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Review Article

Sea breeze systems in the temperate Southern hemisphere: detection methods, regional evidence, and knowledge gaps

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Abstract

Sea breezes are mesoscale atmospheric circulations driven by the daytime thermal contrast between land and ocean surfaces. Their intensity, spatial structure, and inland penetration are controlled not only by this local thermal forcing, but also by interactions with the background synoptic wind field, which give rise to three primary circulation regimes: pure, corkscrew, and backdoor sea breezes. Although the fundamental dynamical mechanisms governing sea breeze formation are universal, the influence of the Coriolis force reverses the geometric relationships defining these regimes between hemispheres, making the analysis of Southern Hemisphere sea breezes a distinct scientific challenge. Despite this fundamental difference, the scientific literature remains strongly biased toward Northern Hemisphere case studies, leaving substantial knowledge gaps regarding the dynamics, frequency, typological distribution, and environmental impacts of sea breezes in temperate regions of the Southern Hemisphere. These gaps have important implications for several applications, including offshore wind resource assessment, coastal air quality forecasting, urban thermal comfort management, and the characterization of coastal ocean dynamics in regions such as South America and Oceania. This review synthesizes the current state of knowledge on sea breeze systems in the temperate Southern Hemisphere, addressing their physical mechanisms, sea breeze front dynamics, typological classification, detection methodologies, numerical modeling approaches, regional climatology, and documented environmental impacts. Particular attention is given to observational and modeling studies conducted in Argentina, Uruguay, Chile, Australia, and New Zealand. Finally, key research gaps are identified and priorities for future investigations are proposed, including the development of classification frameworks adapted to Southern Hemisphere dynamics, the integration of statistically corrected reanalysis products with in situ observations, and the establishment of long-term regional sea breeze climatologies in data-limited coastal environments.

Keywords: sea breeze circulation, Southern Hemisphere coastal meteorology, Mesoscale atmospheric processes

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Abbreviations: CIBL, convective internal boundary layer; ERA5, ECMWF Reanalysis v5; ECMWF, European Centre for medium-range weather forecasts; KHBs, Kelvin–Helmholtz billows; PET, physiological equivalent temperature; PGF, pressure gradient force; SBC, sea breeze circulation; SBF, sea breeze front; SBG. sea breeze gravity; SBH, sea breeze head; TAPM, the air pollution model; UTCI, universal thermal climate index; WeMOi, Western Mediterranean oscillation index; WRF, weather research and forecasting

Introduction

A large proportion of the global population resides in coastal regions, where atmospheric circulation patterns exert a strong influence on local weather conditions, environmental processes, and socioeconomic activities. Among the most characteristic atmospheric phenomena affecting these areas is the sea breeze, a thermally driven coastal circulation generated by the diurnal differential heating between land and ocean surfaces. Sea breeze systems typically extend over spatial scales ranging from approximately 20 to 200 km, placing them within the meso-β category of atmospheric circulations,[1] while their temporal evolution is largely governed by the diurnal solar cycle.

Sea breezes generally develop under clear or partly cloudy conditions, when the land surface warms more rapidly than the adjacent ocean during daylight hours. This differential heating produces horizontal pressure gradients that drive an onshore airflow near the surface and a compensating return flow aloft,[2] establishing a closed mesoscale circulation cell between the ocean and the continental surface. The strength and evolution of this circulation are further modulated by thermal and moisture exchange processes occurring at the land–sea interface, which redistribute heat and momentum within the coastal atmospheric boundary layer.[3]

Despite their relatively limited spatial scale, sea breeze circulation (SBC) constitute a dominant atmospheric forcing mechanism in many coastal environments. Their presence influences atmospheric stability, cloud formation, pollutant dispersion, and the structure of the coastal boundary layer.[4–6] In coastal urban areas, sea breezes act as a natural ventilation mechanism capable of moderating heat stress and partially mitigating the urban heat island effect during warm seasons. Over adjacent coastal waters, these circulations drive systematic diurnal variability in surface currents, wave conditions, and sediment transport. Furthermore, in the context of renewable energy development, the type and intensity of the sea breeze strongly influence the offshore wind energy potential of coastal regions.

From a dynamical perspective, SBC can be interpreted through the Bjerknes circulation theorem, which describes the generation of vorticity under baroclinic conditions.[3] Differential heating between land and ocean produces horizontal density gradients that generate pressure differences between the corresponding air columns. The resulting pressure gradient force (PGF), oriented approximately perpendicular to the coastline, initiates the onshore surface flow and the compensating return flow aloft.[7] Importantly, the structure and intensity of sea breeze systems are not determined solely by this local thermal forcing. Interactions with the background synoptic wind field can substantially modify the circulation, giving rise to three dynamically distinct regimes (pure, corkscrew, and backdoor sea breezes) which differ markedly in terms of onset timing, inland penetration, offshore wind intensity, and associated environmental impacts.

Although sea breeze systems have been widely studied in Northern Hemisphere coastal regions, the existing literature exhibits a pronounced geographical bias that limits our understanding of sea breeze behavior in Southern Hemisphere environments. This imbalance is particularly evident in temperate coastal regions of South America and Oceania, where available studies are often restricted to localized observational analyses at individual meteorological stations or short observational records. Comprehensive reviews synthesizing regional knowledge remain scarce.

This review aims to address this gap by synthesizing the current state of knowledge on SBC in the temperate Southern Hemisphere. Specifically, the objectives of this study are to: (i) describe the fundamental physical mechanisms and structural components of sea breeze systems; (ii) summarize the principal methodologies used for sea breeze detection; (iii) examine the documented environmental impacts associated with these circulations; and (iv) review the available research conducted in Argentina, Uruguay, Chile, Australia, and New Zealand. Through this synthesis, key knowledge gaps are identified and priorities for future research are proposed.

