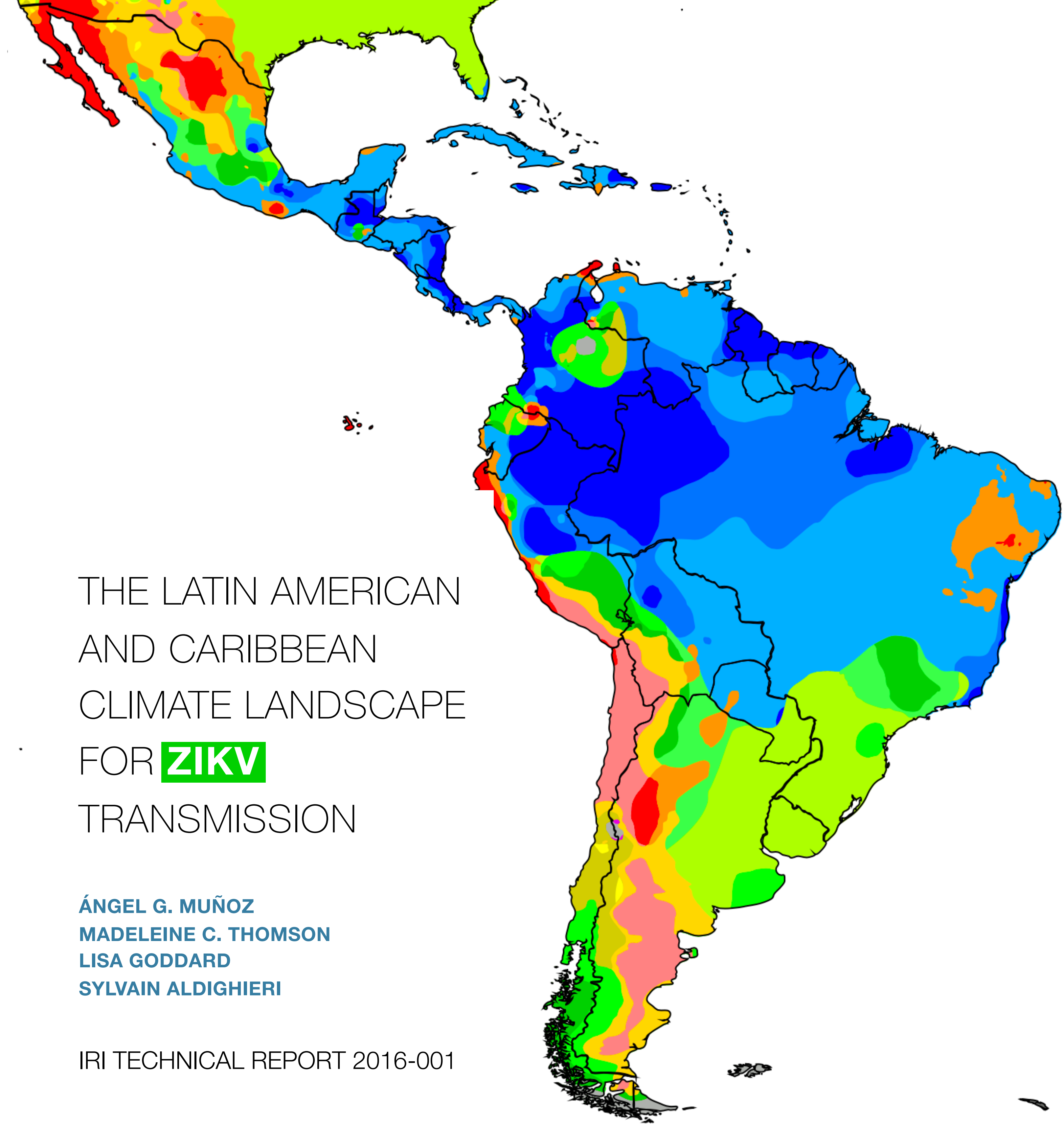

THE LATIN AMERICAN AND CARIBBEAN CLIMATE LANDSCAPE FOR ZIKV TRANSMISSION

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The Latin American and Caribbean Climate Landscape for ZIKV Transmission

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EXECUTIVE SUMMARY AND RECOMMENDATIONS

