



HAL
open science

Characterization of south central Pacific Ocean wind regimes in present and future climate for pearl farming application

Cyril Dutheil, Serge Andréfouët, Swen Jullien, Romain Le Gendre, Jérôme Aucan, Christophe E. Menkès

► To cite this version:

Cyril Dutheil, Serge Andréfouët, Swen Jullien, Romain Le Gendre, Jérôme Aucan, et al.. Characterization of south central Pacific Ocean wind regimes in present and future climate for pearl farming application. *Marine Pollution Bulletin*, 2020, 160, pp.111584. 10.1016/J.MARPOLBUL.2020.111584 . hal-03281920

HAL Id: hal-03281920

<https://hal.science/hal-03281920v1>

Submitted on 5 Sep 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Characterization of South Central Pacific Ocean wind regimes in present and future climate**
2 **for pearl farming application**

3

4 **Cyril Dutheil^{1,2,3}, S. Andrefouët¹, S. Jullien⁴, R. Le Gendre⁵, J. Aucan¹, C. Menkes¹**

5

6

7 ¹ Institut de Recherche pour le Développement, UMR 9220 ENTROPIE (Institut de Recherche Pour
8 le Développement, Université de la Réunion, Université de Nouvelle-Calédonie, Ifremer, Centre
9 National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New-Caledonia

10 ² IRD, LOCEAN (UMR 7159), BP A5, 98848 Nouméa cedex, New-Caledonia

11 ³ Present address: Department of Physical Oceanography and Instrumentation, Leibniz Institute for
12 Baltic Sea Research Warnemünde, Rostock, Germany.

13 ⁴ IFREMER, Univ. Brest, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS),
14 IUEM, Plouzané, France

15 ⁵ IFREMER, Unité de Recherche Lagons, Ecosystèmes et Aquaculture Durable, ENTROPIE (UMR
16 9220), BP 32078, 98897 Noumea Cedex, New-Caledonia

17 Corresponding author: Cyril Dutheil (cyril.dutheil@io-warnemuende.de)

18 **Abstract**

19 In the South Pacific (SP) pearl farming atolls, wind is the main driver of lagoon water circulation,
20 affecting dispersal and survival of pearl oyster larvae. To characterize typical wind conditions in the
21 SP, wind regime classifications are performed from regional climate simulations using the WRF
22 model, for present-day and for the end of the 21st century under RCP8.5 scenario conditions. At the
23 daily time-scale, 4 regimes are identified: a trade-wind, a north-easterly, and two easterly regimes.
24 Their characteristics are driven by large-scale circulation and climate modes of variability. In future
25 projection, all regimes are characterized by a ~15% wind speed increase, while directions and
26 occurrence frequencies undergo marginal changes. At the monthly time-scale that corresponds to
27 pearl oyster pelagic larval duration, nine wind regimes are determined including three regimes with
28 wind reversals. These regimes can be used to model typical lagoon conditions during larval dispersal.

29

30 **Keywords:** South central Pacific atolls, weather regime, surface wind conditions, pearl farming,
31 climate change.

32

33 **Highlights:**

- 34 • Wind is one of the main drivers of atoll lagoon circulation and larval dispersal
- 35 • Four wind regimes are identified at day-scale based on 10m u-v wind components
- 36 • 30-day long regimes characterize lagoon conditions during larval dispersal
- 37 • Climate change could increase wind speed by 15% in the South Central Pacific

38 **1. Introduction**

39 The high islands and low-lying atolls of the Pacific Ocean host a large amount of biodiversity
40 as well as several human production activities (e.g. fisheries, aquaculture, pearl farming) which are
41 particularly affected by the natural variations of the atmospheric and oceanic conditions. Thus far,
42 much work has been devoted to monitor and study the evolution of sea surface temperature (SST)
43 and air temperature in tropical islands because these parameters are well measured by routine sensors
44 and have a direct effect on the physiology of organisms. For instance, changes in biodiversity patterns,
45 occurrences of coral bleaching and spread of marine diseases have been linked to SST variations (e.g.
46 Harvell et al., 2002; Van Wynsberge et al., 2017a; Claar et al., 2018). In deep and shallow tropical
47 lagoons, wind is one of the main drivers of water characteristics (temperature, residence time,
48 plankton concentration, etc...), biological communities' processes (e.g., pearl oyster population
49 spawning, Fournier et al., 2012) and physical circulation (Lowe and Falter, 2015; Thomas et al.,
50 2011). In atolls with a high degree of aperture to the ocean, remote oceanic waves and tides may also
51 have a strong influence (Lowe and Falter, 2015). Conversely, when atolls are closed or semi-closed
52 by high elevation rims, their lagoons are then far less influenced by remote hydrodynamics (Dumas
53 et al., 2012; Van Wynsberge et al., 2017b) and wind remains the main driver. On one hand, strong
54 wind can generate local lagoon waves, whose effects on biological communities can range from
55 beneficial to destructive. On the other hand, the absence of wind on several atolls during periods of
56 days to weeks have led to dystrophic and massive mortality events primarily due to poor water
57 renewal, stratification and anoxia (Andréfouët et al., 2015).

58 In a pearl farming context, especially in French Polynesia and Cook Islands, productive atolls
59 are closed or semi-closed, and wind conditions are a determinant factor of the spat collection success
60 and, henceforth, of the sustainability of the pearl farming activity (Andréfouët et al., 2012). Indeed,
61 black-lipped pearl oyster, *Pinctada margaritifera*, larval growth and dispersal (Thomas et al., 2012,
62 2014, 2016) vary with wind, as the latter influences not only larvae movements but also the planktonic
63 food dynamics. When these larvae are collected for mariculture purposes, wind conditions can partly
64 explain differences between productive and unproductive locations and periods. The characterization
65 of present-day and future wind regimes in French Polynesia and Cook Islands is thus a critical piece
66 of information to understand the past and future rates of spat collections.

67 A method commonly used to characterize the regional wind conditions is a classification in
68 weather regime (WR, e.g. Hopuare et al., 2019; Lefèvre et al., 2010). A WR can be defined as a large-
69 scale atmospheric structure that appears recurrently in the study area, and induces recurrent local
70 conditions. As they characterize robust yet simplified wind patterns, they have been used for example
71 to study typical fish larval dispersion in the New Caledonian lagoon (Cuif et al., 2014). In addition,

72 three recent studies (Hopuare et al., 2019; Lorrey and Fauchereau, 2018; Specq et al., 2019) have
73 characterized regional WRs in the South Pacific, and studied how the large-scale signals of the
74 Madden-Julian Oscillation (MJO) and El Niño Southern Oscillation (ENSO) modulate the frequency
75 of occurrence of these WRs. These three studies each considered a different spatial domain, but none
76 of them covered all of the atolls of French Polynesia and Cook Islands. In a pearl farming context,
77 Thomas et al. (2014) used a classification method in WR to characterize the 1979-2011 wind
78 conditions on the Ahe atoll in the North Tuamotu Archipelago of French Polynesia (Fig. 1a). They
79 subsequently simulated different scenarios of larval dispersal and connectivity for *P. margaritifera*.
80 However, no additional atoll has yet been studied to our knowledge.

81 The present study aims to investigate the WRs that affect all Polynesian central Pacific atolls
82 at different spatial and temporal scales, with a focus on those hosting pearl farming activities (Fig.
83 1a), and to understand what may be their fate in future climate. Eventually, the assessment of the
84 impact of wind patterns and changes on pearl farming activities requires a model of each lagoon
85 hydrodynamics, which is beyond the scope of the present study (but see Dumas et al 2012, Thomas
86 et al. 2016, and Le Gendre et al. this issue for selected atolls). Here, the scope is regional, and typical
87 weather conditions and their climate variability (ENSO, climate change) are identified. This aims to
88 improve our knowledge of the South Central Pacific wind regimes, and to provide the forcing
89 conditions for future lagoon-dedicated hydrodynamic studies. Within this scope, pearl farming sets
90 the time frame during which wind regimes are relevant. This time frame ranges from 1 day to 30
91 days. Weather can trigger spawning and control larval dispersal during a maximum pelagic larval
92 duration (PLD) time, thus considered here to be 30 days, following Thomas et al. (2014) and Sangare
93 et al. (2020).

94 In the present study, we use a methodology similar to Hopuare et al., (2019) and Specq et al.,
95 (2019) to calculate WRs, but we considered all the South-central Pacific, and projected the present-
96 day WRs into future conditions. To that end, regional atmospheric simulations are performed with the
97 Weather Research and Forecast (WRF) model for present day, and for the end of the 21st century
98 under RCP.8.5 scenario. As climate models are known to have strong biases in the South Pacific
99 region, bias correction methods are applied to reduce the uncertainties of simulations (Dutheil et al.,
100 2019, 2020; Li et al., 2016). We first describe in section 2 the general features of the South Pacific
101 climate and the state of the art of its future projections. The experimental design and the statistical
102 methods for WR classification are described in section 3. In section 4, we describe and validate the
103 present-day WRs at the daily scale, and discuss their projection in the future. The relation between
104 WRs at the monthly and daily time- scale is given in section 5. Finally, in section 6 we discuss our
105 results against previous studies, and highlight perspectives for lagoon modelling.

106 **2. Background on the South Pacific climate**

107 Large-scale weather and climate conditions in the South Pacific (SP) have been widely studied
108 in recent decades (e.g. Brown 2020), and only their main features are summarized here. In the SP, the
109 thermal balance between the equator and the subtropics combined with the Earth rotation produces
110 an east-south-easterly mean flux (Fig. 1b). This large-scale circulation is modulated by the position
111 and intensity of the South Pacific High located around Easter Island, and the low pressure system of
112 the equatorial western Pacific (denoted by the white pressure contours and indicated by “H” and “L”
113 respectively in Fig. 1b). The SP also exhibits the most intense convergence zone of the Southern
114 Hemisphere named the South Pacific Convergence Zone (SPCZ). The SPCZ is a rainfall band
115 diagonally-oriented (northwest to southeast, see pink contour in Fig. 1b), which stretches from Papua
116 New Guinea to French Polynesia, and modulates the low-level circulation according to its position
117 and intensity (e.g. Vincent, 1994; Brown et al., 2020). The SPCZ intensity and position are themselves
118 modulated by many oscillations at different time scales such as seasons, El Niño-Southern Oscillation
119 (ENSO), or the decadal oscillation (e.g. Vincent et al., 2011, Brown et al., 2020). For instance, during
120 extreme El Niño events, the SPCZ undergoes an equatorward swing of up to ten degrees of latitude
121 and collapses to a more zonally oriented structure (e.g. Cai et al., 2012; Vincent et al., 2011),
122 conducting to very different weather conditions in the South central Pacific, such as an increase of
123 potential of tropical cyclone genesis around French Polynesia (Vincent et al., 2011).

124

125 In addition to SPCZ variations, anthropogenic forcing is projected to modify the meridional
126 thermal balance of the Earth with a heterogeneous global warming pattern. At the Pacific Ocean scale,
127 the equator is expected to become warmer than the tropical South Pacific (e.g. Collins et al., 2010;
128 Grose et al., 2014), inducing changes in the projected SP circulation and precipitation (e.g. Cai et al.,
129 2012; Dutheil et al., 2019; Widlansky et al., 2013). Nevertheless, at the local scale, the SST warming
130 pattern from the Coupled Model Intercomparison Project (CMIP) models remains uncertain,
131 especially in southwestern Pacific. Indeed, Li et al. (2015, 2016) showed that the typical “cold tongue
132 bias” found in the CMIP models is associated with insufficient mean precipitation and clouds over
133 the western Pacific warm pool (Fig. 2a), which results in an underestimation of the convective
134 feedback and an excessive SST warming response in the equatorial western Pacific. Li et al. (2016)
135 then developed a statistical method to correct the SST bias, which is applied in this study and shortly
136 explained in section 3.1. Previous works, that have studied the SPCZ changes under future climate
137 scenarios using an SST bias-correction method, have shown a likely drying of the SPCZ with an
138 increase of wind speed in the south central Pacific due to an increase of moisture divergence in
139 response to the changes in SST (Dutheil et al., 2019, Widlansky et al., 2013). On top of these
140 uncertainties on SST projections, the changes in SPCZ interannual variability need to be taken into

141 account. Using a large set of global climate models, Cai et al., (2012) showed a possible strong
142 increase (+81%) of “zonal SPCZ” events (*i.e.* shift of the eastern part of SPCZ towards the equator,
143 which drastically modifies the large-scale circulation) due to anthropogenic forcing, although
144 regional studies with atmospheric models did not reproduce these results (Chung and Power, 2016;
145 Evans et al., 2016; Dutheil et al., 2019). In this study we used a regional dynamical framework that
146 realistically simulates the SPCZ orientation and intensity in present-day conditions, and that projects
147 a significant drying (-25%, see Fig. 6 in Dutheil et al., 2019 or here with the contours in Fig. 2bc) in
148 the south central Pacific region associated to an increase of moisture divergence dominated by
149 changes in large-scale circulation.