Physical mechanisms of sea breeze formation

Sea breeze events can be identified through characteristic variations in several meteorological variables. Typical indicators include abrupt shifts in wind direction toward an onshore flow, moderate increases in wind speed, decreases in air temperature, and increases in relative humidity associated with the arrival of cooler marine air masses. These events are also commonly associated with weak surface pressure gradients, clear or weakly cloudy skies, and the absence of precipitation.[6]

Within the SBC system (Figure 1), several structural components can be distinguished that describe its dynamical configuration.[2] The SBC constitutes a vertically rotating mesoscale cell in which the surface-level flow is directed onshore, air rises over the heated land surface, diffuse subsidence occurs over the open ocean, and a compensating return flow develops within the lower troposphere, typically near the 900 hPa level. The sea breeze gravity current (SBG) corresponds to the low-level landward intrusion of cool, moist marine air that forms the active lower branch of this circulation cell.

The leading edge of the SBG is defined by the sea breeze front (SBF), a narrow transition zone characterized by sharp gradients in temperature, moisture, and wind direction. The arrival of the SBF is frequently accompanied by the formation of fair-weather cumulus clouds over the adjacent land surface. Immediately above and behind this frontal boundary, the sea breeze head (SBH) develops as updrafts from the interacting air masses converge at the leading edge, producing a raised structure typically twice as deep as the feeder flow that follows it (Figure 1).

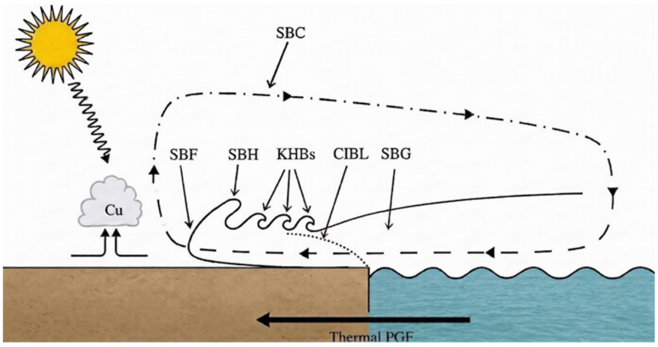

Figure 1 Sea breeze system (SBS). Modified from Miller et al., (2003).[2] SBF: sea breeze front. SBH: sea breeze head. KHBs: Kelvin–Helmholtz billow. CIBL: convective internal boundary layer. SBG: sea breeze gravity current. SBC: sea breeze circulation. PGF: Pressure gradient force. Cu: Cumulus clouds.

Along the upper interface of the SBG, Kelvin–Helmholtz billows (KHBs) may form under conditions of reduced static stability during midday hours. These structures arise from the strong vertical shear between the advancing marine layer and the warmer continental air above. Within the marine air mass itself, an unstable sublayer known as the convective internal boundary layer (CIBL) forms at the coastline and deepens progressively as the air mass moves inland. This layer plays an important role in trapping and concentrating surface-level pollutants, thereby exerting a direct influence on coastal air quality (Figure 1).

The development and intensity of SBC are influenced by two broad groups of factors: meteorological–oceanographic factors, including sea surface temperature, atmospheric humidity, vertical stability, and cloud cover; and geographic–physical factors, encompassing latitude, coastline orientation, surface roughness, and coastal topography.[6] Among these, the meteorological–oceanographic factors are generally considered the most influential, given the predominantly diurnal time scale of the phenomenon.[3]

Among the structural components of the sea breeze system, the SBF has received particular theoretical attention due to its dynamically complex nature. A useful framework for understanding its behavior is the analogy with gravity currents, also referred to as density currents.[8] Within this conceptual framework, the advancing marine air mass behaves as a relatively dense fluid intruding beneath a lighter ambient environment. This process generates characteristic features such as a raised head at the leading edge and a turbulent wake region behind the front.

This analogy has proven physically insightful, as many kinematic and dynamic properties of the SBF, including its propagation speed, depth, and the structure of the interfacial zone, can be approximated using gravity current theory. Both observational and theoretical perspectives on SBF structure have been synthesized,[2] confirming the applicability of the density current framework across a variety of coastal environments. This analysis was subsequently expanded to a wider range of geographic contexts,[9] emphasizing the influence of surface roughness, terrain complexity, and background synoptic winds on SBF propagation. In particular, the inland penetration of the sea breeze has been shown to be strongly controlled by the magnitude and direction of the synoptic wind relative to the coastline.

Within the Southern Hemisphere, however, the characterization of SBF properties has largely been limited to observational studies

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documenting arrival times, temperature decreases, and wind shifts associated with frontal passages. Studies conducted in Argentina[10,11] and Uruguay,[7] for instance, have reported well-defined frontal passages based on abrupt changes in wind and temperature. Nevertheless, systematic characterization of frontal propagation speeds or frontal height structures using the density current framework remains largely absent from the regional literature. This lack of detailed dynamical analyses represents a clear gap in current knowledge and highlights an important avenue for future research.

Typological classification of sea breeze regimes

Historically, sea breezes were interpreted as relatively simple thermally driven circulations resulting from land–sea temperature contrasts. Subsequent research, however, demonstrated that their structure, intensity, and spatial configuration are strongly modulated by interactions with the background synoptic wind field, often referred to as the gradient wind. Based on the orientation of the synoptic flow relative to the coastline, three primary sea breeze regimes have been identified: pure, corkscrew, and backdoor.[12,2] This classification framework has since been widely adopted in the literature and further explored through numerical modelling studies.[13–15]

The practical relevance of this classification extends well beyond theoretical considerations. Idealized simulations with the Weather Research and Forecasting (WRF) model have demonstrated that the type of sea breeze exerts a strong influence on the offshore wind field, with important implications for both coastal and offshore wind energy assessment.[13] Similarly, sea breeze regime has been shown to modulate turbulence intensity and trace gas transport within the coastal atmospheric boundary layer.[16] Importantly, the geometric relationships that define each regime are hemisphere-dependent. Because the sign of the Coriolis parameter is reversed in the Southern Hemisphere, the directional criteria used to distinguish sea breeze types in the Northern Hemisphere must be appropriately adapted before being applied in Southern Hemisphere environments.

