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Editorial

Advances in Air–Sea Interactions, Climate Variability, and Predictability

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1. Introduction

Air–sea interaction remains one of the most dynamic and influential components of the Earth's climate system, significantly shaping the variability and predictability of both weather and climate [1]. The exchanges of momentum, heat, and mass between the atmosphere and ocean not only influence short-term weather phenomena but also play a vital role in long-term climate processes [2,3]. These interactions are particularly complex, involving a wide range of spatial and temporal scales [4], from turbulent fluxes in the marine boundary layer [5] to large-scale climate variability patterns such as the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), and other significant modes of climate variability [6–8].

Recent years have witnessed considerable progress in the observation, modeling, and theoretical understanding of air–sea interactions [9–11]. Advances in observational technology, such as high-resolution satellite measurements and improved in situ monitoring, have enhanced our capability to capture these intricate processes [12]. Meanwhile, innovations in modeling, driven by both physical and data-driven approaches, have allowed for a more accurate representation of air–sea exchanges and their role in climate dynamics [13–16]. These developments have paved the way for improved predictions of climate variability and extreme weather events, which are critical for societal resilience and sustainable development in the face of global climate change.

However, despite these advancements, significant uncertainties remain in our understanding of air–sea interactions, especially at the submeso to synoptic scales and across different regions of the world's oceans. Challenges persist in refining coupled climate models, achieving comprehensive global and regional air–sea flux estimates, and understanding the influence of these processes on climate extremes. In recent years, artificial intelligence techniques have also emerged as powerful tools to enhance our understanding and modeling of these complex interactions, providing new opportunities for tackling unresolved questions. This Special Issue of *Atmosphere* aims to address challenges in understanding air–sea interactions by presenting recent research that highlights innovative observational techniques, advanced modeling approaches, and emerging data-driven methods, with a particular focus on their role in climate variability and predictability.

2. An Overview of Published Articles

The article by Mu et al. (Contribution 1) explores the underlying air–sea interaction and physical mechanisms of the NAO. This research employs advanced data-driven causal discovery techniques to investigate the causality between multiple ocean–atmosphere processes and the NAO. The study finds that the selected predictors of NAO are strongly associated with its development, providing a basis for more accurate forecasts. Using a multivariate air–sea-coupled model for NAO (NAO-MCD), this approach delivers seasonal forecasts with a lead time of 1–6 months, significantly outperforming conventional numerical models. Additionally, the results demonstrate that NAO-MCD can forecast winter events more reliably than current models. In conclusion, the research advances our understanding of NAO dynamics and provides a robust tool for improving NAO predictions, particularly in the seasonal forecasting domain.

The article by Djakouré et al. (Contribution 2) investigates the importance of convective systems for extreme rainfall along the northern coast of the Gulf of Guinea (GG) and their relationship with atmospheric and oceanic conditions. The study applies a comprehensive dataset including data from mesoscale convective systems (MCSs), daily precipitation, sea surface temperature (SST), and moisture flux anomalies. The novelty of this research lies in its use of a multi-source dataset to analyze the spatial and temporal distribution of convective systems and their connection to oceanic and atmospheric conditions. The results show that two-thirds of MCSs crossing Abidjan occur in June, with the majority originating from the continent. In contrast, oceanic MCSs are initiated closer to the coast. The study also highlights the role of moisture fluxes from three critical zones—(i) the seasonal migration of the intertropical convergence zone (ITCZ), (ii) the GG coastline, and (iii) the continent—which all contribute to the formation and sustenance of MCSs. These moisture fluxes are closely linked to oceanic warming events off Northeast Brazil and the northern GG coast, which occurred just before and on the day of extreme rainfall events. Overall, the findings emphasize the importance of oceanic moisture in supporting MCSs and enhancing rainfall along the Gulf of Guinea.

