Background Research
Baseline data and information inherent to the project Galápagos clean / renewable energy development

Developed by

AMBIENS CONSULTORÍA, SUSTENTABILIDAD Y GESTIÓN CLIMÁTICA

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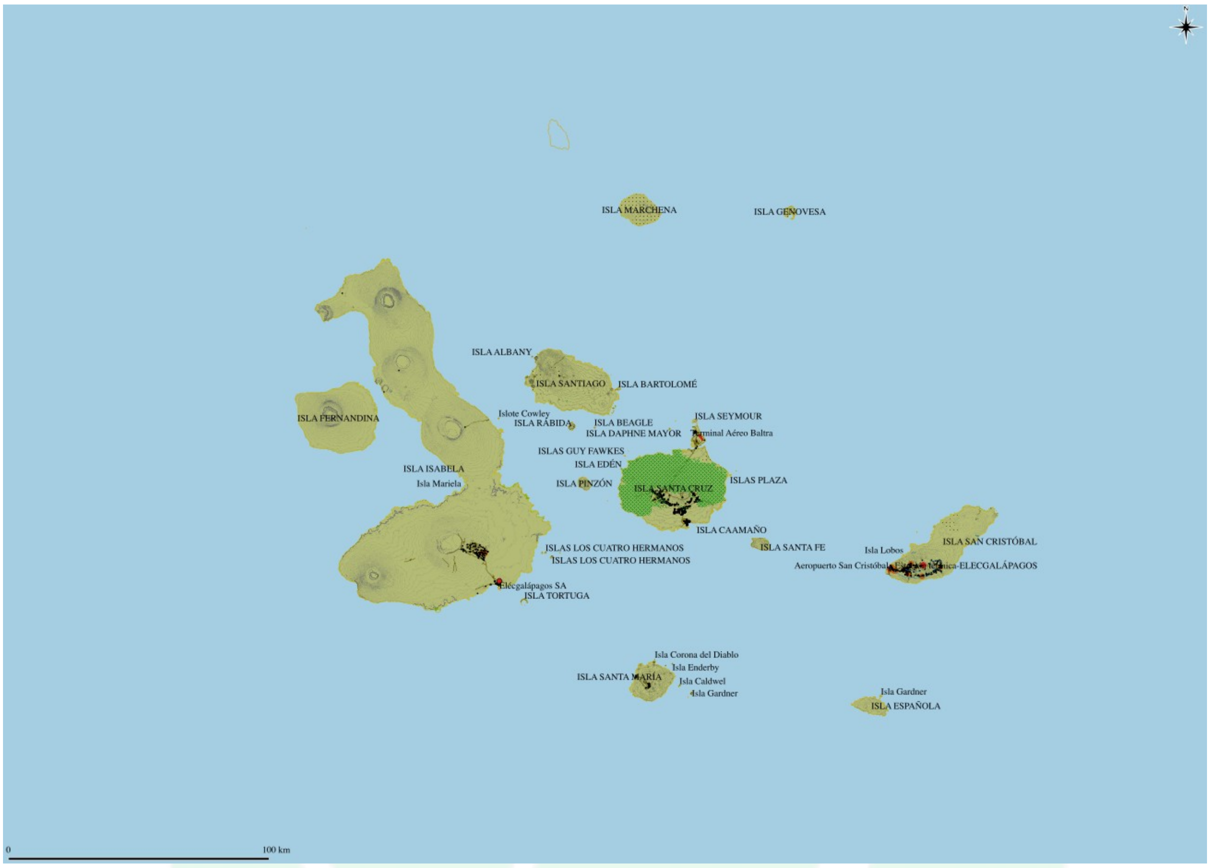
BASELINE DATA AND INFORMATION INHERENT TO THE PROJECT ON GALÁPAGOS CLEAN/ RENEWABLE ENERGY DEVELOPMENT



Source: Instituto Geográfico Militar, 2022, Cartas Topográficas Escala 1:50 000, Formato SHP (GALAPAGOS: features aeropuerto, bosque, central eléctrica, curva nivel, edificio estanque, lago/laguna, línea transmisión eléctrica, manantial, pastizal, pista aterrizaje, pista rodadura, poblado, rio, rodera, sendero, tierra sin vegetacion, via/ruta, zona edificada, zona manglar) processed with QGIS 3.10.

Topography of Galápagos Islands

The Galápagos Islands are an archipelago of volcanic islands in the Eastern Pacific, located around the Equator 900 km west of South America. They belong to the Galápagos Province of the Republic of Ecuador, and there is a Spanish speaking population of slightly over 33 000 inhabitants.

The group consists of 18 main islands, three smaller islands, and 107 rocks and islets. The islands are located at the Galápagos Triple Junction. The archipelago is located on the Nazca Plate (a tectonic plate), which is moving east/southeast, diving under the South American Plate at a rate of about 6.4 cm per year[1]. It is also atop the Galápagos hotspot, a place where the Earth's crust is being melted from below by a mantle plume, creating volcanoes. The first islands formed here at least 8 million and possibly up to 90 million years ago[2].

[1] Pearson, David L.; David W. Middleton (1999). The New Key to Ecuador and the Galápagos (3rd ed.). Berkeley: Ulysses Press.

[2] White, W. M. (2 October 1997). "A Brief Introduction to the Geology of the Galápagos". Cornell University Earth and Atmospheric Sciences. Retrieved 14 December 2011.

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SAN CRISTÓBAL ISLAND

San Cristóbal (extension 557 km^2) is the fifth largest and easternmost island of Galápagos. Its maximum altitude is 730 m, and is comprised of three or four fused volcanoes, all extinct. The town of Puerto Baquerizo Moreno on San Cristóbal is the capital of the Galápagos province. It is home to many government offices, an Ecuadorian Navy facility, and an airport with daily flights to the mainland. There are approximately six thousand residents, making it home to the second largest human population in Galápagos, after Santa Cruz. The majority of inhabitants make their living in government, tourism, and artisanal fishing. The port town is home to the Galápagos Academic Institute for the Arts and Sciences (GAIAS) of the Universidad San Francisco de Quito (USFQ).

Puerto Baquerizo Moreno is the second largest community in Galápagos, after Puerto Ayora on Santa Cruz. The majority of the residents of San Cristóbal live in the port city. It has two main streets, the Malecón Charles Darwin, which runs along the waterfront, where visitors can find restaurants, souvenir shops, and hotels. Parallel to it and a couple of blocks to the east is another main street. From 1991, the number of hotels in San Cristóbal increased from only six to more than 20. Also, the number of restaurants and bars increased from nine to more than 30. Puerto Baquerizo Moreno has also become the focus of the Galápagos' growing reputation among South Americans as a surfing hotspot.

El Progreso is the oldest surviving settlement in Galápagos, established in 1869. About 500 people live in this small farming community, located on the side of an extinct volcano about eight kilometers from Puerto Baquerizo Moreno.

Source: Instituto Geográfico Militar, 2022, Cartas Topográficas Escala 1:50 000, Formato SHP (GALAPAGOS: features acueducto, aeropuerto, bosque, central electrica, curva nivel, edificio estanque, generador, instalacion, lago/laguna, linea transmision electrica, manantial, pastizal, pista aterrizaje, pista rodadura, poblado, rio, rodera, sendero, tierra sin vegetacion, torre agua, via/ruta, zona edificada, zona manglar) processed with QGIS 3.10.

Topography of San Cristóbal Island

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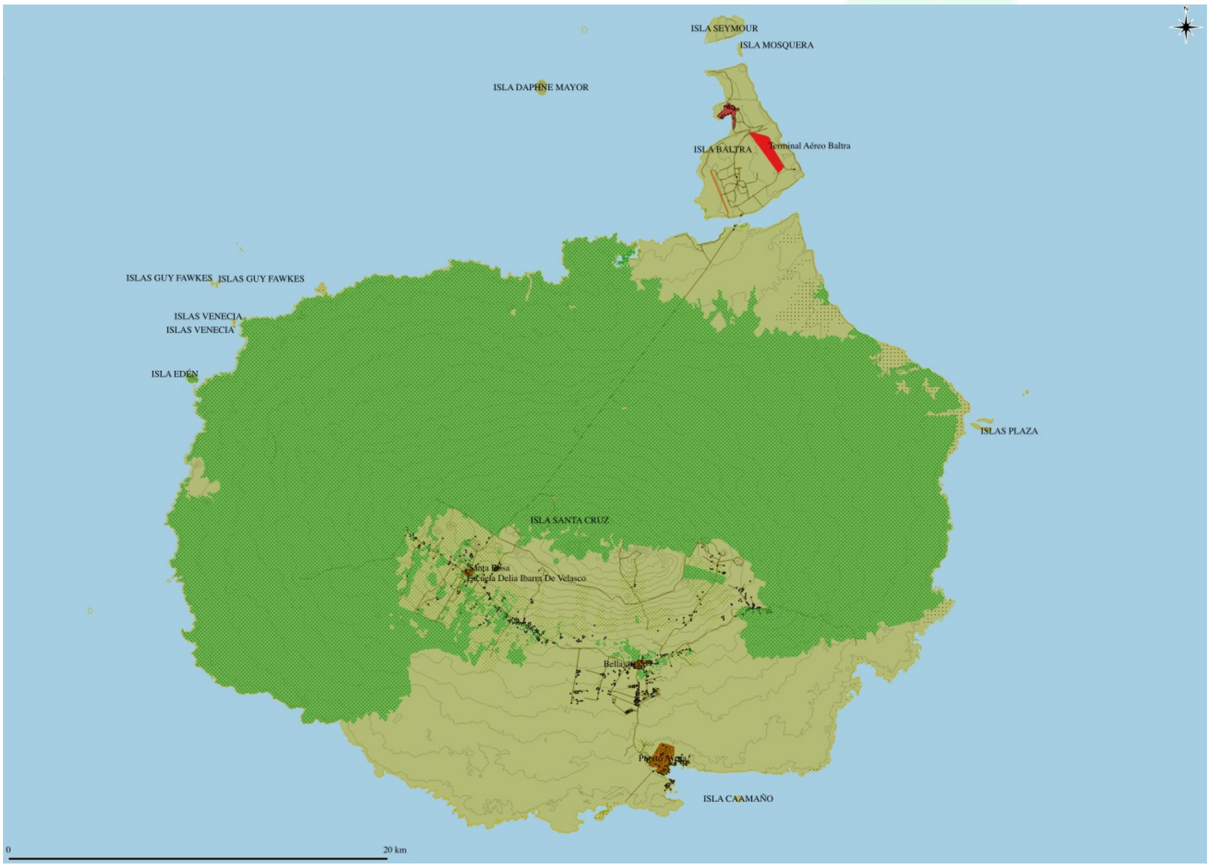
SANTA CRUZ ISLAND

Santa Cruz (area 986 km^2) is the main tourism hub for all of Galápagos, given its proximity to the airport on Baltra to the north. It is the only island in Galápagos where tourists can readily experience the interior and higher elevations of a Galápagos Island (maximum altitude 864 m). Santa Cruz has the longest paved road in Galápagos, which runs north-south across the island, taking people from the airport ferry at Itabaca Canal on the north coast into the highlands and through a few smaller towns on its way down to Puerto Ayora, the island's largest city located on the southern coast of the island in Academy Bay.