Pure sea breeze

The pure sea breeze (Figure 2) develops under conditions in which the gradient wind flows approximately perpendicular to the coastline. Prior to the onset of the SBC, a characteristic zone of weak winds or near-calm conditions often forms along the coast as the synoptic pressure gradient approaches equilibrium with the thermally induced pressure gradient.[12,2] Once the thermal forcing becomes sufficiently strong to overcome this balance, the onshore flow begins to advance perpendicularly to the coastline, and the SBF propagates inland during the afternoon.

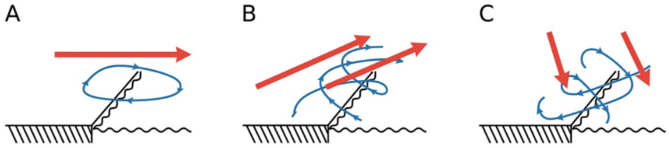

Figure 2 Plan views of *pure* (A), *backdoor* (B), and *corkscrew* (C) sea breeze generating scenarios depicting the effect of gradient winds on a coastline in the Southern Hemisphere. Bold red arrows indicate wind at the top of the planetary boundary layer. Blue arrows indicated SBC related near-surface wind. Modified from Steele et al. 2013.[13]

Pure sea breeze events exhibit a well-defined circulation structure characterized by a distinct frontal boundary, strong low-level convergence, and a compensating return flow aloft. In comparison with other sea breeze regimes, pure sea breezes tend to produce notable reductions in offshore wind speeds, and their inland penetration is more strongly inhibited by increasing gradient wind strength.[13] The onset of this regime is typically marked by an abrupt rotation of wind direction toward an onshore flow, making pure sea breeze events relatively straightforward to identify using surface meteorological observations.[15]

Corkscrew sea breeze

The corkscrew sea breeze develops when the gradient wind blows approximately parallel to the coastline, with the land surface situated to the left of the flow in the Northern Hemisphere or equivalently, to the right in the Southern Hemisphere due to the reversed sign of the Coriolis parameter. Under this configuration, the combined effects of surface friction and Coriolis acceleration generate a divergence zone within the low-level coastal boundary layer. This divergence favors subsidence and mechanically assists the initiation of the SBC.[13]

As a consequence, corkscrew sea breezes can develop under significantly weaker land–sea thermal contrasts than either the pure or backdoor regimes, often resulting in an earlier onset and greater frequency under moderate synoptic forcing conditions.[14] The corkscrew regime produces a helical flow pattern as the SBC spirals along the coastline. At the surface, its arrival is typically marked by a gradual backing of the wind rather than by an abrupt directional shift.[2] From an energy perspective, this regime is particularly important. Numerical modelling studies have shown that corkscrew sea breezes can generate substantially stronger offshore wind speeds than other regimes, with estimated wind energy outputs up to three to four times greater than those associated with pure or backdoor configurations.[13,15,17] Despite this practical relevance, the corkscrew sea breeze has not yet been systematically characterized in Southern Hemisphere coastal environments (Figure 2).

Backdoor sea breeze

The backdoor sea breeze occurs when the gradient wind also flows approximately parallel to the coastline but with the land surface located to the right of the flow in the Northern Hemisphere or to the left in the Southern Hemisphere. In contrast to the corkscrew configuration, this geometry produces low-level coastal convergence, which promotes upward motion near the shoreline and acts as a dynamical barrier that inhibits the inland advance of the marine air mass.

As a result, the backdoor sea breeze requires considerably stronger thermal forcing to penetrate inland than either the pure or corkscrew regimes.[12,2] This regime is typically the weakest of the three, tends to arrive later in the day, and may manifest intermittently or in pulses rather than as a sustained onshore flow.[2]

The arrival of the backdoor sea breeze is usually associated with a veering of the wind direction rather than a backing, corresponding to a clockwise rotation in the Northern Hemisphere.[12] Similar to the corkscrew regime, the backdoor sea breeze may also exhibit a helical structure along the coastline, although rotating in the opposite sense. Among the three regimes, the backdoor sea breeze is generally the least frequently observed and the most difficult to identify using surface meteorological data, since the expected wind direction change may occur gradually and without a clearly defined frontal passage (Figure 2).[15]

Sea breeze detection methodologies

The accurate and reproducible identification of sea breeze events from observational datasets constitutes one of the central methodological challenges in sea breeze research. Detection

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approaches vary considerably in terms of complexity, data requirements, and spatial applicability, and their respective strengths and limitations must therefore be carefully evaluated when constructing regional climatologies or comparing results across studies and geographic settings. A persistent difficulty is that reliance on a single diagnostic threshold may lead to both false detections and underestimations, particularly when synoptic-scale circulation modulates or masks the local thermal signal.[17] This section reviews the principal methodological approaches used to identify sea breeze events, including surface station criteria, automated multi-variable algorithms, SBF identification techniques, remote sensing platforms, and the use of atmospheric reanalysis products.

Station-based and multi-criteria physical methods

The most widely used approach for sea breeze detection relies on meteorological observations collected at surface weather stations. Traditionally, sea breeze occurrences were identified through visual inspection of meteorological time series, with analysts searching for characteristic signatures such as onshore wind direction shifts, simultaneous decreases in air temperature, and increases in relative humidity following a period of mourning surface warming. Although this subjective approach can produce detailed event catalogues, its dependence on expert judgment limits reproducibility and makes it impractical for the analysis of long-term observational records.

To overcome these limitations, more objective detection frameworks have been progressively developed since the early 1960s. A systematic review of the criteria employed in both automated and manual detection algorithms has identified up to eleven distinct meteorological tests used in different combinations across the literature.[18] These include wind speed and direction changes, land–sea air temperature contrasts, surface pressure gradients, cloud cover conditions, relative humidity variations, precipitation absence, and indicators of wind convergence. Their review demonstrated that no single criterion is sufficient for robust detection, and that multi-criteria frameworks consistently outperform single-variable approaches in both precision and reliability. Using a combination of wind, temperature, and pressure criteria, their automated algorithm identified 475 sea breeze events over a six-year period in the Bay of Alicante, compared with 1,414 events detected through a more exhaustive manual procedure, illustrating the trade-off between automation efficiency and detection completeness.

