Extreme Events of Air-Sea Interaction

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Case Studies from the Mediterranean Sea and the Red Sea

By

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LIST OF SYMBOLS

Actual vapor pressure	e_a
Air temperature	T_a
Argon	Ar
Carbon dioxide	CO_2
Carbon monoxide	CO
Centimeter	cm
Cloudiness	C
Daily incoming solar radiation	Q_{sc}
Degree	°
Degree Celsius	°C
hecto Pascal	hPa
Helium	He
Hour	h
Hydrogen sulfide	H_2S
Incoming solar radiation	Q_s
Kilogram	kg
Kilometer	km
Latent heat flux	Q_E
Longwave radiation flux	Q_L
Methane	CH_4
Methyl-iodide	CH_3I
Meter	m
Micrometer	µm
Millibar	mb
Millimeter	mm
Net heat flux	Q_T
Nitrogen	N_2

Nitrous oxide	N_2O
Oxygen	O_2
Ozone	O_3
Per	/
Percent	%
Saturated vapor pressure	e_s
Seawater density	ρ
Seconds	s
Sensible heat flux	Q_H
Significant wave height	H_s
Specific heat capacity	C_p
Water vapor	H_2O
Watt	W
Wave height	H
Wind speed	W
Year	yr

CHAPTER ONE

INTRODUCTION

The atmosphere, oceans, ice masses, land surface and vegetation cover all work together to create the global climate system. Nowadays, it is accepted to say that the structure of this interactive system consists of five subsystems (Houghton et al., 2001): (1) atmosphere: the body of air enveloping the earth, (2) hydrosphere: any water body found on Earth and in air, (3) cryosphere: solid water surface areas on Earth, (4) lithosphere: any inorganic material and (5) Biosphere: all living organisms.

This system (Fig. 1.1) is forced and influenced by various external forcing mechanisms, the most important of which is the sun. Also, the direct effect of human (anthropogenic) activities on the climate system is considered an external forcing (Houghton et al., 2001). Any modification imposed or implemented in one of the above-mentioned elements will have an impact on the nature and functionality of the others. As oceanographers, our interest focuses mainly on the first three subsystems; being the core of diverse oceanographic studies and research involved in the investigation of the climate change and its predictability. To investigate the air-sea interaction processes, the current work will focus solely on the first two elements listed. In fact, the atmosphere and oceans are one system that must be considered together if either is to be properly understood (Warner et al., 2010). What happens in one affects the other, and the two are connected by complex feedback loops. Therefore, this book will start by showing the principal features of these two interactive systems.

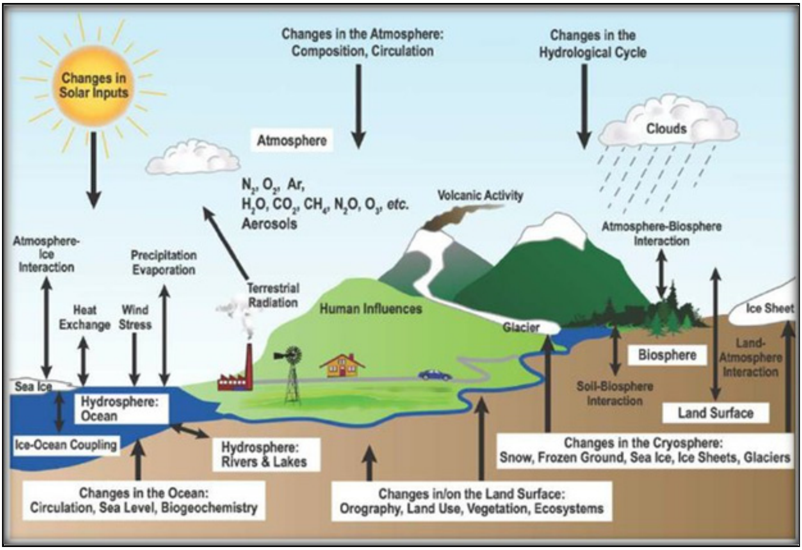

Figure 1.1. A schematic view of the global climate subsystems, their interactive processes (double-ended arrows) and some features that may change (single-ended arrows) (Source: Batisha, 2015)