Volcanic activity has long since ceased on Santa Cruz, the second largest of the Galápagos Islands and located in the center of the archipelago. Santa Cruz (population *circa* twelve thousand) has a long history of human settlement and agriculture, which has left the landscape permanently altered by invasive species. The small towns of Bellavista and Santa Rosa were established in the humid highlands, where farmers raised cattle and planted crops such as avocados, coffee, sugarcane, bananas, oranges, and lemons.

Santa Cruz Island, and more specifically the town of Puerto Ayora, has withstood the brunt of this growth. In addition to the problem of introduced species and the ever-greater probability of introductions, this growth has put increasing pressures on local resources and municipalities in terms of health, education, waste management, and many other aspects of daily life.



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Topography of Santa Cruz Island

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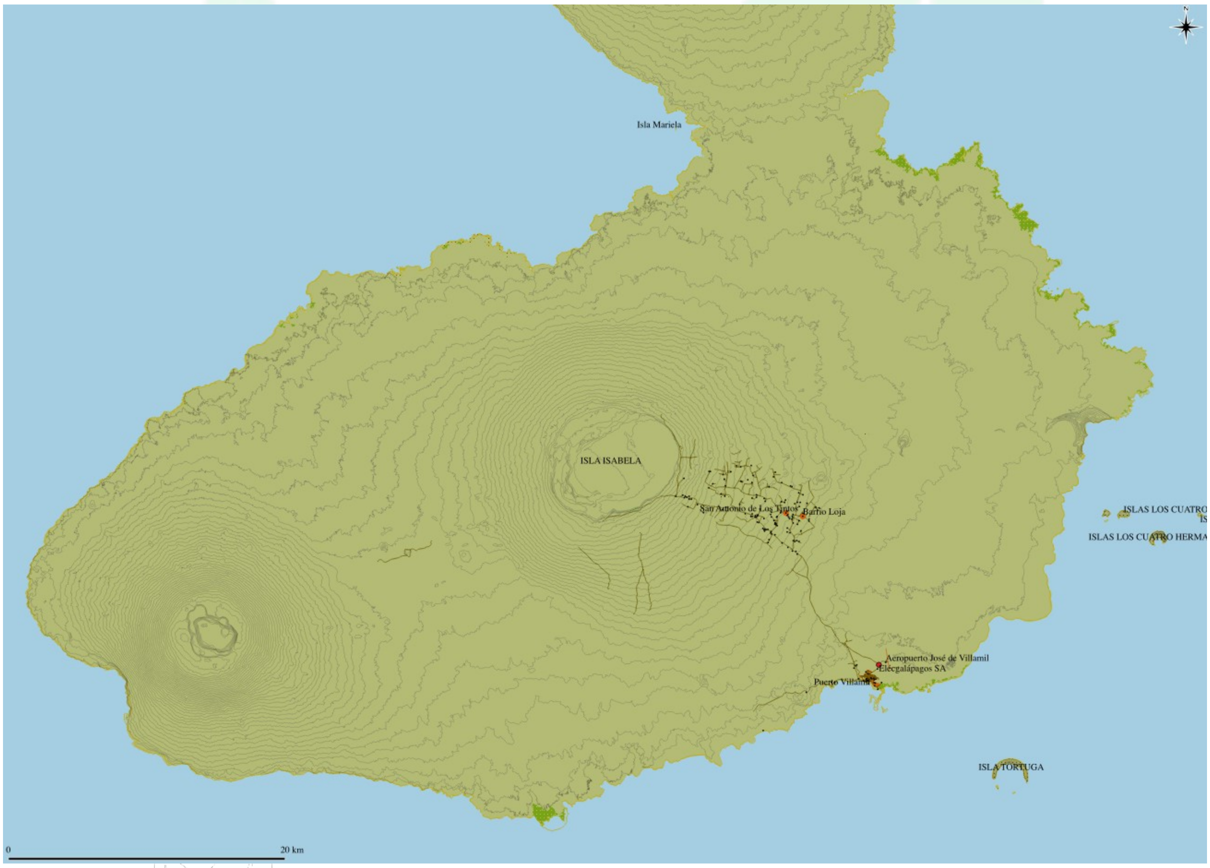
ISABELA ISLAND

It is the largest of all the islands, measuring 120 km long and greater in size than all of the other islands combined with an extension of 4 670 km^2.

One of the younger islands, Isabela Island was formed by the joining of six shield volcanoes; from north to south: Ecuador, Wolf, Darwin, Alcedo, Sierra Negra, and Cerro Azul. All of the volcanoes except Ecuador are still active. The western flanks of Ecuador Volcano have collapsed. Wolf Volcano, with an elevation of 1 707 m, is the highest point in the Galápagos Archipelago. Both Wolf and Ecuador Volcanoes lie directly on the equator. Isabela is one of the more volcanically active islands. Eruptions have been recorded in the last fifty years for Wolf Volcano (1963 and 1982), Alcedo (1993), Sierra Negra (1963, 1979, and 2005), and Cerro Azul (1959, 1979, 1998, and 2008). Isabela provides visitors with excellent examples of the geologic forces that created the Galápagos Islands, including uplifts at Urbina Bay, tuff cones at Tagus Cove, and pumice on Alcedo Volcano.

The majority of Isabela residents -*circa* 1 800- make their living by fishing, farming, and tourism. The center of population is on the southern coast at Puerto Villamil. Unlike the other large islands, the vegetation zones on Isabela do not follow the normal pattern. There are many relatively new lava fields and the surrounding soils have not developed sufficient nutrients to support the varied life zones found on other islands. In addition, the high elevations of Wolf and Cerro Azul Volcanoes reach above the cloud cover, resulting in an arid zone at the top of the island. It is home to more wild tortoises than all the other islands combined, with a separate species on each volcano. On the west coast of Isabela, the upwelling of the nutrient-rich Cromwell Current creates a feeding ground for fish, whales, dolphins, and birds.



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Topography of Isabela Island's southern edge

ENERGY SECTOR OF GALÁPAGOS

The electricity sector of Ecuador has been developing its infrastructure in order to provide the public electricity service under conditions that guarantee adequate continuity, quality and safety, under conditions of sovereignty, prioritizing the use of renewable energy sources, complemented with efficient thermal energy; and the latest technology, which consumes domestically produced fuel; as those as, ensuring the electrical stability of the system and maintaining adequate reserve margins to face even periods of marked drought. In what corresponds to the Galápagos Islands, have been developed the following projects: Baltra wind power, San Cristóbal wind power, Puerto Ayora photovoltaic and the use of biofuel -pine nut oil- at the Floreana Island power station. Currently, achieving 99.6% demand of the Islands[3].

In the province of Galápagos there are more than 25 thousand people[4], 83% are located in the urban area and 17% in the rural area. The annual population growth rate is 1.8%[5]. Regarding the public electricity service, the Galápagos Provincial Electric Company (ELECGALAPAGOS) as of December 2018 supplied around 51 132 MWh of electricity, to provide the service to more than 12 484 users.

The energy demand of commercial sector has the largest participation with 20 thousand MWh reaching 40% and a total of *circa* two thousand users; also, by residential sector with another 20 thousand MWh corresponding to around ten thousand users; the industrial and public lighting sector with 2 350 MWh corresponding to 4.60% and a total of 228 users. Other sectors representing more than five hundred entities, including water supply and other governmental institutions with nine thousand MWh demand. The demand of energy for the province of Galápagos by the year 2027, is estimated as 100 000 MWh powered by 18 MW capacity[6].

Generation Expansion Plan in the Galápagos Isolated System

In order to support the care of the ecosystems and the development of the Galápagos Islands, the need to incorporate sustainability criteria in the planning of the Electrical System of each one of the islands has become evident; spatially conformed by their protected areas (7 731 km^2) and populated areas (264 km^2).

The main guideline constitutes the impulse for the development of the sectors in a sustainable way; with the criteria of energy sovereignty and use of available renewable resources, in order to reduce the use of fossil fuels for electricity generation.

Therefore, the provision of a safe, reliable, quality, efficient and environmentally friendly service requires the implementation of plants with the most modern technological advances in non-conventional renewable generation, in order to contribute to the sustainable development of the insular region.

Initiative "Zero Fossil Fuels in Galápagos"

The Ecuadorian State maintains the environmental conservation of the Galápagos Islands as a policy, for this reason in 1986 the Government of Ecuador declared the Galápagos Archipelago a Biosphere Reserve and in 1990 a Whale Sanctuary. In 1998 the Organic Law of Special Regime for the Conservation and Sustainable Development of the Province of Galápagos was approved, where the Galápagos Marine Reserve was established, recognizing its ecological, cultural, educational, and economic value for the conservation and maintenance of unique species in the world. By 2001 Galápagos was included by the UN in the list of Natural Heritage of Humanity.

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[3] Ministerio de Energía y Recursos Naturales no Renovables, Plan Maestro de Electricidad, Capítulo 2 Transformación y Situación Actual del Sector Eléctrico.
[4] Estimated by Estadísticas INEC in 2015.
[5] Estimated by Estadísticas INEC in 2015.
[6] Ministerio de Energía y Recursos Naturales no Renovables, Plan Maestro de Electricidad, Capítulo 3 Estudio de la Demanda Eléctrica.

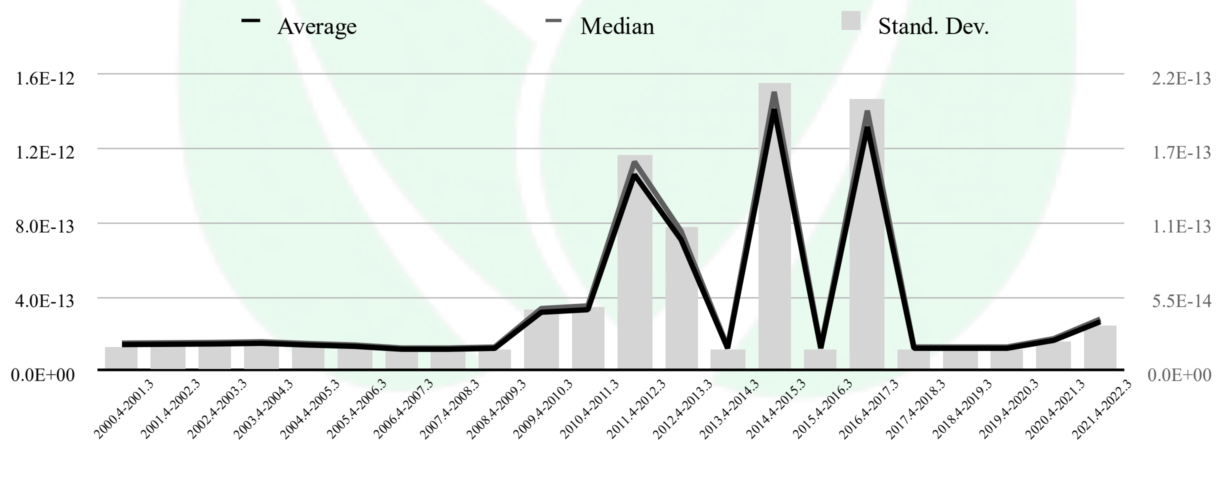
Nevertheless, the constant transportation of fossil fuels by sea to the Islands is endless risk with the probability of accidents and spills. Likewise, and due to the use of fossil fuels for electricity generation, harmful gases are emitted to the environment, causing health impacts to the local population, and significant environmental impacts in an area that has a high endemism that allows it to be separated as a unique biogeographic region, constituting a refuge for species. threatened and a tourist attraction.