1. **Climate is an important driver of ZIKV transmission.** High rainfall may result in an increase in outdoor breeding sites for ZIKV vectors while drought years may result in increased use of water storage, and thereby increase domestic breeding sites. Warming temperatures increase the development rates of both vector and virus
2. **Climate should be considered as a significant driver of the seasonality,** year to year variability and longer term trends in geographic distribution of Zika and other arboviruses transmitted by *Aedes spp* mosquitoes including *Aedes agypti* and *Ae. albopictus*.
3. **Climate information may be used to improve** the timing and targeting of ZIKV interventions.
4. **Climate information, relevant to the problem** and at the right spatial and temporal scale, should be accessed from an authoritative source and, if possible, climate experts should be involved in analyzing the data in conjunction with health experts.
5. **While rainfall exhibits considerable seasonal and year-to-year variation,** long-term trends —likely associated with climate change— tend to have a relatively weak contribution to the total rainfall signal in most parts of Latin America and the Caribbean.
6. **While temperature exhibits seasonal and year-to-year variations**, long-term trends have a relatively strong contribution to the total temperature signal.
7. **ZIKV was introduced and has spread** in Latin America during a period of prolonged drought and at a time when the region's temperature has been anomalously warm – with 2014 and 2015 the warmest years on record until now —a result of both the warming trends and the strong 2015/2016 El Niño.
8. **There is a high likelihood of La Niña conditions** following the current El Niño which, while temporarily cooling the climate, will likely result in increased rainfall in many Latin America and Caribbean countries which may further increase transmission rates. Forecasts of the region's climate are available and routinely updated.

INTRODUCTION

Zika virus (ZIKV) has recently been identified as a major global health threat with potentially two billion people at risk of infection (Messina et al., 2016). While the majority of ZIKV infections are asymptomatic or result in mild disease the spread of ZIKV in Brazil in 2015 has been accompanied by an unprecedented rise in the number of children being born with microcephaly. In addition, several countries, including Brazil, reported a steep increase in Guillain-Barré syndrome (Cao-Lormeau et al., 2016; PAHO, 2016) —a neurological disorder that could lead to paralysis and death.

On 1-2 March, PAHO convened the first global meeting of technical, public health and academic research partners to exchange information and present current knowledge on the Zika virus; to discuss the laboratory platforms needed for surveillance and for research activities; and to develop a research agenda for the public health implications of the ZIKV outbreak in the Americas. This meeting was convened in response to the declaration by the World Health Organization (WHO) in February 2016 that ZIKV constituted a Public Health Emergency of International Concern (PHEIC).

At the meeting, climate was considered a key determinant of the seasonal timing of ZIKV infection, a possible contributor to the explosive epidemics observed in 2015 (a strong El Niño year) and a long-term concern for its wider spread given the potential expansion of the range of its mosquito vectors in a warming climate.

Evidence to date suggests ZIKV is principally transmitted globally and in Latin America and the Caribbean (LAC) by the container breeder mosquito *Aedes aepgyti. Ae. albopictus*, alongside 18 other *Aedes spp*., has been identified as a minor vector but one with significant potential to be a major vector in the future because of its recent rapid spread (Messina et al. 2016). Although ZIKV transmission depends on several factors including human behavior, it is well established that the associated vectors are sensitive to variations in environmental temperature and rainfall and weather based early warning systems for dengue have been suggested in different regions of the world. Temperature has long been understood as being a significant driver of the development rates of juvenile *Aedes aegypti* and *Ae. albopictus* and adult feeding/egg laying cycles along with the length of extrinsic incubation period and viral replication of arboviruses (Brady et al., 2013, 2014). Both excess rainfall and drought have been implicated in the creation of breeding sites for *Aedes* vectors of ZIKV and associated epidemics of DENV and CHIKV. The former may result in the development of outdoor breeding sites in a wide range of artificial containers (Stewart-Ibarra & Lowe, 2013; Stewart-Ibarra et al., 2014) whereas the latter may encourage water storage in domestic pots, drums and tanks which, if improperly managed, can result in the creation of household breeding sites as is indicated in Brazil in 2015 (Paz et al. 2016).

This document presents a short review of the basic climate of Latin America and the Caribbean (LAC), focusing on the rainfall and temperature regional differences at multiple timescales, and where present climate forecasts tend to be more skillful for these two variables. The paper aims to provide information to understand how the regional climate plays an important role in vector borne diseases in general and ZIKV in particular. As an emerging disease a great deal of basic information on ZIKV transmission dynamics is lacking. Knowledge on other Flaviviruses such as chikungunya virus (CHIKV) and dengue virus (DENV), also transmitted by the same mosquito vectors may therefore be used to impute likely climate-related impacts.

