Chapter 5

Summary and Conclusion

5.1 Introduction

An unmistakable characteristic of the global salinity of the oceans surface is the considerable salinity difference between the Pacific and the Atlantic Oceans at the fringes of Central America. This remarkable characteristic was explored in the celebrated paper of Warren (1983) as one of the relevant factors in relation to the formation of North Atlantic Deep Water (NADW) and, as such, it has an important role in the global oceanic circulation. Moreover, the work of Broecker (1987, 1991) offered further support to this idea by suggesting that this difference could be a resultant characteristic of the formation of a Global Conveyor Belt (GCB). Broecker introduced the concept of a GCB as a resultant of many features (geography, atmospherics and ocean circulation), and this process would be characterized by the evaporation on the Atlantic, causing the increase of the salinity levels in its surface waters, while in the Pacific, the precipitation would dilute the surface waters. Rahmstorf (1996, 2003) and Rahmstorf *et al.* (2005) endorses the idea of the exportation of freshwater from one ocean to another; however, he disagrees that the exported amount would influence the GCB formation and, concomitantly, the global oceanic circulation. Even with the maintenance mechanisms of the GCB still in debate, it is an accepted fact within the scientific community that the net freshwater exported from the Atlantic to the Pacific Ocean, across the Central America Isthmus, is responsible for the difference in the surface salinity of the respective coasts although this phenomenon has yet to be quantitatively tested. A comprehensive description of this atmospheric freshwater link between the oceans was the prime motivation for this study.

Within this context, the atmospheric circulation, particularly in the Pacific Ocean basin, becomes important, since processes in the atmosphere are seen to form an integrated system with the ocean (cause and effect), where an alteration in one of them has a consequence in the other. Oort & Yienger (1996) described the relations between the major atmospheric circulation cells, the Hadley and the Walker circulations, with the ENSO cycle. Their findings show that the strengthened of the meridional circulation (Hadely cell) prevails over the zonal circulation (Walker cell) during the El Niño events in the winter hemisphere, while during normal and La Niña events, the opposite happens. In this context yet, a study of McGuffie & Henderson-Sellers (1997) presents the imbalance in the intensity of the wind components on the Inter-Tropical Convergence Zone (ITCZ) region, with the dominance of the meridional component over its zonal counterpart. Also, focusing the ITCZ in the eastern Pacific and western Atlantic, Yang *et. al.* (2001) and Xu *et al.* (2005) described how part of the easterly Trade Winds are divert in the equatorial Atlantic Ocean towards Mexico and North America, weakening the northern hemisphere Trade Winds that reach the eastern equatorial Pacific Ocean. Yet, in Mitchell & Wallace (1992) is discussed how the SST can drive the displacement of the ITCZ in the eastern tropical Pacific.

Therefore, concerning the considerable salinity difference between the East and West coastal zones of Central America, and taking into account that the ITCZ region has the highest levels of rainfall in the world, other regional atmospheric factors could not be neglected. Thus, the variability in the supply of freshwater entering into the region, as a consequence of the influences of the conditions in the ITCZ, would essentially induce changes in the dilution of the surface salinity of the oceanic waters of the easternmost tropical Pacific.

Thus, this work was developed with the aim of characterizing and quantifying the independent role of moisture transport from the Atlantic to the Pacific across the Central America land bridge on one hand, and condensation and rainfall in the ITCZ on the other, in order to investigate the modulation of both processes by El Niño-Southern Oscillation (ENSO). A study of the implication of these influential processes in the surface salinity was also carried out.

With these centers of attention in mind, the atmospheric dataset proceeding from the 40 year Re-Analysis of the European Centre for Medium-range Weather Forecasts (ECMWF-ERA40) data server was used in conjunction with an oceanic application. The numerical modeling of the ocean was achieved by applying a widely used hydrodynamic model (Modular Ocean Model - MOM) in association with a model for the mixed layer. An important characteristic of this association was the use of the atmospheric flow of freshwater as an independent variable of input. The salinity in the upper oceanic layers of the eastern tropical Pacific Ocean, as the main parameter of the investigation under the oceanic perspective, required that the numerical approach would be of high credibility.

However, during the process of validation of the proposed oceanic numerical approach some features emerged with regard to the salinity field in the upper layers of the eastern tropical Pacific which had not been explored in their total extension in the published previous works. Although these gaps gave the possibility to pursue an expansion of the knowledge with respect to salinity in the upper layers of the Pacific Ocean, their results should be seen as complementary studies within the main objectives pursued here. Therefore these complementary studies provided a bonus for a better understanding of the ENSO cycle in relation to the salinity field. In this final chapter they will not be explicitly discussed. Rather they will be regarded as a supplementary bonus, apart from the main theme and acquired en route as it were.