Given the existing energy problems in the Islands, since 2007, the Government of Ecuador has been promoting the Initiative "Zero Fossil Fuels in the Galápagos", which sets out the objective of reducing the use of petroleum derivatives in this area of high environmental sensitivity and as an important part of the national conservation strategy of the Archipelago, in compliance with the commitments that the Ecuadorian State has assumed with the international community and its specialized organizations. For the execution of the initiative within the scope of its competence, the Ministry of Non-Renewable Energy and Natural Resources (MERNNR) in conjunction with the Empresa Eléctrica Provincial Galápagos S.A. (ELECGALAPAGOS S.A.) are designing and executing projects that aim to replace the generation electricity based on thermal energy of fossil origin by renewable energy based on solar, wind, hydraulic, biofuel and geothermal resources.

ATMOSPHERIC FEATURES IN THE GALÁPAGOS

Carbon monoxide emission

Carbon monoxide (CO) is a poisonous, odorless, and colorless gas. It is produced by incomplete combustion of fossil fuels, biomass burning, and the oxidation of methane and other hydrocarbons. CO is not a direct greenhouse gas; however, CO and other pollutants can affect tropospheric ozone, carbon dioxide, and methane. Thus, CO can have an indirect effect on climate.



Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_chm_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Carbon Monoxide and Ozone Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data, and Information Services Center (GES DISC), Accessed: July 8, 2023, 10.5067/WMT31RKEXK8I. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Carbon monoxide emissions (kg/m^2-s) in San Cristóbal Island

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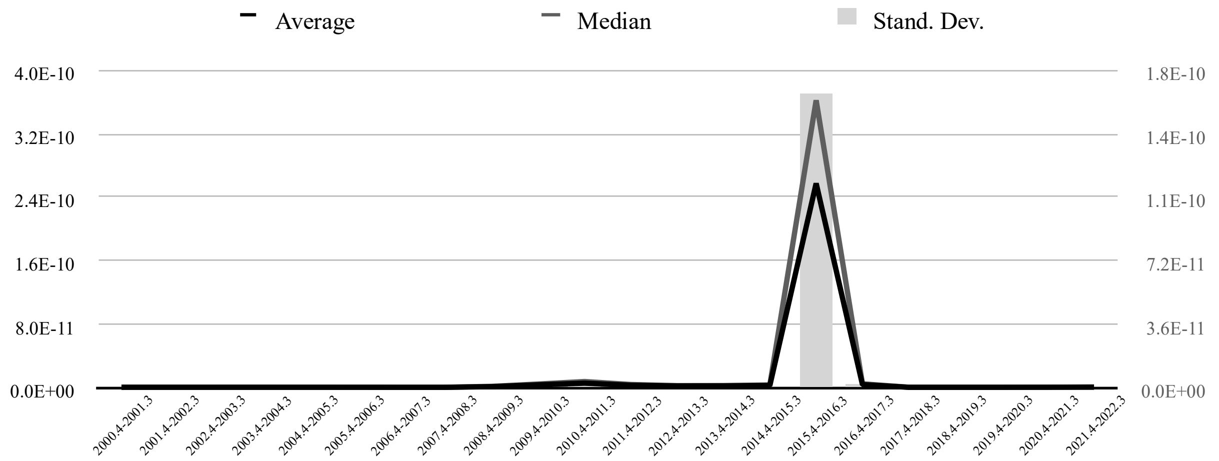

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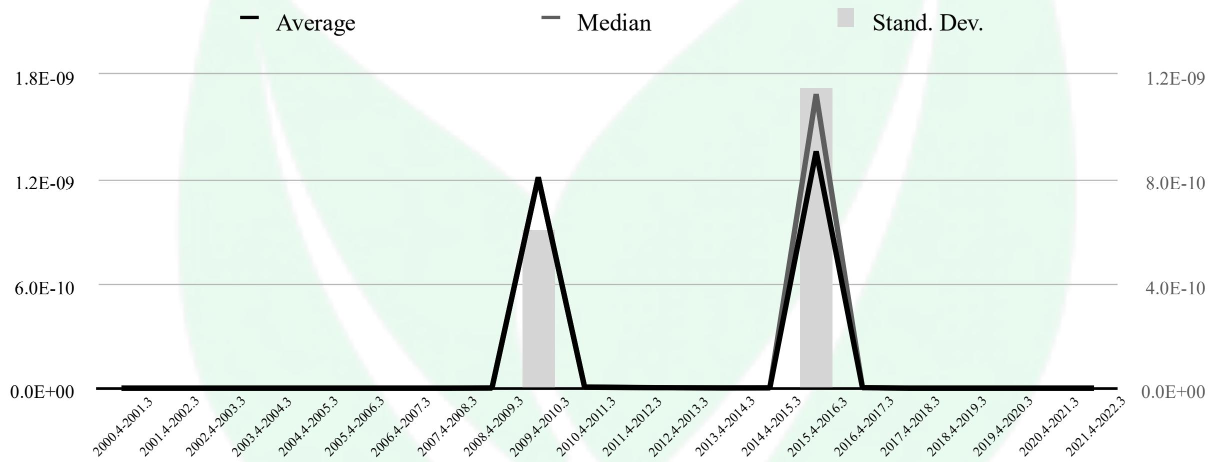
Carbon monoxide emissions (kg/m^2-s) in Santa Cruz Island

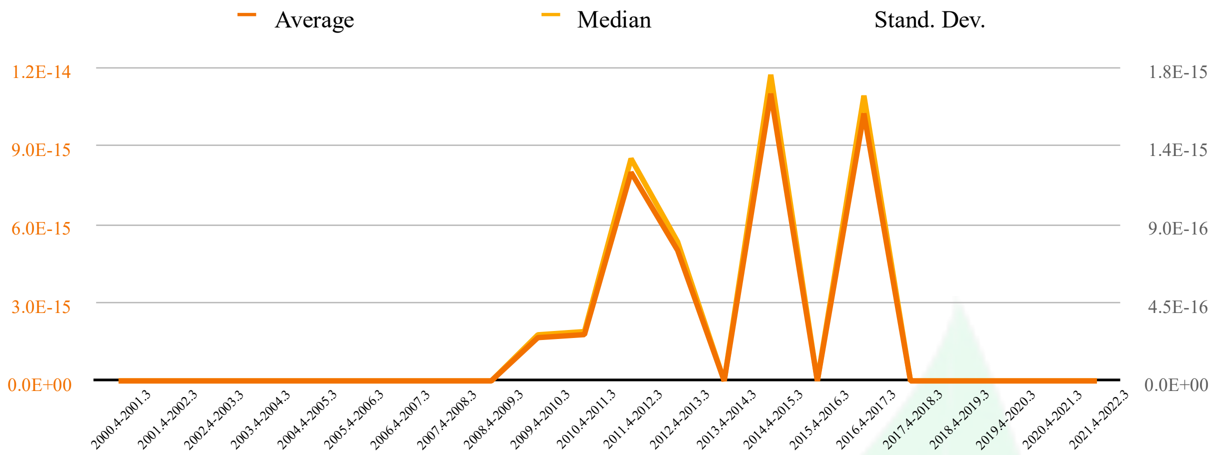


Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_chm_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Carbon Monoxide and Ozone Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data, and Information Services Center (GES DISC), Accessed: July 8, 2023, 10.5067/WMT31RKEXK8I. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Carbon monoxide emissions (kg/m^2-s) in Isabela Island

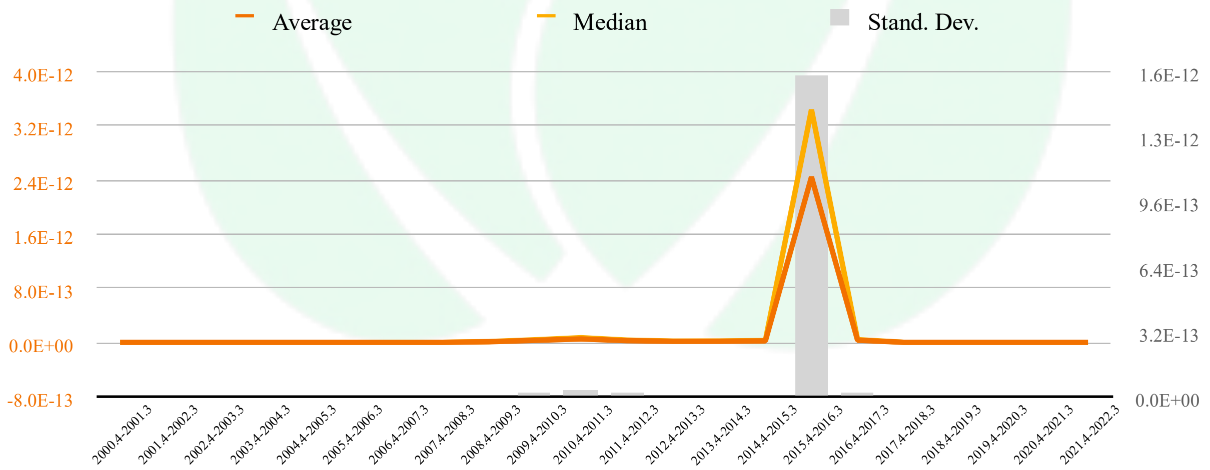
Sulfur dioxide burning biomass emissions.

Forest fires in sulfur-enriched soil areas maybe are driven the sulfur dioxide emissions in the Galápagos.



Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_adg_Nx: 2d, Monthly mean, Time-averaged, Single-Level, Assimilation, Aerosol Diagnostics (extended) V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data, and Information Services Center (GES DISC), Accessed: July 11, 2023, 10.5067/RZIK2TV7PP38. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Sulfur dioxide biomass burning emissions (kg/m^2-s) in San Cristóbal Island



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Sulfur dioxide biomass burning emissions (kg/m^2-s) in Santa Cruz Island

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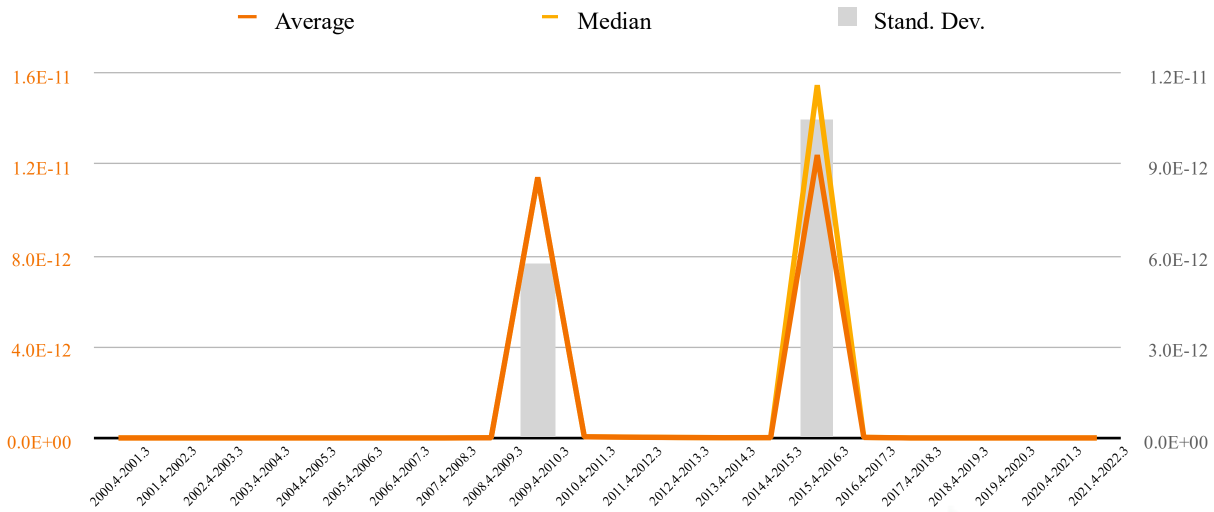

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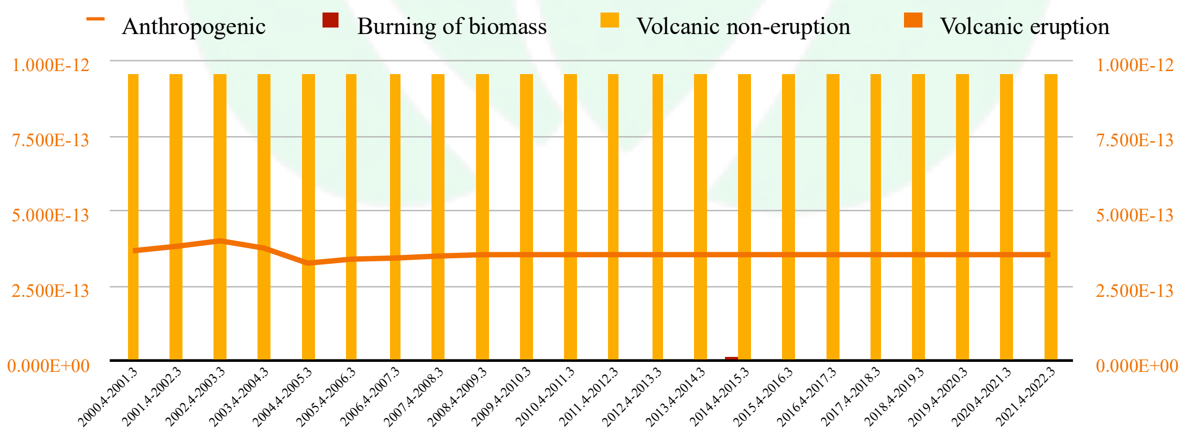
Sulfur dioxide biomass burning emissions (kg/m^2-s) in Isabela Island

As can be seen, the behavior of sulfur dioxide and carbon monoxide emissions are identical. Given the situation, it is possible to infer that both emissions are driven by the burning of biomass, such as forest fires.

Sulfur dioxide emissions: anthropogenic, volcanic, and burning of biomass

The atmospheric concentration of sulfur dioxide. It occurs naturally as a component of volcanic emissions, and is also produced by human activity, mainly the burning of fossil fuels containing sulfur.



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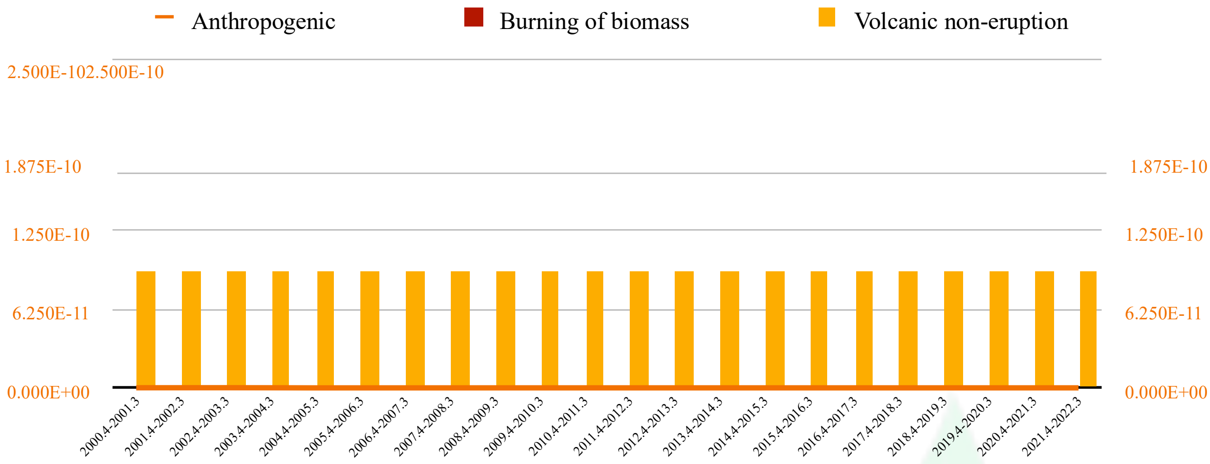
Sulfur dioxide emissions (kg/m^2-s) in San Cristóbal Island

Sulfur dioxide concentrations in San Cristóbal have been constantly affected mainly by volcanic emissions. These emissions are not necessarily those generated on the island, but from the neighboring islands, especially from Isabela.



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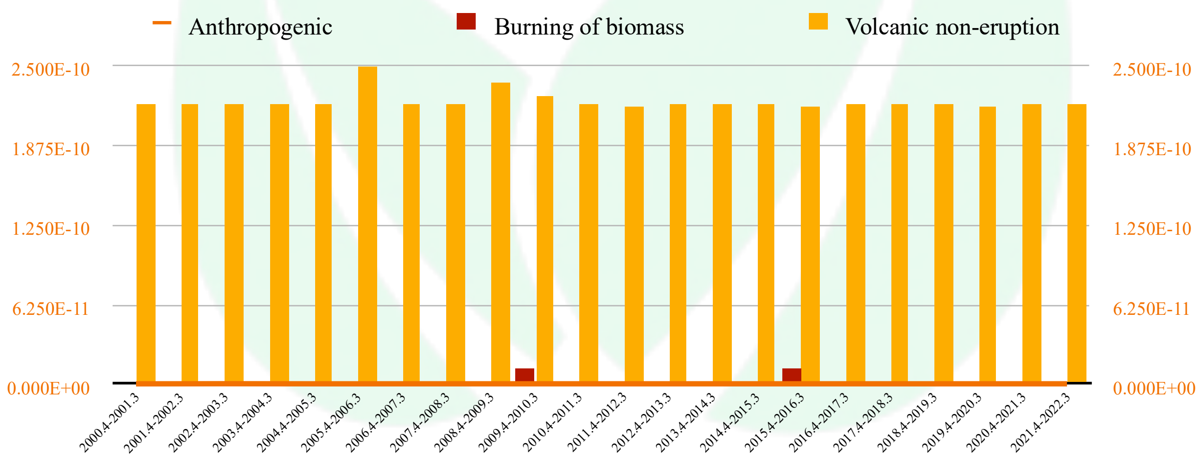
Sulfur dioxide emissions (kg/m^2-s) in Santa Cruz Island

In the same way as in San Cristóbal, volcanic emanations impact with high concentrations of sulfur dioxide. Due to the proximity to Isabela, relatively higher concentrations are observed.



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Sulfur dioxide emissions (kg/m^2-s) in Isabela Island

The highest concentrations of sulfur dioxide are observed in Isabela, evidencing the existence of active volcanoes on the island. Emissions due to biomass burning suggest they are generated by forest fires associated with volcanic eruption events.

The impact of anthropological origin is notorious only in San Cristóbal, being approximately half of that of volcanic origin.

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ENVIRONMENTAL PARAMETERS IN THE GALÁPAGOS

The government of Ecuador has designated 97% of the land area of the Galápagos Islands as the country's first national park (7 995.4 km^2). The remaining 3% is distributed between the inhabited areas of Santa Cruz, San Cristóbal, Baltra, Floreana and Isabela.

Although the islands are located on the equator, the Humboldt Current brings cold water to them, causing frequent drizzles during most of the year. The weather is regularly influenced by the El Niño events, which occur every three to seven years and bring warmer sea surface temperatures, a rise in sea level, greater wave action, and a depletion of nutrients in the water. This cycle can greatly affect the precipitation from one year to another. At Charles Darwin Station, the precipitation during the month of March in the particularly wet year of 1969 was 249 mm, but during March 1970 the next year it was only little bit more than one millimeter.[7]

Most of the Galápagos is covered in semi-desert vegetation, including shrublands, grasslands, and dry forest. A few of the islands have high-elevation areas with cooler temperatures and higher rainfall, which are home to humid-climate forests and shrublands, and montane grasslands (pampas) at the highest elevations. There are about 500 species of native vascular plants on the islands, including 90 species of ferns. About 180 vascular plant species are endemic. The islands are well known for their distinctive endemic species, including giant tortoises, finches, flightless cormorants, Galápagos lava lizards and marine iguanas, which evolved to adapt to islands' environments.[8]

Vegetation index

Vegetation refers to the ground cover provided by plants. The MOD13C2 Version 6 product of NASA provides a Vegetation Index value at a per pixel basis. There are two primary vegetation layers. The first is the Normalized Difference Vegetation Index (NDVI) which is referred to as the continuity index to the existing National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) derived NDVI. The second vegetation layer is the Enhanced Vegetation Index (EVI), which has improved sensitivity over high biomass regions.

The Climate Modeling Grid (CMG) consists of 3 600 rows and 7 200 columns of 5 600 meter pixels. In generating this monthly product, the algorithm ingests all the MOD13A2 products that overlap the month and employs a weighted temporal average. Global MOD13C1 data are cloud-free spatial composites and are provided as a Level 3 product projected on a 0.05 degree (5 600 m) geographic CMG. The MOD13C2 has data fields for the NDVI, EVI, VI QA, reflectance data, angular information, and spatial statistics such as mean, standard deviation, and number of used input pixels at the 0.05 degree CMG resolution.

Enhanced vegetation index correlations with precipitation and photosynthetically available radiation

Below are graphs correlating EVI with meteoric precipitation and photosynthetically available radiation (PAR). The values have been normalized to the average value of the observation period for each of the islands, in order to plot them on the same scale.