1.1. Atmosphere

The earth's atmosphere is a layer of gases that surrounds the planet and is held in place by gravity (Cornish and Ives, 2009). This gaseous envelope is made up primarily of nitrogen (N_2; 78%) and oxygen (O_2; 21%), with minor amounts of other gases, including carbon dioxide (CO_2) argon (Ar), helium (He) and ozone (O_3), in addition to a variable amount of water vapor (H_2O) (Cornish and Ives, 2009). Clouds of liquid water and ice crystals are nested in the atmosphere (Ahrens, 2018). Our bodies require oxygen to burn (oxidize) food and release energy to our cells (Trujillo and Thurman, 2011). CO_2 is an important greenhouse gas (GHG) since it traps a considerable segment of the earth's outgoing energy. CO_2 is mostly released into the atmosphere through the decomposition of vegetation, but it is also released by volcanic eruptions, animal exhalations, fossil fuel combustion, and deforestation (Ahrens, 2018). Sadly to say, most of mathematical model experiments that anticipate future atmospheric conditions predict a worldwide warming of surface air between 1 °C and 3.5 °C by the year 2100 as a result of rising CO_2 (and other GHG) levels (Ahrens, 2018). The ozone layer shielded life forms from the sun's ultraviolet radiation (Wells, 2011). This layer has been affected over years, since the industrial revolution era, by the release of huge amounts of Chlorofluorocarbons (CFCs), which depleted the O_3-layer in the stratosphere leading to evident climate change in both Northern and Southern Hemispheres. The amount of water vapor in the atmosphere is of primary interest in meteorology. This amount present at any given time varies greatly due to temperature changes, evaporation from water surfaces, condensation, and precipitation (Cornish and Ives, 2009). When water vapor transforms from vapour to liquid water or ice, it releases a substantial amount of heat known as latent heat. Latent heat is a significant source of energy in the atmosphere, particularly during storms like thunderstorms and hurricanes (Ahrens, 2018). Furthermore, because it absorbs a large percentage of the earth's outgoing radiant radiation, water vapor is a powerful GHG. As a consequence, it is important in the earth's heat energy balance (Halo, 2016; Mahongo, 2016).

The atmosphere plays a major role in many processes affecting life on Earth. This includes the creation of different thermal zones over the earth; the variation in air temperature distribution and unequal heating that results in changes in atmospheric pressure and in turn initiation of the global wind system. Moreover, the formation of clouds, rain and snow. Furthermore, atmosphere shields life forms from dangerous solar radiation while also maintaining the gases that keep the planet alive.

1.1.1. The vertical structure of the atmosphere

The atmosphere has a mean mass of around 5.148×10^{18} kg, with three-quarters of it within 11 Km of the surface (Ahrens, 2018). With rising altitude, the atmosphere grows thinner, and there is no defined barrier between the atmosphere and outer space (Cornish and Ives, 2009). At an altitude of roughly 120 km, atmospheric effects become visible during atmospheric re-entry of spacecraft (Ahrens, 2018). Based on features such as temperature and composition, the atmosphere can be divided into several layers. The vertical layers composing our atmosphere are shown in Figure (1.2). This comprises (Ahrens, 2018; Wells, 2011):

1. Troposphere: is the earth's initial and lowest layer of atmosphere, containing 75% of the planetary atmosphere's total mass, 99% of the overall mass of water vapor and aerosols, and where most meteorological phenomena occur. It extends vertically up to 18-20 km above the mean sea level (MSL). This layer is characterized by a general drop in the air temperature, with a rate of 1 °C/km. The

temperature ranges from +15 °C to -56 °C. The troposphere ends with the tropopause separating it from the stratosphere. At all latitudes, the tropopause rises in the summer and falls in the winter.