Mindful of the fact that this study as a whole constitutes a contribution to knowledge rather than a definitive work, it focuses on the existing complexity of environmental factors in the region, either with respect to the ocean or the atmosphere, indeed as a result of oceanic interaction. Clearly, the region is just one part of the vast conundrum of global circulation which involves these two systems. For this reason, the presented study has evolved and gained complexity in a natural and independent way. For example, the studies with regard to the spatially integrated form of the atmospheric fields had suggested, at some stages, behaviors contrary to those expected. Thus, with the intention of elucidation of such questions, the study evolved in the direction of the more elaborated statistical procedures. Consequently then, restricting this summary to the main objectives and the scientific inquiry which led to the conclusions reached, the latter may be summarized as follows.

5.2 Synthesis of "Atmospheric freshwater sources for eastern Pacific surface salinity"

Aiming for the first time to reach a comprehensive characterization of the role of the components of freshwater transported into the region and their relation to the local precipitation, statistical techniques were applied in a domain that obeyed the geographic characteristics of the region, using the data set available from the ECMWF-ERA40.

The freshwater balance analyses between the atmospheric transports of freshwater into the region confirmed that most of the freshwater which precipitated as rainfall in the eastern tropical Pacific Ocean originates from the Atlantic side of Central America. This conclusion was reached by an investigation of the spatially integrated atmospheric fields, which demonstrated that the atmospheric freshwater transported from the Atlantic Ocean across Central America by the northern hemisphere Trade Winds

(FTr) exceeded the atmospheric freshwater transported by the Southerly winds operating along the west coast of South American (FSth). Moreover, the analysis provided clear evidence that this relationship is altered by the ENSO cycle. For example, during El Niño periods, the volume of the atmospheric freshwater received via FTr decreases while the volume of the atmospheric freshwater carried out by FSth feeds the region with water vapour. Conversely, during La Niña periods the opposite happens, with the strengthening of the atmospheric freshwater most of the volume of water vapour is exported into the region by FTr and there is a resultant decrease in the volume of the water vapour exported to the region by FSth.

Also undertaken was the analysis of the behavior of the atmospheric freshwater exported to the region in order to consider those transports which act independently in altering the pattern of local Precipitation (P). The spatially integrated precipitation rate was compared with the spatially integrated atmospheric freshwater transported either by FTr or FSth. The analyses carried out suggested that, in the spatially integrated form, the FTr is less important than the FSth with respect to their influence on the variance of the local precipitation, even more so if the correlation indices between the time series are taken into account.

This apparent contradiction was later refuted when the time series were statistically analysed using the Single Value Decomposition technique (SVD), which demonstrated, with regard to the respective variances, that the coupling between P and FTr is higher than the coupling between P and FSth. Furthermore, the analyses revealed that the most significant signals of atmospheric freshwater transported into the region permitted the quantification of their relationship with precipitation in the eastern tropical Pacific Ocean. Thus, the first three SVD modes of the coupling between P and FTr account for 80% of the total variance of the precipitation, while that of the first three SVD modes of the coupling between P and FSth were responsible for up to 67% of the total variance of the precipitation. However, the SVD analyses were not able to extract all nuances in those couplings. An analysis of period/frequency of those signals needed to be performed in order to address such issues. Thus, the Wavelet technique was applied to elucidate those couplings.

The Wavelet technique was applied to the leading SVD modes, either for the coupling between P and FTr or the coupling between P and FSth, and this supported the previous suggestions reached in using the integrated atmospheric freshwater transport analyses: on the one hand a decrease in the atmospheric freshwater transported by the FTr had occurred during El Niño periods, which induced a decrease in the variability of the precipitation in the region; while on the other hand, the increase in the atmospheric freshwater exported into the region by the FSth, was responsible for an increase in the variability of the precipitation in the region. In addition, the Wavelet analysis was able to capture the influences of the ITCZ migration in the region.

The atmospheric analyses, applied to the integrated fields and by statistical techniques, allow us to estimate the extent to which these independent transports are able to influence the Sea Surface Salinity (SSS). At this juncture, the numerical modeling of the ocean became relevant. The proposal was to explore such atmospherical influences through a numerical oceanic model in which the atmospheric flow of freshwater was used as an independent variable of input. In such a manner, the task would be to estimate how each one of the atmospheric transports of freshwater acts exclusively and independently in the SSS. Thus, after the validation of the model (the "Control Run" - Ctrl) with the observed data and comparisons with previously published works, two independent runs of the oceanic numerical approach were carried out in which the variable $(E-P)$ was employed as the atmospheric freshwater input variable. The precipitation field was reconstructed using the mean field from the time-averaged precipitation downloaded from the ECMWF data server, while its variance was reconstructed based on the first three leading SVD modes from the previous atmospheric analyses.

