

Future increase in extreme El Nino events under greenhouse warming increases Zika virus incidence in south America

V. Brahmananda Rao¹, K. Maneesha², Panangipalli Sravya³, Sergio H. Franchito¹, Hariprasad Dasari⁴ and Manoel A. Gan¹

1. Instituto Nacional de Pesquisas Espaciais, INPE

C.P. 515, 12245-970, São José dos Campos, SP, Brazil

2. CSIR -National Institute of Oceanography - Regional Centre
Visakhapatnam, India

3. CSIR - CCMB, Hyderabad, India

4. Division of Physical Sciences and Engineering, King Abdulla
University of Science and Technology, Tuwal, Saudi Arabia

Abstract:

The Zika virus (ZIKV) was first found in Zika forest, Uganda in 1947¹. This disease is caused by flavivirus, isolated for the first time in 1947 from the blood of a sentinel rhesus monkey (*Macaca mulatta*) in the Zika forest. Later, from 2007 to 2015 it spread across the pacific to America. The disease appeared in Americas in May 2015 in Northeast Brazil². In most of the reported cases, the disease was associated with microcephaly and other birth defects. ZIKV propagated rapidly across the Americas and the World Health Organization (WHO) in February 2016 declared this as a public health emergency of international concern³. The temperature conditions related to extreme El Niño of 2015-16 were exceptionally favorable for ZIKV spreading in South America⁴. The infection had further spread to several other countries becoming pandemic. In March 2016, the WHO reported that ZIKV was circulating in 38 countries and territories³. For the recent spreading of ZIKV, in Americas, Northeast Brazil was the starting point and it was associated with the extreme El Niño 2015-16. Paz and Semenza⁵ found that there is a striking overlap when the regions with extreme climatic conditions in one month are juxtaposed with the geographic distribution of ZIKV in subsequent months. They found that the unique climatic conditions generated by extreme El Niño event of 2015-16 are congenial for the dispersal of ZIKV in the Americas. This not a just coincidence and many authors^{6, 7, 8, 9} noted that ZIKV vector *Aedes aegypti* is strongly dependent on surface climate conditions that occur during extreme El Niño events. Further, recently a team of researchers¹⁰ found that extreme El Niño events will double in future in response to green house warming. Also it was discovered¹¹ that the increase of extreme El Niño frequency will continue long after 1.5°C warming stabilization. Here we analyze future extreme El Niño events and associated surface temperature. Vectorial capacity gives vectors propensity to transmit ZIKAV taking into account human, virus and vector interactions. We calculated the ZIKAV quantitatively in future extreme El Niño and found that large parts of South America are highly favorable for the spread of the disease.

Introduction

The extreme El Niño events such as those in 1982-83, 1997-98 and 2015-16 were responsible for several natural disasters. The anomalous climatic conditions caused worldwide environmental disruptions including in South America (SA). In SA, Amazon and Northeast Brazil experienced severe droughts and catastrophic floods occurred in Peru¹². For example 1997-98 extreme event alone caused worldwide US\$ 36 billion in damage and an estimated 22,000 people died^{12, 13}. In addition to severe changes in climate, the El Niños alter the ecosystems, disrupt agriculture, cause hurricanes and favoring simultaneously the breeding of disease spreading vectors Zika, Dengue and Malaria. The study of Hopp and Foley¹⁴ finds that strong interannual variations in climate significantly affect disease vector ecology. They presented a modeling analysis showing, on a global scale, connections between climate and the development, potential distribution and population dynamics of *Aedes aegypti*, the principle vector of Zika. The authors found good agreement between the observed and modeled global distribution of mosquito.

Examining the impact of climate variability on disease intensity is vital especially in regions where the disease is already a global pandemic. Malaria epidemics in African highlands cause high mortality and are strongly related to the climate associated with El Niño events. For example Malaria epidemic in a high land region off South west Uganda in 1998 was associated with the extreme El Niño event of 1997-1998²⁸. El Niño events cause the Dengue epidemics in many tropical countries. It was found³⁴ that there is a statistically significant correlation between El Niño and Dengue epidemic in French Guiana and Indonesia. Also, studies of malaria have revealed large occurrences on the Indian subcontinent³⁸, in Colombia³⁷, Venezuela^{37,35} and Uganda³⁶ during El Niño events.

The vectors of Zika virus, *Aedes aegypti* have established temperature thresholds of survival and these temperature dependent variations regulate their population. Provided sufficient moisture and warmer temperatures, within the survival ranges, exist mosquito activity increases and decrease the EIP (Extrinsic incubation period) or duration of sporogony²¹. Peridomestic (living in and around human dwelling) day-biting mosquito's, *Aedes aegypti* feeds preferentially on human blood. The mosquito development and survival strongly depends on temperature²². Further, during warmer months the mosquito's latitudinal range increases as does the density. In addition to temperature, rainfall variations also effect Zika virus breeding. When the rainfall is high the breeding capacity of the mosquito increases because of water logging in ponds, even in dry season during El Niño event over North and South America the stored water for household purposes may also breed mosquitoes.

In view of the highly devastating impacts associated with extreme El Niño events it is necessary to find out whether green house warming will affect the frequency of extreme El Niño events. In a recent work¹¹ it was found that the extreme El Niño events will double in future. Here we define the extreme events when the Niño 3.4 SST is greater or equal 2°C. This criterion was used by others¹⁵ and reproduces correctly the previous El Niño events including the extreme events of 1982-83, 1997-98 and 2015-16.