Among pressure-based approaches, an automated detection technique based on regional sea-level pressure differences using the Western Mediterranean Oscillation index (WeMOi) has been introduced.[19] By requiring sea-level pressure over the western Mediterranean to exceed a defined threshold relative to the Atlantic, this method effectively filtered out synoptically disturbed days and enabled the construction of multi-decadal sea breeze climatologies from long-term station archives. This approach demonstrated the methodological viability of pressure-based automated detection techniques for large datasets.

A complementary method applies simultaneous physical thresholds across several meteorological variables to distinguish genuine marine air intrusions from other atmospheric circulations. Following established detection methodologies,[6,20] five concurrent criteria are typically required: a decrease in air temperature, an increase in relative humidity, a shift in wind direction, a wind speed between 2 and 35 km/h to exclude strong synoptic forcing,[17] and low or absent cloud cover to ensure sufficient land–sea thermal contrast. Event onset is defined by the initial temperature decrease, persistence must be maintained for at least one continuous hour, and termination is typically marked by an abrupt drop in relative humidity or a sustained rotation toward offshore wind directions.

Sea breeze front detection

Complementary to the station-based identification of sea breeze events is the detection of the SBF which involves characterizing the spatial propagation of the marine air mass as it advances inland. This approach presents additional methodological challenges, since the SBF represents a moving boundary whose detection ideally requires either a spatially distributed network of meteorological stations or remote sensing observations.

An objective algorithm for SBF identification along the northeastern coast of Brazil has demonstrated that frontal characteristics can be systematically extracted from meteorological station networks using criteria based on wind and temperature gradients.[21] In Argentina, an early method to detect SBF based on fluctuations in meteorological variables observed at Marisol Beach has been proposed,[10] representing one of the first attempts at systematic SBF identification in South America, though its analysis was limited to a single station, restricting the ability to resolve the spatial structure of the frontal boundary.

Radar and satellite detection

Radar and satellite-based techniques offer the possibility of detecting SBF and associated convection at spatial and temporal resolutions that are not achievable using surface station networks alone. Doppler weather radar systems can identify the fine-scale convergence zones and reflectivity signatures associated with the advancing SBF, while geostationary satellite imagery can track the development of cumulus cloud lines that frequently form along the frontal boundary.

The value of combining multiple observational platforms to characterize SBF passages within the coastal atmospheric boundary layer has been demonstrated,[16] while radar observations have been highlighted as an indirect but informative tool for tracking SBF propagation.[22] Satellite imagery has also been used in conjunction with surface station data to identify sea breeze occurrences in Uruguay[7] and to analyze sea breeze-induced cloud formation in northern Australia.[23]

Reanalysis-based detection and the role of ERA5

In recent decades, atmospheric reanalysis products have become fundamental tools for long-term atmospheric analysis owing to their temporal consistency, global spatial coverage, and hourly temporal resolution. ECMWF Reanalysis v5 (ERA5) provides a horizontal grid spacing of approximately 31 km and enables the construction of continuous climatological time series in regions with sparse or heterogeneous observational networks, making it particularly attractive for sea breeze research in data-limited environments such as the temperate Southern Hemisphere.

However, coastal environments present particular challenges for reanalysis products. The strong land–sea thermal gradients, surface heterogeneity, and complex coastal topography that drive sea breeze formation are partially smoothed at the model grid scale, which can attenuate or distort mesoscale and local circulations. Systematic wind speed biases in ERA5 at coastal locations have been documented,[24] with identified systematic underestimations of coastal wind speeds using ASCAT scatterometer observations, biases that may directly affect the identification of sea breeze events.

Consequently, the direct application of raw ERA5 fields for sea breeze detection may introduce systematic errors in wind direction, temperature, and humidity that influence both event identification and the estimation of their characteristics. From this perspective, statistical bias correction and spatial downscaling are often necessary methodological steps for adapting reanalysis data to the physical scale of the sea breeze process.[25] Despite these challenges, relatively few studies have systematically evaluated how statistical adjustment of reanalysis data affects sea breeze detection and characterization, particularly along the temperate coastlines of the Southern Hemisphere.

Numerical modelling of sea breezes

Numerical weather prediction and mesoscale atmospheric models have become essential tools for investigating sea breeze dynamics, enabling researchers to isolate causal mechanisms, test theoretical hypotheses, and simulate sea breeze behavior under a wide range of environmental conditions. Unlike observational approaches, numerical simulations allow controlled sensitivity experiments in which individual parameters can be varied independently to evaluate their influence on sea breeze structure and type.

Idealized sensitivity experiments using the WRF model have demonstrated that offshore wind fields are strongly modulated by sea breeze type, with corkscrew configurations producing substantially higher wind energy outputs than pure or backdoor regimes.[13] The Air Pollution Model (TAPM) model has also been applied to simulate sea breeze flows in southwestern Australia, showing its capability to reproduce observed pollutant surface concentrations and fumigating plume behavior, thereby demonstrating the usefulness of mesoscale models for coastal air quality studies.[26]

The strong sensitivity of local sea breeze dynamics to background synoptic forcing has been confirmed through examination of the influence of synoptic-scale troughs on sea breeze timing and intensity near Perth.[27] One of the earliest Southern Hemisphere modelling studies simulated sea breeze interactions over the topographically complex Auckland region in New Zealand, demonstrating the feasibility of applying mesoscale atmospheric models in such environments.[28]

More recent studies increasingly employ high-resolution simulations combined with improved sea surface temperature datasets in order to better represent the coastal gradients responsible for initiating SBC. The growing use of ERA5 as a boundary condition or validation dataset in these simulations has renewed attention to the limitations of coarse-resolution reanalysis fields in coastal environments, reinforcing the need for statistical correction or dynamical downscaling when ERA5 data are used to drive or evaluate mesoscale sea breeze simulations.

Impacts of sea breeze

Sea breezes exert a wide range of environmental and socioeconomic impacts in coastal regions, influencing atmospheric composition, urban thermal conditions, offshore wind energy production, and coastal ocean dynamics. The following sections review the principal impact categories identified in the literature, with particular emphasis on evidence from the Southern Hemisphere when available.