[7] Vinueza, L.; Branch, G.; Branch, M.; Bustamante, R. (2006). "Top-down herbivory and bottom-up El Niño effects on Galápagos rocky-shore communities". Ecological Monographs. 76 (1): 111–131. doi:10.1890/04-1957. S2CID 84748689.

[8] Source: "Galápagos Islands xeric scrub". Terrestrial Ecoregions. World Wildlife Fund.

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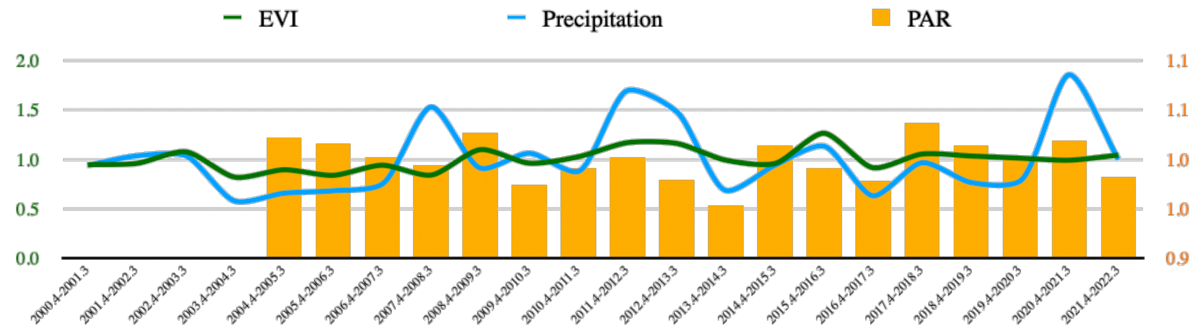
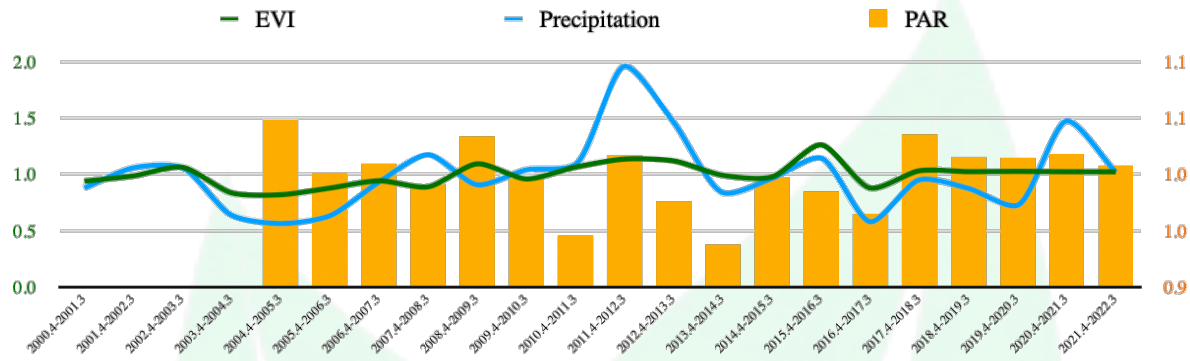
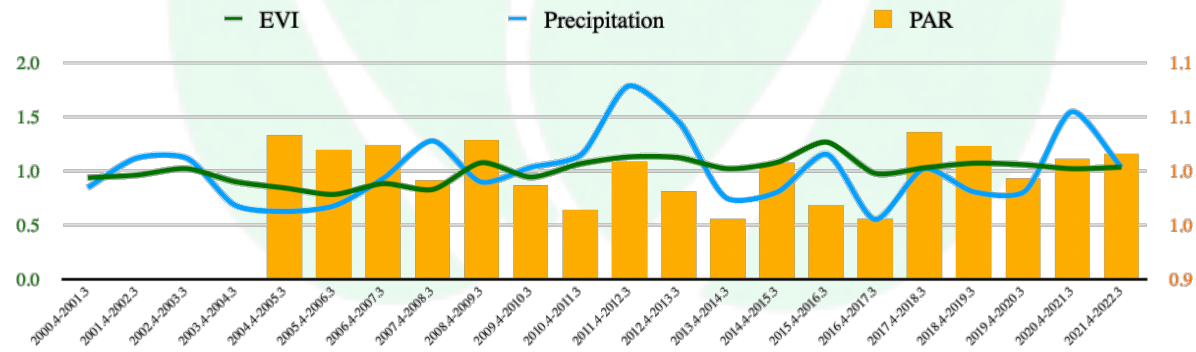


San Cristóbal Island



Santa Cruz Island



Isabela Island

Sources: 1) EVI: DOI: 10.5067/MODIS/MOD13C2.006; 2) Precipitation: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_flx_Nx: 2d,Monthly mean, Time-Averaged, Single-Level, Assimilation, Surface Flux Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July, 7 2023, 10.5067/0JRLVL8YV2Y4; 3) PAR: DOI: 10.5067/AQUA/MODIS/L3M/PAR/2022. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

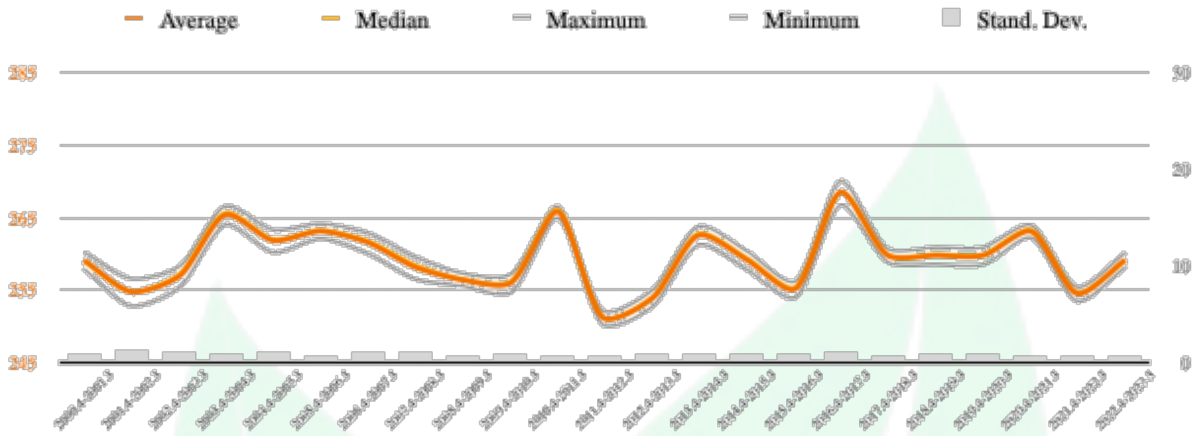
Correlation of EVI with Precipitation and Photosynthetically available radiation

Solar radiation

Net radiation is a measure of the difference between incoming solar radiation and outgoing radiation from the Earth's surface. Net shortwave radiation can be expressed by the amount of incident solar shortwave radiation absorbed on the earth surface per unit of area.

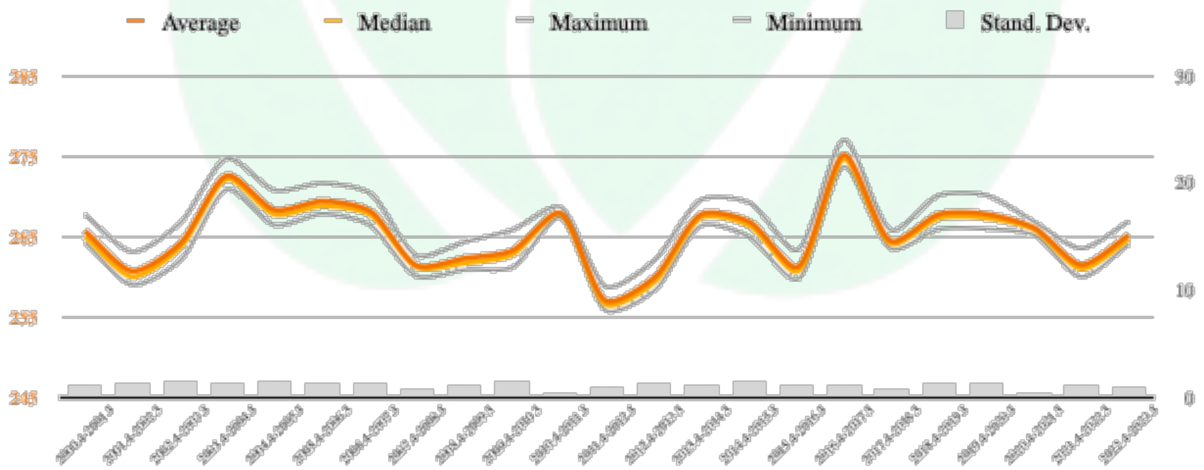
Photovoltaics are best known as a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons by the photovoltaic effect. The efficiency of the solar cells used in a photovoltaic system, in combination with latitude and climate, determines the annual energy output of the system.

The downward surface shortwave flux refers to the radiative energy in the wavelength interval (0.3 µm, 4.0 µm) reaching the Earth's surface per time and surface unit. It essentially depends on the solar zenith angle, on cloud coverage, and to a lesser extent on atmospheric absorption and surface albedo.



Source: Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Net downward shortwave radiation (W/m²) in San Cristóbal Island



Source: Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Net downward shortwave radiation (W/m2) in Santa Cruz Island

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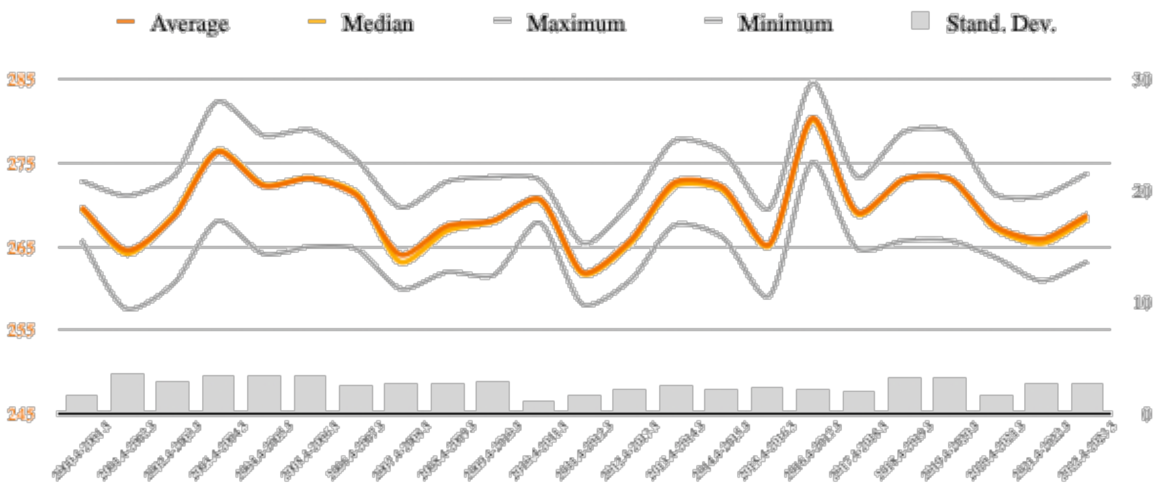