150

151 **3. Material and Methods**

152 **3.1 Regional model configuration and experimental design**

153 The atmospheric modeling framework used here is fully detailed in Dutheil et al., (2020). A
154 brief summary is given here. We used the Weather Research and Forecasting (WRF) Model version
155 3.6.1 (Skamarock and Klemp, 2008) with a parent domain at 105 km resolution that encompasses the
156 tropical Pacific region [101°E-59°W; 26°N-42°S]. A two-way nested domain over the South-West
157 (SW) Pacific [145°E-130°W; 32°S-2°S] with an increased resolution of 21 km is included (see Fig.
158 1b). Both domains share the same 32 vertical levels.

159 A present-day (PD) simulation is first performed over the 1980-2016 period (37 years).
160 Surface and lateral boundary conditions for the parent domain are prescribed from the 6-hourly
161 outputs of the NCEP2 reanalysis (Kanamitsu et al., 2002).

162 To assess the WR response to anthropogenic forcing, we also perform a climate change (CC)
163 simulation. This simulation is conducted by prescribing monthly anomalies for surface (SST) and
164 lateral (wind velocity, air temperature, humidity and geopotential height) boundaries from the CMIP5
165 projections under the RCP8.5 scenario for the late twenty-first century. These future anomalies are
166 computed as the difference between the 2080-2100 and 1989-2009 periods of multi-model mean
167 monthly climatology from 31 CMIP5 models. This method is sometimes referred to as the pseudo-
168 global warming (PGW) approach (Dutheil et al., 2019; Zhang et al., 2016). With this process, the
169 synoptic and interannual variability at the boundaries keeps the same phase and amplitude as the PD
170 simulation. In addition, as the SST warming pattern from the CMIP models remain uncertain
171 especially in the SW Pacific with a typical “cold tongue bias”, the SST projection bias is corrected
172 according to Li et al. (2016) statistical method, named “emergent constraint” method. It consists in a
173 correction of the SST anomaly projection based on the linear relationship between the historical

174 precipitation bias and the SST warming in the equatorial western Pacific in CMIP5 models (Fig. 2b).
175 This correction increase the meridional and zonal gradient of SST warming (Fig. 2cd), and allows to
176 reduce the inter-model (CMIP5) spread in SST warming, and is supposed to improve the reliability
177 of SST warming pattern projections. This strategy is fully explained in Li et al. (2016), and was
178 applied by Dutheil et al. (2019, 2020) to assess changes in the SPCZ and SP tropical cyclone activity.

179

180 **3.2 Identification of regional weather types by clustering**

181 WRs are identified in a large domain around the targeted atolls [165°W-130°W;25°S-9°S]
182 (blue box in Fig. 1b) using statistical classification methods. To that end, daily average of the 10-m
183 zonal and meridional wind components (u,v), hereafter referred as surface winds, are computed from
184 the WRF simulation for the 37 available years (from January 1980 to April 2016), thus including
185 13270 consecutive days. The data are first normalized and standardized using their mean and standard
186 deviation computed over the 37-year period; then two classifications are performed: a first
187 classification to extract the main WR patterns at the daily scale over the area of interest; and a second
188 classification to determine typical 30-day sequences of weather events that can impact pearl oyster
189 larvae growth and dispersal.

190 In order to extract the main modes of spatial variability of surface winds, we first perform a
191 principal component analysis (PCA; Jolliffe, 2011) on the 13270 days of u and v data, each day of
192 (u,v) being treated as an individual for the PCA. The twenty-first principal components are kept,
193 representing 95% of the cumulative total variance. In that reduced space, the 13270 days are then
194 classified using the k-means classification algorithm (Diday, 1971) to determine wind patterns (or
195 regimes). This classification is referred hereafter as the ‘daily classification’.

196 A second type of classification is performed to analyze sequences of 30 consecutive days
197 instead of individual days. The 30-day length corresponds to the generally agreed maximum PLD for
198 *Pinctada margaritifera* (Thomas et al., 2011, 2014). As the average persistence of daily WRs is
199 between 3 and 6 days (Fig. 5a), the 30-day sequences are separated by 10 days, similarly to Thomas
200 et al. (2014). This ensures to avoid double counting an event, and to limit the gaps between sequences,
201 which might miss events. The same type of classification described above is then performed. Each
202 30-day sequence of (u,v) maps is considered as an individual. First, a PCA is performed on the 1337
203 30-day sequences to identify the main modes of spatial variability. The 30 first principal components,
204 representing 70% of the cumulative total variance, are then kept to perform the k-means classification.
205 This second classification is named the “30-day classification”.

206 One of the limitations of the k-means clustering algorithms is that they require to define *a*
207 *priori* the number of clusters (k), and many methods have been developed to determine the optimal

208 number of clusters. The 'NbClust' function in factoextra R package allows comparing 26 of these
209 methods, the reader could refer to Charrad et al., 2014 for a complete description of all these methods.
210 The number of clusters kept in each approach (*i.e.* daily or 30-day classification) corresponds to the
211 consensus between these 26 methods (Fig. 3).

212 Finally, to infer WRs in the future, two options are possible. First, the future WRs can be
213 determined by projecting the future conditions on the present WR clusters, or the future WRs can be
214 computed from future conditions, independently from present WRs, by clustering future conditions.
215 The first option allows looking at how the future wind conditions may shift from a given prevailing
216 regime to another, with respect to the present day conditions, but it will not show the future typical
217 weather regimes unless one assumes that the regimes are stationary. This assumption is unlikely
218 because an evolution of large-scale tropical fields is expected due to climate change (Dutheil et al.,
219 2019; Gastineau et al., 2008; Tokinaga et al., 2012; Vecchi et al., 2006, 2008). Therefore, the second
220 option is chosen, and future WRs are computed using surface winds from the CC simulation.
221 However, in that case, it is not possible to track which of the present-day regimes transform into
222 which of the future regimes. Nevertheless, future WRs can be compared with their closest present
223 WRs. To do so, a distance matrix providing the distance between the centroid of each present and
224 future WR is computed. The present and future clusters that have the minimum distance between
225 them are paired, assuming that the closest future regime to a given PD regime tracks the regime
226 evolution with climate change. The classification of future WRs is performed only for the daily WRs.
227 Indeed, the ecological WRs (*i.e.* 30-day classification) are too variable in wind speed and direction
228 to determine unambiguously an evolution from a present to a future regime, and the distance matrix
229 indicates that several future regimes can be associated with the same PD regime. In the following, the
230 WRs at daily scale will be noted “R”, and the WRs at 30-day scale will be noted “S” (for sequence).

231

232 **3.3 ENSO modulation**

233 As ENSO is the main mode of interannual variability in the SP, we characterize its influence
234 on the occurrence of the WRs. To do so, we separate ENSO variations into 4 classes based on the
235 ONI index (Oceanic Niño Index, https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php): La Niña
236 (ONI<-0.5), neutral (-0.5<ONI<0.5), moderate El Niño (0.5<ONI<1.5), and extreme El Niño
237 (ONI>1.5) conditions. Extreme El Niño events are characterized by a 10° northward shift of the
238 SPCZ, the wind anomalies are stronger and move eastward relative to moderate El Niño events. It is
239 therefore likely that the probabilities of occurrence of each WR will be different for these two El Niño
240 modes. For each WR, the occurring days are distributed over the 4 phases of ENSO to derive the
241 observed WR distribution per ENSO class (O: number of days of regime occurrence for each ENSO
242

243 phase). The expected distribution (E) for each phase is computed assuming that the distribution of
 244 regimes does not depend on ENSO, it is thus equal to the total WR distribution weighted by the
 245 number of days of each phase. We then use a Chi-square test as in Lefèvre et al. (2010) to evaluate if
 246 the null hypothesis is verified, *i.e.*, if O is equal to the expected distribution E and thus the distribution
 247 of regimes would not depend on ENSO, or not.

$$\chi^2 = \sum_{i=1}^4 \frac{(O_i - E_i)^2}{E_i}$$

250 The probability that a random distribution provides a value larger than χ^2 is given by the χ^2 p-
 251 value. In our analysis, neutral ENSO conditions are included, implying a Chi-square test with 3
 252 degree of freedom. The χ^2 goodness-of-fit does not indicate which phases are significant. This is done
 253 by the standardized residual $R = (O - E) / (E)^{1/2}$, which determines which phases are major
 254 contributors when the null hypothesis has been rejected. When R has a magnitude greater than 2.0,
 255 the corresponding ENSO phase significantly influence the occurrence frequency of WR (Lefèvre et
 256 al., 2010; Leroy, 2006; Specq et al., 2019).

257

258 3.4 Observations datasets

259 To illustrate the mean climate conditions in the Pacific we use the Climate prediction center

260 M

261 e

262 r

263 g

264 e

265 4. Results: Daily WRs

266 4.1 Climatological features in present-day

267 A

268 n Four WRs are identified using the k-means clustering algorithm (Fig. 4, Table 1). The first
 269 a WR is a trade wind regime with a strong homogeneous east-south-east flow (Table 1, Fig. 4e). It is
 270 the most frequent, occurring ~30% of the time (Table 1), with a seasonal predominance in austral
 271 winter (Fig. 5b). R2 and R3 are two easterly regimes (Fig. 4fg), which are also quite frequent (25-
 272 s 30% of the time, Table 1), but have different seasonal variations and persistence (Fig. 5ab). R2 occurs
 273 i all year long and is the less persistent (Fig. 5a), lasting more than 3 days in only 40 % of its
 274 s occurrences, while R3 is more frequent in austral summer (Fig. 5b), and is the most persistent, lasting
 275 more than 3 days in more than 50%, and more that 6 days in 20% of its occurrences (Fig. 5a). R4 is
 276 o a north-easterly flow (Fig. 4h), which mainly occurs during austral summer and almost disappears
 277 f during winter (Fig. 5b), and is the least frequent of the WRs (Table 1).

278

279 P

280 r

400 In general, WRs computed from ERA5 and WRF PD winds are in good agreement (Fig. 4abcd
401 vs 4efgh; Table 1), with similar pattern, magnitude and occurrence, even if the PD simulation shows
402 slightly stronger gradients than ERA5 with stronger strong winds and weaker weak winds ($\sim\pm 0.2\text{m.s}^{-1}$).
403 This could be associated to some biases in WRF but also to a slightly increased effective resolution
404 in WRF compared with ERA5 allowing the resolution of stronger gradients. Overall, the favorable
405 comparison underlines the ability of our model to realistically represent WRs in this region.

406 To understand the synoptic-scale context in which each WR occurs, composites of
407 atmospheric conditions (*i.e.* sea-level pressure, surface wind and rainfall) for each daily WR over a
408 larger domain [$160^{\circ}\text{E}-90^{\circ}\text{W};40^{\circ}\text{S}-5^{\circ}\text{N}$] are displayed in Figure 6. R1, the trade wind WR, is mainly
409 associated with an intense high pressure system located in the south of Tahiti commonly called
410 Kermadec High (identified by the “K” letter in Fig. 6), and a low pressure system in the southwest
411 equatorial Pacific. This situation mainly occurs in austral winter (Fig. 5b), when the SPCZ is
412 contracted toward the west and the equator (pink line in Fig 5a), and when the Kermadec High is
413 located eastward (around 140°W) to its usual location (near Kermadec islands as in Fig. 6d). This
414 position of the Kermadec High (*i.e.* south of Tahiti) combined with the strong intensity of the
415 equatorial low pressure zone explains the tightened isobars in the central South Pacific and the strong
416 south-easterly flux (Table 1).

417 R2 is driven by two intense high pressure systems, the Kermadec High (K) centered at 160°W
418 and the South Pacific High (identified by the “SP” letter in Fig. 6) to the east of our domain (Fig. 6b).
419 The SP High causes an easterly flow which occurs in the east of the domain. The Kermadec High is
420 located further west than in R1, producing a south-easterly flow that occurs in the southwestern part
421 of the WR domain (blue box in Fig. 6b).

422 R3 is an easterly flow mainly driven by the SP High centered to the east of 90°W (Fig. 6c).
423 This WR occurs mainly in austral summer (Fig. 5b), when the Kermadec High is replaced by the
424 Tasman High pressure system in the Tasman Sea west of New Zealand (identified by “T” letter in
425 Fig. 6c). The easterly flow is deviated southward west of 150°W , tilting the isobars to the South, due
426 to the gap between the South Pacific High and the Tasman High pressure systems. The decrease of
427 wind speed from east to west is associated to the untightened isobars in the west of the WR domain.