2. Stratosphere: is the second atmospheric layer, which extends up to 50 km above the MSL. There is 1000 times less H_2O and 1000 times more O_3 in the stratosphere than in the troposphere. The temperature rises with altitude in this region. Heat is produced during the formation of O_3, and this heat is responsible for temperature increase ranging from an average of -51 °C at the tropopause to a maximum of about -15 °C at the stratosphere's top. The stratosphere is also known to be a cloud-free layer. Because there is little turbulence, most aircraft fly above the clouds and through the stratosphere. This layer is home to the ozone layer that protects life from the sun's ultraviolet radiation. This layer ends with the stratopause.
3. Mesosphere: This layer extends from 50 km above the MSL to about 85 km. As one ascends, the gases, including O_2 molecules, become lighter. As a result, the temperature decreases as one ascends, reaching around -90 °C near the top-edge of this layer, known as mesopause.
4. Thermosphere: This is known as the upper atmosphere and extends between 85 km and 690 km above the MSL.
5. Exosphere: above 690 km above the MSL, where atoms and molecules shoot off into space is the exosphere, which represents the top upper limit of our atmosphere.

In contrast to variant thermal behaviour at different atmospheric layers and altitudes, atmospheric pressure always falls as we rise in altitude: it falls swiftly at beginning, then more slowly at higher levels, similar to air density. The vertical thermal and pressure structures in the atmospheric layers are depicted in Figure (1.3).

It is worth mentioning that the topic of interest, air-sea interaction, can only be detected within the layer of the troposphere.

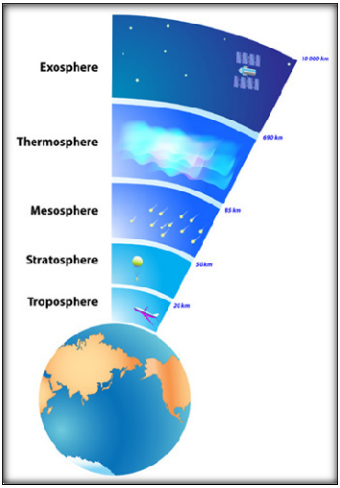

Figure 1.2. Vertical Structure of Atmosphere
(Source: http://ete.cet.edu/gcc/?/volcanoes_layers/)

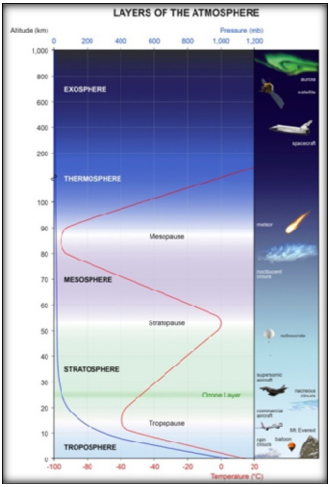

Figure 1.3. The vertical thermal and pressure structures in the atmosphere
(Source: https://phys.org/news/2014-05-earth-magnetic-field-important-climate.html)

1.2. The Oceans

Oceans cover more than 70% of the earth’s total surface area. They represent an interconnected water world. While the northern hemisphere is covered by 60% oceanic waters, ocean covers 80% of the southern hemisphere total surface area. The Pacific Ocean is the largest water body all over the globe representing 50.1% of the total oceanic surface areas, followed by the Atlantic Ocean (26%), followed by the Indian Ocean (20.5%) and followed by the Arctic Ocean (3.4%) (Pinet, 2009; Trujillo and Thurman, 2011). The Southern Ocean is mainly made of ice sheets and ice bergs (Pinet, 2009). It is important to briefly describe the main features of the global oceans; being the main regulators of the surrounding atmosphere.

1.2.1. The Pacific Ocean (Fig. 1.4) is the largest and oldest known ocean basin. This asymmetrical basin, which covers more than one-third of the earth's surface, is the world's greatest geographical feature (Trujillo and Thurman, 2011). It is characterized by the worldwide "Ring of Fire", i.e., it is geologically active by the existence of lots of trenches, island arcs, and volcanic mountain ranges. The Pacific Ocean is also featured by many sea mounts and guyot. The Pacific-Indian Ocean border runs from the Malay Peninsula to Sumatra, Java, Timor, Australia's Cape Londonderry, and Tasmania (Stewart, 2008).

