An Evaluation of Water Circulation and Contaminant Transport Models for the Intra-American Seas.

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ABSTRACT

The Intra-American Seas (IAS) consists of a number of small islands with high coastline to area ratios. These coastal areas often support the majority of an islands population, are utilized for various socio-economic activities and provide habitats for unique, fragile ecosystems. The islands and the juxtapose landmasses that make up the Caribbean Region are interconnected by the water bodies that surround them. Interaction with coastal sea processes generated by the surrounding waters can pose a potential threat to sustainability of these systems, by providing a medium for the transport of contaminants introduced by accidental spillage, unregulated dumping and river discharge. This paper has examined water circulation in the IAS to identify the regional processes and characteristics that contribute to the dynamics of water circulation. Seasonal and inter-annual variations in tidal regimes, currents, air and sea surface temperatures in addition to bathymetry all seem to contribute to the observed circulation and dispersion of the waters contents. The identified processes were then used to inform the evaluation of a number of existing circulation models for the IAS. A number of circulation models exist that can in general be adapted for the region with some modifications and limitations, however the POM and NRL/NLOM were identified as being most relevant. The capabilities of these models in terms of their computational methodology to determine the influence of regional characteristics on the transport of contaminants have been evaluated to determine potential limits to their operations as they relate to the Region.

Key words: Water circulation, Contaminant transport, Models, Intra-American Seas.

1. INTRODUCTION

Meridional circulation and the existence of a number of major oceanic gyres induce circulation, which connect the world’s Oceans (Challenger Expedition (1872-6)). Schmitz and Richarson (1991) found that almost one-half of the Florida current transport is of South Atlantic origin and is based on inter hemispheric and inter gyre upper-ocean transport. The resultant circulation provides a medium for the transport of substances from distant sources. Water circulation in the Intra-Americas Seas (IAS) is largely influenced by the anticyclonic North Atlantic Sub Tropical Gyre. The Tropical and Subtropical North Atlantic Ocean provide the major inflow into the Region, and a general east west orientation of the flow through the Caribbean Sea results as the Trade Winds and to a lesser extent the prevailing Westerlies interact with the lower region of the Sub Tropical Gyre (Duncan *et al*, 1982). The warm waters of the stable Northern Equatorial Current which makeup the lower region of the gyre travel along a westward shift to the poles, through the Yucatan Channel and the Florida Straits. The narrow Gulf Stream forms the western component and flows eastward interacting with the unstable Portugal and Canary southeasterly currents on route to the Equator (Moores and Maul, 1998). The circulation induced by the Sub Tropical gyre act in concert with eddy and current systems that permeate the region and riverine input to produce the circulation experienced in the IAS (Figure 1a and 1b).

Figure 1a and 1b

The IAS is a major transport route for waterborne petroleum trade (Reinburg, 1984), and is the base for a number of petroleum, refinery and bunkering operations (Trinidad and Tobago, Mexico, Venezuela, US Virgin Islands, the Netherlands Antilles and Martinique). Depending on the fate and toxicity of these substances ecologically sensitive offshore and coastal areas may be at risk in the event of a spill. The coastal regions of the IAS support the majority of the population, socio-economic activity and fragile marine ecosystems of these island states. Sustainability of these activities are at risk from contaminants from river discharge, accidental spillage and unregulated dumping (Cowen and Castro, 1994). In the late 70’s the Region was the stage for a number of major oil spills in the Gulf of Mexico (Ixtoc I, 1979; The Burmah Agate, 1979), and The Atlantic Empress and Aegean Captain (1979), which occurred 20 miles northeast of Tobago (42.7 million gallons of oil spilled). It should be noted that while tankers are a natural target of suspicion for oil spills, all ships have the capability of causing water contamination through a variety of operational causes. In addition to petroleum products, the region is influenced by the discharge from a number of rivers. Plumes from the discharge of these rivers have been observed hundreds of miles from their respective river mouths and the contents of the plumes could adversely affect sensitive areas (Muller-Karger, 1993).

Predicting the rate of spreading and the trajectory of contaminants is complicated by the physical regional characteristics of IAS, the rapid variations in the speed and direction of the wind and current systems. Numerical water circulation models have been used extensively to predict the environmental impact assessment of oil and other contaminant spills (French-McCay, 2001). These models often accommodate the simultaneous incorporation of non-linear terms fed by the changing dynamics of the driving forces and complex topography, informing potential impact scenarios.