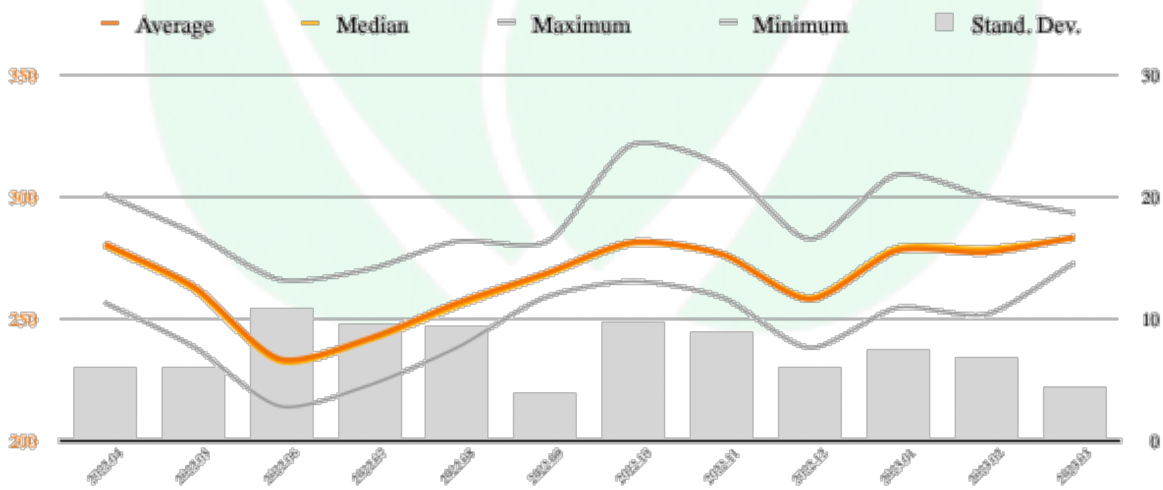
Source: Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Net downward shortwave radiation (W/m2) in Isabela Island

The graphs show the radiation values for annual periods between April and March of the following year between the years 2000 and the current in each island. The highest radiation values are observed on Isabela Island, possibly due to the heights of the volcanoes that are generally above the clouds.

Monthly behave of solar radiation

The following graph shows the behavior of solar radiation during the period April 2022 - March 2023, with the lowest values being observed in the month of June.



Source: Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Annual net downward shortwave radiation (W/m2) in The Galápagos

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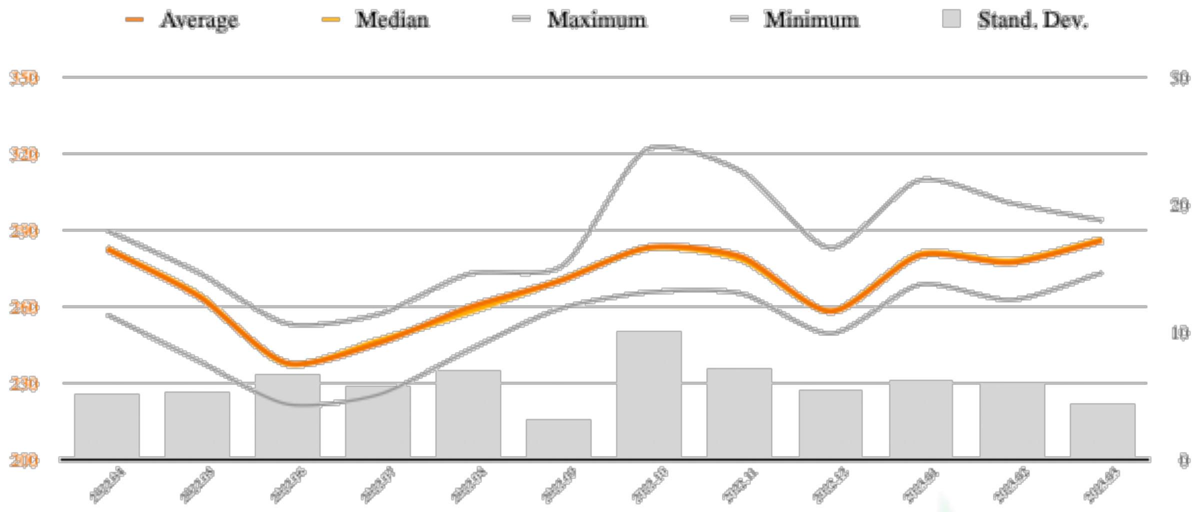


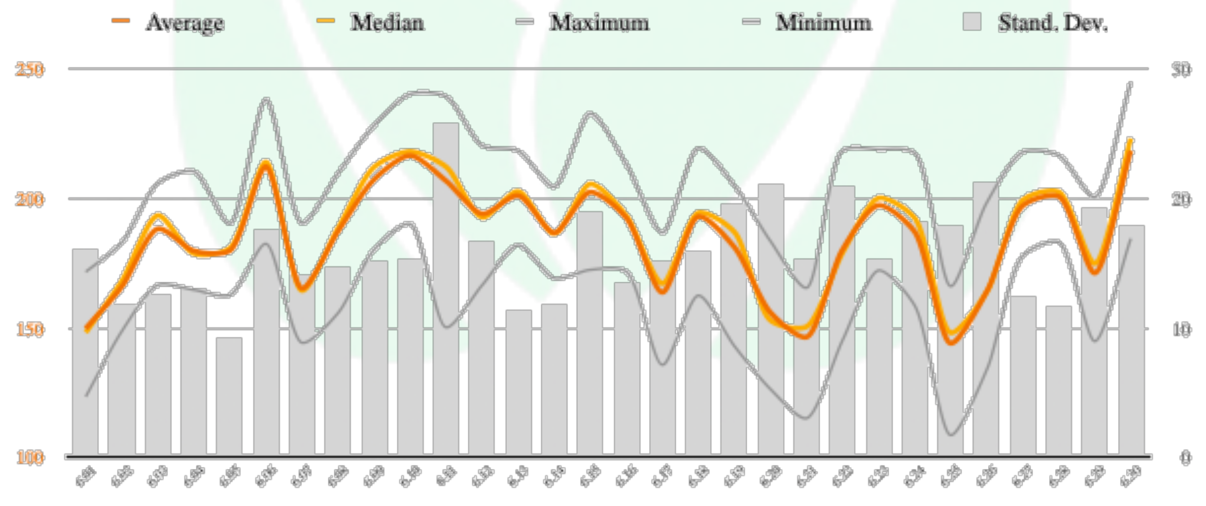
Source: Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Monthly net downward shortwave radiation (W/m2) in The Galápagos

In the case of the graph, corresponding to the annual period between April 2022 and March 2023, the average values were the minimum in the month of June. Below is the graph corresponding to daily values for the month of June 2023.

Daily behave of solar radiation

The minimum values of solar radiation in the month of June 2022 were observed on the 25th.



Source: Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Daily net downward shortwave radiation (W/m2) in The Galápagos

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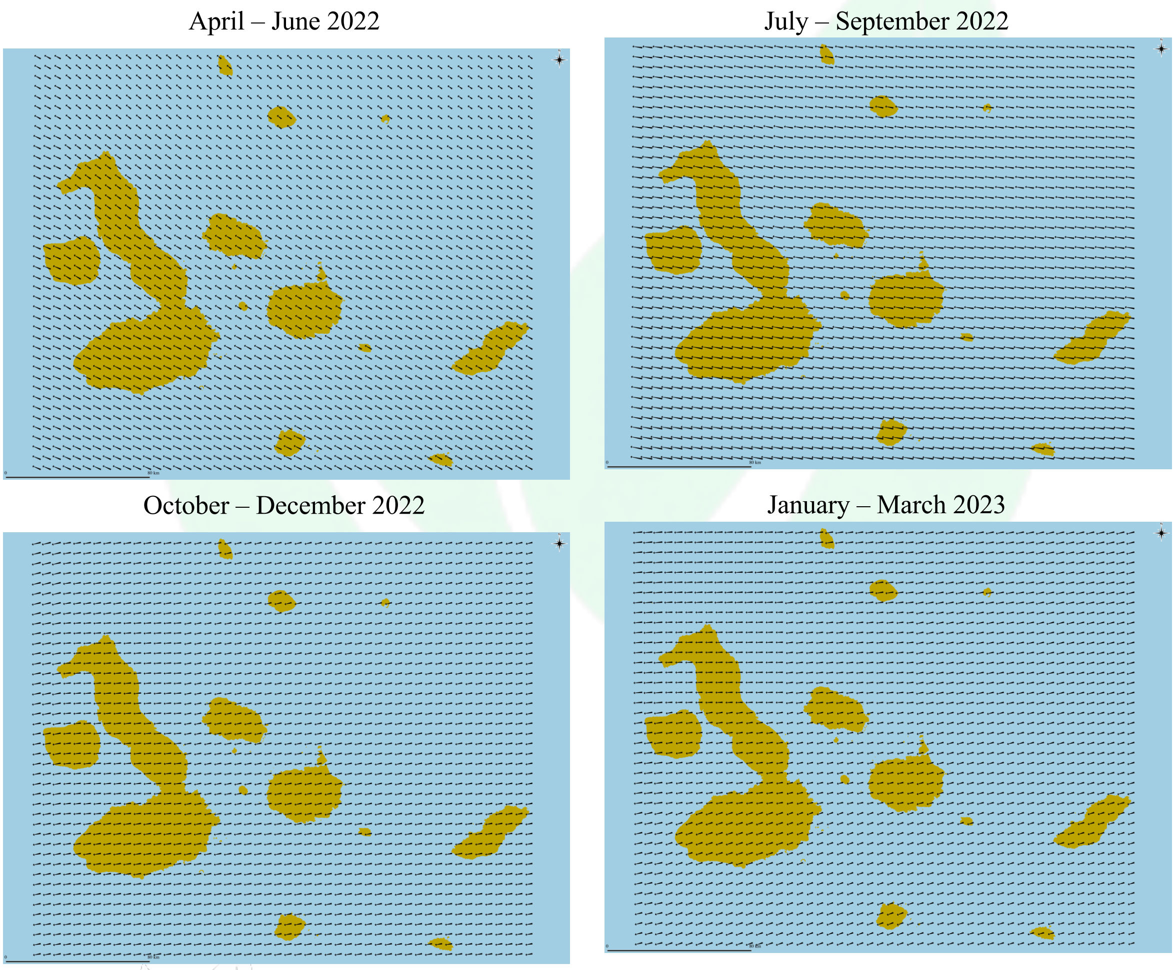
Wind direction and speed

Wind power is considered a sustainable, renewable energy source, and has a much smaller impact on the environment compared to burning fossil fuels. However, wind power is variable, and during low wind periods, it may need to be replaced by other power sources. Transmission networks presently cope with outages of other generation plants and daily changes in electrical demand, but the variability of intermittent power sources such as wind power is more frequent than those of conventional power generation plants.