CLIMATE CLASSIFICATION

Latin America and the Caribbean (LAC) exhibit very diverse patterns of weather and climate, including tropical, subtropical and extra-tropical features. According to the widely used Köppen-Geiger classification system (Figure 1) (Peel, Finlayson, & McMahon, 2007), defined in terms of annual cycles of rainfall and temperature, the climate across LAC varies from arid zones (red) and transitions through semi-arid regions (gold) to humid tropical environments (blue). Humid subtropical climates (green) are features found predominantly in South Eastern South America (SESA). In some regions these widely diverse climates co-exist within relatively small areas and rainfall amount and seasonality (for example) may change significantly over tens of kilometers.

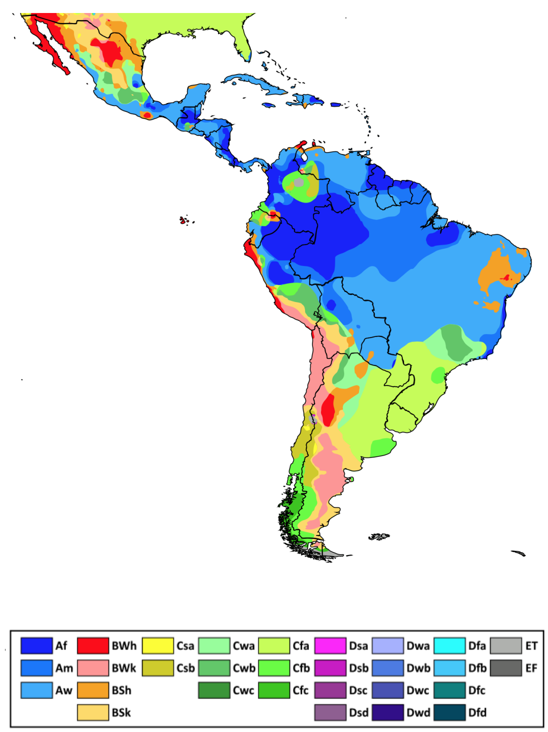

Figure 1 *Köppen-Geiger climate classification for Latin America and the Caribbean (see main text).*

CLIMATE CHANGES ON DIFFERENT TIMESCALES

The climate at any location varies from its mean historical climate state on a number of time scales, ranging from short term (from a few weeks to several months) to near-term (a few decades) and long-term (climate change). In order to better understand how much of the total variance in rainfall and temperature is explained by each timescale, this section briefly discusses how anomalies over a time period can be correctly attributed to variations in climate drivers representing different time periods. The process, called "timescale decomposition", is described in detail by Greene, Goddard & Cousin (2011). Baethgen and Goddard (2015) employed the methodology to analyze climate-change adaptation in Latin America's agriculture sector. This process filters the associated anomalies of a climate time series into three components: the inter-annual (year-to-year), decadal and long-term trend signals. The analysis shows how important each timescale is for explaining the entire climate signal observed in any particular location.