428 Finally, R4 is driven by the Kermadec High and the South Pacific High (Fig. 6d). The South
429 Pacific High is located further north than the Kermadec High, which produces a strong tilt of the
430 isobars in the gap between these two systems between 130°W and 150°W . West of 150°W , the isobars
431 straighten up and the wind direction is south-east.

432 The spatial heterogeneity of each regime produces contrasting conditions between atolls in
433 the region, but also within the same archipelago. For instance, for R2, wind speeds are higher in the
434 Cook Islands than in the west and then the east Tuamotu Archipelago, but it is the opposite for R3

435 (Fig. 4fg). Similar conclusions can be made about wind direction. Therefore, independently of other
436 parameters that may influence the circulation in the lagoon, the same WR may have different impacts
437 on the circulation of lagoons in two different archipelagos or even within the same archipelago.

438

439 **4.2 Interannual variability: ENSO modulation**

440 The tropical Pacific SST pattern is modulated by large-scale climate modes at different
441 timescales, such as ENSO at inter-annual scale (Timmermann et al., 2018), or the Interdecadal Pacific
442 Oscillation (Salinger et al., 2001) at decadal timescales. In this subsection we explore and characterize
443 the influence of ENSO modes on the occurrences of each WR.

444 The results of the Chi-square test (Table 2) suggest that all WRs are significantly influenced
445 by ENSO. The extreme El Niño phase is the only ENSO mode that significantly influences the
446 occurrence of all WRs, with R2 and R4 being more frequent and R1 and R3 conversely less frequent.
447 Despite the radical behavior of the extreme El Niño phase (Fig. 7e), it is the moderate El Niño phase
448 that has the strongest influence on R1. The neutral phase has almost no influence on R1, R2 and R3,
449 while it negatively influences R4 (*i.e.* less occurrences). Finally, La Niña phase has an opposite
450 influence on the occurrences of each WRs compared to El Niño phases.

451 As expected, ENSO influences the frequency of occurrence of the WRs and their anomalies.
452 We compared the anomaly of each WR (difference between the WR pattern and the whole simulation
453 average pattern) and the ENSO anomaly pattern (difference between ENSO phase and the whole
454 simulation average pattern). The anomalies (Fig. 7) are similar when the given ENSO mode has a
455 positive influence on regimes (*i.e.*, increase in the WR frequency of occurrence). For instance, R2 is
456 positively influenced by extreme El Niño phases ($R=6.3$ in Table 2), and the wind anomalies in R2
457 (Fig. 7b) are consistent with the wind anomalies during extreme El Niño events (Fig 6e), with a
458 similar dipole in both cases (spatial correlation of 0.88, Table 3). Furthermore, R4 is positively
459 influenced by moderate El Niño phase ($R=3.9$ in Table 2). The wind anomalies in R4 (Fig. 7d) are
460 negative on almost the entire domain with a minimum in the northwest corner, and a similar wind
461 anomaly pattern is representative of the moderate El Niño events (spatial correlation of 0.80, Table
462 3).

463 Between pearl farming atolls in the studied regions, ENSO influences differently the wind
464 regimes, contributing to a further differentiation of their environment at decadal scale. As explained
465 in section 2, during extreme El Niño events the SPCZ is moved of 10° northward, resulting in an
466 increase of moisture transport convergence at the equator and a decrease in the South Central Pacific.
467 Therefore, extreme El Niño events tend to increase the wind speed in Cook and Society Islands and
468 decrease in Tuamotu (Fig. 7e). Conversely, during moderate El Niño events the SPCZ moves less
469 northward (compared to extreme events) and the eastern part of the SPCZ is almost unaffected.

470 Therefore, the decrease of moisture transport convergence occurs further west and has no impact on
471 the South Central Pacific. Thus, equatorial east wind anomalies can propagate further south, and wind
472 speed is reduced for almost all atolls in the South Central Pacific. Finally, during La Niña events, the
473 SPCZ moves southward, resulting in an increase of the moisture transport convergence in the South
474 Central Pacific associated with north-east wind anomalies and very slight increase of speed.

475

476 **4.3 Daily WRs in future conditions**

477 In general, future WRs are similar to the present WRs, with marginal changes in their main
478 characteristics (Fig. 4). All WRs in future conditions exhibits stronger wind speed and slight changes
479 in wind direction and frequency of occurrence (Table 1).

480 The large-scale changes for R1 show strong positive pressure anomalies in the southern part
481 of the domain centered on the Kermadec High, while in the northern part of the domain the positive
482 pressure anomalies are weaker (Fig. 6i). These surface pressure anomalies result in an increase in the
483 surface pressure gradient that generates stronger wind over the entire domain ($+0.8\text{m.s}^{-1}$; Fig. 4eim
484 and Table 1). The highest surface pressure anomalies are also associated with negative precipitation
485 anomalies (i.e. drying).

486 For R2, the wind speed increases all over the domain except in the south-east corner (Fig.
487 4fjn). These changes are associated to a surface pressure increase of the South Pacific High and the
488 Kermadec High which dries the entire domain south of 10°S except for a small plume-shaped area
489 between 140°W and 110°W (Fig. 6bfj). This wetter region coincides with the area of reduced wind
490 speed (Fig. 6j). In addition, this regime becomes less frequent in future conditions, with a relative
491 decrease of $\sim 18\%$.

492 For R3, strong off-center surface pressure anomalies at about 30°E from the center of the
493 South Pacific High occur in the southwest. The surface pressure anomalies display a south-north
494 gradient (Fig. 6k) that increases the absolute surface pressure gradient (Fig. 6g) and the wind speed
495 (Fig. 4gko) in the CC simulation. These changes also slightly alter the wind direction ($+6.6^{\circ}\text{N}$), and
496 the frequency of occurrence is 11% higher relative to present conditions.

497 Finally, for R4, the wind direction is shifted by $+12^{\circ}\text{N}$, while the wind speed ($+0.4\text{ m.s}^{-1}$) and
498 frequency of occurrence ($+6\%$) experience minor changes (Fig. 4hlp and Table 1). In the north-east
499 part of the domain, wind speed increases ($\sim +0.6\text{ m.s}^{-1}$) and wind direction of anomalies are south-
500 east, while in the south-west part of the domain the wind speed decreases (-0.4 m.s^{-1}) and the wind
501 direction of anomalies turn north-west (Fig. 6dhl). These changes are associated with an
502 intensification of both SP and T high pressure systems (Fig. 6dhl). The increase in surface pressure is
503 accompanied by a gradient of south-north and east-west surface pressure anomalies, which

504 strengthens wind speed in the entire domain south of 10°S, except in the area between both high
505 pressure systems. In this area, the space between the isobars is large, wind speed decreases (Fig. 4p),
506 and precipitation increases (Fig. 6l).

507 The general picture is that, in future conditions, the high pressure systems located south of the
508 domain tend to intensify (contours in Fig. 6ijkl) inducing a stronger south-north surface pressure
509 gradient which generates stronger winds (Fig. 4mnop). Small areas of lower wind speeds appear
510 concurrently with increased precipitation in regions of heavy rainfall (see pink lines in Fig. 6, Fig.
511 4mnop vs. 6ijkl), where the convergence of surface moisture increases mainly due to an increase in
512 wind convergence (not shown). Globally, the consequences of CC would be stronger and more
513 southerly winds for R1, R2 and R3 in all atolls of South Central Pacific except Gambier archipelago
514 where it is predicted a decrease of wind speed for R2. For R4, the wind speed decreases in all the
515 archipelagos except in the north of Tuamotu where there are virtually no changes.

516

517 **5. Results: 30-day regimes**

518 **5.1 General description**

519 The 30-day classification leads to nine WRs. To discuss and summarize these nine 30-day
520 WRs, a typology based on the variations of wind direction is designed and the synthesis is displayed
521 in Table 4. Discriminating WRs based on the variation of wind direction is justified as regimes
522 experiencing shifts in directions should generate more complex larval dispersal trajectories (Thomas
523 et al., 2014).

524 The S3, S4, S6, S7, S8 and S9 regimes exhibit a steady east direction throughout the 30-day sequence
525 with minor variations in their directions (Fig. 8b). The difference between each of these regimes is
526 mainly due to wind speed (Fig. 8a). S3 (brown line, Fig. 8a) is the most intense, with a steady wind
527 speed exceeding 6 m.s⁻¹ throughout the 30-day sequence. S4 (blue line, Fig. 8a) exhibits an intense
528 wind speed during the first 15 days (~5.7 m.s⁻¹), then it decreases to ~3.8 m.s⁻¹. S6 and S7 (red and
529 black lines in Fig. 8) are relatively steady throughout the 30-day sequence (~4.5 m.s⁻¹) with some
530 weak variations (+-0.5 m.s⁻¹) which are in opposition of phase between S6 and S7. In S8 (light blue
531 line, Fig. 8a), the wind speed is moderate at the start (~4 m.s⁻¹) then it increases until the 22nd day and
532 stabilizes afterward around 6.2 m.s⁻¹. S9 (yellow line, Fig. 8a) is the least intense of the six regimes
533 (~3.3 m.s⁻¹ in average), and its wind speed varies little. All these regimes occur almost 10% of the
534 time each, except S6 (red), which is the most frequent (~15% of the time).

535 By contrast, S1, S2 and S5 exhibit significant changes in wind direction throughout the 30-
536 day sequence (see Fig. 8d and Table 4). For S1, the wind direction is first oriented from the east, then
537 at day 10, it deviates from north-eastward (grey line, Fig. 8d). In parallel, wind speed decreases from

538 4.7 m.s⁻¹ to 3.0 m.s⁻¹ (Fig. 8c). This regime is the second most frequent regime (more than 14% of the
539 time) after S6. For S2 (purple line, Fig 7cd), the wind direction deviates gradually from east-north-
540 east to north-north-east until day 15, and then gradually comes back to east-north-east at the end of
541 the 30-day sequence, while the wind speed slightly decreases along the 30-day period (from 3.7 to
542 2.7 m.s⁻¹). This regime is the least frequent (6.2% of the time). Finally, S5 (green line, Fig. 8d) exhibits
543 first winds from the north-east which eventually shift eastward. In parallel, wind speed is initially
544 weak (>3.0 m.s⁻¹), and rises up to 4.5m.s⁻¹ at the end of the 30-day sequence (Fig. 8c).

545

546 **5.2. Relationships between the 30-day and the daily regimes**

547 In the previous section, the spatial average of the 30-day WRs have been computed to
548 characterize the temporal evolution of these regimes. In order to describe their regional pattern, and
549 their relation to the daily WRs, the 30-day sequences are split into five 6-day sequences, and each of
550 the 6-day sequence is associated to a daily WR. The pattern evolution of the direction-changing 30-
551 day WRs (S1, S2, and S5) is presented in Figure 9.

552 S1 starts with a moderate easterly wind over the whole domain as in R2 (Fig. 9a vs 4f). Then,
553 in the western part of the domain, the wind direction is deviated from east to north-east, similarly to
554 R3 (Fig. 9c vs 4g). At the end of the 30-day sequence, the wind direction is north-east in almost all
555 of the domain, except in the south-western part where the wind direction is south-east, similarly to
556 R4 (Fig. 9e vs 4h). For S2, the spatial pattern of wind is first quite similar to R3, with an east flux in
557 the east part of domain and a north-east flux in the western part of domain, and the wind speed
558 decreases gradually from north-east to south-west (Fig. 9f vs 4g). Then the wind direction is deviated
559 to north-east, and the wind speed decreases, like in R4 (Fig. 9h vs 4h). At the end of the 30-day
560 sequence, the pattern seems to return to its initial state, *i.e.* in R3 configuration (Fig. 9j vs 4g), with a
561 wind direction mostly easterly, except in the western part where the orientation is always northeast.
562 S5 exhibits first a spatial pattern similar to R4 with a north-east flux (Fig. 9k vs 4h). Then the wind
563 speed increases and the wind is gently deviated from north-east to east, with a spatial pattern similar
564 to R3 (Fig. 9m vs 4g). Then the wind continues to increase, and the direction clearly stabilizes east at
565 the end of the 30-day sequence, thus resembling to R1 (Fig. 9o vs 4e).