At first glance, the results of the oceanic numerical approach did not promptly achieve relevant conclusions; even so, it was possible to discern some features from their finer analyses. For example, when the oceanic numerical model was forced by the variability in the precipitation as induced by the FTr only, during El Niño periods, the results as output from the model were more saline than the Ctrl (SSS(Ctrl)). After the El Niño periods, the difference between the time series stabilized, continuing parallel to the time series in the result of the Ctrl. Although, when the model was forced by the variability in the precipitation as induced by the FSth persistently the time series for the surface salinity was saltier than the surface salinity as output from the Ctrl. This result could suggest that the atmospheric freshwater transported by Southerly winds does not have an important role in the rainfall of the eastern Pacific Ocean, and as such may not usefully resolve the question of existing anomalies in surface salinity which are not accounted for by the atmospheric freshwater transported by Atlantic Trade Wind analyses.

For both runs, those features were particularly evident in the eastern equatorial Pacific Ocean, while further west, the time series output from those runs provided the same features with reduced amplitude and some time lag. This latter characteristic suggested that the Atlantic freshwater signal was advected along the Equator.

Then, a signal of the salinity anomaly was conceived (ΔS = SSS(FSth) - SSS(FTr)) considering that the anomalies in the SSS experience their influences through the anomaly in the precipitation induced by the nominated atmospheric transports. The time lag analysis applied to the ΔS presented a time delay of approximately 8 months to the salinity anomaly in order to propagate from the eastern tropical Pacific Ocean, induced either by the FTr or by the FSth, so as to reach the western boundary of the oceanic numerical domain. This latter result allowed the establishment of the propagation rate of the signal of salinity anomaly across the domain of the study along the Equator.

Finally, it is suggested that the present study accomplished its main objectives described on page 12. The independent roles of the atmospheric freshwater exported to the region have been established and quantified for the first time, together with their relationships to local precipitation, and consequently to the salinity anomalies in the eastern tropical Pacific. Furthermore, additional features of the salinity field in the oceanic upper layers of the eastern equatorial Pacific Ocean were contemplated during the processes of validation of the oceanic numerical model approach. Thus, the final conclusions of this study are listed as follows:

- Most of the atmospheric freshwater that reaches the eastern tropical Pacific Ocean region has its source on the Atlantic Ocean side of Central America, being exported by the northern hemisphere Trade Winds; The relative proportion between the volume of the water vapour transported by the northern hemisphere Trade Winds (FTr) and that transported by the Southerly winds along the west coast of South America (FSth) is invariably greater than 1 and is often larger than 2-3, indicating that FTr dominates over FSth. In the mean, FTr is a factor 1.8 times larger than FSth.

- The observed annual cycle of the relative proportion between the volume of the water vapour transported by the northern hemisphere Trade Wind (FTr) and by the Southerly winds along the South American coast (FSth), expressed as a ratio index of FTr/FSth, maintains a clear coupling between the latitudinal displacements of the ITCZ and the North American monsoon system. This annual cycle is altered from time to time in accordance with the state of the ENSO cycle, in that, for example the ratio decreases during El Niño events. This latter result confirms the weakness of the northern hemisphere Trade Winds in the eastern Pacific as a consequence of the failing of the Walker Circulation and strengthened of the Hadley Circulation.

- At least 74% of the total variance of the precipitation in the region can be explained by the atmospherically imported freshwater, reaching the region as transported by the northern hemisphere Trade Winds and/or by the Southerly winds along the west coast of South America;

- Whatever the source of the rainfall over the eastern tropical Pacific might be, the mechanism which converts the imported freshwater into rain is the ITCZ. There is also a significant seasonal variability in the freshwater import from the Atlantic Ocean, but it feeds into the ITCZ throughout the year. Whether this freshwater rains out immediately after crossing Central America or is advected further across the Pacific depends on the intensity of the ITCZ over the region at the time;

- The variance of the precipitation is better explained during the La Niña periods by the freshwater exported to the region by northern hemisphere Trade Winds, while, during the El Niño periods, this variance is better explained by the freshwater exported to the region by the Southerly winds along the west coast of South America;

- A two month time lag is observed between the SOI signal and its effects to be felt in the precipitation and, consequently in the sea surface salinity in the eastern tropical Pacific Ocean;

- Since the precipitation regime has been modified in the region, the induced sea surface salinity anomalies propagate westward along the Equator at a rate of 0.25 $m.s^{-1}$ (6.1 degrees per month), approximately.