1.2.2. The Atlantic Ocean (Fig. 1.4) is a symmetrical ocean, i.e., there is symmetry in its east-west continental margins, in its abyssal plains and in its Mid Ocean Ridge (MOR). Relatively, few trenches and island arcs (Caribbean) exist within the Atlantic basin. The meridian of Cape Agulhas marks the border between the Atlantic and Indian Oceans, while the line from Cape Horn to the South Shetland Islands represents the border with the Pacific Ocean (Stewart, 2008). The Atlantic Ocean is characterized by its adjacent (Gulf of Mexico) and marginal seas (Mediterranean Sea).

1.2.3. The Indian Ocean (Fig. 1.4) is to some extent smaller than the Atlantic Ocean, but it has almost the same average depth of 3840 m (Trujillo and Thurman, 2011). It is symmetrical about an "upside-down Y" created by a "triple junction". It is mostly in the southern hemisphere, formed due to Antarctic, African, Australian, Indian, and Asia plates movements (Pinet, 2009). Like the Atlantic, the Indian Ocean is featured by its adjacent seas, e.g. The Red Sea and Arabian Gulf.

1.2.4. The Arctic Ocean (Fig. 1.4) has the smallest ocean basin among the global system of oceans (~7% of the Pacific surface area) (Trujillo and Thurman, 2011). It is entirely land-locked except for its connection with the North Atlantic, and is characterized by very wide continental shelves.

1.2.5. The Antarctic Ocean (Fig. 1.4), oceanographers have recognized an additional ocean close to the continent of Antarctica in the southern hemisphere, south of latitude 50 °S and encircling Antarctica (Trujillo and Thurman, 2011). This has been named the Antarctic Ocean or the Southern Ocean. The Southern Ocean has experienced fast climate changes over the last 30 years, resulting in alterations in the marine ecology (Constable et al., 2014).

Figure 1.4. World Ocean Map
(Source: https://www.britannica.com/story/just-how-many-oceans-are-there)

The above-mentioned oceans, with their adjacent and connected seas, absorb and hold significantly more solar energy than land and atmosphere due to the large heat capacity of water (Halo, 2016). Consequently, oceans are able to change the overlying atmospheric conditions and weather. What happens is that the upper ocean connects surface forces from winds, heat, and fresh water to the quiescent deeper ocean, where this heat and fresh water are stored and released over longer time and planetary scales (Sprintall and Cronin, 2009; Sutherland et al., 2014). The released outgoing longwave radiation and latent heat flux return over half of the solar energy absorbed at the sea surface back to the atmosphere (Halo, 2016). Latent heat flux produces atmospheric vapor pressure, which is a key player in the earth's energy balance and drives important processes within the earth's hydrological cycle and diverse air-sea interaction processes (Talley et al., 2011). According to Bengtsson (2010), the total volume of accessible water on Earth's surface is around 1.5 x 10^9 km^3, of which 1.4 x 10^9 km^3 is oceanic, i.e. oceans retain more than 90% of the available water on Earth. Land ice and glaciers contain about 29 x 10^6 km^3 of water, while groundwater contains about 15 x 10^6 km^3 (Bengtsson, 2010). This reveals that the global hydrological cycle and the processes of interaction with the overlying layer of the atmosphere will interact differently among oceans and land masses over the earth. Also, differences will exist in the interaction process among the global water bodies of oceans and seas.

It is important not to forget that any interaction process between the ocean and the overlying atmosphere is conducted only in the surface layer of ocean not in the deeper layers. This surface layer comprises both an upper mixed layer exposed to direct atmospheric impact and a highly stratified zone below the mixed layer with severe vertical property gradients (Sprintall and Cronin, 2009), i.e. the surface and the cline layers (Fig. 1.5). The depth of this layer may vary from a few meters to a several hundred of meters depending on a density threshold relative to a reference depth (Sutherland et al., 2014).