566 Overall, the patterns of the 30-day WRs time slices can be seen as a succession of daily WRs,
567 even if the latters show smoother patterns in Figure 4 due to the large averaging (numerous days are
568 averaged in Figure 4, while Figure 9 shows the evolution of the barycenter of each of the 30-day
569 WRs). To summarize, S1, S2 and S5 can be seen as a succession of daily WRs:

570 S1: R2 → R3 → R4

571 S2: R3 → R4 → R3

572 S5: R4 → R3 → R1

573

574 **5.3. Regimes for selected atolls**

575 As illustrated in Figures 4 and 9, the WR patterns show a quite large regional variability in
576 terms of wind speed and direction which will affect the different sub-regions of interest (Fig. 1a).

577 Therefore, we aim to emphasize here that despite the low distance between the atolls, certain
578 regimes can have very different characteristics some regimes may have very different characteristics
579 from one regime to another. Although more computations and comparison can be done to reinforce
580 this idea, we first characterize the wind conditions for specific pearl farming sites of the south central
581 Pacific region, especially focusing on the three 30-day WRs with wind changing directions. To that
582 end, we selected six sites considering their history of scientific research (Fig. 1a): namely Ahe, Raroia
583 and Hao atolls in the Tuamotu archipelago, Mangareva which is the main Gambier island, and
584 Aitutaki and Manihiki in the Cook Islands, and we extracted their 30-day WRs (Fig. 10).

585 Regarding the wind direction, for the three 30-day WRs, the three Tuamotu atolls show a very
586 similar 30-day pattern, with only Hao exhibiting slightly more pronounced NNE and NE direction
587 shifts when the wind direction is lower than 60°. Interestingly, its slightly southern location
588 (compared to Raroia) has a certain influence on its characteristic 30-day WRs. Mangareva, which is
589 at the most south-eastern part of the domain shows the largest wind direction variations for the three
590 30-day WRs. Manihiki and Aitutaki are located on the western part of the domain but at a very
591 different zonal position. Consequently, they exhibit quite different wind directions, Manihiki in the
592 north exhibiting a temporal evolution close to the Tuamotu atolls while Aitutaki in the south showing
593 abrupt changes in wind direction particularly for S2.

594

595 **6. Discussion**

596 **6.1. Regional daily WRs**

597 In this study we characterized the weather regimes in the south central Pacific region at
598 different temporal scales (i.e. daily and 30-day scales), in present and future conditions. The weather
599 regimes are identified from two regional simulations (i.e. in present-day and climate change
600 conditions) performed with the WRF model in a nested configuration at 21 km resolution. The climate
601 change simulation is performed under the RCP.8.5 scenario for the end of the 21st century. We used a
602 PGW approach and an emergent constraint method to correct at the same time historical and projected

603 SST biases in order to reduce the uncertainties of the climate simulations. Then, two types of
604 classification by weather regimes are performed from simulated surface winds, at the daily and 30-
605 day scales. The “daily classification” revealed four weather regimes: a strong trade wind, two easterly
606 flows, and a north-easterly flow. A similar classification from ERA-5 reanalysis shows a very good
607 agreement with the weather regimes identified from the PD simulation.

608 Two recent studies (Hopuare et al., 2019; Lorrey et Fauchereau 2018) also performed a
609 weather classification in the South Pacific, but over different periods (1979-2015 and 1950-2014,
610 respectively) and domain extents ([205.5°E-215.25°E;12°S-22.5°S] and [160°E-230°E;30°S-10°N],
611 respectively) and from different data sets (surface wind from NCEP2 reanalysis and geopotential
612 heights from NCEP/NCAR1, respectively). Despite a different domain size between Hopuare et al
613 (2019) and this study, the four weather regimes identified in Hopuare et al., (2019) are very close to
614 ours, a likely explanation is that the two domain centers are almost co-located (*i.e.* near to Tahiti). By
615 contrast, six WRs were found in Lorrey et Fauchereau (2018) instead of four in Hopuare et al., (2019)
616 and the present study. This difference can be likely explained by the domain extent that encompasses
617 a wider region and the domain center which is much further west and north than ours, thus capturing
618 weather conditions and synoptic structures that are not included here as the north-west Pacific
619 monsoon or Tasman high.

620

621 **6.2. Influence of climate modes of variability and future projections**

622 The regimes identified here are mainly controlled by the position and intensity of synoptic
623 structures (e.g. western equatorial low, Kermadec High etc...) themselves modulated by the season
624 and ENSO mode. Indeed, the occurrence of the four WRs is modified by the ENSO mode, and the
625 strongest influence occurs during extreme El Niño events.

626 In future climate, the projections show an intensification of these regimes, with a 15% increase
627 in wind speed mainly explained by an intensification of meridional pressure gradient in response to
628 SST changes. The strength of our framework, thanks to an emergent constraint method (Li et al.,
629 2016) and a PGW approach, is to correct for the known SST biases in CMIP models (such as double
630 ITCZ or cold tongue biases) which limit the confidence that can be given to climate projections in
631 the South Pacific (e.g. Brown et al., 2020). The impact of the emergent constraint method has been
632 evaluated by comparing with an experiment without correction. This experiment revealed significant
633 consequences for R4, in particular a more intense drying in the northwest and a stronger decrease in
634 wind speed in the southeast in the corrected simulation compared to the uncorrected one (not shown).
635 The main limitation of this correction is the assumption of a linear relationship between the present-

636 day precipitation and the projected SST pattern in CMIP5 models in the western equatorial Pacific
637 (Fig. 2b), which is not perfect ($r=-0.57$).

638 The PGW approach has also some shortcomings. Namely, it does not allow assessing the
639 influence of a change in ENSO variability, since the inter-annual variability in SST is kept constant
640 in the climate-change simulation compared to the present-day simulation, because only monthly
641 climatology anomalies are added. However, recent studies predicted an increase of extreme El Niño
642 events frequency in warming climate (e.g. Cai et al., 2012, 2014, 2018), with especially an increase
643 of 81% of SPCZ zonal events for the end of the 21st century in the RCP8.5 scenario (Cai et al., 2012).
644 Therefore, it is likely that these changes in ENSO variability will alter the frequency of occurrence
645 of the weather regimes that have been determined here. Under present conditions, extreme El Niño
646 events increase the frequency of R2 and R4 and inversely for R1 and R3, therefore if we consider this
647 process and if we follow the results of Cai et al. (2012), it is likely that this trend will add to the trend
648 due to the mean climate change alone. Thus, this trend due to change in inter-annual variability could
649 increase or decrease (according to the WR considered) the frequency changes found in this study.
650 Furthermore, R2 and R4 being the most spatially contrasting regimes, changes in inter-annual
651 variability could accentuate the differences in wind conditions between the eastern and western atolls
652 of the SCP.

653

654 **6.3. WRs and their relevance to pearl farming**

655 The main purpose of this study was to provide information on the wind conditions that prevail
656 on pearl farming atolls across a vast Pacific Ocean domain, at different time scales. In addition to the
657 daily-scale, a maximum PLD time considered here was 30 days. Thomas et al. (2014) also performed
658 a “30-day classification” but only on Ahe atoll in the western Tuamotu and using ERA-Interim wind
659 surface over the 1979-2011 period, to characterize periods of pearl oyster larval dispersal. They
660 identified twelve 30-day wind regimes with average characteristics quasi-similar to those determined
661 here (wind speed between 3.7 and 7.6 m.s⁻¹ and wind direction between 76°N and 100°N). However,
662 Thomas et al. (2014) did not identify 30-day regimes with a changing wind direction contrast to the
663 present regional-scale study. The synoptic scale of our work allows demonstrating that, even with a
664 limited-number of wind regimes, the different atolls are exposed to significant weather variations
665 across the domain. This variability has important consequences for pearl farming.

666

667 Knowledge of wind regimes opens fresh perspectives to create new products relevant for pearl
668 farming management. First, lagoon hydrodynamics and connectivity modeling studies (Dumas et al.,

669 2012; Thomas et al., 2012, 2014, 2016) can help understanding sink areas for *Pinctada margaritifera*
670 larvae and therefore the most suitable areas for spat collection. For this application, hydrodynamic
671 modeling of atoll lagoons requires high resolution dedicated model for each location, including a
672 good representation of the local geomorphology, and the influence of other forcing factors such as
673 waves and tides (Le Gendre et al. this issue), but wind remains a key component. These ‘sink’ areas
674 should have good potential for spat collecting (although we point out that actual recruitment and
675 survival of the spats is not guaranteed). In this context, atoll hydrodynamic models can be run for
676 different types of regimes in order to understand the distribution of the sink areas according to a range
677 of recurrent wind conditions. It is recommended to customize the analysis for atolls located far apart,
678 since we observed difference between six specific atolls and islands distributed far apart (Manihiki,
679 Aitutaki, Ahe, Raroia, Hao and Mangareva). Weighting the results by the frequency of the local
680 regimes (Fig. 8) can provide a way to identify what would be, statistically speaking, suitable areas
681 for the activity for a typical year. This information can further be used for the spatial planning of
682 concessions. Indeed, the French Polynesia lagoon managers are currently establishing zoning plans
683 of pearl farming lagoons that typically reserve areas to rear stocks, and areas to collect spats.

684 Nevertheless, lagoon hydrodynamics and connectivity modeling studies (Dumas et al., 2012;
685 Thomas et al., 2012, 2014, 2016) can help understanding sink areas for *Pinctada margaritifera* larvae
686 for a given regime and therefore the most suitable areas for spat collection in a ‘regime’ condition.

687 Other relevant products would be to use atoll hydrodynamic and dispersal models forced by
688 the different wind regimes, to estimate where would be the best ‘source’ areas to maximize
689 reproduction and spat collection. This time, instead of identifying sinks for spat collection as
690 described just above, the objectives would be to identify the best sources of larvae to target spat
691 collecting in existing concessions, and, for instance, replenish natural stocks in these source areas to
692 maximize the reproduction success. All these applications on stock management, or spatial planning,
693 will benefit from model outputs computed in all regime conditions weighted by their frequency of
694 occurrence, thus representing a number of recurrent conditions throughout the year with a known
695 frequency.

696 Finally, Andréfouët et al. (2015) previously investigated the environmental conditions that
697 could explain massive benthic mortalities in Tuamotu and Cook Islands atoll lagoons. These events
698 remain a constant threat for the pearl farming industry, and the most recent case occurred in 2013-
699 2014 in Takaroa atoll, where all the activity was stopped abruptly after that an algal bloom impacted
700 directly the resources (Rodier et al; 2019). As in 2020, the farming activity has not yet recovered in
701 Takaroa. A conclusion from Andréfouët et al. (2015) was that mortality could impact very selectively
702 some atolls but not others due to the spatial scale of distribution of the calm, environmental conditions

703 that trigger mortalities. The results of the present study confirm that atolls are not equal in term of
704 their wind regimes, even if there are a low number of regimes overall. The relationships between
705 regimes, their occurrences, and the occurrence of calm periods necessary to trigger mortalities warrant
706 further investigations.

707 To the best of our knowledge, these applications will be the first case of resource management
708 in South Pacific Islands that would be constrained by appropriate knowledge and characterization of
709 wind regimes, at present time and in the future. It is anticipated that such tools will be tested and
710 implemented in a short future in French Polynesia.

711

712 **Acknowledgements**

713 This study was funded by grant ANR-16-CE32-0004 MANA (Management of Atolls project).
714 The authors acknowledge the Pôle de Calcul et de Données Marines (PCDM) for providing
715 DATARMOR storage and computational resources (<http://www.ifremer.fr/pcdm>).

716

717 **References**

Andréfouët, S., Charpy, L., Lo-Yat, A., and Lo, C. (2012). Recent research for pearl oyster aquaculture management in French Polynesia. *Marine Pollution Bulletin* 65, 407–414.

Andréfouët, S., Dutheil, C., Menkes, C.E., Bador, M., and Lengaigne, M. (2015). Mass mortality events in atoll lagoons: environmental control and increased future vulnerability. *Global Change Biology* 21, 195–205.

Brown, J.N., Langlais, C., and Sen Gupta, A. (2015). Projected sea surface temperature changes in the equatorial Pacific relative to the Warm Pool edge. *Deep Sea Research Part II: Topical Studies in Oceanography* 113, 47–58.

Brown, J.R., Lengaigne, M., Benjamin R. Lintner, Widlansky, M.J., van der Wiel, K., Dutheil, C., Linsley, B.K., Matthews, A.J., and Renwick, J. (2020). South Pacific Convergence Zone dynamics, variability, and impacts in a changing climate. *Nature Reviews Earth and Environment*, *accepted*.

Cai, W., Lengaigne, M., Borlace, S., Collins, M., Cowan, T., McPhaden, M.J., Timmermann, A., Power, S., Brown, J., Menkes, C., et al., (2012). More extreme swings of the South Pacific convergence zone due to greenhouse warming. *Nature* 488, 365–369.

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L., et al., (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change* 4, 111–116.