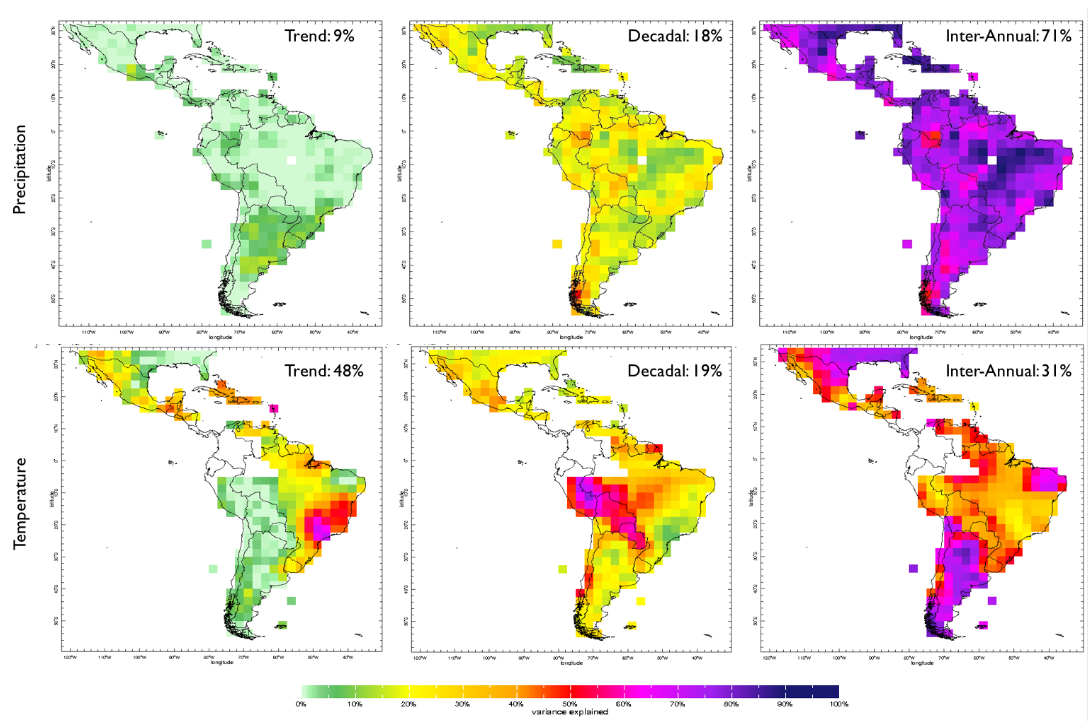

Figure 2 *Timescale decomposition for annual rainfall (upper row) and temperature (lower row), indicating the total explained variance for the long-term trend (first column), decadal (middle column) and inter-annual variability (right column). Data: CRUv3.21.*

Last century's decomposition for annual rainfall (Figure 2, upper row) and annual mean temperature (Figure 2, lower row) signals in LAC shows sharp differences in the variability explained by each timescale. On average, the total explained variance associated with the climate change signal is on the order of 9% for rainfall (Figure 2, upper left) and about 48% for temperature (Figure 2, lower left). It is clear that the climate change signal has a higher impact on surface air temperature than on rainfall, especially in a large region involving Central America, the Caribbean, Northern South America and most of Brazil; coincidentally, these regions correspond to the ones with the highest number of reports associated with typical arbovirus vectors (Kraemer et al., 2015). The contribution of climate change to rainfall is most important in SESA and most part of Argentina.

The decadal signal over the entire LAC explains around 19% of the total variance for both rainfall and surface air temperature (Figure 2, middle panels). Regions in white indicate places where the lack of data may degrade the analysis and thus the corresponding signal has been removed by the screening process described by (Greene et al., 2011). For rainfall, the decadal signal tends to be more important in vast regions of México, Central America, the Eastern Caribbean, Western Venezuela, Northern, Northeast and Southwestern Brazil, and most parts of Colombia, Ecuador, Chile and Bolivia. For temperature, the highest (over 50%) explained variance for the decadal signal is found in Southern Peru, Bolivia, Paraguay and Southern Chile.

Seasonal to inter-annual (year-to year) variations in rainfall typically account for the majority (over 70%) of its overall variance. The Caribbean basin, the coast of Northern South America, the Amazonia and Northern Peru exhibit values over 80% of the total explained variance. For surface air temperature, most parts of LAC show values over 50% of the total explained variance, especially Northeast Brazil, Argentina and Chile.

Results are similar when particular seasons are considered (not shown): for rainfall the most important scales are inter-annual and decadal, while for surface temperature the long-term trend tends to explain the higher amount of variance, followed by the inter-annual signal.

RAINFALL AND TEMPERATURE SEASONAL CYCLES

The characterization of seasonal cycles is important for outbreak preparedness activities. For countries with clear seasonal patterns, climate information could support the planning of prevention and control activities for different high risk areas, such as training of personnel in different aspects of the outbreak early warning and response system (Schneider et al., 2012).

Seasonal changes define the dominant characteristics of regional climate and it consequently drives the seasonal pattern of vector borne diseases across LAC. Since there is high predictability in the seasonality of variables like temperature, frequency of frost days (as a particular measure of cold conditions), rainfall amounts and frequency of rainy days (Figure 3), it is important to analyze the seasonal cycle more closely.