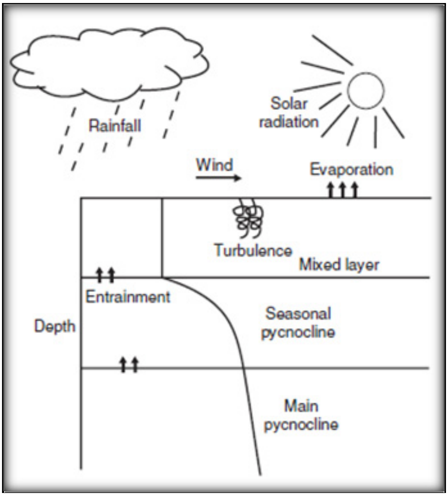

Figure 1.5. The vertical structure in the surface layer, as well as the forces and physics that regulate its existence. The mixed layer depth, the seasonal pycnocline, and the main pycnocline are all shown (Source: Sprintall and Cronin, 2009)

The two mentioned systems: atmosphere (1.1) and oceans (1.2) are continuously interacting and affecting each other; regulating the climate of the earth, maintaining its global cycles and impacting the anthropogenic activities. This interaction with its different and various processes, especially the abnormal ones, has motivated the performance of the present work to address the subject of ‘Extreme Air-Sea Interaction with a Special Attention to the Mediterranean Sea and Red Sea’.

1.3. Aim and Objectives

This work aims at highlighting the processes induced by the air-sea interaction and the possible associated extreme vents, and to feature this within the basins of the Mediterranean and Red Sea.

The objectives of this work are: (1) To declare the importance of the air-sea interaction through its different processes, and the available tools to assess it, (2) To introduce the meaning of an extreme event in general and in air-sea interaction in particular, and (3) To spotlight extreme events in air-sea interaction in the basins of the Mediterranean and Red Sea, taking Marine Heatwaves (MHWs) as exemplar case studies.

This book consists of eight chapters, including this introductory one. The second chapter examines the air-sea interaction, including its importance, processes and quantification methodologies. Chapters three and four, respectively, focus on extreme events and MHWs. While chapter five shows information about the Mediterranean Sea, including examples of extreme events, using MHWs as a case study, chapter six shows the same information about the Red Sea. Conclusions and recommendations, and future perspectives are given in chapters seven and eight, respectively.

CHAPTER TWO

AIR-SEA INTERACTION PROCESSES

2.1. Definition of air-sea interaction

The air-sea interaction is one of the earliest subjects that attracted researchers in oceanography and meteorology for investigation and examination. This is dated back to the late 1940s, e.g. Schmidt (1947), who examined the sea-land breeze process, and early 1950s, e.g. Charnock (1951), who pointed out that despite the fact that the energy carried by the wind to the ocean is a tiny fraction of the radiation absorbed at the surface, wind-driven currents substantially dictate the locations where ocean energy is recycled back into the atmosphere, which establishes the cloudiness pattern.

According to Rogers (1995); Csanady (2004); Sprintall and Cronin (2009); Janssen et al., (2013); Mahongo (2016); Ren et al. (2020); Sauvage et al. (2020) and others, the air-sea interaction process can be defined as a two-way energy transfer mechanism, in which energy is transferred in one way from the atmosphere to the ocean surface mixed layer, and in turn energy is fed back from the ocean surface to the atmosphere. While the first mechanism affects the surface hydrography of oceans and drives the ocean circulation, the second drives variabilities in weather and climate (Rogers, 1995; Csanady, 2004; Trujillo and Thurman, 2011).

2.2. Importance of air-sea interaction

The air-sea interaction is a large field of research with significant progress made in many areas, e.g. El Nino, the circulation of oceans, the hydrological cycle, the heat fluxes, global climate change, etc.

The importance of the subject stems from the effect this interaction has on both the atmosphere and oceans on both small and large scales. The former comprises the heat exchange, evaporation rates and exchange of trace elements across the air sea interface and other important dynamical movement such as surges. The latter, on the other hand, comprises global climate and global circulation systems, e.g. winds and ocean surface circulation belts. The small-scale processes are important to solve global scale problems and to set boundaries and parameterization in ocean and climate general circulation models (Rogers, 1995). Generally speaking, the importance of the air-sea interaction processes can be pointed out as follow (Butterfield et al., 2005; Oliver, 2005; Suthers et al., 2011; Trujillo and Thurman, 2011; Christakos et al., 2014, 2016; Mahongo, 2016):