Air quality

One of the most extensively studied impacts of sea breezes concerns their role in controlling the transport, dispersion, and recirculation of atmospheric pollutants in coastal environments. The mechanisms through which sea breezes influence air quality are complex and not always beneficial. While the onshore flow of marine air can dilute pollutants emitted near the surface, the same circulation may also recirculate those pollutants back inland through the land–sea breeze cycle, potentially leading to episodes of elevated pollutant concentrations.

The SBF acts as a low-level convergence zone capable of concentrating pollutants transported by both marine and continental air masses. Lagrangian particle dispersion under sea breeze convergence conditions has been examined,[29] demonstrating how frontal dynamics influence pollutant transport pathways and the degree of recirculation within the coastal boundary layer.

This recirculation mechanism is particularly relevant in coastal cities where morning land-breeze conditions transport locally emitted pollutants offshore, only for the afternoon sea breeze to return them inland. The CIBL plays a key role in this process. As the marine air mass advances inland, the growing unstable sublayer traps surface-level emissions beneath its capping inversion, progressively concentrating pollutants with distance from the coast.

The importance of accurately simulating this process when predicting fumigating plumes associated with industrial emissions in coastal southwestern Australia has been demonstrated,[26] highlighting the relevance of sea breeze modelling for regulatory air quality management. The combined effects of heat waves and sea breezes on pollutant concentrations have further been examined,[30] showing that while sea breezes can moderate extreme temperatures, they may also redistribute pollutants across the coastal boundary layer under certain meteorological conditions.

Urban thermal comfort

In many coastal cities, sea breezes act as an important climatic regulator of the urban thermal environment during the warm season. Their onset is typically associated with decreases in air temperature, increases in wind speed, and reductions in thermal stress indices such as Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI), thereby improving perceived thermal comfort in coastal zones.[20,30]

Studies conducted in several coastal cities, including Sydney, Adelaide, Sendai, and Funchal, have documented temperature reductions ranging from approximately 2 to 8 °C following sea breeze onset.[30–33] These cooling effects are generally strongest near the shoreline and weaken progressively with distance inland as the marine air mass warms and mixes with continental air.

However, the thermal comfort benefits associated with sea breezes are not spatially uniform. In dense urban environments, building morphology can obstruct ventilation pathways and limit the inland penetration of marine air, maintaining elevated heat stress levels within sheltered urban canyons. Conversely, the presence of urban green corridors and ventilation pathways can enhance the inland reach of sea breeze cooling.

Offshore wind energy

The interaction between sea breezes and offshore wind resources has become an increasingly important research topic due to the rapid expansion of offshore wind energy infrastructure worldwide. SBC generate systematic diurnal variations in near-surface wind speeds that are superimposed on the ambient synoptic wind field, and these variations must be accurately characterized in order to produce reliable offshore wind resource assessments.

High-resolution WRF simulations have been used to detect and classify sea breeze regimes along the northeastern coast of the United States, demonstrating that sea breeze activity generates coherent diurnal signals in offshore wind speeds that vary significantly depending on sea breeze type.[15] This analysis has been extended by examining the energy implications of sea breeze classification, confirming that corkscrew regimes can produce wind energy outputs up to three to four times greater than those associated with pure or backdoor configurations.[17]

These findings highlight the importance of applying sea breeze typological classification frameworks to coastal regions of the Southern Hemisphere, where offshore wind energy development is rapidly expanding but where the influence of sea breeze regimes on wind resources remains poorly documented.

Coastal ocean dynamics

Sea breezes also exert significant mechanical and thermodynamic forcing on coastal ocean dynamics, generating systematic variations in nearshore currents, wave conditions, and sediment transport. These oceanographic effects can have important implications for coastal geomorphology, marine ecosystems, and nearshore infrastructure.

The influence of sea breeze cycles on nearshore processes in southwestern Australia has been documented,[34] showing that daily wind forcing drives systematic variations in wave height, sediment suspension, and littoral drift. Sea breezes have further been shown to generate coherent diurnal current signals across the inner continental shelf off southwest Western Australia, with water column velocities responding directly to the daily wind forcing cycle.[35]

In certain settings, resonance between the sea breeze forcing frequency and the local inertial frequency of the ocean can significantly amplify these surface currents, a process documented for southern Australian coastal waters.[36] These results emphasize that sea breezes should be considered not only as atmospheric phenomena but also as key drivers of coupled land–sea–ocean interactions in coastal environments.

Sea breezes in the temperate southern hemisphere: current state of knowledge

A review of the available literature reveals a pronounced geographical imbalance in sea breeze research. The majority of observational and numerical modelling studies examining sea breeze dynamics, typology, and impacts have been conducted in Northern Hemisphere coastal environments. In contrast, investigations in the Southern Hemisphere remain comparatively scarce and are frequently limited to localized case studies or short observational records.

This geographical bias is particularly evident with respect to typological classification. While the pure, corkscrew, and backdoor framework has been extensively used in Northern Hemisphere coastal research, its application to Southern Hemisphere environments remains largely unexplored in the literature. Consequently, most studies conducted in the region focus primarily on the identification, frequency, and basic meteorological characteristics of sea breeze events rather than on their dynamical classification.

Existing research in the Southern Hemisphere can be broadly grouped into two principal regions (South America and Oceania) where the phenomenon has been examined from different scientific perspectives and using a variety of methodological approaches. Figure 3 illustrates the geographic distribution of the countries considered in this review, while Table 1 summarizes the principal study sites documented in the literature for each region.