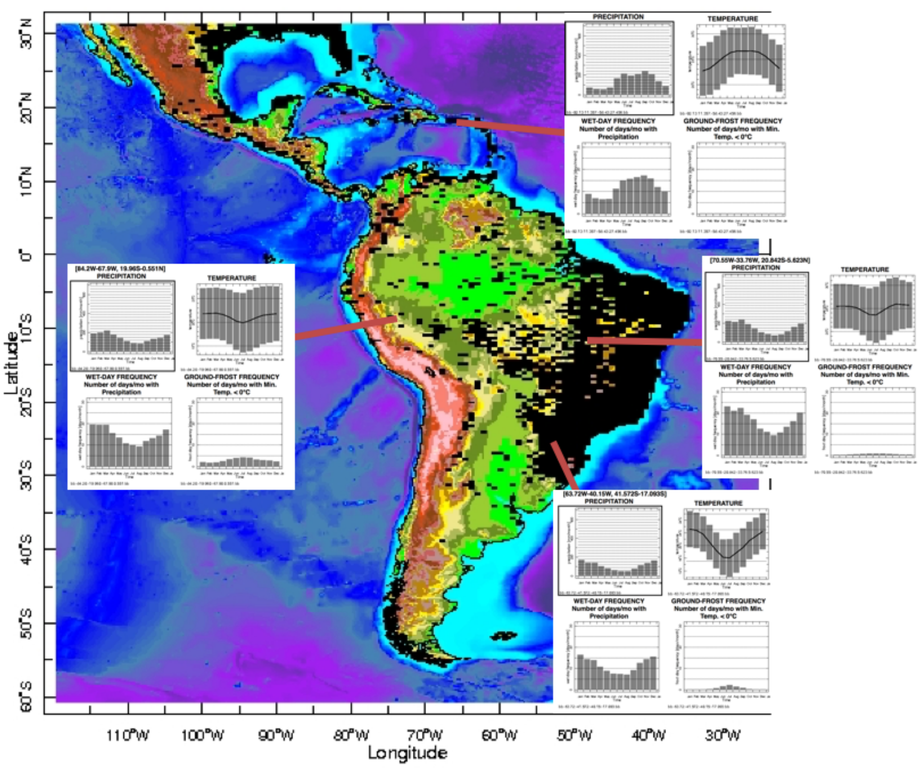

Figure 3 *Seasonality of rainfall (upper left panels), temperature (upper right), frequency of rainy days (lower left) and frequency of frost days (lower right) for different regions of Latin America and the Caribbean. The black dots on the map indicate reported occurrences of A. aegypti. (Climate data: CRUv2.1; Ae. aegypti data: (Kraemer et al., 2015)).*

Central America, the Caribbean and Northern South America tend to have a bimodal distribution with a two-month long mid-summer drought right between the two maxima (Figure 3); surface temperature oscillates around 23-27 ºC along the year, with a maximum in August. Other regions, like coastal Brazil and part of the Amazon, SESA and the tropical western coast of South America, exhibit just one peak of rainfall along the year, usually between the end and beginning of the year (Figure 3). As expected, surface temperatures in the Southern South America tend to exhibit higher variability and lower values for locations with higher latitudes, with minima in August. The frequency of rainy days follows the same distribution as rainfall, while the frequency of frost days tends to follow an inverse relationship to the mean temperature, and it is mainly a function of the latitude and altitude.

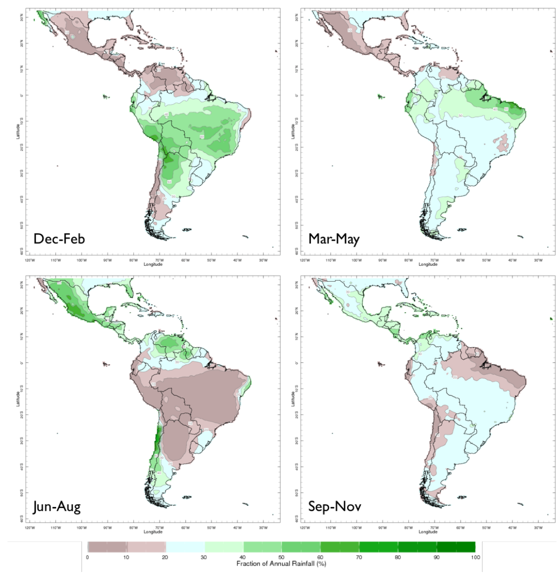

Figure 4 *Fraction of mean seasonal rainfall for DJF, MAM, JJA, and SON. (CPC-Unified dataset, 1981-2010).*

The large seasonal variations in rainfall that distinguish different climate zones is seen clearly in Figure 4, which indicates the fraction of mean annual rainfall occurring within the seasons December-January-February (DJF), March- April-May (MAM), June-July-August (JJA), and September-October-November (SON). The main drivers behind the rainfall seasonality tend to be associated with migrations of the Inter-Tropical Convergence Zone (ITCZ), producing the bimodality observed in Northern South America, Central America and the Caribbean, and monsoonal rainfall, which is typically associated with regions with a single rainy season.