The article by Zanchettin et al. (Contribution 3) explores the predictability of the Antarctic dipole and its implications for Antarctic sea-ice predictability using hindcasts from a state-of-the-art decadal climate prediction system initialized between 1979 and 2017. The study employs advanced climate prediction models to understand the dynamics of the Antarctic dipole, specifically focusing on the relationship between sea-ice cover in the Weddell and Ross Seas. The authors find that the forecast skills for the Antarctic dipole are low, particularly in the first hindcast year, where the March values show a strong relaxation toward climatology and September anomalies are overestimated. This discrepancy is linked to the predominance of local drift processes over large-scale initialized dynamics. Furthermore, they highlight that the forecast skills for the Antarctic dipole and total Antarctic sea-ice extent are uncorrelated. The study also reveals the dipole's limited predictability under specific conditions, such as during strong El Niño–Southern Oscillation events. The authors suggest that the initialization timing and model drift contribute to the poor predictive skills.

The article by Alsubhi and Ali (Contribution 4) explores the variability of dust aerosol optical depth (DAOD) over the Arabian Peninsula (AP) during the spring season, a region greatly influenced by desert dust activity. This research employs the MERRA-2 DAOD reanalysis dataset from 1981 to 2022 and identifies a significant trend in DAOD during the spring season compared to other seasons. The study reveals that the leading Empirical Orthogonal Function (EOF) explains 67% of the total DAOD variance in spring, particularly over central and northeastern AP. It further identifies a link between the upper-level divergence in the western Pacific and mid-tropospheric positive geopotential height anomalies over AP, which contributes to warmer, drier conditions and increased DAOD. A statistically significant negative correlation is found between DAOD over AP and the ENSO, with La Niña conditions correlating with higher DAOD and El Niño conditions with lower DAOD. The study suggests that ENSO phases, through their influence on mid-tropospheric geopotential height anomalies, could be a predictor for dust variability at a seasonal timescale. This research highlights the potential of ENSO as a precursor for forecasting seasonal dust variability over the Arabian Peninsula.

The article by Shan et al. (Contribution 5) develops a diagnostic model for evaporation ducts using the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) and the Naval Postgraduate School (NPS) models. This research innovates by conducting sensitivity tests under extreme weather conditions to investigate wave processes' impact on evaporation ducts. The results show that wave processes affect evaporation duct heights by altering sea surface roughness and dynamical factors, with decreased local roughness leading to higher wind speeds and evaporation ducts at higher altitudes. Changes in evaporation ducts are influenced by regional circulation, with stronger local impacts in the eastern South China Sea and more complex effects in the central and western regions. This study underscores the role of wave processes and regional circulation in evaporation duct formation under extreme weather conditions.

The article by Mochizuki (Contribution 6) focuses on the relationship between climate variability and extreme rainfall events on Kyushu Island in Japan. This study investigates the interannual fluctuations in the extreme daily rainfall values, using large-ensemble simulations of a global atmospheric model. The innovative aspect of this research lies in its identification of two distinct physical processes influencing the rainfall variability: large-scale moisture transport anomalies linked to subtropical high-pressure changes, and tropical cyclone activity. The study finds that the 90th-percentile rainfall is influenced by changes in the subtropical high, which are often linked to basin-scale warming in the Indian Ocean after El Niño events. Additionally, low-frequency modulations of sea surface temperatures in the Indian and Pacific Oceans are connected to global warming trends and interdecadal climate variability. In contrast, the 99th-percentile rainfall is mainly driven by tropical cyclone activity, which is modulated by sea surface temperatures in the tropical Pacific. In conclusion, this research highlights the complex interplay between different climate phenomena and their combined effects on rainfall extremes, offering valuable insights for understanding future trends in extreme weather events in the context of a changing climate.