Table 1 Study sites reviewed in sea breeze research across the temperate Southern Hemisphere

Country	*Study site*	*Coordinates*
Argentina	Puerto Madryn	42°46'S, 65°02'W
	Cabo San Antonio	36°40'S, 56°42'W
	Pinamar	37°06'S, 56°51'W
	Monte Hermoso	38°59'S, 61°17'W
	Mar del Plata	37°59'S, 57°33'W
	Necochea	38°33'S, 58°44'W
	Marisol	38°55'S, 60°32'W
	Pehuén Co	39°00'S, 61°33'W
	Golfo Nuevo	42°46'S, 65°02'W
Uruguay	Río de la Plata	—
	Atlantic coast / Río de la Plata	—
	Garzón	34°34'S, 54°36'W
Chile	Punta Hualpén	36°45'S, 73°11'W
	Isla Santa María	37°02'S, 73°30'W
	Concepción	36°50'S, 73°03'W
	Punta Lavapié	36° 24'S, 73°48'W
	Pisco	14°48'S, 76°36'W
	Tongoy / Pta. Lengua de Vaca	30°00'S, 72°12'W
	Paposo	25°01'S, 70°27'W
	Antofagasta	3°24'S, 70°24'W
	Iquique	20°01'S, 70°09'W
Australia	Perth	31°57'S, 115°51'E
	Adelaide	34°56'S, 138°36'E
	Sydney	33°52'S, 151°12'E
	Brisbane	27°28'S, 153°01'E
	Northern Australia	—
	East coast	—
	SW shelf	—
New Zealand	Auckland	36°50'S, 174°45'E
	Bay of Plenty	37°40'S, 176°10'E
	South Island coast	—

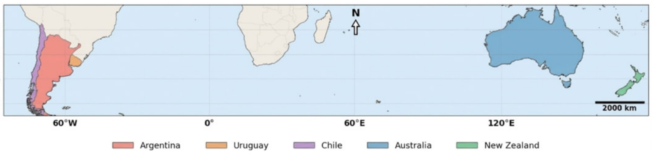

Figure 3 Study area map.

South America

Research on SBC along the South American coastline has primarily focused on the statistical characterization of local events, including their frequency, timing, intensity, and inland penetration. Most studies rely on in situ meteorological observations collected at individual stations or short observational campaigns, and systematic multi-station or reanalysis-based approaches remain relatively uncommon.

Argentina

Argentina accounts for a significant portion of sea breeze studies conducted in South America, with a research tradition spanning approximately five decades. However, despite this long-standing research activity, the overall number of investigations remains

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relatively limited when compared with the extensive body of literature available for coastal regions of the Northern Hemisphere. One of the earliest systematic analyses was conducted in Puerto Madryn (Table 1), examining sea breeze activity between September 1974 and March 1975.[37] Results indicated that sea breeze events occurred most frequently between late spring and early autumn, typically initiating around midday and lasting between 7 and 8 hours, with mean wind speeds of approximately 4 m/s and occasional gusts exceeding 8.3 m/s. Inland penetration distances averaged around 5 km, with exceptional cases reaching up to 17 km.

Further north along the Buenos Aires Province coastline, sea breeze characteristics in the Cabo San Antonio region (Table 1) were investigated,[38,39] showing that events were most frequent during spring and summer, with onset generally occurring between 09:00 and 13:00 local time. Mean duration was approximately 8.5 hours during summer and 5.6 hours during winter, with wind speeds ranging from calm conditions to approximately 7.7 m/s.

Upper-air measurements conducted in Pinamar (Table 1) revealed that the sea breeze layer typically reached depths between 800 and 1000 m, with a low-level jet core located between 300 and 400 m above the surface and frontal penetration distances extending up to 70 km inland.[40]

In Monte Hermoso (Table 1), 131 sea breeze events recorded between December 1980 and February 1982 were analyzed,[41] reporting frontal heights ranging between 650 and 750 m and mean maximum wind speeds between 4.16 and 5.5 m/s. Sea breeze onset most frequently occurred between 10:00 and 11:00, while termination typically occurred between 18:00 and 19:00. Notably, cumuliform cloud development over the continental surface accompanied the SBF in approximately 80% of observed cases.

In Mar del Plata (Table 1), sea breeze activity between August and April over the period 1964–1984 was documented, identifying a maximum event frequency between 14:00 and 20:00 local time.[42] Temperature drops of 2–6 °C in Mar del Plata and greater than 7 °C in Necochea associated with SBF passages were subsequently reported, with mean wind speeds of 2.36 m/s and 5 m/s respectively.[43]

A detection methodology for SBF based on fluctuations in meteorological variables at Marisol beach (Table 1) was later developed, with proposed application in early warning systems for pollutant dispersion along the Buenos Aires coastline.[10] A revisit of Monte Hermoso between 2007 and 2010 identified 40 sea breeze events characterized by predominant ESE–SE winds, mean wind speeds of approximately 4.5 m/s, and an average duration of 2.5 hours.[11] In the Golfo Nuevo region (Table 1), 147 sea breeze events between 2006 and 2008 were documented, indicating that sea breezes accounted for diurnal thermal variability on 52% of spring days and 61% of summer days, highlighting their role as a dominant forcing mechanism controlling daily temperature cycles in northern Patagonian coastal environments.[44]

A detailed case study of two well-developed sea breeze events in the Río de la Plata region, employing surface observations, satellite imagery, and hydrostatic boundary-layer model simulations, has been conducted.[45] Both events occurred under offshore regional flow that enhanced horizontal convergence and intensified the SBC. Results indicated that the inland propagation speed of the SBF estimated from model simulations exceeded that of associated cloud bands observed in satellite imagery, and that local coastline geometry influenced frontal penetration depth, illustrating the complexity of interpreting sea breeze signatures in estuarine coastal environments.

More recently, 718 sea breeze events in Mar del Plata were identified, with examination of thermal contrasts between coastal and inland areas and their implications for urban thermal comfort, reporting mean sea breeze wind speeds of approximately 4.08 m/s.[46] Collectively, these investigations provide a progressively detailed characterization of sea breeze behavior along the temperate South Atlantic coastline of Argentina. Nevertheless, most studies remain descriptive and based on observations from individual stations, and none has explicitly addressed sea breeze typological classification.