THE RECENT CLIMATE (2013–2015)

This section discusses rainfall and temperature anomalies for the three years following the likely first introduction of ZIKV to LAC sometime between May-Dec 2013 (Faria et al., 2016).

The spatial patterns for both temperature and rainfall anomalies (departures with respect to the normal) were fairly similar in 2014 and 2015 (Figure 5), which were, at their respective terminus, the hottest years on record since its start in 1880 (NOAA, 2015, 2016). In terms of temperature anomalies, year 2013 was normal for most part of LAC, although the warming pattern in the Amazon that occurred in the following years is already visible (Figure 5). In the Amazon, annual rainfall anomalies for 2013 were slightly wetter than in the following years, but the general drier-than-normal signal exhibited for 2014 and 2015 was already present.

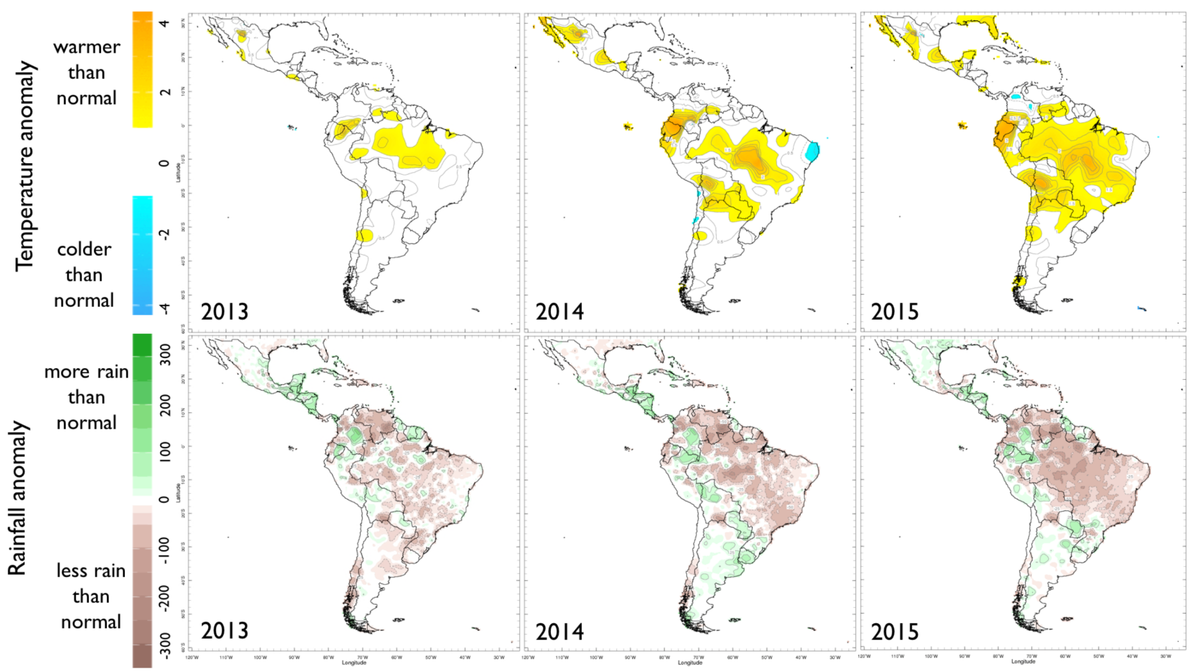

Figure 5. *Annual temperature (upper row) and rainfall (lower row) anomalies for 2013-2015. Units are ºC and mm, respectively. White indicates normal values.*

Overall, surface air temperature anomalies were considerably warmer than the 1981-2010 normal in most part of Brazil, Bolivia and Paraguay, all of Ecuador and Northern Peru, and in certain locations in Mexico, Chile and Northern Argentina (Figure 5). Basically all Brazil, Northern South America and Western Ecuador experienced rainfall deficits, while regions in SESA, the Peruvian Amazon, Central America, Eastern Cuba and parts of Argentina exhibited above-normal rainfall.

The combination of El Niño related very warm temperatures and drought conditions in Eastern and Central Brazil could have contributed to set the scenario for local ZIKV transmission via *Ae. aegypti* and *Ae. albopictus*. These patterns are also being observed during the first few months of 2016, but they could change as the year progresses, since a La Niña is expected to develop and persist for several months. The next section discusses further details about the typical impacts of El Niño and La Niña.