Results and discussions : Future SST (sea surface temperature) variations over Niño 3.4 have been extracted from CMIP5¹⁶ models. In a study of CMIP5 models, Weare³² found that in 20 models, nearly in all the models, surface temperatures, precipitation and 250hPa geopotential height departures in the tropics are in good agreement with observations. Overall recent versions of earlier models improved in their ability to simulate El Niño teleconnections. The CMIP5 16 models are forced with historical anthropogenic and natural forcings and future greenhouse gas emission scenarios of Special Report on Emission Scenarios (SRES A2) and Representative Concentration Pathway (RCP 8.5) respectively, each covering a 200 year period i.e from 2000-2200. The available models for the selected study period (2070-2100) are: 1. GFDL-CM3_rli1p1_1, 2. GISS-E 2-H_rli1p1_1, 3. GISS-E2-R_rli1p1_1, 4. IPSL-CM5A-LR_rli1_1, 5. MPI-ESM-LR_rli1_1, 6.

NorESM1-M_rli1_1. Of these models, two (1 &4) are in the selected list of models by Weller t.al.³³ which can successfully simulate their criteria of extreme El Niño events. Ocean Niño index for the Niño 3.4 region has been computed during 2070-2100 by centered 30-year base periods updated every 5 years according to CPC (Climate Prediction Centre) (<http://origin.cpc.ncep.noaa.gov>). Different extreme El Niño years have been identified from different models (Fig. 1). Surface (2m) air temperature data from the corresponding models have been taken for the selected years over SA. All the model's data are available with a resolution less than 2°. We noted 6 extreme El Niño years: 2074-75, 77, 81, 83, 85 and 99. Since the ZIKV breeds preferentially in austral summer we take January month representing austral summer.

The mean surface (2m) air temperature data for the period 1981-2010 in °C in figure 2 have been taken from NCEP2¹⁷. This figure can be compared with that from Collins et al¹⁸ for the period 1976-2007, December, January and February. The general features seem to agree well, the minimum temperature of 21°C between Minas Gerais and São Paulo States, a high temperature zone of around 25°C in Amazon State and a high temperature zone of 29°C on the lee side of Andes Mountains.

Surface air temperature anomalies for the 6 extreme El Ninos: 2075, 2077, 2081, 2083, 2085 and 2099 are respectively shown in Fig.3(a,b,c,d,e,f). The general pattern of anomalies in surface air temperature over SA is very similar in all figures, giving confidence to the results from the CMIP5 models. In all the extreme El Niño years the anomalies are positive over the entire SA. There is a region of high positive anomalies in Bahia and northern Minas Gerais States in Brazil with maximum values of 6°C, 9°C, 8°C, 6°C, 6°C in the years 2075, 2077, 2083, 2085 and 2099, respectively. In the year 2081 the maximum anomaly region is shifted to Mato Grosso do Sul with a value of 7°C. There is another region of high positive anomalies over Venezuela, Columbia, Guiana, northern Roraima State in Brazil and Amazon region. The corresponding maximum values of anomalies in the 6 El Niño years are around 7°C, 10°C, 11°C, 10°C, 5°C and 9°C, respectively. It is well known that Amazon region is adversely affected during El Ninos¹⁹. During the recent severe El Niño of 2015-16 the warming over Amazon forest is termed as record breaking²⁰. The increase of temperature during the future extreme El Niño over Amazon forest is more than that in the record breaking 2015-16 warming. A third region of high positive anomalies on the lee side of Andes Mountains in the western Argentina and Southern Chile is also seen. The corresponding high anomalies are 8°C, 11°C, 10°C, 10°C, 9°C and 8°C, respectively, in 2075, 2077, 2081, 2083, 2085 and 2099. In the mean anomaly of all the 6 extreme El Ninos (Fig. 4) also the pattern is similar with the above mentioned three regions of high positive anomalies, with maximum positive anomalies of 5°C, 8°C, and 10°C, respectively. The temperatures of 2016 January in these three regions also are high (Fig. 5) with values much less than those in the 6 extreme El Niño years in future (see supplement Fig. 1).

Developmental rate of *Aedes aegypti* eggs increases exponentially between 27°C and below 40°C with increase of temperature²². Since temperatures during future extreme El Niño events (Fig. 3) in all the above mentioned three areas are higher than 27°C and below 40°C, these conditions are highly favorable for the proliferation of *Aedes aegypti* or Zika virus in SA.

In order to calculate the vectors ability to spread disease among humans, we used the expressions given in Liu-Hermenson et al.²⁹ These are given in the methods and data section. VC (Vecotial Capacity) relative to the vector -to - human population ratio can be expressed as

$$VC = a^2 b_h b_m e^{-\mu_m n} / \mu_m$$

The main vector for the spread of Zika virus *Aedes aegypti* is the same as for the disease Dengue.

Regarding the effect of temperatures during extreme El Niño events in fig(2), the corresponding biting rates are respectively 0.19,0.21 and 0.23 (fig 6.a), that is female *Aedes aegypti* mosquito takes less time for the average blood meal with increasing frequencies.

The probability of infection from human to vector per bite (b_m) for the lower temperature range, fig(6b) varies from 0.7- 0.9 for the above mentioned three regions and in figure the corresponding probability for the second temperatures range shows the high probability for almost entire south America indicating the high imminent risk of acquiring the disease in future extreme El Niño events . The probability of transmission from vector to human per bite (b_h) is almost similar to the previous fig.(6c)

The Extrinsic incubation period (n) for higher temperatures during the extreme El Niños varies from 7-14 days in Brazil, Bolivia, Paraguay and Argentina, whereas the incubation period increases with the increase in the temperature anomalies over Peru and Chile (fig.6d).

The mortality rate increases with the increase in temperature anomalies during extreme El Niños in Peru and Chile i.e from 0.03 -0.07. In the remaining parts for the temperature ranges of 21-29°C the mortality rate varies from 0.03-0.035(fig.6e)

Vectorial capacity(VC) depicts the spreading of the diseases in human during the future extreme El Niños. It varies from 0.5 to 1.25 where as more spreading has been observed in Amazon and its surroundings, Bolivia, Sao paulo state and Argentina.