Wind speed or wind velocity is a measure of the speed of air movement relative to a fixed point on the Earth. It expresses the strength of the horizontal movement of the air. Zonal wind is the wind component along the local parallel of latitude; meanwhile, Meridional wind is the wind component along the local parallel of longitude. Having these two parameters it is possible to compose wind direction and wind speed in a determined location.

M2TMNXSLV is a time-averaged 2-dimensional monthly mean data collection in Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). This collection consists of meteorology diagnostics at popularly used vertical levels, such as air temperature at 2-meter (or at 10-meter, 850 hPa, 500 hPa, 250 hPa), wind components at 50-meter (or at 2-meter, 10-meter, 850 hPa, 500 hPa, 250 hPa), sea level pressure, surface pressure, and total precipitable water vapor. MERRA-2 is the latest version of global atmospheric reanalysis for the satellite era produced by NASA Global Modeling and Assimilation Office (GMAO) using the Goddard Earth Observing System Model (GEOS) version 5.12.4. The dataset covers the period of 1980-present with the latency of ~three weeks after the end of a month.



Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_slv_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 14, 2023, 10.5067/AP1B0BA5PD2K. Processed with QGIS 3.10.

Wind direction and speed averages of the Galápagos computed for the period April 2022 - March 2023

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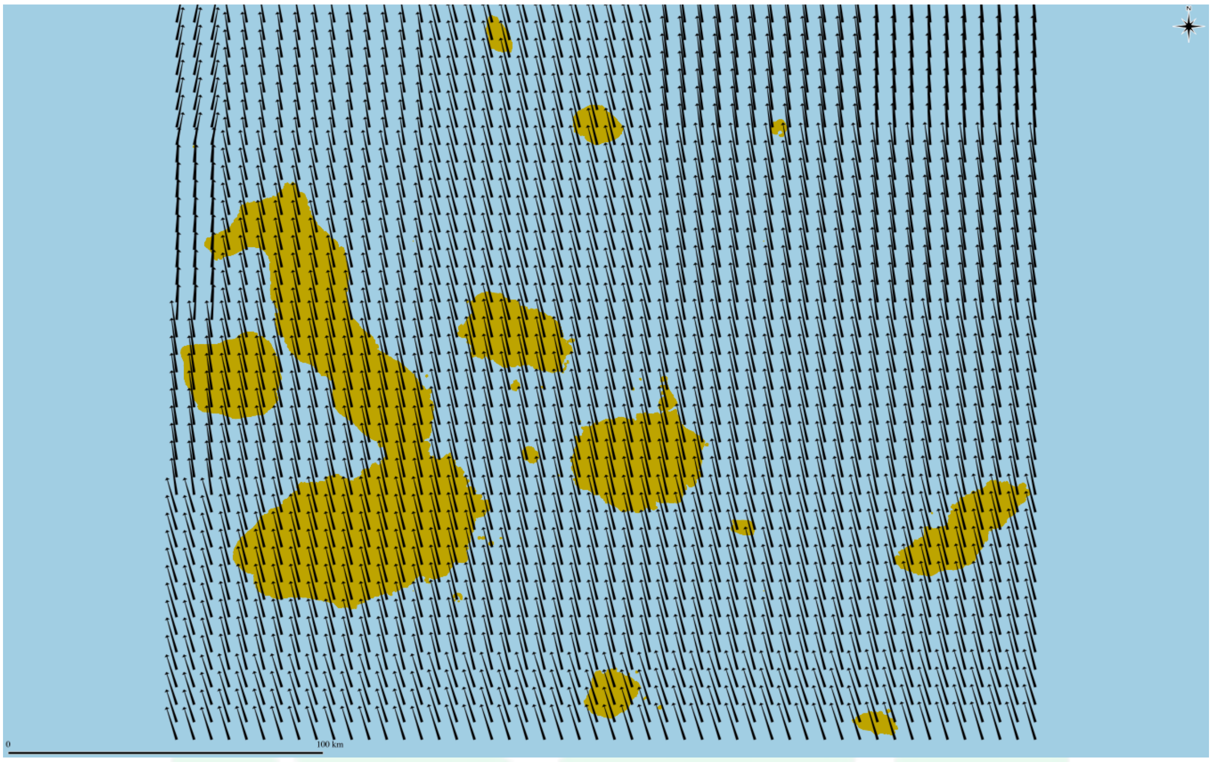
The graph shows the result of the simulation using data of eastward and northward wind speeds at a range of heights equivalent to 850 hPa. The size of the arrows are proportional to the value of the resulting speed at each point. 3-month time-averages are taken to plot the graphs. These simulations can also be performed for daily and hourly periods with historical data that can go back to the 1980s. As for the near surface wind speed, also 3-hourly measurements are available for further analysis.



Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_slv_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 14, 2023, 10.5067/AP1B0BA5PD2K. Processed with QGIS 3.10.

Wind direction and speed averages of the Galápagos computed for the day June 25, 2022

Wind speed/direction and net shortwave radiation flux

Below is the graph correlating the speed and direction of the wind and net shortwave radiation flux in Puerto Ayora registered on June 25, 2022. The values of wind direction and radiation are referred to on the secondary axis.

The fluctuation range of the wind speed oscillated between 4.7 to 7.2 m/s, around SE-NE direction.

Regarding solar radiation, its availability was for a period of approximately ten hours, with a maximum of 360 W/m^2.

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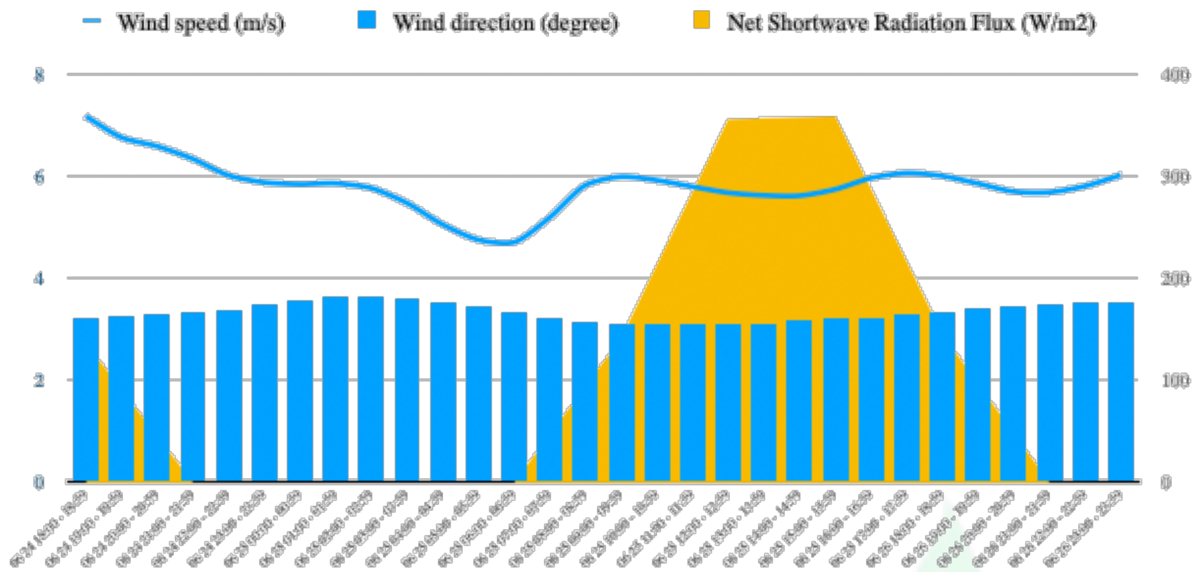


Sources: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_slv_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 14, 2023, 10.5067/AP1B0BA5PD2K. Amy McNally NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: July 22, 2023, 10.5067/5NHC22T9375G. NetCDF format data processed with QGIS 3.10 plugin Raster Analysis, Sampling Raster Values.

Wind speed (m/s)/direction and net shortwave radiation flux (W/m2) in Puerto Ayora (June 25, 2022)

GEOTHERMAL PROPERTIES

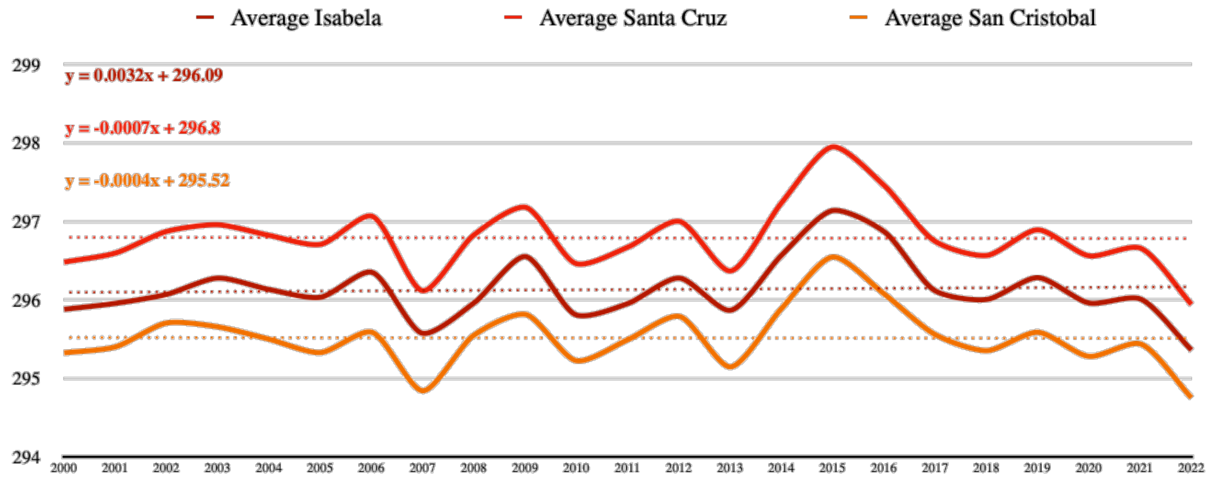
Soil Temperature

Geophysical exploration of geothermal resources deals with measurements on the physical properties of the earth. The emphasis is mainly on parameters that are sensitive to temperature and fluid content of the rocks, or on parameters that may reveal structures that influence the properties of the geothermal system. Thermal methods include direct measurements of temperature and/or heat, and thus correlate better with the properties of the geothermal system than other methods. Despite their limitations and their dependence on information from wells, thermal methods are important in geothermal exploration. They include mapping of thermal distribution at the surface based on soil temperature measurements in the uppermost meter.[9]

Average layer soil temperature is the depth-averaged temperature beneath the soil surface at a specified layer. These soil temperatures may contribute to the low frequency variability of energy and water fluxes. They are important measured quantities in analyzing of the ground heat flux, and then the energy and water cycles.

The following graph shows the soil temperatures at depth 100-200 cm, average values of the Isabela, Santa Cruz, and San Cristóbal islands. As can be shown, these behave paths are similar among the islands, been the highest values recorded for the Santa Cruz island, and the lowest at San Cristóbal. The temperature gaps are uniformly in a range of *circa* one grade (Kelvin). The tendency resulted in a biased path with slight increase for Isabela island; meanwhile, decrease tendencies for Santa Cruz and San Cristóbal islands.