Cai, W., Wang, G., Dewitte, B., Wu, L., Santoso, A., Takahashi, K., Yang, Y., Carréric, A., and McPhaden, M.J. (2018). Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature* 564, 201–206.

Charrad, M., Ghazzali, N., Boiteau, V., and Niknafs, A. (2014). NbClust : An R Package for Determining the Relevant Number of Clusters in a Data Set. *J. Stat. Soft.* 61.

Chung, C.T.Y., and Power, S.B. (2016). Modelled impact of global warming on ENSO-driven precipitation changes in the tropical Pacific. *Climate Dynamics* 47, 1303–1323.

Claar, D.C., Szostek, L., McDevitt-Irwin, J.M., Schanze, J.J., Baum, J.K., 2018. Global patterns and impacts of El Niño events on coral reefs: A meta-analysis. *PLoS ONE* 13, e0190957.

Collins, M., An, S.-I., Cai, W., Ganachaud, A., Guilyardi, E., Jin, F.-F., Jochum, M., Lengaigne, M., Power, S., Timmermann, A., et al., (2010). The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience* 3, 391–397.

Cuif, M., Kaplan, D.M., Lefèvre, J., Faure, V.M., Caillaud, M., Verley, P., Vigliola, L., and Lett, C. (2014). Wind-induced variability in larval retention in a coral reef system: A biophysical modelling study in the South-West Lagoon of New Caledonia. *Progress in Oceanography* 122, 105–115.

Dumas, F., Le Gendre, R., Thomas, Y., and Andréfouët, S. (2012). Tidal flushing and wind driven circulation of Ahe atoll lagoon (Tuamotu Archipelago, French Polynesia) from in situ observations and numerical modelling. *Marine Pollution Bulletin* 65, 425–440.

Dutheil, C., Bador M., Lengaigne M., Lefèvre J., Jourdain N. C., Vialard J., Jullien Swen, Peltier A., Menkes C. (2019). Impact of surface temperature biases on climate change projections of the South Pacific Convergence Zone . *Climate Dynamics* , 53(5-6), 3197-3219.

<https://doi.org/10.1007/s00382-019-04692-6>

Dutheil, C., Lengaigne, M., Bador, M. et al. Impact of projected sea surface temperature biases on tropical cyclones projections in the South Pacific. *Scientific Reports* 10, 4838 (2020).

<https://doi.org/10.1038/s41598-020-61570-6>

- E. Diday (1971). Une nouvelle méthode en classification automatique et reconnaissance des formes la méthode des nuées dynamiques. *Revue de Statistique Appliquée* 19–33.
- Evans, J.P., Bormann, K., Katzfey, J., Dean, S., and Arritt, R. (2016). Regional climate model projections of the South Pacific Convergence Zone. *Climate Dynamics* 47, 817–829.
- Folland, C.K. (2002). Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. *Geophysical Research Letters* 29, 211–214.
- Fournier, J., Levesque, E., Pouvreau, S., Pennec, M.L., and Moullac, G.L. (2012). Influence of plankton concentration on gametogenesis and spawning of the black lip pearl oyster *Pinctada margaritifera* in Ahe atoll lagoon (Tuamotu archipelago, French polynesia). *Marine Pollution Bulletin* 65, 463–470.
- Gastineau, G., Treut, H.L., and Li, L. (2008). Hadley circulation changes under global warming conditions indicated by coupled climate models. *Tellus A: Dynamic Meteorology and Oceanography* 60, 863–884.
- Grose, M.R., Brown, J.N., Narsey, S., Brown, J.R., Murphy, B.F., Langlais, C., Gupta, A.S., Moise, A.F., and Irving, D.B. (2014). Assessment of the CMIP5 global climate model simulations of the western tropical Pacific climate system and comparison to CMIP3: assesment of CMIP5 climate models for the western tropical pacific. *International Journal of Climatology* 34, 3382–3399.
- Harvell, C.D., 2002. Climate Warming and Disease Risks for Terrestrial and Marine Biota. *Science* 296, 2158–2162.
- Hopuare, M., Guglielmino, M., and Ortega, P. (2019). Interactions between intraseasonal and diurnal variability of precipitation in the South Central Pacific: The case of a small high island, Tahiti, French Polynesia. *Int J Climatol* 39, 670–686.
- Jolliffe, I. (2011). Principal Component Analysis. In *International Encyclopedia of Statistical Science*, M. Lovric, ed. (Berlin, Heidelberg: Springer Berlin Heidelberg), pp. 1094–1096.
- Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M., and Potter, G.L. (2002). NCEP–DOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society* 83, 1631–1643.
- Kiladis, G.N., von Storch, H., and Loon, H. (1989). Origin of the South Pacific Convergence Zone. *Journal of Climate* 2, 1185–1195.

- Lefèvre, J., Marchesiello, P., Jourdain, N.C., Menkes, C., and Leroy, A. (2010). Weather regimes and orographic circulation around New Caledonia. *Marine Pollution Bulletin* 61, 413–431.
- Leroy, A. (2006). Utilisation des Prévisions Saisonnières en Nouvelle-Calédonie. Note de la DP n° 6, Météo-France, DP/DCLIM.
- Li, G., Du, Y., Xu, H., and Ren, B. (2015). An Intermodel Approach to Identify the Source of Excessive Equatorial Pacific Cold Tongue in CMIP5 Models and Uncertainty in Observational Datasets. *Journal of Climate* 28, 7630–7640.
- Li, G., Xie, S.-P., Du, Y., and Luo, Y. (2016). Effects of excessive equatorial cold tongue bias on the projections of tropical Pacific climate change. Part I: the warming pattern in CMIP5 multi-model ensemble. *Climate Dynamics* 47, 3817–3831.
- Lorrey, A.M., and Fauchereau, N.C. (2018). Southwest Pacific atmospheric weather regimes: linkages to ENSO and extra-tropical teleconnections: Southwest Pacific atmospheric weather regimes: linkages to ENSO and extra-tropical teleconnections. *Int. J. Climatol* 38, 1893–1909.
- Lowe, R.J., and Falter, J.L. (2015). Oceanic Forcing of Coral Reefs. *Annual Review of Marine Science* 7, 43–66.
- Rodier, M., Longo, S., Henry, K., Ung, A., Lo-Yat, A., Darius, H., Viallon, J., Beker, B., Delesalle, B., Chinain, M., 2019. Diversity and toxic potential of algal bloom-forming species from Takaroa lagoon (Tuamotu, French Polynesia): a field and mesocosm study. *Aquat. Microb. Ecol.* 83, 15–34. <https://doi.org/10.3354/ame01900>
- Salinger, M.J., Renwick, J.A., and Mullan, A.B. (2001). Interdecadal Pacific Oscillation and South Pacific climate. *Int. J. Climatol.* 21, 1705–1721.
- Skamarock, W.C., and Klemp, J.B. (2008). A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *Journal of Computational Physics* 227, 3465–3485.
- Specq, D., Bellon, G., Peltier, A., Lefèvre, J., and Menkes, C. (2019). Influence of subseasonal variability on the diurnal cycle of precipitation on a mountainous island: the case of New Caledonia. *Mon. Wea. Rev.* MWR-D-19-0177.1.
- Thomas, Y., Garen, P., Courties, C., Charpy, L., 2010. Spatial and temporal variability of the pico- and nanophytoplankton and bacterioplankton in a deep Polynesian atoll lagoon. *Aquatic Microbial Ecology* 59, 89–101.

Thomas, Y., Le Gendre, R., Garen, P., Dumas, F., and Andréfouët, S. (2012). Bivalve larvae transport and connectivity within the Ahe atoll lagoon (Tuamotu Archipelago), with application to pearl oyster aquaculture management. *Marine Pollution Bulletin* 65, 441–452.

Thomas, Y., Dumas, F., and Andréfouët, S. (2014). Larval Dispersal Modeling of Pearl Oyster *Pinctada margaritifera* following Realistic Environmental and Biological Forcing in Ahe Atoll Lagoon. *PLoS ONE* 9, e95050.

Thomas, Y., Dumas, F., and Andréfouët, S. (2016). Larval connectivity of pearl oyster through biophysical modelling; evidence of food limitation and broodstock effect. *Estuarine, Coastal and Shelf Science* 182, 283–293.

Timmermann, A., An, S.-I., Kug, J.-S., Jin, F.-F., Cai, W., Capotondi, A., Cobb, K., Lengaigne, M., McPhaden, M.J., Stuecker, M.F., et al., (2018). El Niño–Southern Oscillation complexity. *Nature* 559, 535–545.

Tokinaga, H., Xie, S.-P., Deser, C., Kosaka, Y., and Okumura, Y.M. (2012). Slowdown of the Walker circulation driven by tropical Indo-Pacific warming. *Nature* 491, 439–443.

Van Wynsberge, S., Menkes, C., Le Gendre, R., Passfield, T., and Andréfouët, S. (2017a). Are Sea Surface Temperature satellite measurements reliable proxies of lagoon temperature in the South Pacific? *Estuarine, Coastal and Shelf Science* 199, 117–124.

Van Wynsberge, S., Andréfouët, S., Gaertner-Mazouni, N., Wabnitz, C.C.C., Menoud, M., Le Moullac, G., Levy, P., Gilbert, A., and Remoissenet, G. (2017b). Growth, Survival and Reproduction of the Giant Clam *Tridacna maxima* (Röding 1798, Bivalvia) in Two Contrasting Lagoons in French Polynesia. *PLoS ONE* 12, e0170565.

Vecchi, G.A., Soden, B.J., Wittenberg, A.T., Held, I.M., Leetmaa, A., and Harrison, M.J. (2006). Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* 441, 73–76.

Vecchi, G.A., Clement, A., and Soden, B.J. (2008). Examining the tropical Pacific's response to global warming. *Eos, Transactions American Geophysical Union* 89, 81–83.

Vincent, D.G. (1994). The South Pacific Convergence Zone (SPCZ): A Review. *Monthly Weather Review* 122, 1949–1970.

Vincent, E.M., Lengaigne, M., Menkes, C.E., Jourdain, N.C., Marchesiello, P., and Madec, G. (2011). Interannual variability of the South Pacific Convergence Zone and implications for tropical cyclone genesis. *Climate Dynamics* 36, 1881–1896.

Widlansky, M.J., Timmermann, A., Stein, K., McGregor, S., Schneider, N., England, M.H., Lengaigne, M., and Cai, W. (2013). Changes in South Pacific rainfall bands in a warming climate. *Nature Climate Change* 3, 417–423.

van der Wiel, K., Matthews, A.J., Joshi, M.M., and Stevens, D.P. (2016). Why the South Pacific Convergence Zone is diagonal. *Climate Dynamics* 46, 1683–1698.

Xie, P., and Arkin, P.A. (1997). Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. *Bulletin of the American Meteorological Society* 78, 2539–2558.

Zhang, C., Wang, Y., Hamilton, K., and Lauer, A. (2016). Dynamical Downscaling of the Climate for the Hawaiian Islands. Part II: Projection for the Late Twenty-First Century. *Journal of Climate* 29, 8333–8354.

718 **Figure 1:** (a) Map representing the domain where the weather regimes are computed. The
719 archipelagos studied here are surrounded by different colors, and the pearl farming sites selected are
720 indicated. (b) Annual mean climatologies of precipitation from CMAP (shading; in mm.day⁻¹), mean
721 sea level pressure (contours; in hPa) and surface winds (vectors, in m.s⁻¹) from NCEP2 reanalysis.
722 The entire displayed domain (d01) represents the parent domain of WRF simulations, the d02 domain
723 (black box) represents the child domain of WRF simulations, and the “WR domain” (blue box)
724 represents the domain where the weather regime were calculated. The letters “H” and “L” indicated
725 the mean position of South Pacific High and equatorial low pressure zone, respectively. The pink
726 contour displays the 5mm.day⁻¹ average rainfall in south Pacific indicating the SPCZ limits.
727

728 **Figure 2:** Top: (a) Multi-model mean (MMM) CMIP5 of precipitation bias (in mm.day⁻¹) relative to
729 observations (CMAP). (b) Relationships between the SST projected changes (°C) and the historical
730 mean precipitation (mm.day⁻¹) in the equatorial western Pacific (160°E-170°W;2°S-2°N) among 31
731 CMIP5 models (red dots). The inter-model correlation (r) is shown at the bottom-left. The dashed
732 lines on the panels b denote the observed mean precipitation in the equatorial western Pacific.
733 Bottom: DJF climatology (shading, in °C) of (e) ΔSST_{CMIP} and (f) ΔSST_{COR} . ΔSST_{CMIP} and
734 ΔSST_{COR} are respectively the uncorrected and the corrected projected SST pattern. The contours
735 represent the DJF climatology of precipitation (in mm.d⁻¹) changes between (e) CC and PD, (f)

736 COR and PD simulations. The dashed lines indicate negative values, while the thick lines indicates
737 positive values.