The Zika virus epidemic potential VC is shown in fig.7. Assuming that the Human to mosquito ratio, equals 1 and using a typical infectious period of 5 days, the threshold value for a dengue epidemic outbreak using VC is estimated to be 0.2 per day. In this figure (fig.7), in all areas that exceed the threshold value of 0.2 per day, the Zika virus epidemic outbreak is imminent (if the other necessary conditions, sufficient presence of humans and vectors exist). In fig.7 we see the main favorable regions for the outbreak of ZIKAV (more than 0.2) are the three regions of higher temperatures mentioned earlier namely Amazon and its surroundings, Brazil (southern Minas Gerais , Sao paulo state), Bolivia, and Argentina. The high values of 1.25 per day are seen in northern Argentina, Paraguay, Parana and Matagross states in Brazil and Western Amazon. Also, over large areas in south America a value of 1 per day is seen indicating the high potential of ZIKAV outbreak in future extreme El Niño events.

Since ZIKV shares a considerable degree of genetic identity and structural homology with other flaviviruses including Dengue virus²³ and there is proof that Dengue virus antibodies enhance ZIKV infection (Clinical and Translations Immulogy, 16 Dec 2016), patients previously affected by Dengue are much likely susceptible to Zika virus infection leading to complications in treatment. In a very recent paper²⁴, studies on mice showed that "during adulthood, ZIKV replication persisted in neonatally infected mice and animals showed increased susceptibility to chemically induced seizures neuro degeneration and brain calcifications". This shows that neonatal ZIKV infection may have long term complications and may have a lasting impact on brain.

In conclusion, the effect of extremely calamitous future climate change, under greenhouse warming particularly the increase of temperature by several degrees during extreme El Niños in SA is twofold: 1) It is highly congenial for the increase in the breeding and spread of vector borne diseases such as Zika virus, and 2) is highly prejudicial to delicate balance of biodiversity in Amazon forest , Sao Paulo and nearby states in Brazil, western Argentina, Chile, Venezuela and Roraima State in Brazil. Thus it is necessary to make policy arrangements for the mitigation of these adverse climate change effects.

Methods :

The spatial distribution of various vector parameters related to Zika vector *Aedes aegypti* has been computed using mechanistic models which are statistically significant from the previous literatures (Liu-Helmersson et.al.²⁹, and Lambrechts et al.,³⁰). The equations are based on the particular temperature ranges that are favourable for the vector growth.

The equation for the average blood meal frequency i.e the biting rate 'a' is

$$a(T) = 0.0043T + 0.0943 \quad (21^\circ C \leq T \leq 32^\circ C) \quad (1)$$

The probability of infection from human to vector per bite is 'b_m(T)' is

$$b_m(T) = 0.0729T - 0.9037 \quad (12.4^\circ C \leq T \leq 26.1^\circ C) \quad (2)$$

$$b_m(T) = 1 \quad (26.1^\circ C \leq T \leq 32.5^\circ C)$$

The prospect of transmission from vector to human per bite 'b_h' is computed by the equation

$$b_h(T) = 0.001044T(T - 12.286)\sqrt{32.461 - T} \quad (12.286 \leq T \leq 32.461)$$

Extrinsic incubation period 'n' for the temperature range 12°C to 36°C is

$$n(T) = 4 + e^{5.15 - 0.123T} \quad (3)$$

Fourth order polynomial function is used to find the mortality rate by following Yang et al.(2009)

i.e.

$$\mu_m(T) = 0.8692 - 0.1590 + 0.01116T^2 - 3.408 * 10^{-4}T^3 + 3.809 * 10^{-6}T^4 \quad (4)$$

The above equations are utilized to understand the epidemic potential of zikav over south America in the Future El Nino years.

Data availability:

The temperature (T), SST data has been taken from 4 CMIP5 models (MPI,GFDL,IPSL,NorESM1) for 7 extreme El Nino years. APDRC regrided CMIP5 data grids into a fixed 1° by 1° has been taken from <http://apdrc.soest.hawaii.edu>. The various vector parameters equations related to Zika vector *Aedes aegypti* has been adopted from the mechanistic models (ref : 28,29)

Acknowledgements: The authors acknowledge NCEP centre for providing the climatology data. CMIP5 model data have been obtained from APDRC (<http://apdrc.soest.hawaii.edu>). The lead authors are thankful to Director INPE Brazil, Director CSIR-NIO, Scientist-in-Charge NIO RC Visakhapatnam for their support. The authors also thankful to heads of the institutes CCMB, Hyderabad and University of Science and technology, King Abdulla for their support and encouragement in carrying out the collaborative work. This has the NIO contribution no. XXXX

References

1. Dick, G. W., Kitchen, S. F. & Haddow, A. J. Zika virus. Isolations and serological specificity. *Trans. R. Soc. Trop. Med. Hyg.* 46, 509–520 (1952)
2. World Health Organization. Zik-virus infection Brazil and Colombia (<http://www.who.int/csr/don/21%20october-2015-zika/eu/>). Accessed December 29. 2015, 2015