Minimizing the potential loss associated with the treat of contaminant transport to the sensitive coastal waters requires the identification of valid water circulation models, which can predict the Lagrangian particle pathways and rates of contaminants based on the circulation characteristics and the intraseasonal, seasonal and interannual time scales variations. Knowledge of these statistics can facilitate the identification of vulnerable areas, promoting mitigation and aiding management. Currently no comprehensive management plan is in place for the Region.

This paper attempts to identify the circulation issues in the IAS and evaluate the applicability of available water circulation models for predicting the trajectory and transport of contaminants in the IAS. A valid model operating in conjunction with an up-to-date inventory of land use and habitats of the coastal regions of the IAS would support informed decision to reduce environmental impact.

2. STUDY AREA

The increasing knowledge base suggests that circulation in the IAS is interconnected by physical transports (Moores and Maul, 1998). The Gulf Stream System through flow serves to link the IAS by the physical transport of nutrients, pollutants, fish eggs and larvae, presenting a treat to marine ecosystems as well as socio-economic activities, which support local economies. In 1979 the Atlantic Empress/Aegean Captain collision, occurred in region of fairly strong currents flowing parallel to the Tobago coast. That combined with the low viscosity of the crude oil, high water temperatures, a lessening of the wind and solar radiation, the slicks significantly dissipated naturally in 2 days, averting significant environmental damage, a contrasting scenario to the Exxon Valdez spill of 1989 (Horn and Neal, 1979). The region may not be as lucky if another accident of that nature occurs. Work executed by Atwood *et al*, (1987a,b) has revealed that the surface waters of the major east to west flow in the region including the Caribbean Current, the Gulf Loop Intrusion and the Straits of Florida contain significant levels of floating tar. Unfortunately the Islands present obstacles in the main through flow and provide prime areas for strandings. Strandings greatly reduce the transport mobility, but adversely increases the concentration and potential impact as the oil becomes attached and entrained in ecologically sensitive coastal areas, where natural weathering processes are limited. Past observations have shown that in general, beaches on the eastern coast from Barbados to Florida, which are exposed to the prevailing southeast Trade Winds, are more heavily soiled with floating tar than beaches on the Leeward side (Atwood *et al*, 1987). Continued soiling could adversely affect the economy of island states that utilize beaches for tourism. In addition to petroleum-based products, the Region is also under threat from contaminants contained in river plumes. In July 1999, the Southeastern part of the Region (Guyana to St Lucia) was the victim of an extensive fish kill, resulting in the loss of a significant number of reef fish. It was suggested that the fish kill resulted from the bacterium Streptococcus iniae. Concerns with the Orinoco river influence on the Region came into question since, Streptococcus iniae is a bacterium usually found in fresh water (CPACC, 1999).

Untangling which effects are most important remains the major issue with model development and although there are number of models developed for the IAS only a limited number are suitable for predictive or prognostic work. Moores and Maul (1998) have identified that there are still serious scientific issues that remain unsettled with respect to setting open boundary conditions, whether in the Caribbean Sea or the North Atlantic. In general, the ventilation of the Caribbean Sea and the Gulf of Mexico is only partially understood, and there is limited information on deepwater circulation in the Caribbean (Morison and Nawlin, 1982). A mean cyclonic flow along bottom topography in both the Caribbean Sea and Gulf of Mexico has been suggested based on dynamical reasoning (Moores and Maul, 1998). In addition to these concerns the influence of climatology and the river runoff regime are essential to the forecast system.