The article by Chen et al. (Contribution 7) investigates extreme precipitation events (EPEs) in the middle and lower reaches of the Yangtze River (MLYR) during the Meiyu season from 1961 to 2022, using rain gauge observations and ERA5 reanalysis data. This research explores the different characteristics of EPEs associated with the Northeast China cold vortex and ordinary EPEs. The study's innovation lies in its identification of the contrasting atmospheric patterns that influence these events. The analysis shows that EPEs linked to the cold vortex are marked by stronger westerlies and a well-defined wave train pattern extending from Europe to Northeast Asia. This configuration enhances moisture convergence from southwestern China to the MLYR, increasing rainfall. In contrast, ordinary EPEs are driven by a weaker Rossby wave propagation and less moisture transport, resulting in weaker rainfall. The main conclusion of the study is that the intensity of EPEs in the MLYR is heavily influenced by the atmospheric conditions associated with the Northeast China cold vortex. These findings suggest that stronger Rossby wave energy and the westward extension of the subtropical high are critical in determining the severity of extreme rainfall events. Overall, the study offers valuable insights into the atmospheric dynamics driving precipitation variability in the region during the Meiyu season.

3. Conclusions

This compilation of articles presents recent advances in understanding air–sea interactions, climate variability, and predictability. The studies cover a wide array of topics, including the predictability of the NAO, drivers of extreme rainfall, Antarctic sea-ice dynamics and predictability, seasonal dust variability over the Arabian Peninsula, wave impacts on evaporation ducts, and the atmospheric patterns influencing precipitation in East Asia. Together, these contributions provide the latest insights into air–sea interactions and deepen our understanding of climate dynamics and predictability across diverse regions and environmental conditions.

Despite these advancements, significant gaps and challenges remain in the science community. Key areas of ongoing difficulty include the following:

(1) Scale variability and model resolution: Capturing variability across spatial and temporal scales—from the submesoscale to synoptic patterns—requires enhancing model resolution to accurately represent sub-mesoscale and mesoscale eddy activities, as well as subsurface ocean dynamics, which are crucial to understanding air–sea interactions.
(2) Model design and multi-model frameworks: Robust coupled model designs should be developed and multi-model frameworks should be implemented to improve the integration of atmospheric and oceanic systems while addressing limitations related to model initialization and consistency across models.
(3) Data scarcity and observational enhancements in remote regions: The lack of observational data in remote areas, such as the open ocean and polar regions, should be addressed through the use of satellite data, advanced observational techniques, and improved sensor networks. Enhanced observational tools and remote sensing technologies are critical for obtaining accurate, high-resolution data, which can help fill gaps in data-scarce regions and improve model validation.
(4) Flux estimate uncertainty: Uncertainties in the estimation of fluxes of heat, momentum, and moisture between the atmosphere and ocean, which are essential for accurate climate modeling, should be reduced. Enhanced parameterization schemes, better measurement techniques, and the integration of in situ data with satellite observations are critical for improving these estimates and minimizing biases in climate models.
(5) Complex physical and biogeochemical processes: The intricate interactions between physical and biogeochemical processes, such as nutrient cycles, carbon exchange, and plankton dynamics, within the marine boundary layer should be investigated. Understanding these processes is essential for predicting ocean health, carbon sequestration, and the broader impacts of marine biogeochemical cycles on climate systems.
(6) Climate change impacts on air–sea interactions: How climate change alters air–sea dynamics should be examined, including effects on extreme weather events (e.g., tropical cyclones, heatwaves, and storm surges), shifts in seasonal patterns, and the intensification of oceanic and atmospheric heat and moisture transport. Research in this area is vital for predicting future climate scenarios and understanding how these changes influence global climate systems.
(7) AI and machine learning integration: Leveraging AI techniques such as machine learning could enhance the analysis, modeling, and prediction of complex air–sea interactions. These technologies enable the processing of large datasets, improve model parameterizations, and allow for the development of predictive algorithms that can capture non-linear and multiscale interactions, advancing our ability to predict climate dynamics and extreme events with greater accuracy.

As a final note, we are pleased to announce the second edition of the Special Issue Recent Advances in Air–Sea Interactions, Climate Variability, and Predictability, which will continue gathering cutting-edge research on these important topics.

Conflicts of Interest: The author declares no conflicts of interest.

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