3. World Health Organization. [http://www.who.int/media-centre/statements/2016/zika-update-3-16/eu/March 22, 2016](http://www.who.int/media-centre/statements/2016/zika-update-3-16/eu/March-22-2016). Accessed April 12, 2016 (2016)
4. Caminade, C. & et al. Global risk model for vector-borne transmission of Zika virus reveals the role of El Niño 2015. *PNA* 114, 119-124 (2017)
5. Paz, S. & Semenza, J. C. El Niño and climate change—contributing factors in the dispersal of Zika virus in the Americas? *The Lancet*, 387, DOI: [https://doi.org/10.1016/S0140-6736\(16\)00256-7](https://doi.org/10.1016/S0140-6736(16)00256-7) (2016)
6. Monaghan, A. J. et al. On the Seasonal Occurrence and Abundance of the Zika Virus Vector Mosquito *Aedes Aegypti* in the Contiguous United States. *PLOS Currents*, doi: 10.1371/currents.outbreaks.50dfc7f46798675fc63e7d7da563da76 (2016)
7. da Cruz Ferreira et al. Meteorological variables and mosquito monitoring are good predictors for infestation trends of *Aedes aegypti*, the vector of dengue, chikungunya and Zika. *Parasites & Vectors*. <https://doi.org/10.1186/s13071-017-2025-8> (2017)
8. Khormi, H. K. & Kumar, L. Climate change and the potential global distribution of *Aedes aegypti*: spatial modelling using geographical information system and CLIMEX. *Geospatial Health* 2, 405-415 (2014)
9. Martens, W. J. M., Jetten, T. H. , Rotmans, J.B & Niessen, L. W. Climate change and vector-borne diseases: A global modelling perspective. *Global Environ. Change* 5, 195-209 (1995)
10. Cai, W. et al. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat. Clim. Change* 7, 257–262 (2017)
11. Wang, G. et al. Continued increase of extreme El Niño frequency long after 1.5°C warming stabilization. *Nat. Clim. Change* 7, 568–572 (2017)
12. Buizer, J. L., Foster, J. & Lund, D. Global Impacts and Regional Actions: Preparing for the 1997–98 El Niño. *Bull. Amer. Meteor. Soc.* 81, 2021-2139 (2000)
13. Sponberg, K. Navigating the numbers of climatological impacts. (<http://www.cip.noaa.gov/docs/navimpact.pdf>) (1999).
14. Hopp, M.bn & Foley, J. Global-scale relationships between climate and dengue fever vector *Aedes Aegypti*. *Clim. Change*. 48, 441-463 (2001)
15. ggweather.com/enso/oni.htm
16. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* 93, 485–498 (2012)
17. Kanamitsu, M. et al. NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Am. Met. Soc.* <https://doi.org/10.1175/BAMS-83-11-1631> (2002)
18. Collins, J. M., Chaves, R. R. & Marques, V. S. Temperature Variability over South America. *J. Climate*, 22, 5854-5869 (2009)

19. Espinoza, J. C. et al. Climate variability and extreme drought in the upper Solimões River (western Amazon Basin): Understanding the exceptional 2010 drought. *Geophys. Res. Letters*, 38, L13406, doi:10.1029/2011GL047862 (2011)
20. Jimenez-Munoz, J. C. et al. Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. *Scientific Reports*, 6, article number 33130 (<https://www.nature.com/articles/srep33130>) (2016)
21. Patz, J. A., Epstein, P. R., Burke, T. A. & Balbus, JM. Global climate change and emerging infectious disease. *J. Amer. Med. Association*, 275, 217-273 (1996)
22. Focks, D. A., Haile, D. G. & Mount, G. A. Dynamic Life Table Model for *Aedes aegypti* (Diptera: Culicidae): Analysis of the Literature and Model Development. *J. Med. Entomology*. <https://doi.org/10.1093/jmedent/30.6.1003> (1999)
23. Priyamvada, L. et al. Humoral cross-reactivity between Zika and dengue viruses: implications for protection and pathology. *Emerging Microbes and Infection*, 6, doi: 10.1038/emi.2017.42 (2017)
24. Nem de Oliveira Souza, I. et al. Acute and chronic neurological consequences of early-life Zika virus infection in mice. *Sci. Trans. Medicine*. doi: 10.1126/scitranslmed.aar2749 (2018).
25. Bouma, M. J. & van der Kaay, H. J. The El Niño Southern Oscillation and the historic malaria epidemics on the Indian subcontinent and Sri Lanka: an early warning system for future epidemics? *Trop. Med. Int. Health* 1, 86–96 (1996).
26. Poveda, G. et al. Coupling between annual and ENSO timescales in the malariaclimate association in Colombia. *Environ. Health Perspect.* 109, 489–493 (2001).
27. Bouma, M. J. & Dye, C. Cycles of malaria associated with El Niño in Venezuela. *J. Am. Med. Assoc.* 278, 1772–1774 (1997).
28. Lindblade, K. A., Walker, E. D., Onapa, A. W., Katungu, J. & Wilson, M. L. Highland malaria in Uganda: prospective analysis of an epidemic associated with El Niño. *Trans. R. Soc. Trop. Med. Hyg.* 93, 480–487 (1999).
29. Liu-Helmersson, J., H. Stenlund, A. Wilder-mith, J. Rocklov: Vectorial capacity of *Aedes aegypti*: effects of temperature and implications for global dengue epidemic potential (2014), *PLoS One*, 9 (3)
30. Lambrechts L, Paaijmans KP, Fansiri T, Carrington LB, Kramer LD : Impact of daily temperature fluctuations on dengue virus transmission by *Aedes aegypti* (2011). *Proc Natl Acad Sci U S A* 108: 7460–7465.
31. Yang HM, Macoris ML, Galvani KC, Andrighetti MT, Wanderley DM: Assessing the effects of temperature on the population of *Aedes aegypti*, the vector of dengue. (2009) *Epidemiol Infect* 137: 1188–1202.
32. Bryan Weare : El Niño teleconnections in CMIP5 models (2013) *Climate Dynamics* 41(7-8).
33. Weller, E., and W. Cai, 2013: Asymmetry in the IOD and ENSO teleconnection in a CMIP5 model ensemble and its relevance to regional rainfall. *J. Climate*, 26, 5139–5149.

34. Gagnon AS, Bush ABG, Smoyer-Tomic KE: Dengue epidemics and the El Niño southern oscillation (2001) *Climate Research*, Vol. 19: 35–43
35. Bouma MJ, Dye C (1997) Cycles of malaria associated with El Niño in Venezuela. *J Am Med Assoc* 278:1772–1774.
36. Kovats SR (2000) El Niño and health. *Bull WHO* 78:1127–1134
37. Alexandre S. Gagnon · Karen E. Smoyer-Tomic Andrew B. G. Bush The El Niño Southern Oscillation and malaria epidemics in South America *Int J Biometeorol* (2002) 46:81–89, DOI 10.1007/s00484-001-0119-6
38. Ramesh CD, Soma S : El Niño Southern Oscillation as an early warning tool for malaria outbreaks in India (2017) *Malar J.*2017;16:122.