1. The major importance is the impact of the air-sea interaction processes on weather and climate because the global climate is determined by the mean exchange of heat, and anomalies in this exchange result in differences in local weather patterns.
2. The water exchange supplies almost the third of precipitation amount over the land, with a global mean surplus of evaporation over precipitation of 36×10^{15} kg/yr.
3. The exchange of climatically important gases, e.g. hydrogen sulphide (H_2S), nitrous oxide (N_2O), methane (CH_4), methyl iodide (CH_3I), carbon monoxide (CO), many of which play an important role in the greenhouse effect; influences the global climate on a long-term scale.
4. With phytoplankton in the oceans producing about half of the world's oxygen and releasing it into the atmosphere, the oceans operate as massive CO_2 sinks.
5. Oceans are an important supply of salt particles, which serve as a natural seeding source for cloud coalescence processes.
6. The fundamental cause of ocean circulation, particularly surface currents, is the exchange of momentum between the atmosphere and the ocean surface through wind stress.
7. Observed variations in sea surface temperature (SST) worldwide are mainly attributed to the air-sea interaction processes. The SST, in consequence, is the key player in the observed steric sea-level variations
8. Drought, heavy rain, heat waves, rogue waves, storm surges, and other observable extremes in atmospheric weather and oceanic status, are all linked to air-sea interaction and changes in atmospheric and oceanic conditions.
9. A revised modelling of air-sea interaction will contribute to the design of offshore wind farms using floating wind turbines, as the global interest in renewable energy grows.
10. Forecasting air-sea interaction processes also offers a better understanding of their nature and provides early warnings about damages caused by associated extreme events.

11. Ocean warming due to air-sea interaction processes will stress species by causing thermic changes in their environmental envelopes as well as increasing interspecies competition. These shifts become even more significant in shelf seas. Changes in coastal currents, for example, affect everything from primary production to fisheries productivity in south-eastern Australia.

The fundamental processes connecting the two domains: atmosphere and oceans are the energy input to the ocean by wind, the net freshwater flux and net surface heat flux. So, how does atmosphere affect oceans and how does the ocean, in turn, affect the overlying atmosphere? The answer can be briefly outlined as follow:

Variations in the air circulation have an impact on ocean circulation. The force of the wind blowing on the water surface exerts frictional drag on the ocean's surface layer and drives the surface currents in oceans and seas. The wind also mixes surface waters, forming the mixed layer, which has little vertical temperature variation. The thermocline, a narrow zone of rapidly declining temperature, lies underneath the mixed layer. The density of the water, which is affected by temperature and salinity, drives the circulation in the deep ocean below the thermocline (thermohaline circulation). Heat is stored in the deep ocean and released back into contact with the atmosphere thanks to vertical motions through and below the thermocline. In return, Oceans change atmospheric conditions and weather because of their ability to hold large amounts of heat and moisture. Tropical storms, for example, initially formed over warm ocean waters, provide the energy that allows hurricanes and typhoons to expand and move, often over land. Winter storms that deliver rain to the western United States originate over the North Pacific Ocean. Upwelling provides a cold differential in air temperature over the ocean and land in many coastal places, such as California, which is conducive to regular summer fog.

2.3. Examples of air-sea interaction processes

Before we go through the different types of fluxes and processes featuring the air-sea interaction phenomenon, it is worthwhile to start by addressing the mechanism of initiation (Stewart, 2008; Trujillo and Thurman, 2011; Wells, 2011) of such dynamical processes and movements.

Sun rays do not hit the earth equally. Between 35° and 40° north (N) and south (S) the equator, the sunlight strikes the earth at high angles and more energy is absorbed that is reflected back to the space. However, close to the poles the sunlight strikes the earth at lower angles, and with the abundance of a large ice cover energy reflected back to space is higher than that absorbed (Fig. 2.1). This is mainly attributed to the declination of the earth's axis with respect to the sun with an angle of 23.5°. The earth spins around its axis every 24 hours and in an elliptic orbit around the sun every 365 ¼ days. Therefore, with this tilt of rotation axis, the earth receives uneven heat amount gained by the oceans, and seasons develop over the year round (Fig. 2.2).