SEASONAL PREDICTABILITY OF RAINFALL AND TEMPERATURE

Since rainfall and temperature modulate key aspects of the vectors associated with ZIKV, determine the extrinsic incubation period of the virus, and it is possible nowadays to provide skillful forecasts for these variables, this section briefly discusses the main source of predictability after the seasonal cycle signal —El Niño-Southern Oscillation (ENSO)— and its typical implications.

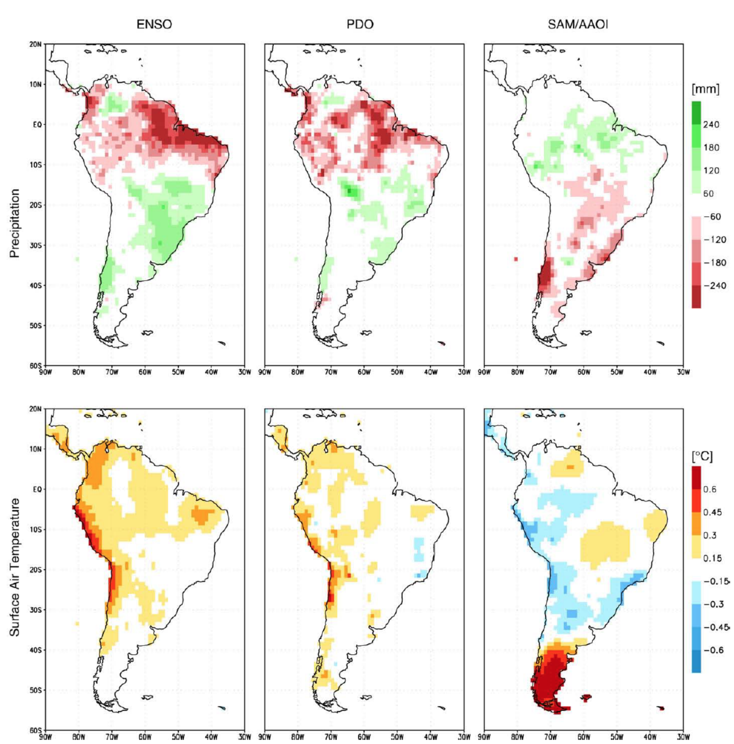

Figure 6. *Annual mean rainfall (upper panels) and surface temperature (lower panel) regressed upon El Niño-Southern Oscillation (left column), the Pacific Decadal Oscillation (middle column) and the Southern Annular Mode (SAM). (After Garreaud et al. (2009)).*

Several climate drivers influence the behavior of rainfall and surface air temperature in LAC, and their signals tend to interact with each other. For example, the Southern Annular Mode (SAM, frequently described by the Antarctic Oscillation index, AAOI) contributes to the modulation the seasonal behavior of temperature and rainfall, especially south of 40oS (Figure 6), and its phase is in turn modified by ENSO events, or enhanced tropical intra-seasonal variability (Carvalho, Jones, & Liebmann, 2004; Garreaud, Vuille, Compagnucci, & Marengo, 2009), like the Madden-Julian Oscillation. Furthermore, the frequency of a particular ENSO phase and the phase of the Pacific Decadal Oscillation (PDO) are also related [e.g., (Garreaud et al., 2009)], their spatial influence on LAC being very similar (Figure 6); for example, both El Niño and a positive phase of the PDO tend to bring more rainfall to SESA and below-normal rainfall to Northwestern South America, and most locations on the western and northern coast of South America and Northeast Brazil exhibit warmer-than-normal temperatures (Figure 6).

As indicated, the most important source of seasonal skill for rainfall and surface temperature is ENSO, and forecasts are generally better during those events. The typical impacts during El Niño and La Niña are well documented for LAC, and tend to occur at different times of the year (Figure 7).