- The associated salinity of the South Equatorial Current - North branch (SEC(N)) has its main mode of the variance (42%) tied to the annual period. Its relation to the ENSO cycle, based on this approach, only appeared during the last strong El Niño (1997/98).

- The main mode of the variance (61%) of the associated salinity to the Equatorial Under Current (EUC) is susceptible to the ENSO cycle. During El Niño events, the variance associated with the main mode is maintained for a period of one year, whereas in La Niña events, its periodicity becomes shorter.

- The main mode of the variance of the associated salinity to the SEC - South branch (SEC(S)), which accounts for 57% of the total variance, presents similar behavior to the first variance mode of the EUC in relation to the ENSO cycle.

- The entrainment of the salinity in the mixed layer is more concentrated in the oceanic equatorial region when looked at by its time-average, but one case study, along the Longitude of the 95°W, showed that, for that particular region, the salt entrainment is only weakened or suppressed during El Niño periods, while for the residual time the salt entrainment is commonly well-developed.

- If on the one hand the time variation of the SSS is mainly related to the atmospheric flow of freshwater under the track of the ITCZ, alternatively, it is possible to identify the effect of the three main gaps located in the mountain range of Central America (the Chivela Pass at the Isthmus of Tehuantepec in Mexico, the Lake District lowlands of Nicaragua inland of the Gulf of Papagayo, and the central isthmus of Panama), as factors that influence the time variation of the SSS outer the ITCZ track.

5.3 Final words

The question of the difference in the SSS between the two oceans as the driving force of the GCB will certainly be a subject for debate for some time yet. Nevertheless, despite a measure of difference in the opinions of the scientific community, one may sense a growing consensus to accept as fact that water vapour collected over the tropical Atlantic is in fact delivered to the Pacific and that this occurs in the vicinity of the Central American land bridge. Although suspected, this process had not previously been quantified, and it was the challenge presented by this lacuna which was the motivation for the present study. It is hoped that what has been achieved will be seen as a significant enhancement of support for this basic concept.

This study offers for the first time a detailed characterization of the transport of atmospheric freshwater proceeding from the Atlantic Ocean (FTr) to the eastern Pacific Ocean as the main source of atmospheric freshwater to the region. In addition the relative composition of the volume of water vapour which reaches the eastern tropical Pacific region has been quantified, together with the inclusion of the atmospheric transport of freshwater sourced in the Pacific itself (FSth). Moreover, the interaction between these two systems of atmospheric transport of freshwater, FTr and FSth, in the precipitation of the eastern tropical Pacific Ocean is characterized, and their consequent imposed alterations in the SSS as an induced response to such systems. This study has also provided the relationships of all the treated systems and their respective responses to the ENSO cycle.

In addressing the general circulation of the global ocean, at first glance it would seem unlikely that processes occurring in such a small region as that, which provides the focus of this study, should play such a dominant and wide ranging role. In so doing it is relevant to draw attention to the fact that it is extremely rare that a position has been reached which allows for a definitive and final conclusion to an environmental problem, even of this scale. Nevertheless, given the importance of the Pacific Ocean thermohaline circulation upon the global circulation and, as a consequence for the climate system, it may be suggested that future development based on the techniques adopted and developed here can further contribute to the analysis and identification of the interactions of the atmospherical exportation of freshwater from the Atlantic to the Pacific Ocean through Central America Isthmus as presented. As a proposal, a General Circulation Model study may be undertaken that includes the atmospheric flow of freshwater as a prescribed independent forcing parameter. Thus, the impacts of atmospherical freshwater forcing applied in the eastern Pacific Ocean to the high latitude ocean basins would be assessed in an attempt to offer a more inclusive method, and special interest would be delivered into the return of the oceanic freshwater back to the Atlantic Ocean, through Bering Strait. In this context, the proposed study would be focused in the freshwater exportation from the northern Pacific Ocean to the northern Atlantic Ocean, closing the freshwater cycle by including the transport back to the Atlantic Ocean. Indeed, in this proposed work, the role of the water vapour atmospherically exported from the Atlantic to the Pacific Ocean as part of the global freshwater cycle would be evaluated together with its influence to the Atlantic overturning circulation.