738

739 **Figure 3:** Distribution of the number of clusters for all indicators included in NbClust for (a) daily
740 WRs and (b) 30-day WRs.

741

742 **Figure 4:** Surface winds (shading and vectors, in m.s^{-1}) composite maps showing the four weather
743 regimes over the 37-years period from (1st row) the ERA-5 reanalysis, (2nd row) PD simulation, (3rd
744 row) and (4th row) changes between CC and PD.

745

746 **Figure 5:** (a) Percentage of days of each weather regime included in homogeneous spells lasting at
747 least 3, 6, 9 and 12 days; (b) Monthly mean occurrence of weather types.

748

749 **Figure 6:** Surface winds (vectors, in m.s^{-1}), surface pressure (contours, in hPa) and precipitation
750 (shading, in mm.day^{-1}) composite maps showing the four weather regimes 37-years period from (1st
751 row) PD, (2nd row) CC, and (3rd row) changes between CC and PD. The blue box shows the domain
752 on which the weather regimes were calculated (Fig. 1). The pink contours show the isoline 6mm.day^{-1}
753 ¹ representing SPCZ limits.

754

755 **Figure 7:** Surface wind anomalies (in m.s^{-1}) in PD for each weather regime (first row) and each
756 ENSO phase (second row). The anomalies are computed in relation to the period-average.

757

758 **Figure 8:** Surface wind speed (left; in m.s^{-1}), and direction (right; in °N) for the barycenter of each
759 nine 30-day weather regimes over 1980-2016 period from the PD simulation. The right-hand boxes
760 show the colors to identify each regime, and the occurrence frequency (in %) is indicated.

761

762 **Figure 9:** Surface wind (shading and vectors, in m.s^{-1}) composite maps showing the barycenter of
763 S1, 2 and 5 from PD simulation. The 30-day sequences are split in five 6-days sequences. Each panel
764 represents the time average of a 6-day sequence.

765

766 **Figure 10:** Surface wind speed (left; in $\text{m}\cdot\text{s}^{-1}$), and direction (right; in $^{\circ}\text{N}$) for S1, 2 and 5 for the
767 period 1980-2016 from the PD simulation. The right-hand boxes show the colors that identify each
768 regime.

WR domain

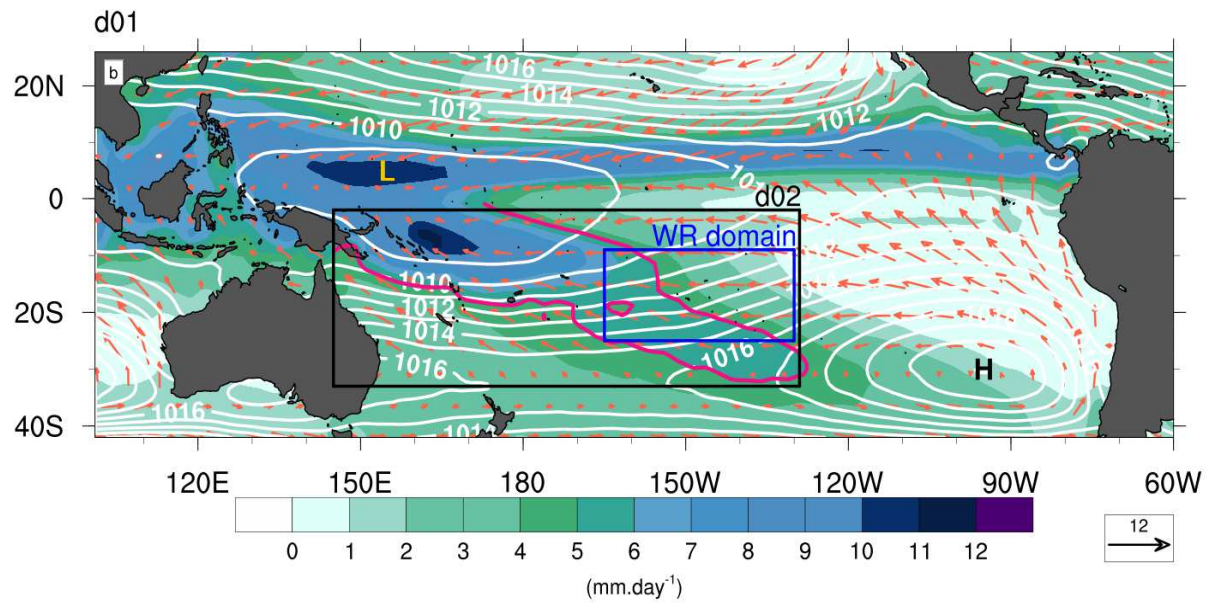
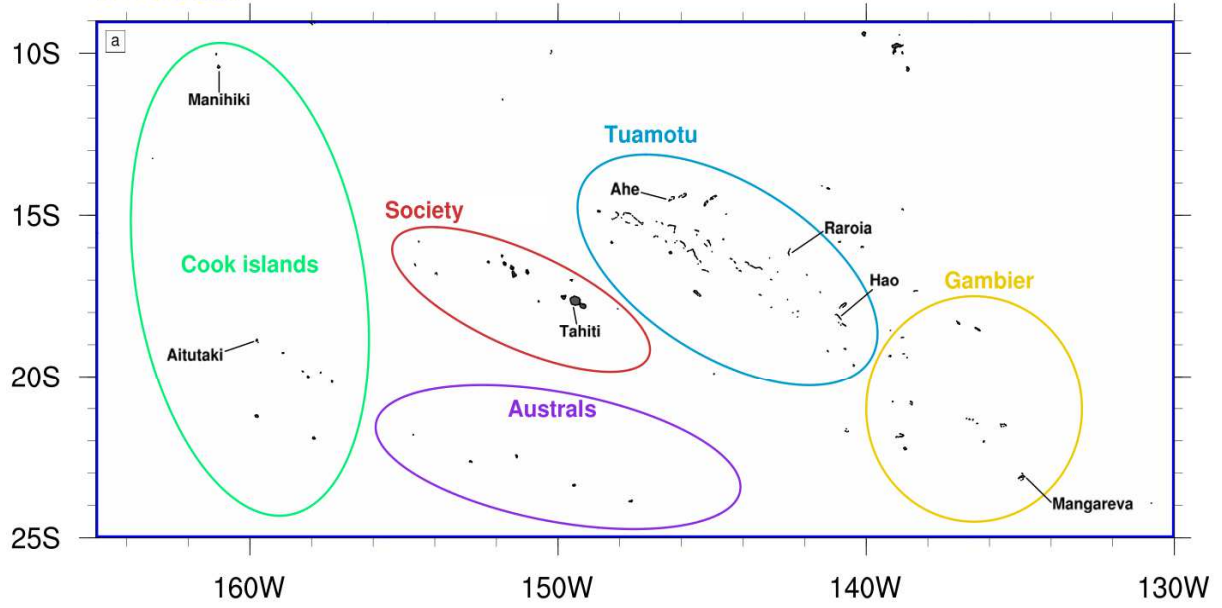


Figure 1

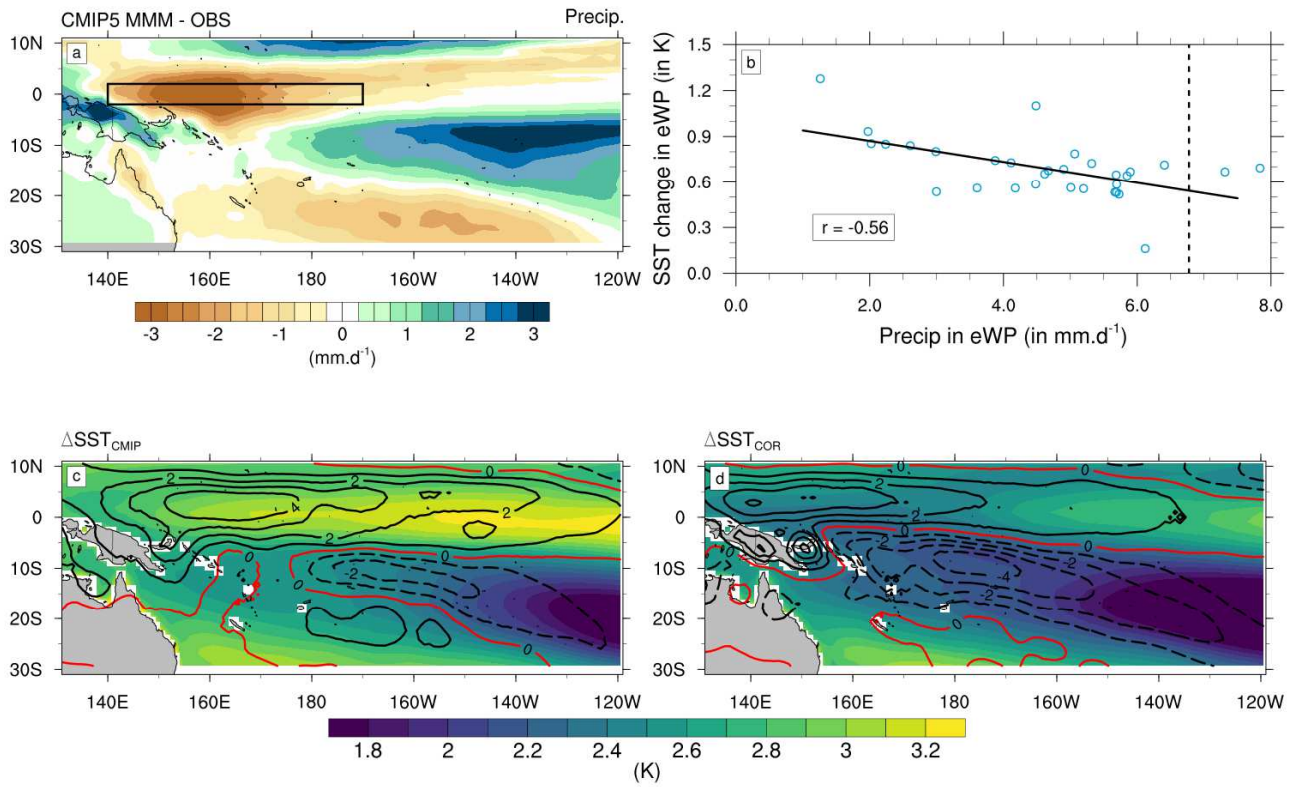


Figure 2

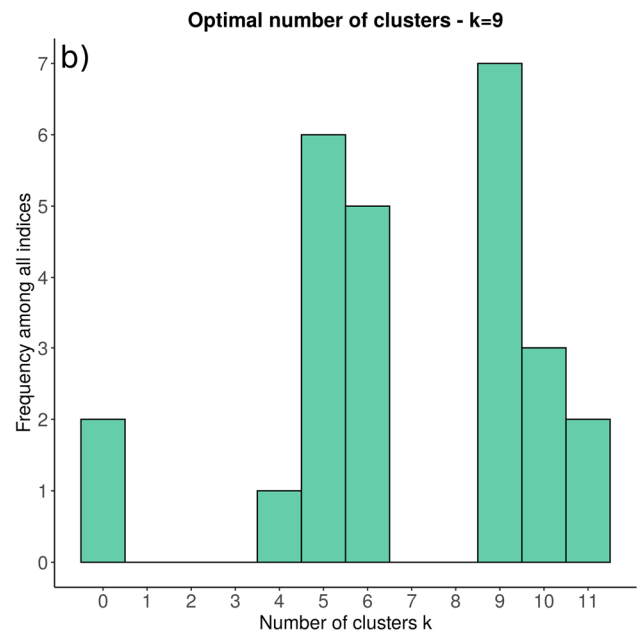
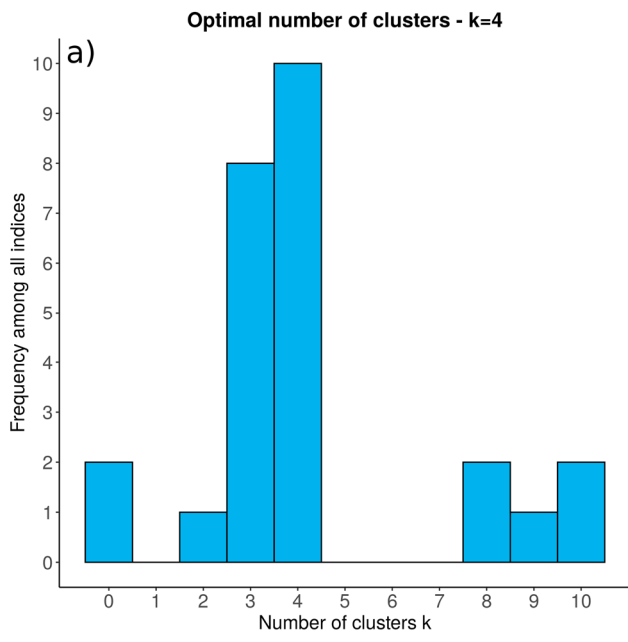