Uruguay

Compared to Argentina, the scientific literature on sea breezes in Uruguay is relatively recent and limited in scope. Sea breeze occurrences between 2011 and 2016 have been analyzed using data from 16 meteorological stations combined with satellite imagery and reanalysis datasets.[7]

The study identified approximately 120 sea breeze events per year, with a clear seasonal maximum during summer months. Notably, differences were observed between the Atlantic coastal sector and the Río de la Plata estuarine region. In the oceanic sector, sea breezes typically initiated around 11:00 local time with southeast winds, whereas in the estuarine region they began later, around 12:00, with predominantly southern winds. Inland penetration distances of up to 55 km were reported.

Later research confirmed the strong seasonality of the phenomenon, with most events occurring between December and March and reaching maximum wind speeds of approximately 4.16 m/s during the afternoon.[47] Additional studies have also explored the influence of mesoscale wind systems on agricultural productivity, highlighting the role of sea breezes in moderating temperatures and reducing thermal stress in vineyards producing Tannat grapes, based on observations from a commercial vineyard located in Garzón (Table 1).[48]

Chile

The Chilean coastline has been the subject of several sea breeze investigations addressing a diverse range of scientific questions, from boundary layer dynamics and synoptic climatology to coastal ocean forcing and stratocumulus cloud dissipation. While the total number of studies remains limited relative to the length and meteorological complexity of the Chilean Pacific coast, the available research reveals a distinctive sea breeze regime shaped by the interaction between thermally driven diurnal circulations and the dominant equatorward low-level jet of the southeast Pacific anticyclone.

The earliest documented studies were conducted in the Gulf of Arauco. Sea breeze activity was analyzed using 1991 data from Punta Hualpén (Table 1) and Santa María Island (Table 1), finding that events were most frequent in summer with predominantly south to southwest winds, onset between 09:00 and 10:00 local time, and mean wind speeds of 10 m/s at Punta Hualpén and 6 m/s at Santa María Island.[49] Wavelet transform analysis applied to the same dataset confirmed the cyclic diurnal nature of the phenomenon and identified phase differences in the diurnal evolution between the two stations.[50]

The broader atmospheric context within which Chilean sea breezes operate has been characterized through meteorological observations along the northern Chilean coast during the VOCALS-REx campaign, covering stations at Paposo (~25°S) and Iquique (~20°S).[51] Results demonstrated that within the coastal marine boundary layer, sea–land breeze circulations are superimposed on the prevailing southerly flow, producing light northeasterly winds from midnight to early morning and strong southwesterlies in the afternoon. The daytime phase of this diurnal cycle is consistent with enhanced coastal subsidence driven by the interaction between the coastal jet and dry convective heating over the western Andean slopes—a mechanism that distinguishes Chilean sea breezes from those in other temperate Southern Hemisphere settings where such orographic modulation is absent.

The synoptic-scale framework within which these diurnal circulations are embedded has been further examined through a synoptic climatology of near-surface winds along the Chilean and Peruvian coast, identifying prominent low-level jet maxima at Pisco (14.8°S), Punta Lengua de Vaca (30.0°S), and Punta Lavapié (36.4°S), and documenting the seasonal cycle of high-wind events at each location.[52] The fine-scale mesoscale circulation near Punta Lengua de Vaca and Tongoy Bay (30°S) has been analyzed in detail, documenting the interaction between the coastal jet, the sea breeze, and the complex local topography of the marine terrace.[53] Observations revealed that in the morning a shallow sea breeze penetrates from Tongoy Bay onto the marine terrace, but is overridden by the strengthening southerly flow in the afternoon — a dynamic interplay between the thermally driven diurnal circulation and the prevailing synoptic-scale forcing that has direct implications for the detectability of sea breezes in this region using standard meteorological criteria.

The oceanographic consequences of sea breeze forcing along the central Chilean shelf have been examined through characterization of diurnal-period ocean current variability on the inner shelf off Concepción (36°–37°S).[54] Using current velocity measurements collected during spring 2007 and summers of 2006 and 2008, diurnal-band current variability was shown to explain up to 40% of total current variance in the upper 15 m of the water column, with sea breeze amplitude modulated by synoptic-scale variability over periods of three to fifteen days. This study established one of the clearest quantitative links between sea breeze activity and shelf ocean dynamics in the Southern Hemisphere outside of Australia.

Most recently, the role of the sea breeze in the dissipation of coastal stratocumulus clouds at Antofagasta (Table 1) has been investigated, comparing observations with those from San Diego, California.[55] Results showed that despite differences in meteorological conditions between the two sites, the stratocumulus dissipation sequence followed a consistent pattern at both locations: sunrise, followed by sea breeze onset approximately 43 minutes later, then cloud fragmentation and eventual dissipation. While the sequential timing suggested a causal role for the sea breeze in triggering cloud fragmentation, statistical analysis indicated that solar radiation and thermodynamic variables were the primary drivers, with the sea breeze playing a secondary but measurable role—more pronounced at Antofagasta than at San Diego. This study represents the most recent dedicated sea breeze analysis conducted in Chile and highlights the interaction between sea breeze dynamics and the persistent stratocumulus deck that characterizes the northern Chilean coastal climate.

Taken together, these studies reveal that sea breezes in Chile operate within a uniquely complex atmospheric environment shaped by the combination of strong synoptic equatorward flow, orographic modulation by the Andes and coastal ranges, cold upwelled sea surface temperatures, and a persistent low-cloud deck.

Oceania

Compared with South America, research on sea breezes in Australia and New Zealand is considerably more extensive and covers a wider range of scientific topics. Australia hosts one of the most well-documented sea breeze regimes in the Southern Hemisphere.

