range from 3 m/year between 1956 and 1974 to 18,33 m/year nowadays. Aeolic events create a sediment transport in the E-W direction. This produces a different behaviour on the dune profiles. Thanks to the dune monitoring based on the topographic levellings, a preliminary appreciation of the dune evolution has been determined. While profiles 4 and 5 are loosing sand volume, profiles 1 and 2 are increasing their growth.

Meteorological conditions make dune advance seasonally dependent. East winds together with low rainfall and humidity values favour volume accretion.

Slope and volume changes are often generated by anthropic activities, as soft techniques and sand by-passes. Important erosion rates were detected between campaigns 2 and 3 (-30 m^3/ml/year) and from 2003 to 2006 (-21,88 m^3/ml/year). Slope changes were more evident during campaign 5 due to human intervention. Leeward and windward slopes decreased until 40% and 17,33%, respectively. Wooden fences settle and *Ammophila arenaria* sowing help to increase dune slope percentage, and therefore, dune top elevation.

ACKNOWLEDGMENTS

This research was partially funded by the Spanish Ministry of Education, under CGL2005-04189.

REFERENCES

Anthony, E.J., Vanhee, S. and Ruz, M.H. (2006). "Short-term beach-dune sand budgets on the north sea coast of France: Sand supply from shoreface to dunes, and the role of wind and fetch". *Geomorphology*, 81 (3-4): 316-329.

Avis, A.M. (1989). "A review of coastal dune stabilization in the Cape Province of South Africa". *Landscape & Urban Planning,* 18 (1): 55-68.

Carter, R.W.G. (1995). "Coastal environments: An introduction to the physical, ecological and cultural systems of coastlines". *5th edn. London: Academic Press ltd,* 617 pp.

Cooper, J.A.G. and Mclaughlin, S. (1998). "Contemporary multidisciplinary approaches to coastal classification and environmental risk analysis". *J. of Coastal Research*, 14 (2),512-524.

Dingler, J.R., Hsu, S.A. and Reiss, T.E. (1992). "Theoretical and measured aeolian sand transport on a barrier island, Lousiana, USA". *Sedimentology,* 39, 1031-1043.

Gares, P.A. (1966). "Beach/dune changes on natural and developed coasts". *Coastal Zone '83 proc. Third symp. on Coastal and Ocean Management. Am. Soc. Civ. Engrs,* session 27, 1178-1194.

Gomes, N., Domingos, J., Jardim, N. and Santos, R., (2002). "Wind distribution over beach/dune surface: Improving aeolian sand transport estimation". *Journal of Coastal Research,* SI 36, 317-324.

Gómez-Pina, G., Muñoz-Pérez, J.J., Ramírez, J.L. and Ley, C. (2002). "Sand dune management problems and techniques, Spain". *Journal of Coastal Research*, SI 36: 325-332 *(ICS 2002 Proceedings) Northern Ireland.*

Hugenholtz, C.H. and Wolfe, S.A. (2004). "Recent stabilization of active sand dunes on the Canadian prairies and relation to recent climate variations". *Geomorphology,* 68, 131-147.

Levin, N. and Ben-Dor, E. (2003). "Monitoring sand dune stabilization along the coastal dunes of Ashdod-Nizanim, Israel, 1945-1999". *Journal of Arid Environments,* 58 (3): 335-355.

Levin, N., Kidron, G.J. and Ben-Dor, E. (2007). "Surface properties of stabilizing coastal dunes: Combining spectral and field analyses". *Sedimentology*, 54 (4): 771-788.

Martinez, M.L., Gallego-Fernández, J.B., García-Franco, J.G., Moctezuma, C. and Jiménez, C.D. (2006). "Assessment of coastal dune vulnerability to natural and anthropogenic disturbances along the Gulf of Mexico". *Environmental Conservation*, 33(2):109-117.

Mountney, N.P. and Russel, A.J. (2006). "Coastal Aeolian dune development, Sólheimasandur, southern Iceland". *Sedimentary Geology,* 192 (3-4): 167-181.

Qiu, G.Y., Lee, I.B., Shimizu, H., Gao, Y. and Ding, G., (2003). "Principles of sand dune fixation with straw checkerboard technology and its effects on the environment". *Journal of Arid Environments*, 56 (3), 449-464.

Ramírez Díaz, L. and Torres Martínez, A. (1977). "Tipología y dinámica de los complejos ambientales del sistema de dunas móviles de la reserva biológica de Doñana". *Boletín de la Estación Central de Ecología.* Vol. 6, 3-11.

Román Sierra, J., Navarro Pons, M., Muñoz-Pérez, J.J., Gómez Pina, G. and Fages Antiñolo, L. (2004). "Ecosistemas dunares en la provincia de Cádiz. Estabilizaciones en Bolonia y Valdevaqueros, T.M. Tarifa". *Revista de Obras Públicas*, 3.450, 65-76.

Ruz, M.H., Anthony, E.J. and Faucon L. (2005). "Coastal dune evolution on a shoreline subject to strong human pressure: the Dunkerque area, northern France". *Dunes and Estuaries 2005, Proceedings of the International Conference on Nature Restoration Practices in European Coastal Habitats,* 441–449.

Sharp, W.C. and Hawk, V.B. (1977). "Establishment of woody plants for secondary and tertiary dune stabilization". *International Journal of Biometeorology,* 21 (3) : 245-255.

Siljestrom, P.A. and Clemente, L.E. (1990). "Geomorphology and soil evolution of a moving dune system in southwest Spain (Doñana National Park)". *Journal of Arid Environments,* 18 (2): 139-150.

Tsoar, H. (2005). Sand dunes mobility and stability in relation to climate. *Physica A: Statistical Mechanics and its Applications,* 357 (1), 50-56.