This imbalance of heat creates high and low pressure zones and, consequently, results in convention and moving air (winds) and water around the globe. The Coriolis force develops as the earth rotates, deflecting winds and surface currents to the right in Northern Hemisphere and to the left in Southern one. This way the global surface wind and surface current systems develop and dynamical movement of air-sea interaction is set.

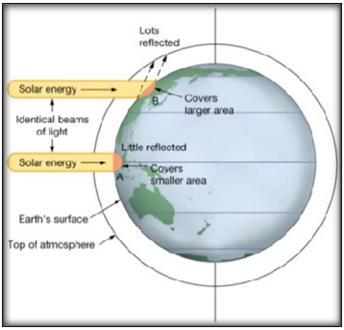

Figure 2.1. Uneven solar radiation on Earth (Source: Trujillo and Thurman, 2011)

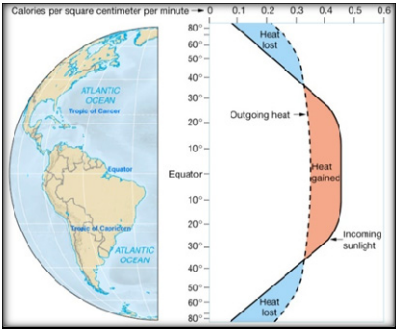

Figure 2.2. Heat gained and lost from the global ocean system (Source: Trujillo and Thurman, 2011)

Once in movement, the wind at the lower atmospheric boundary develops primitive air-sea interaction processes on local scale, e.g. sea and land breezes, sea fog and radiation fog. On regional scales, other processes develop influenced by the interaction between the sea surface and the overlying atmosphere, e.g. at mid latitudes storm systems featured by low pressure and warm/cold fronts occur; tropical cyclones, known in pacific and Atlantic regions as hurricanes, develop over tropical oceans where warm water results in moisty warm rising air to develop and by the sufficient effect of the Coriolis force rotation is enhanced and effects of cyclone appear.

Of course, on both local and regional scales, there are more air-sea interaction processes that can be detected and investigated. These depend not only on the variations in pressure and wind schemes solely, but also on differences in temperatures, surface ocean wave actions, sea-level variations and amounts of exchangeable gases. These processes will be discussed later.

The observed, investigated and simulated processes of air-sea interaction are termed fluxes (Ye et al., 2020). According to the examined process, these fluxes are named and categorized in four main types:

I. Momentum flux: this is the stress of the winds acting on the sea surface. This results in friction between the sea surface and atmosphere, which is a key component in air-sea interaction (He et al., 2018). On one hand, wind stress exports mechanical energy and participates in the turbulent exchange of heat and moisture in the atmosphere. On the other hand, wind stress drives ocean movement from the oceanic side (Ye et al., 2020). This stress sets up the ocean gyres and current systems, which in turn, redistribute heat and hydrographic properties in oceans.

II. Moisture flux: the source of water that sustains life on the planet is moisture fluxes over the ocean, i.e. evaporation and precipitation. Without the presence of water vapor in the atmosphere, the earth would be significantly colder and life as we know it would not exist (Stephens et al., 2020). These moisture fluxes are connected to the air-sea heat fluxes through the latent heat of evaporation. The ocean influences the atmosphere primarily through certain heat fluxes at the interaction boundary. This comprises the shortwave radiation flux (insolation), the net longwave flux (heat output from the sea surface towards the atmosphere), and the sensible and latent heat fluxes, which also usually transfer heat from sea to air. The former is the transfer of heat caused by the difference in temperature between the sea surface and the overlying air, while the latter is the heat absorbed on vaporization of the water (Csanady, 2004; Cronin et al., 2019). The latent heat is released to warm the atmosphere when the vapor condenses to form clouds (Cornish and Ives, 2009; Cronin et al., 2019).

III. Energy flux: is the amount of energy transferred from the blowing wind to the sea surface to create and influence surface ocean waves (He and Xu, 2016; He et al., 2018). Growing ocean waves have an impact on air-sea momentum and heat transmission, whereas breaking ocean waves have an impact on upper ocean mixing processes (Janssen et al., 2013).