[9] Georgsson, L.S. 2009. Geophysical methods used in geothermal exploration. United Nations University Geothermal Training Programme. Orkustofnun, Reykjavik, Iceland.

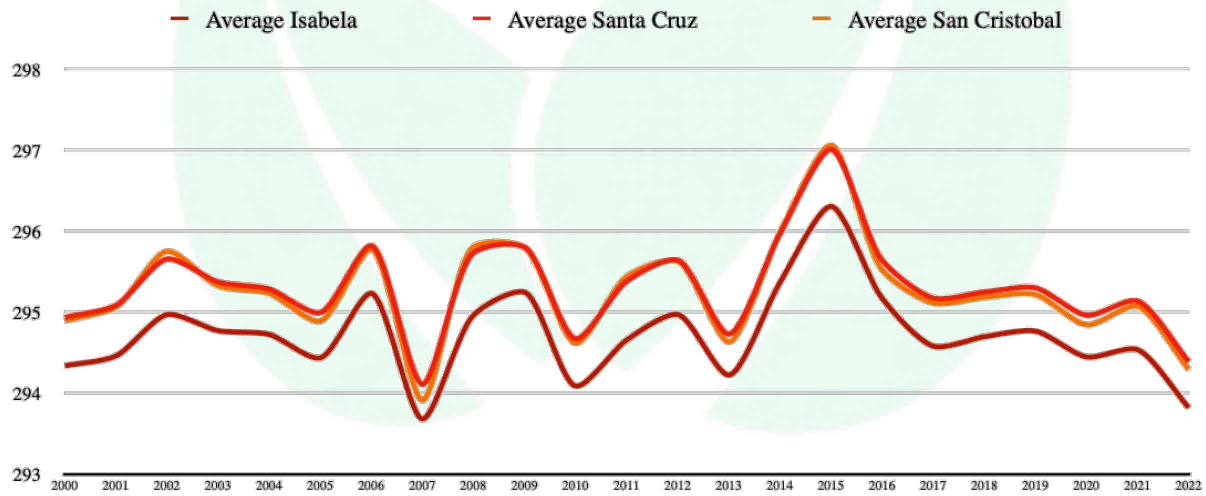


Source: Beaudoing, H. and M. Rodell, NASA/GSFC/HSL (2019), GLDAS Noah Land Surface Model L4 monthly 0.25 x 0.25 degree V2.0, Greenbelt, Maryland, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: August 1, 2023, 10.5067/9SQ1B3ZXP2C5. Processed with QGIS 3.10.

Soil temperature (K) annual averages at depth 100-200 cm

Surface air temperature

Air temperature is the measurement of the atmospheric kinetic energy at a given location in the atmosphere. The following graph shows the surface air temperature annual averages of the main three islands of Galápagos.



Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_flx_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Surface Flux Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: August 5, 2023, 10.5067/0JRLVL8YV2Y4. Processed with QGIS 3.10.

Surface air temperature (K) annual averages

As shown in the above graph, the surface air temperature of Santa Cruz and San Cristóbal islands behaved in the same path and equal values. With the same path but a degree lower behaved at Isabela island. Maybe the higher altitudes at Isabela influenced these behavior.

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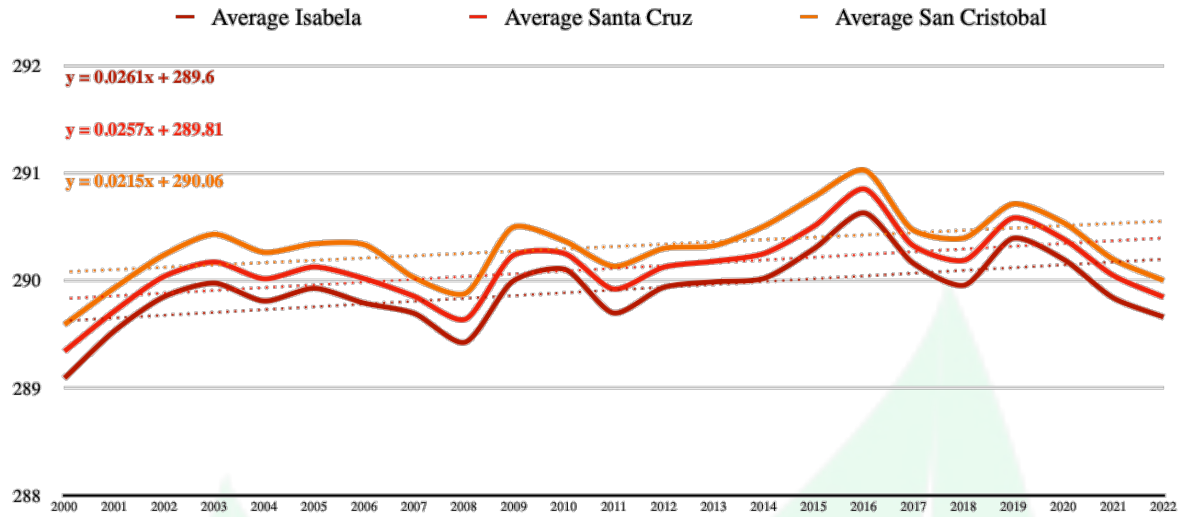
Air temperature at 850 hPa

The following graph shows the air temperature annual averages at altitude equivalent to 850 hPa for Isabela, Santa Cruz, and San Cristóbal islands.



Source: Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_slv_Nx: 2d, Monthly mean, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: August 6, 2023, 10.5067/AP1B0BA5PD2K. Processed with QGIS 3.10.

Air temperature (K) annual averages at 850 hPa equivalent altitudes

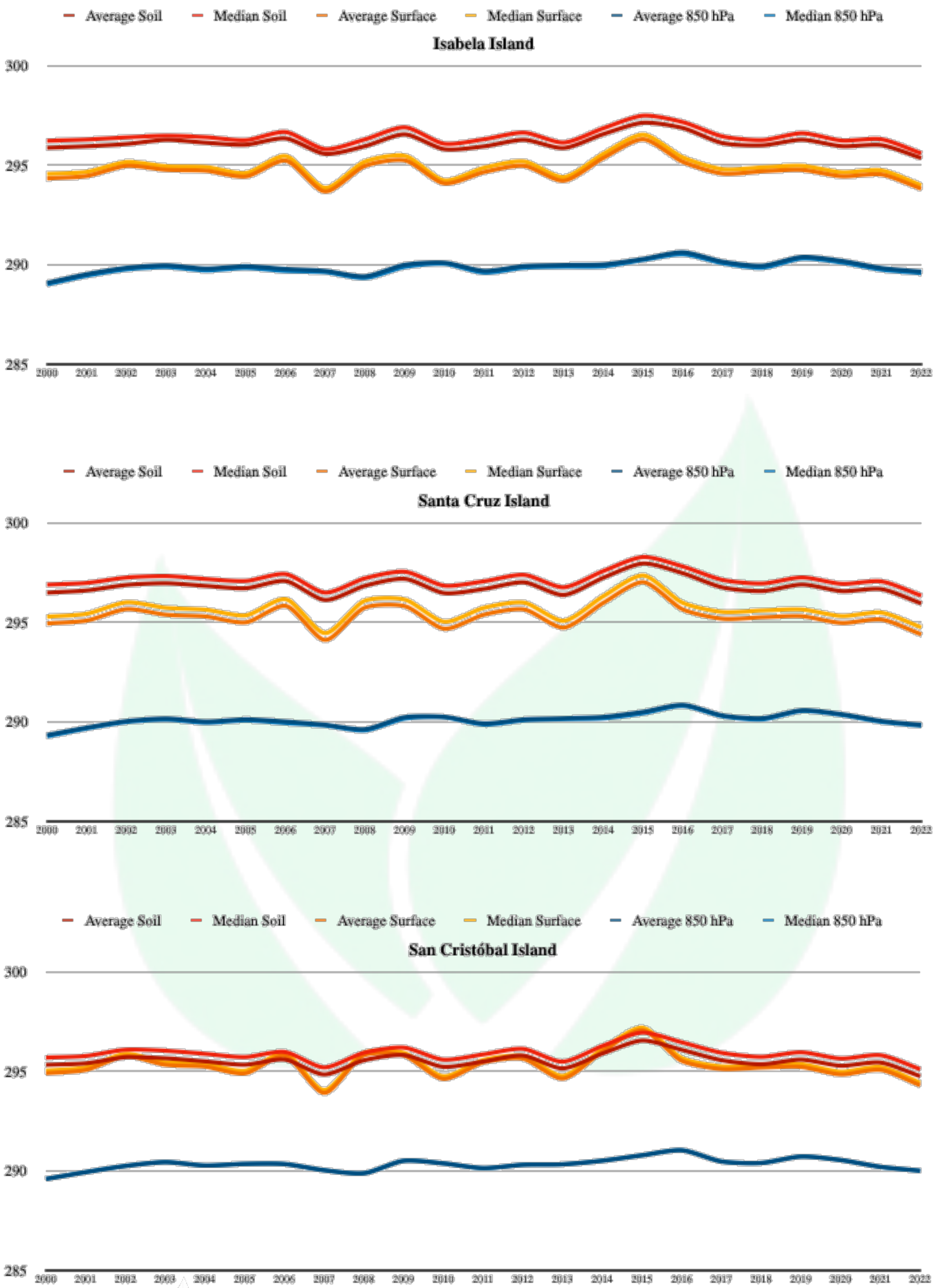
As can be shown in the above graph, all annual average values of air temperatures behaved in the same path. The higher values was observed for San Cristóbal island, and the lowest in Isabela island. Temperature increase tendencies are shown for all of three. However, a notorious decrease tendency is observed from year 2019.

Comparison among soil-, surface air-, and 850 hPa equivalent altitude air temperatures

In the below graph is shown the comparison of temperatures for each island correlating the behaves of soil temperature at 100-200 cm depth, surface air temperature, and air temperature at 850 hPa equivalent altitude.

The higher values are shown for uppermost soil layer temperatures, followed by surface air temperatures behaving with the same path of the former. These scenarios infer that surface air temperatures are driven by the beneath soil temperature. In the case of San Cristóbal island the gap between soil temperature and surface air temperature is minimum, showing a reversal behave in year 2015.

Much lower temperatures were observed for air temperatures at 850 hPa equivalent altitudes.



Sources: Beaudoing, H. and M. Rodell, NASA/GSFC/HSL (2019), GLDAS Noah Land Surface Model L4 monthly 0.25 x 0.25 degree V2.0, Greenbelt, Maryland, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: August 1, 2023, 10.5067/9SQ1B3ZXP2C5. Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavgM_2d_slv_Nx: 2d, Monthly mean, Time-Averaged, Single-Level,Assimilation, Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: August 6, 2023, 10.5067/AP1B0BA5PD2K. Processed with QGIS 3.10.

Soil-, surface air-, and 850 hPa equivalent altitude air temperatures (K)