Figure captions:

Fig .1. Niño index from differnt models of CMIP5

Fig. 2. Mean surface Air temperature duiring 1998-2010

Fig.3. Air temperature anomalies from the mean to extreeme El Niños

Fig.4.Mean air temperature anomalies during all extreeme El Niños

Fig.5.Air temperature during 2016 extreeme El Niño.

Fig.6. The effect of temperature on various vector parameters.

Fig.7. The effect of temperature on vector parameters and vectorial capacity

Conflict of Interest :

The authors declare that there are no conflict of interest

Author Contributions: V. Brahmananda Rao conceived the idea, K. Maneesha made all the calculations and interpretation of El Niño - virus relations, Panangipalli Sravya helped in the interpretation of biological aspects, all the authors contributed for the development of final manuscript.

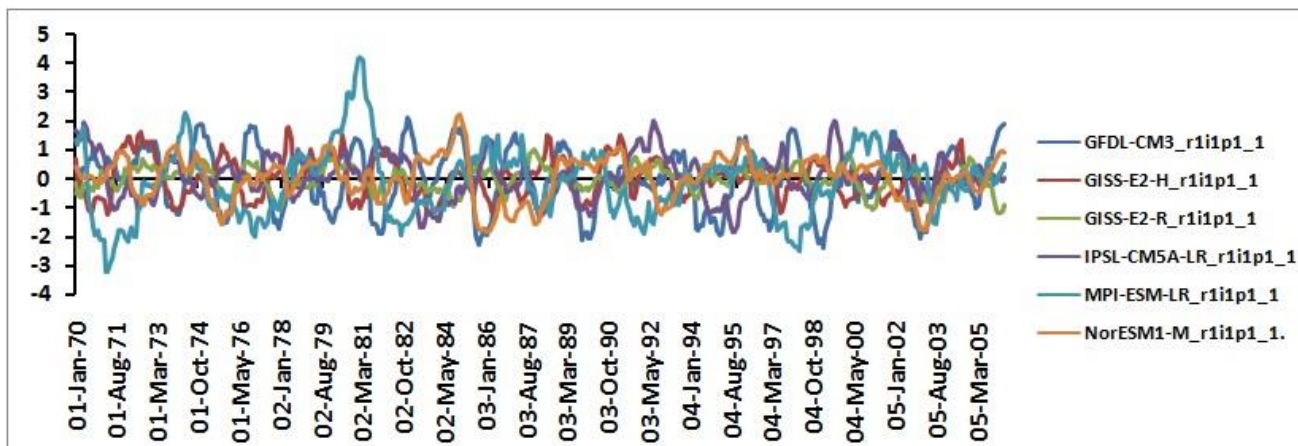


Fig.1

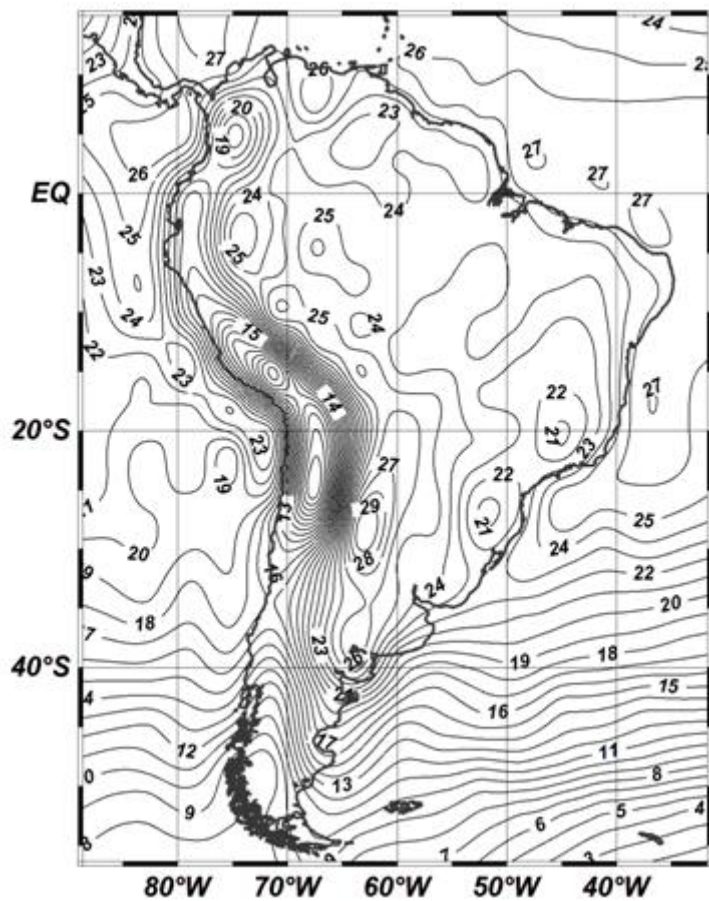