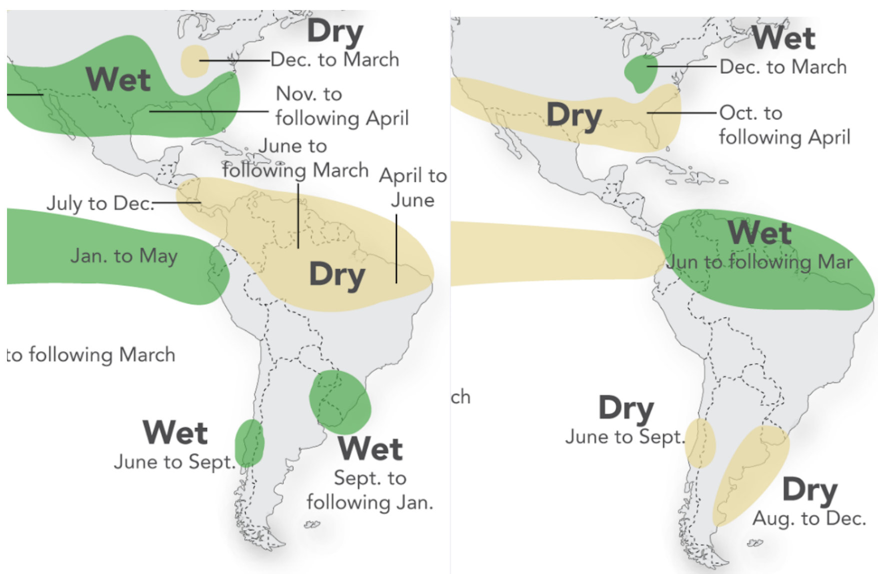

***Figure 7** Likely El Niño (left) and La Niña (right) rainfall impacts in Latin America and the Caribbean.*

Overall, the rainfall seasonal skill of the best forecast systems available is better for the Western Caribbean, Southern Central America, Northwestern South America, coastal Ecuador, Northeast Brazil and SESA (Figure 8, left). As a mean, the skill for surface temperature is higher than for rainfall, and it is especially high for most part of Brazil, Northern South America, Ecuador, Panama, Costa Rica and the Caribbean (Figure 8, right). This is an opportunity to exploit as these are regions with already reported cases of ZIKV.

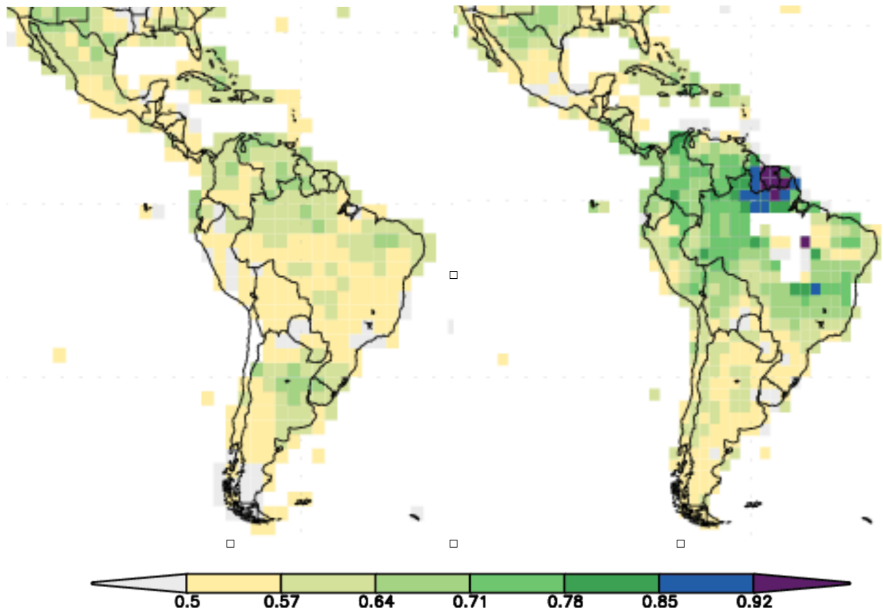

Figure 8 *Forecast skill using the Generalized ROC metric, showing the degree of correct probabilistic forecast discrimination for all seasons. Regions in gray are places with no forecast skill. Rainfall (left) and surface temperature (right). (Source: IRI).*

CONCLUSION

The full social and economic brunt of the ZIKV outbreak in LAC and the rest of the world has not yet been fully realized. Mobilization of financial and medical resources is currently occurring but without a vaccine prevention is dependent on the limited capacity of public and private sector services along with civil society to control vector populations and limit vector-human contact. In this environment, pooling the collective resources of different disciplines to improve understanding of disease transmission and target control efforts is essential. Knowledge of large-scale climate drivers may assist in a better understanding of the distribution of populations at risk, the seasonal timing of interventions and year-to-year variability in transmission dynamics and likely longer term changes associated with our warming climate. As the 2015/2016 El Niño fades there is an increasing probability that La Niña conditions will prevail in late 2016 and early 2017 with expected cooler temperatures and higher rainfall in some LAC regions (Figure 7; for the most updated ENSO forecast, the reader can consult http://iri.columbia.edu/our-expertise/climate/forecasts/#ENSO_Forecasts). The consequences of such changes are not yet known but should be considered an important near-term research priority as they may have a significant impact on the short-term dynamics of the epidemic.

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