IV. Gas flux: CO_2, N_2O, and CH_4 exchange between the oceans and atmosphere are a crucial component of the climate system, and the oceans' tendency to absorb and desorb these gases alters both spatially and temporally (Holding et al., 2019).

As shown, air-sea interaction processes are diverse. Therefore, only selected examples will be discussed hereafter. Examples are downscaled from global to regional to local.

2.3.1. Examples of global scale air-sea interaction processes

By global scale air-sea interaction processes we mean these processes which occur all over the earth and their impacts extend to be sensed all over the globe. This can be presented by global wind systems, the global surface current system and its gyres, the balance of the different criteria such as heat, water and salt, etc.

2.3.1.1. Global wind system

The global wind system, also known as the global circulation system, is the first air-sea interaction process affecting the globe. The observed wind systems with their annual and seasonal variations comprise the global atmospheric circulation, which is the primary factor in determining the distribution of climatic zones, whereas variations in atmospheric and oceanic circulations are responsible for many of the observed longer-term fluctuations in climate (Ahrens, 2018). Inequalities in radiation distribution over the earth's surface and the earth's rotation are the two major controls on global wind circulation. The global atmospheric circulation is driven by global radiation distribution and gravity, while the earth's rotation determines its shape (Oliver, 2005). In this global circulation system, the atmosphere transports warm air towards the poles and the cold air towards the equator (Cornish and Ives, 2009; Ahrens, 2018). Although it appears to be simple, the actual air flow is complex and not everything is known about it to date (Ahrens, 2018).

This circulation system was first examined by George Hadley who made three assumptions to describe the global air flow (Oliver, 2005; Stewart, 2008; Trujillo and Thurman, 2011: (1) the earth is totally covered with water with no land mass, so that there is no thermal variation on the earth surface. (2) Sun is 100% normal to the earth so that there is no seasonality and (3) Earth does not rotate, so that the Coriolis force is ignored and the only acting force deriving the motion is the pressure gradient. Accordingly, Hadley got the atmospheric cell flow named after him, and his theory is named the single cell model theory (Fig. 2.3).

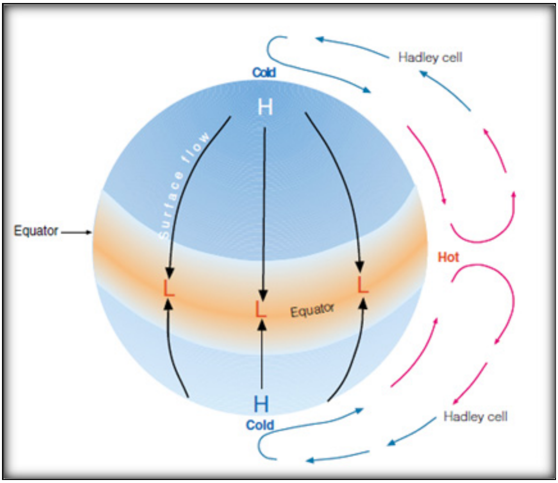

Figure 2.3. Hadley's single cell model describing the global surface air flow (Source: Oliver, 2005)

As the earth is actually rotating, different pressure zones develop from the equator poleward, and as air flows its pathway is deflected to the right in the northern hemisphere and to the left in the southern hemisphere affected by the Coriolis force. This pattern of deviation has led to what is known as the three cell wind system, which describes the global surface wind system. This system (Fig. 2.4) consists of three cells as follow:

(1) Hadley Cell: developed at the equator, where the air is warm over equatorial waters, horizontal pressure gradients are weak, and winds are light. The 'doldrums' are a term used to describe this area. This low pressure zone extends to 30° N/S where air becomes denser and sinks to flow equatorward. Winds in this zone are known as 'Tarde Winds'

(2) Ferrell Cell: Not all surface air moves equatorward at latitude 30° N/S. Some air flows towards the poles and deflects toward the east, resulting in a more or less westerly air flow in both hemispheres,