Fig.2

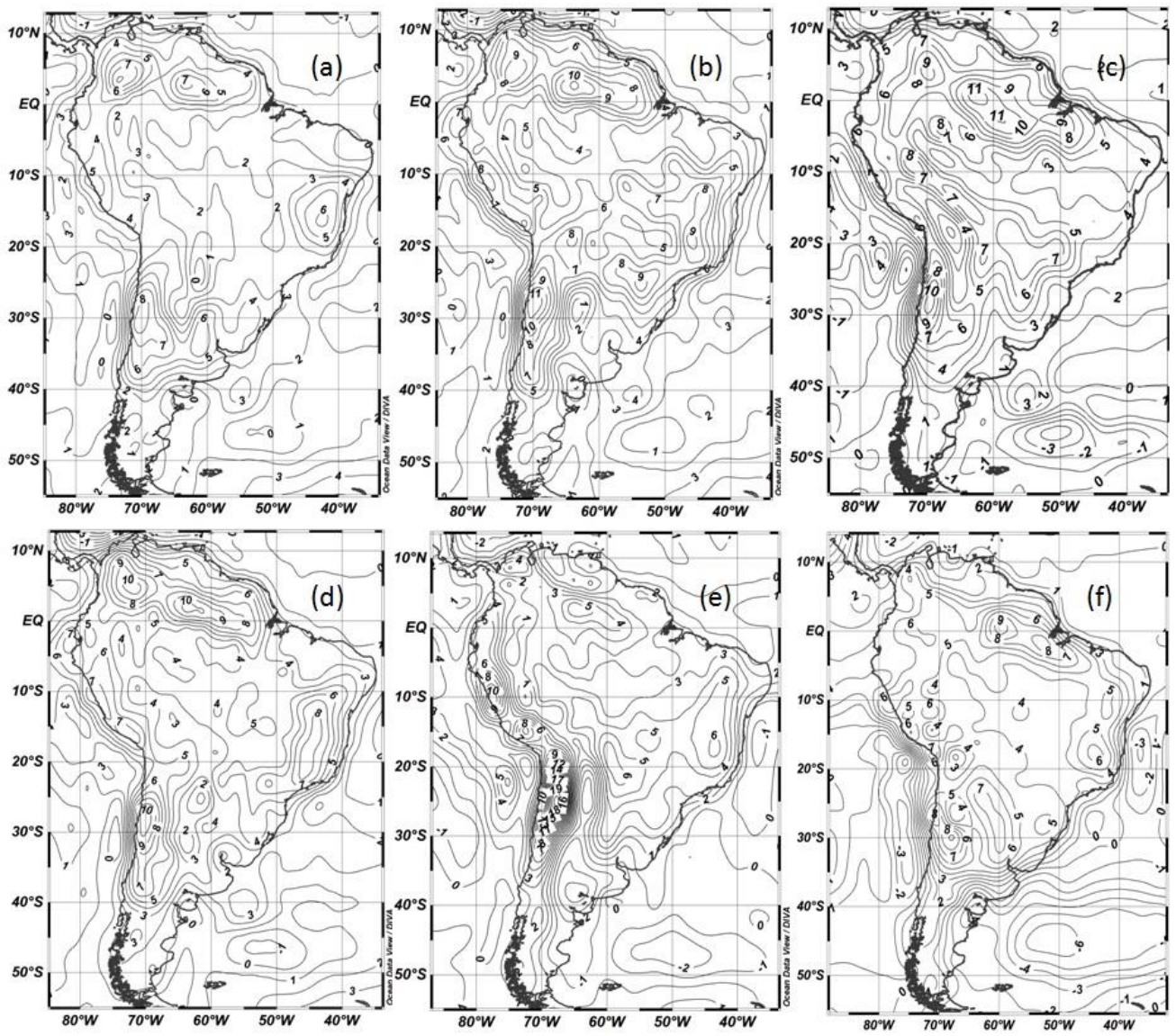


Fig.3

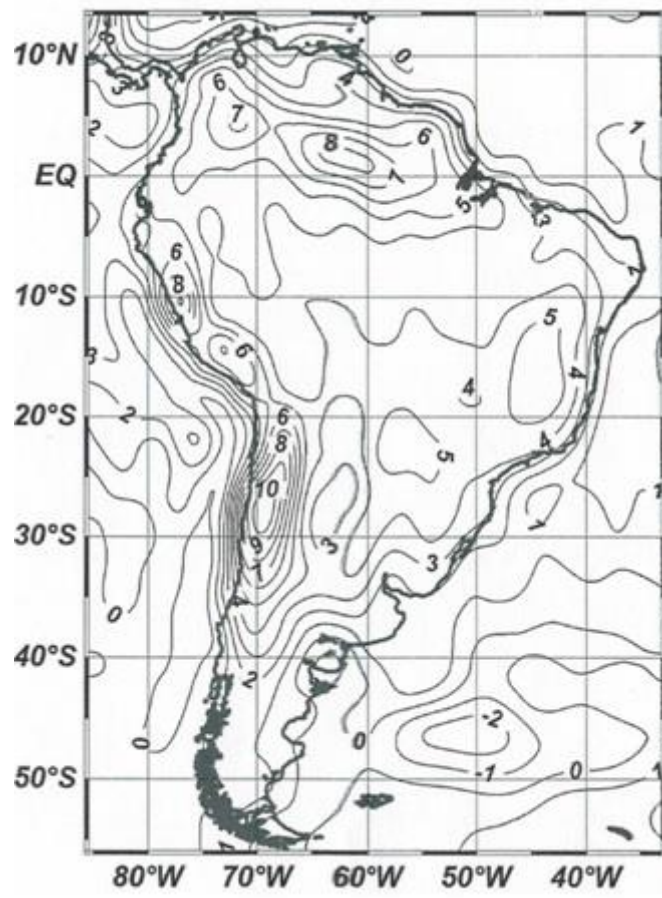


Fig .4

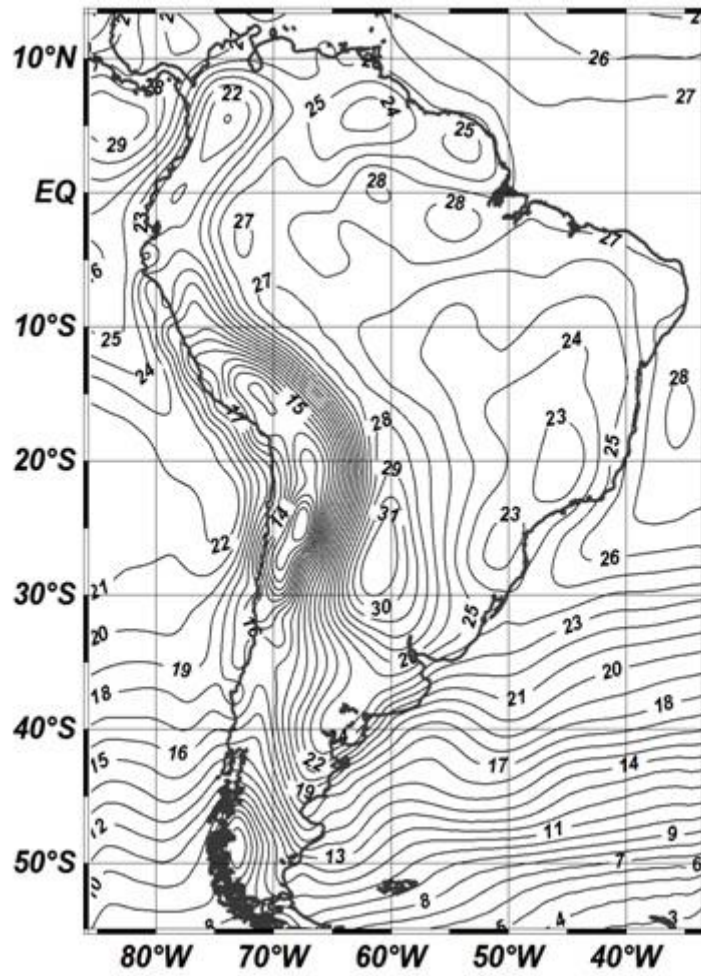


Fig .5

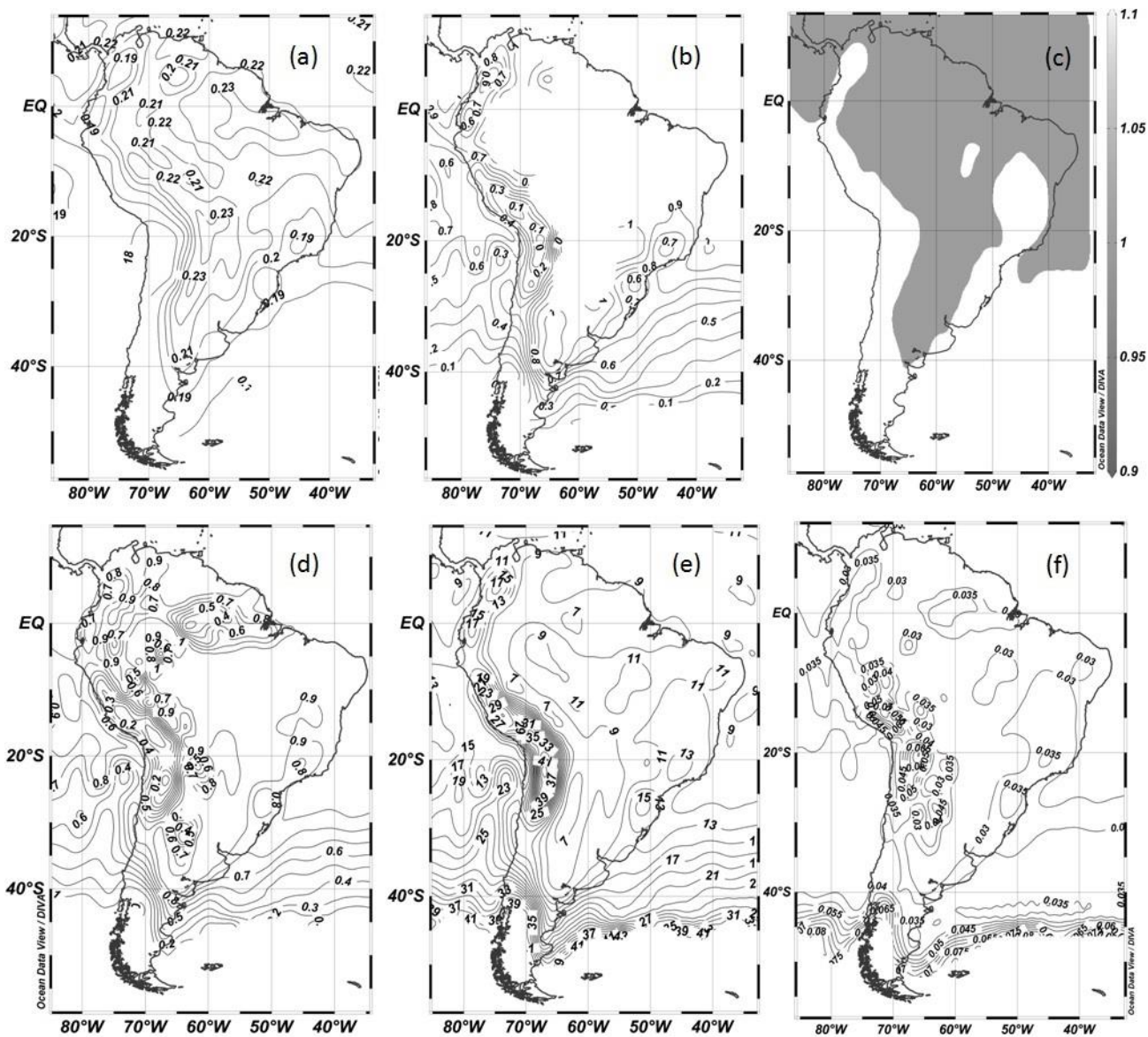


Fig.6

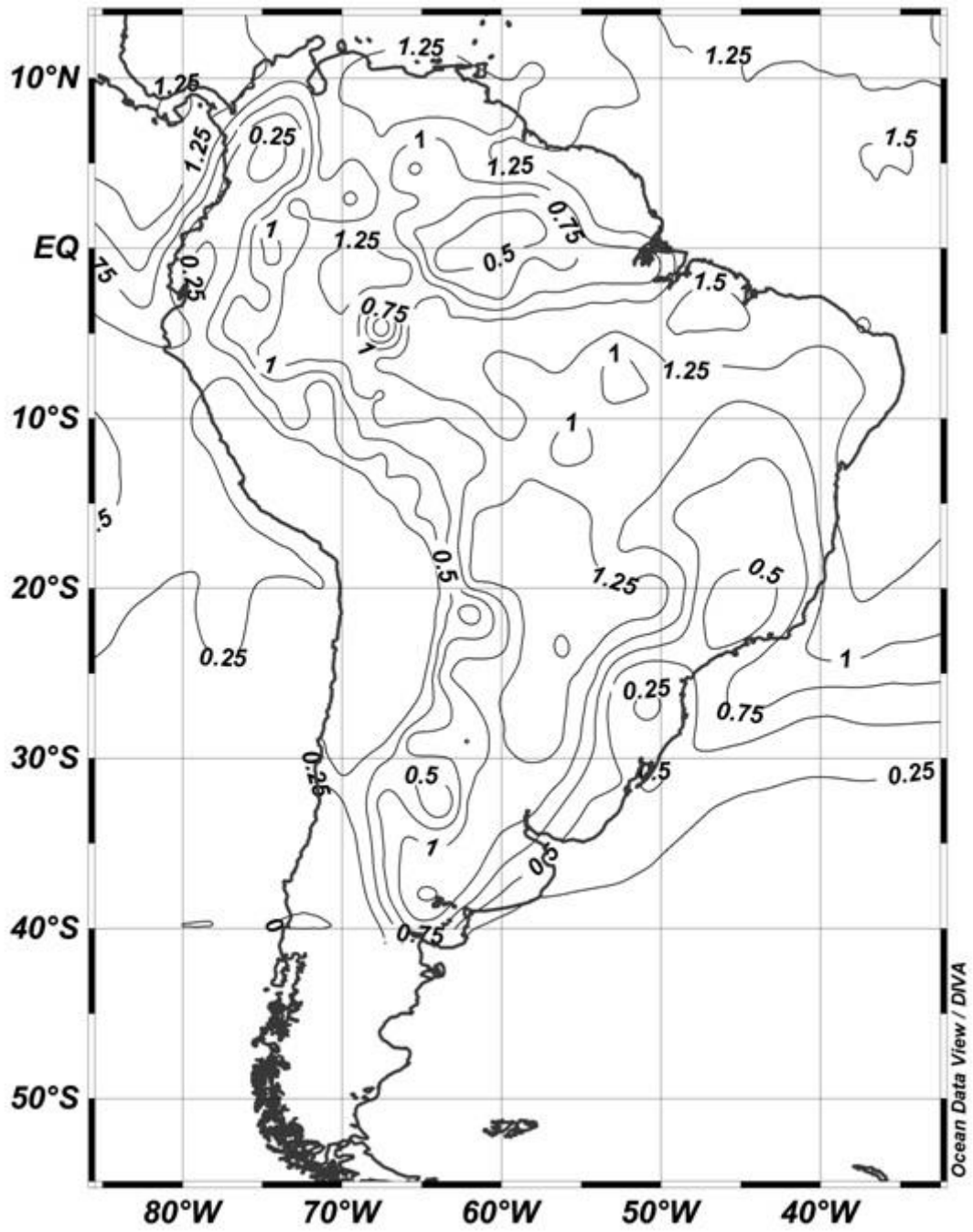


Fig.7

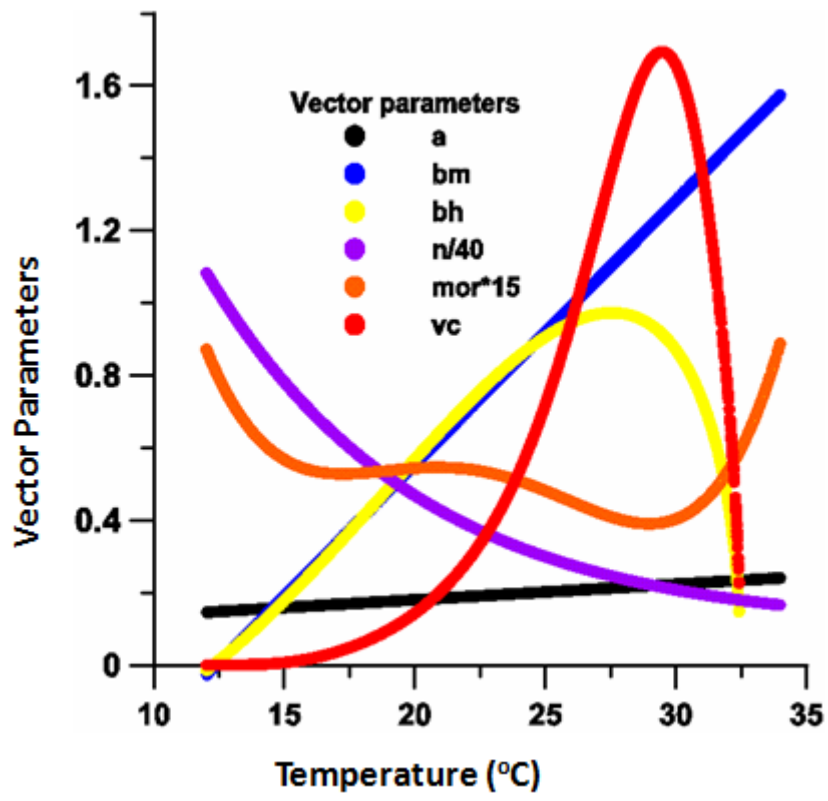


Fig .8