In Perth, approximately 200 sea breeze events occur annually with mean wind speeds around 5.7 m/s.[56] These circulations have been shown to significantly influence coastal processes, including wave formation, sediment transport, and nearshore currents.[34] Numerical modeling studies have also explored the interaction between synoptic conditions and sea breeze development. The evolution of synoptic-scale troughs has been shown to strongly modulate the development of SBC,[27] and the capability of TAPM to simulate sea breeze dynamics with reasonable accuracy has been demonstrated, making it a suitable tool for pollutant dispersion studies.[26]

Additional research has investigated the relationship between sea breezes and cloud formation in northern Australia,[23] the occurrence of severe hailstorms along the east coast,[57] and the influence of aerosols during the 2019–2020 megafires in Brisbane, which significantly weakened sea breeze intensity.[58] Sea breezes also play an important role in coastal ocean dynamics. Studies have documented increases in surface current velocities and directional changes throughout the water column associated with daily sea breeze cycles.[35] In some cases, resonance between atmospheric forcing and oceanic inertial responses can further intensify surface currents.[36]

In addition to their oceanographic effects, sea breezes contribute to temperature regulation in coastal cities. For instance, research conducted in Sydney demonstrated that sea breeze winds play a critical role in moderating urban temperatures and mitigating heat stress.[32] In Adelaide, the SBF typically reaches the metropolitan area approximately 67 minutes after formation, producing cooling rates between 0.7 and 0.9 °C per hour per kilometer.[33]

Discussion and future research directions

The body of literature reviewed in this study reveals a research field that is geographically uneven, methodologically heterogeneous, and still evolving toward a unified conceptual framework. Although substantial progress has been achieved over recent decades, the distribution of research efforts remains highly uneven. While certain coastal regions particularly in Australia and, to a lesser extent, along the Argentine Atlantic coast, now possess multi-decadal observational records and diverse analytical approaches, extensive stretches of the Southern Hemisphere coastline remain essentially unexplored from the perspective of sea breeze dynamics.

One of the principal methodological limitations concerns the relationship between observational simplicity and physical completeness. Most detection criteria used in South American studies are designed primarily to identify the arrival of a sea breeze at a specific location. While these methods are useful for constructing local climatologies of event frequency, they provide little information regarding the spatial structure of the circulation, its inland propagation characteristics, or its interaction with the synoptic wind field.

This limitation has practical consequences. Different sea breeze regimes have been shown to produce substantially different wind energy outputs, temperature gradients, and pollutant dispersion patterns.[13,15,17] Consequently, a detection framework that does not distinguish between pure, corkscrew, and backdoor regimes is insufficient for many applied contexts, including renewable energy assessment and coastal air quality management.

A second methodological challenge concerns the use of atmospheric reanalysis products in the study of mesoscale coastal circulations. ERA5 provides an unprecedented combination of temporal continuity, global spatial coverage, and hourly resolution, making it an attractive resource for long-term climatological analyses.

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However, the phenomenon operates at spatial scales that are frequently smaller than the effective resolution of global reanalysis products.

The approximately 31 km grid spacing of ERA5 smooths sharp land–sea thermal gradients and modifies the coastal wind field, potentially introducing systematic biases in sea breeze detection. Although statistical bias correction can reduce mean errors in wind speed and temperature, such corrections do not necessarily preserve the diurnal structure or phase of the sea breeze signal. Because the diurnal cycle is fundamental to sea breeze dynamics and typological classification, evaluating whether corrected reanalysis data retain this signal is essential for reliable climatological analysis.

A related limitation involves spatial coverage. Many Southern Hemisphere investigations rely on data from a single meteorological station, preventing the reconstruction of SBF propagation, alongshore variability, or interactions with local coastal geometry. The Chilean coastline provides a clear example: observations from Tongoy Bay, Antofagasta, and the Gulf of Arauco suggest substantial regional variability in sea breeze behavior driven by differences in coastal jet intensity, topographic modulation, and sea surface temperature. Yet no study has attempted a comprehensive spatial synthesis of these processes.

Looking forward, the most promising research directions involve the integration of multiple observational and modelling approaches. Combining bias-corrected ERA5 fields with surface meteorological observations and high-resolution mesoscale simulations could enable the construction of long-term sea breeze climatologies capable of capturing both spatial variability and typological diversity. In this context, the explicit application of the pure–corkscrew–backdoor classification framework should become a central component of future research.

Finally, the potential influence of climate change on sea breeze dynamics represents an important and largely unexplored research frontier. Long-term changes in land–sea temperature contrasts, coastal sea surface temperatures, and synoptic circulation patterns may alter the frequency, intensity, and typological distribution of sea breeze events. Improved understanding of these changes is particularly relevant for offshore wind energy development, coastal urban climate management, and air quality regulation in rapidly growing Southern Hemisphere coastal cities.

Conclusion

SBC constitute a fundamental component of coastal atmospheric dynamics in the temperate Southern Hemisphere, exerting measurable influences on local meteorology, coastal ocean processes, air quality, urban thermal comfort, and renewable energy production. This review has synthesized the current state of knowledge across five countries, Argentina, Uruguay, Chile, Australia, and New Zealand highlighting both the progress achieved through several decades of regional research and the structural gaps that continue to limit its scientific scope and practical applicability.

Three principal conclusions emerge from this synthesis. First, the physical and dynamical framework governing sea breeze formation, frontal propagation, and typological classification is well established in the global literature, yet its systematic application to Southern Hemisphere coastal environments remains incomplete. The pure–corkscrew–backdoor classification framework has been widely applied in Northern Hemisphere studies but remains largely absent from Southern Hemisphere research. Second, methodological limitations arise from the mismatch between the spatial scale of the phenomenon and the resolution of the observational and modelling tools commonly available for long-term analysis. While ERA5 reanalysis offers temporal continuity and global coverage unmatched by regional observational networks, its spatial resolution smooths the land–sea thermal gradients that drive sea breeze development and may introduce systematic biases in event detection.

Third, the geographical imbalance documented in the literature reflects not only differences in publication volume but also disparities in observational infrastructure, research investment, and the integration of sea breeze science into applied domains such as renewable energy planning, air quality management, and urban climate adaptation.

Future progress will likely depend on the development of integrated observational and modelling frameworks capable of capturing both the spatial variability and dynamical diversity of sea breeze systems in the Southern Hemisphere. The construction of long-term climatologies combining corrected reanalysis fields with surface observations, together with the systematic application of typological classification schemes, represents a particularly promising avenue for advancing this research agenda. Improved scientific understanding of sea breeze dynamics will be of direct relevance for multiple applied sectors, including offshore wind energy development, coastal urban planning, and environmental management in the rapidly expanding coastal regions of South America and Oceania.

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Conflicts of interest

The authors declare no conflict of interest.

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