Figure 3

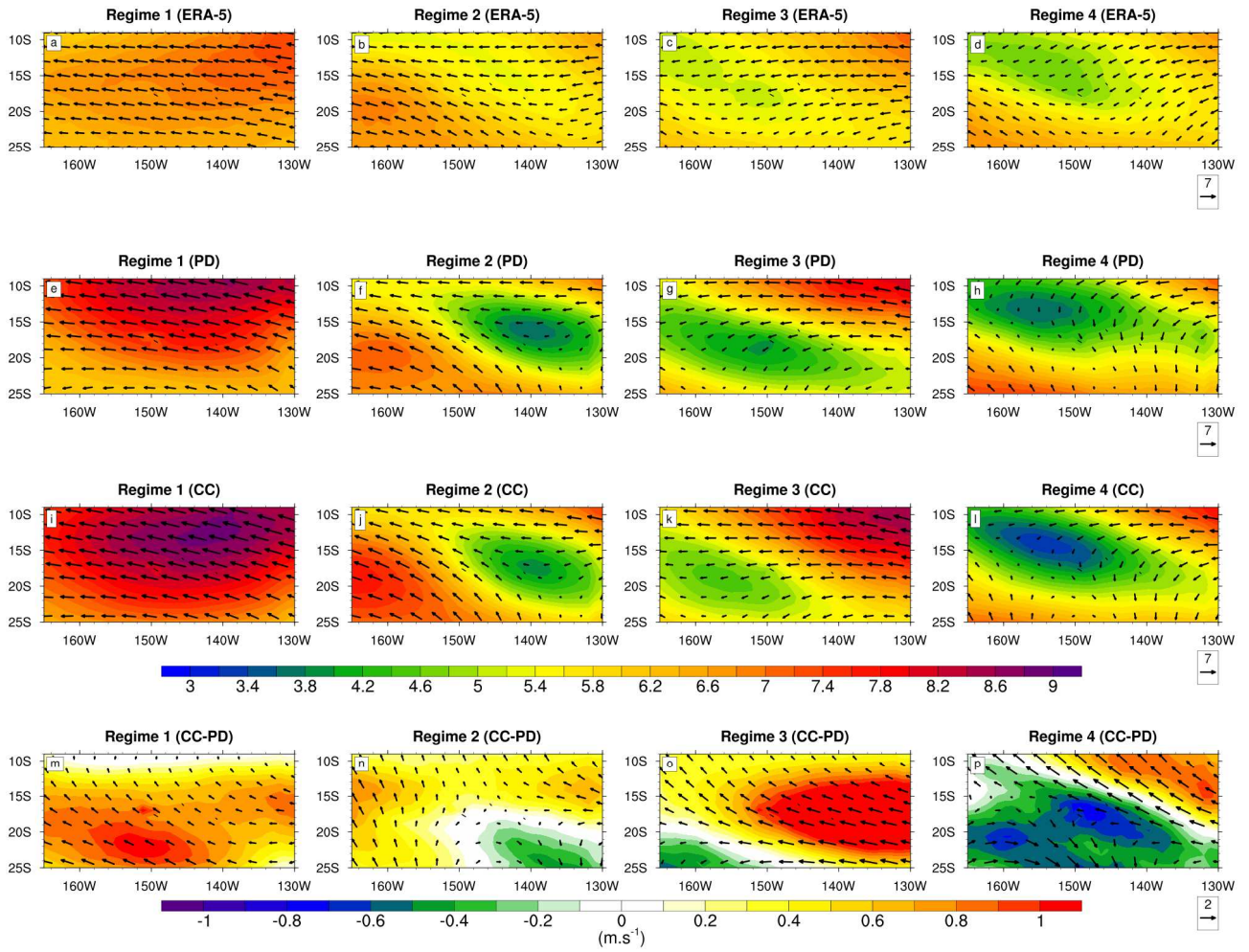


Figure 4

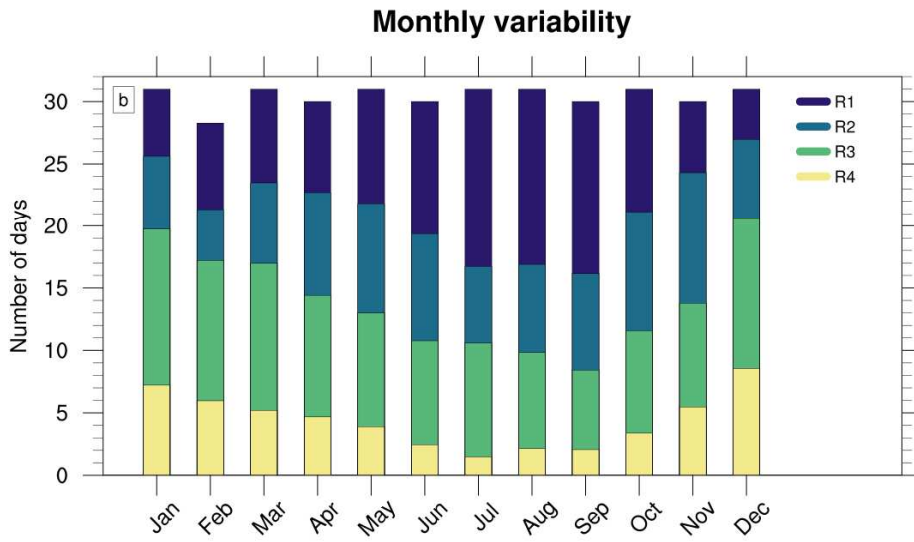
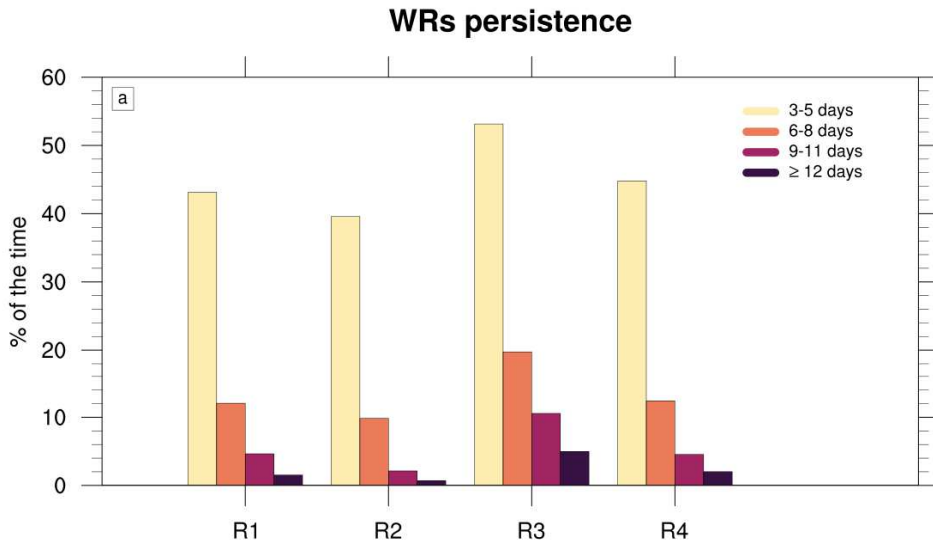


Figure 5

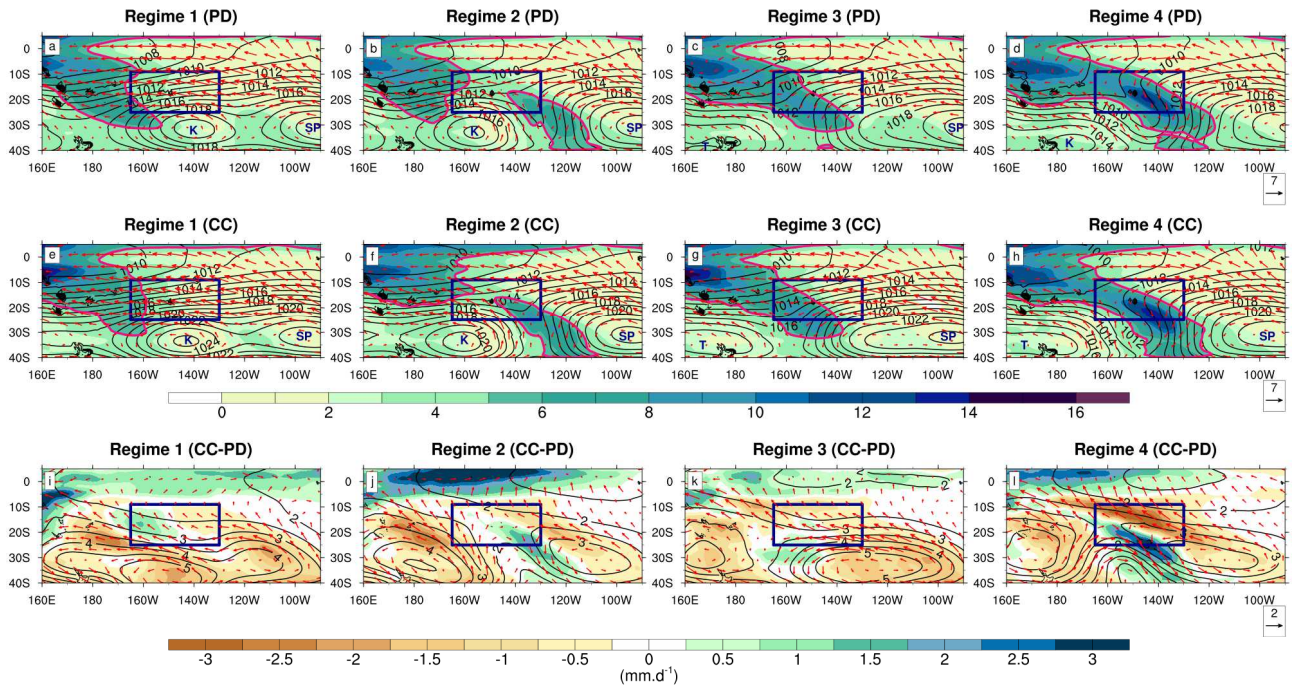


Figure 6

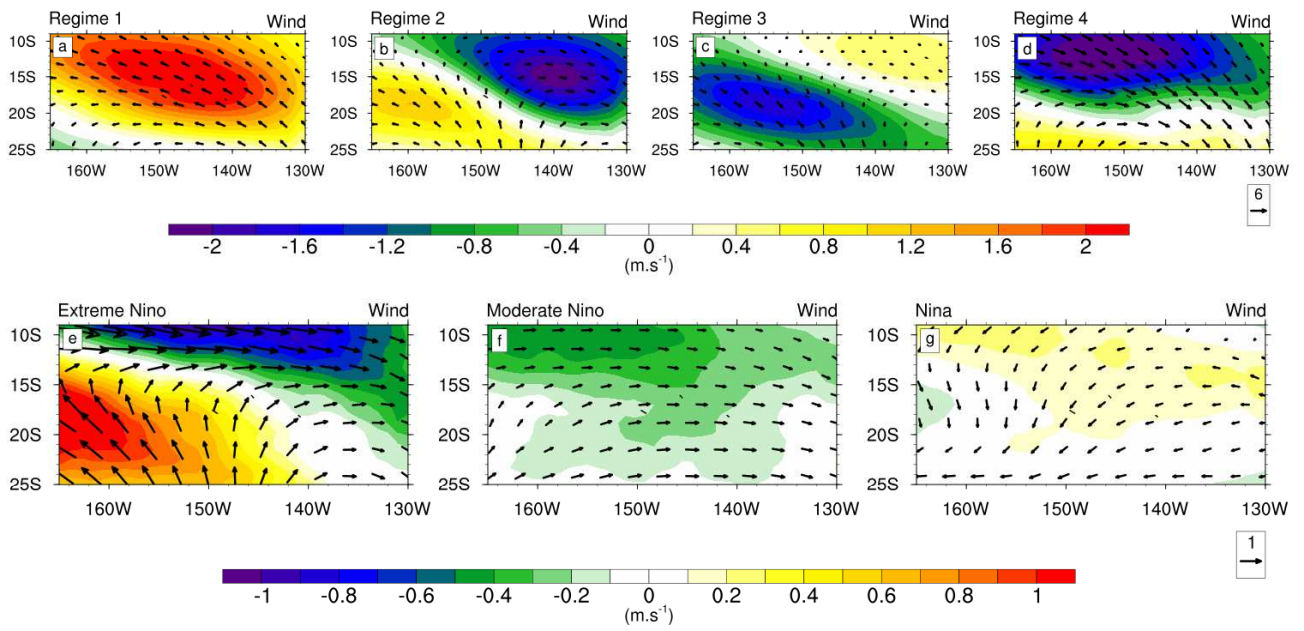


Figure 7

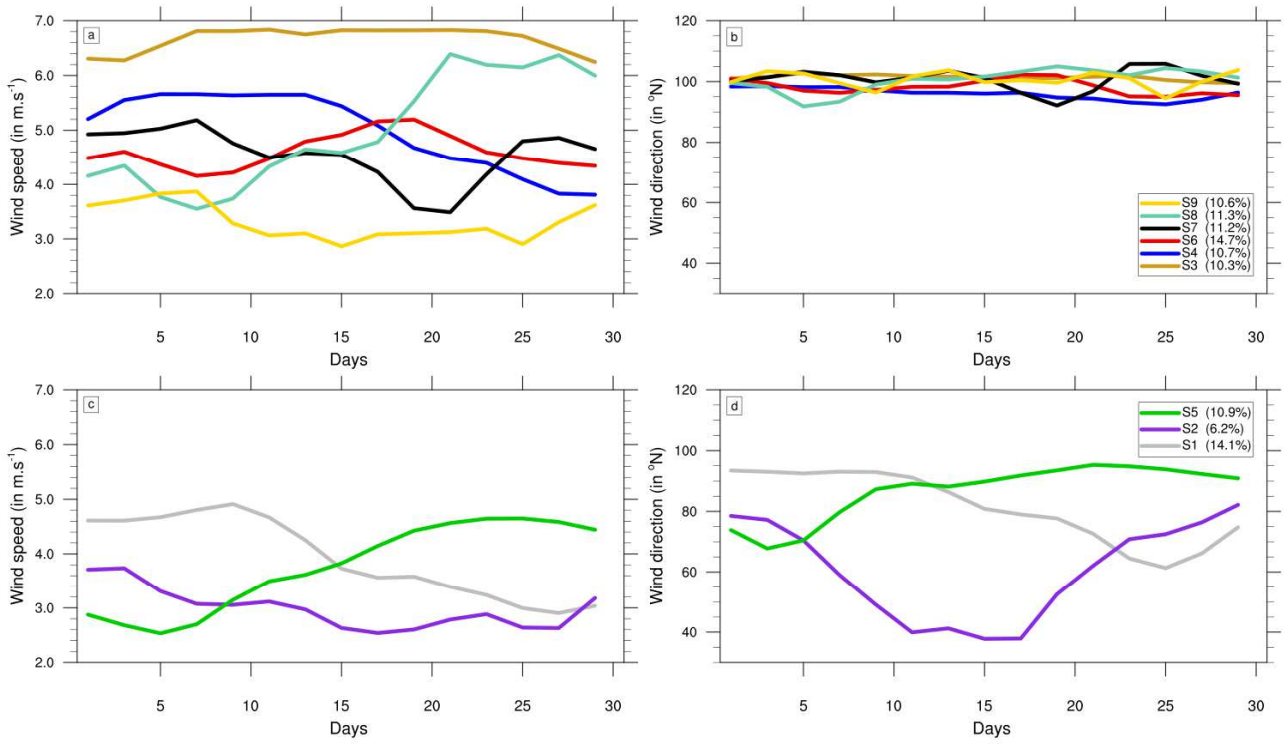


Figure 8

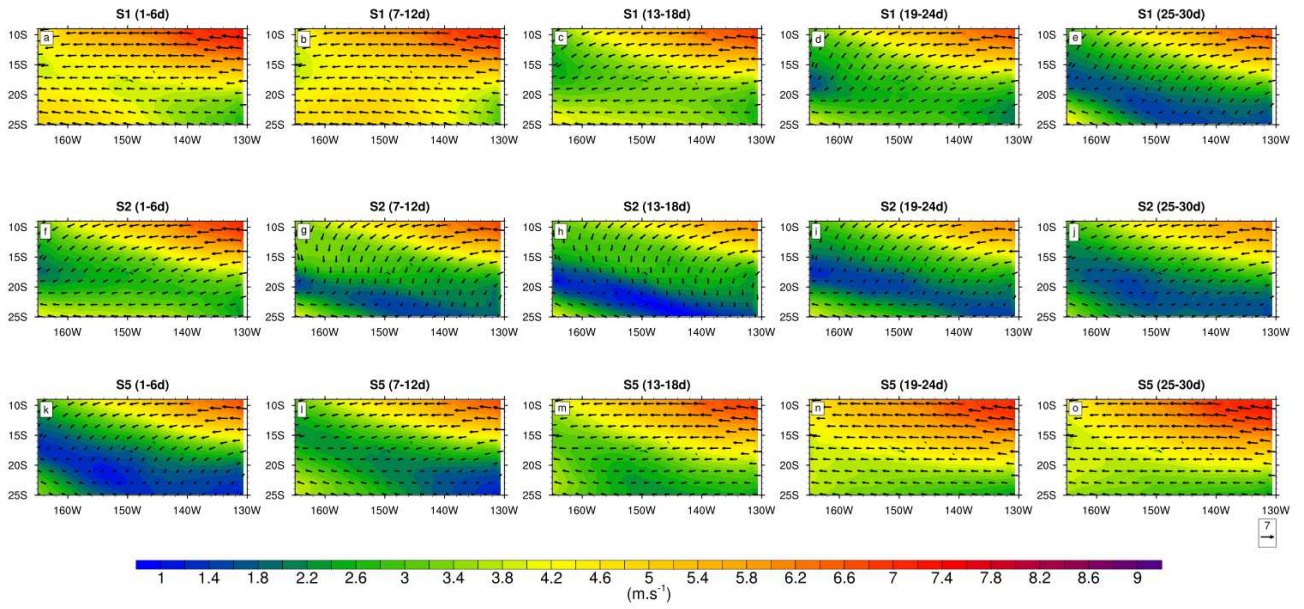
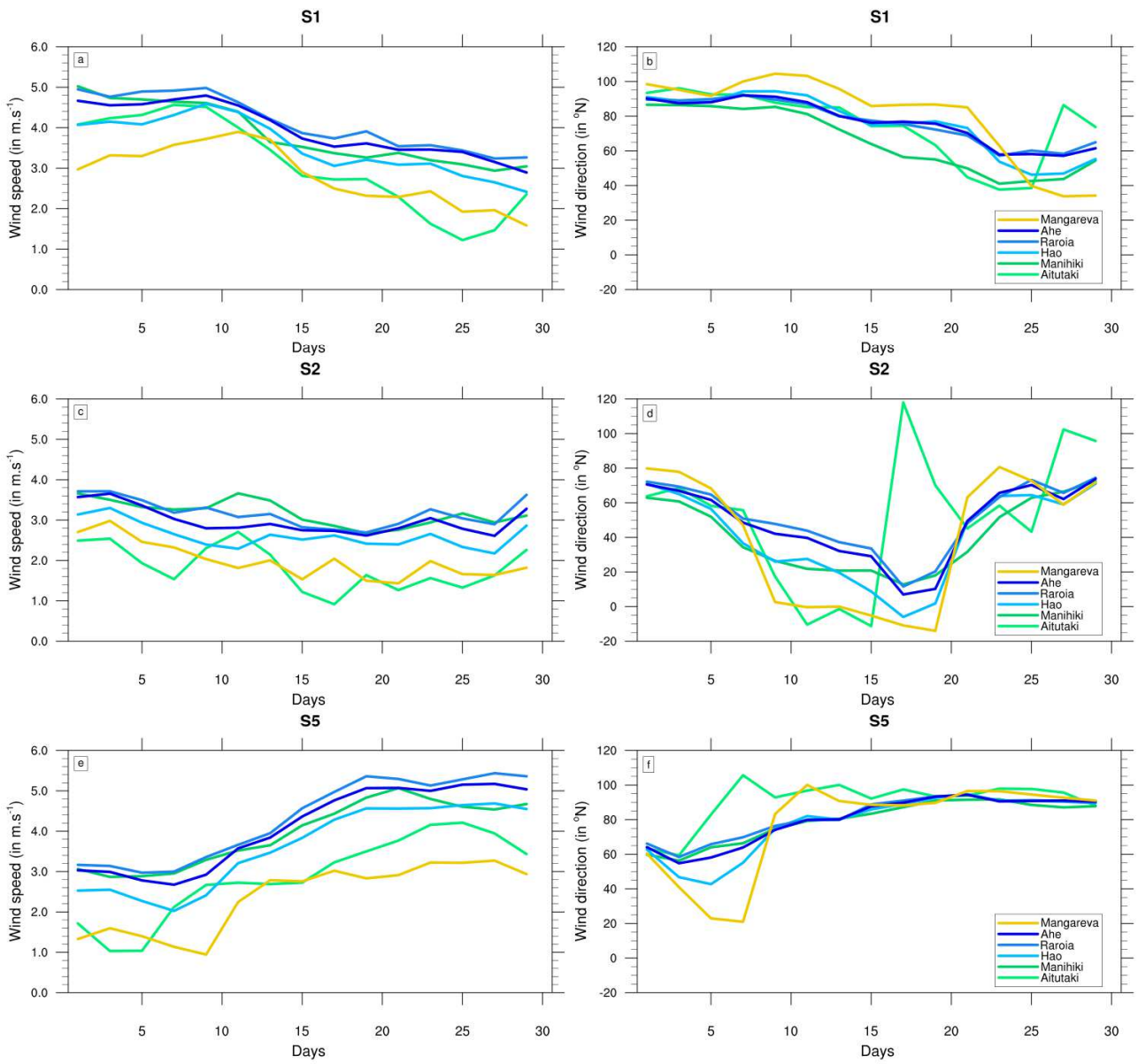


Figure 9



778

Figure 10

779

780 **Table 1:** Statistics of wind composite parameters (speed and direction in average) computed from
781 ERA5 reanalysis, and the PD and CC simulations over 37-years period (1980-2016 for ERA5 and
782 PD; and 2072-2108 for CC).
783

	Frequency			Wind speed (in m.s ⁻¹)			Wind direction (°N)		
	ERA5	PD	CC	ERA5	PD	CC	ERA5	PD	CC
R1	4559 (34.3%)	3944 (29.7%)	3936 (29.7%)	6.3	6.8	7.6	99.3	102.1	104.8
R2	3042 (22.9%)	3250 (24.5%)	2670 (20.1%)	4.4	4.2	4.5	107.5	109.2	113.0
R3	3846 (29.0%)	4164 (31.4%)	4640 (35.0%)	3.9	4.0	5.2	75.3	84.7	91.3
R4	1823 (13.7%)	1912 (14.4%)	2024 (15.3%)	3.0	2.7	3.1	64.9	61.0	73.1

784
785
786
787

788 **Table 2:** Results of the goodness-of-fit test between observed and expected days, assuming that the
789 distribution of the weather type does not depend on ENSO phases. O: Observed; E: Expected; R:
790 standardized residual. Absolute values of R greater than 2 are in bold; positive (negative) values
791 indicate that regime is likely (unlikely) to occur during the corresponding phase.

		R1	R2	R3	R4
Extreme El Niño	O	251	354	227	205
	E	308	254	325	149
	R	-3.3	6.3	-5.4	4.6
Moderate El Niño	O	681	754	827	472
	E	813	670	858	394
	R	-4.6	3.2	-1.1	3.9
Neutral	O	1840	1437	1881	720
	E	1747	1440	1844	847
	R	2.1	-0.08	0.9	-4.7
La Niña	O	1172	705	1229	515
	E	1076	887	1136	522
	R	2.9	-6.1	2.8	-0.3
Chi-square	p-value	<0.001	<0.001	<0.001	<0.001

792

793 **Table 3** : Spatial pattern correlation of surface wind composites anomalies between each daily
 794 weather regime and ENSO mode. The anomalies are calculated from the average over the 1980-
 795 2016 period. Absolute spatial pattern correlation values greater than 0.6 are in bold.

	R1	R2	R3	R4
Extreme El Niño	-0.51	0.88	-0.86	0.58
Moderate El Niño	-0.63	0.40	-0.34	0.80
La Niña	0.61	-0.66	0.55	-0.64

796

797

798

799 **Table 4** : Typology on wind direction of nine 30-day regimes.

Easterly steady direction	East + North-north-east	East + North-east	North-east + East
S3, 4, 6, 7, 8 and 9	S2	S1	S5

800

801