2.1 Water Circulation

The Tropical and Subtropical North Atlantic Ocean flow provides the major input to the Guyana Current and exhibits vigorous mesoscale variability on a time scale of 2 months (Figure 1a, 1b). This flow interacts with the plume of the Amazon and Orinoco rivers, and then flows westward through several major passages in the Antillean Archipelago and forms the Caribbean current system (Figures 1a, 1b and 2). There is a great deal of uncertainty about the distribution of inflow through the various passages (Murphy *et al,* 1999). The variable sill depths and bottom topography encountered by the flow result in spatially complex patterns of undercurrents, counter currents and bottom trapping, with temporal variability on time scales of months and years being observed with no clear annual cycle experienced (Moores and Maul, 1998). In general, circulation in the Caribbean Sea is dominated by an east to west through flow, and forms the root of the Gulf Stream as it passes through the Yucatan Channel into the Gulf of Mexico (Molinari *et al*, 1981) (Figure 1a, 1b). Satellite trajectory research executed by Nystuen and Andrade (1993) has shown that large anticyclones shed by the retroflection of the North Brazil Current (NBC) a few times per year interact with the Antillean passages to induce anticyclonic/cyclonic dipoles in the eastern Caribbean. They then propagate to the west inducing cyclones and anticyclones in the Caribbean Sea and contribute to the cyclonic circulation of the Panama-Colombia Gyre (PCG), which exhibits seasonality associated with the prevailing atmospheric forcing, undergoing intrinsic variability. The cyclones are observed to follow a track to the south of the anticyclones. The amount of intensification is strongly affected by the strength of the flow through the Lesser Antilles and the interannual variations in the strength of the Caribbean Current, which lies on the axis of eddy propagation (Murphy *et al*, 1999). These primarily anticyclonic eddies transit a fairly narrow corridor westward across the basin. On average the transit time from the Lesser Antilles to the Yucatan Channel is about 10 months (Murphy *et al,* 1999). High Caribbean eddy activity is anticipated from March to November and low activity from December to March. Their variability contributes to the vulnerability of the regions ecosystems to pollution transport and increases the complexity of modelling (Moores and Maul, 1998). Some of the anticyclones enter the Gulf of Mexico and trigger Loop Current anticyclogenesis, which are one of the essential components of the Gulf Stream (Moores *et al*, 2000). As the Yucatan current traverses the Gulf of Mexico it enters the middle of the Gulf Stream, which exhibits a maximum transport in the summer with a rapid decrease in the fall (STACS; Fabrez-Ortegua, 1985). A southward flow at 1900m deep ($0.1 ms^{-1}$) has been observed at the sill of the Yucatan Channel (Maul *et al,* 1985). The Gulf Stream is partially wind driven but is also augmented by a contribution from the Global thermohaline (Schmitz and Richardson, 1991; Schmitz, 1995). The Gulf Loop current occasionally “pinches off” just north of the Yucatan Straits and becomes an eddy, which moves westward through the Gulf. The major flow exhibits an anticyclonic southward path periodically at intervals of 6 to 20 months to exit east through the Florida Straits until the loop current is ‘rebuilt’ (Molinari *et al*, 1981). The Antilles Current and the Deep Water Boundary Current (DWBC) dominates the mean flow on the oceanic side of the Antilles and Bahamas then merges with the Florida Current. This water movement includes westward propagating mesoscale eddies with time scale of 70 to 100 days. In general, the DWBC flows equator ward at a depth of about 3km along the periphery of the IAS continental shelf. Portions of the DWBC are however characterized by re-circulation, which makes observations of transport and cyclic behaviour difficult (Moores and Maul, 1998).

2.2 Factors Influencing Water Circulation in the IAS

2.2.1 Bathymetry

The landmasses of the semi-enclosed waters of the IAS have very complex topographies and wide or no significant continental shelf (Gade, 1961). Schuchert (1935) and Parr (1937) have suggested that topographically there are three major zones in the IAS i.e. The Gulf of Mexico; the Cayman Sea and the Caribbean Sea with interaction from the Atlantic Ocean (Figure 2). Five major basins makeup the IAS i.e. Gulf of Mexico Basin; Yucatan Basin; Colombian Basin; Venezuelan Basin and the Grenada Basin and numerous islands that create a number of outflow and inflow passages (Figure 2). The Cayman Sea is topographically the most complex zone and is about 400–500m deeper than the Caribbean Sea (Table 1). It consists of the Yucatan Basin, Windward Passage to the north connects the Cayman Sea with the Atlantic Ocean and the Bahamas waters. The ridge between Honduras and Jamaica creates a complex web of banks and passages and separates the Cayman Sea from the rest of the Caribbean. Cayman and Bartlett Trench and a chain of islands and banks created by a submerged ridge extending from the southwest point of Cuba in a westerly direction to tiny Swan Island. The Cayman Trench has the greatest recorded depths of all the Central American Basins. The Windward Passage to the north connects the Cayman Sea with the Atlantic Ocean and the Bahamas waters. The ridge between Honduras and Jamaica creates a complex web of banks and passages and separates the Cayman Sea from the rest of the Caribbean.

Figure 2

The Caribbean Sea is topographically less complex and comprises of three major basins i.e. Colombian Basin, the Venezuelan Basin and the Grenada Basin, with depths generally between 2000 and 2800 fathoms (Table 1). The Colombian Basin is separated from the

Venezuelan Basin by a ridge projecting southward from south central Hispanola, and a ridge running south of the Anegada Passage separates the Venezuelan Basin from the Grenada Basin (Parr, 1936). The Grenada Basin rims the western side of the entire Lesser Antilles, except for Barbados and Watlington and Rooth (1994); Parr (1937) have suggested that the basins divide the deep circulation. The Caribbean Sea opens to the Atlantic in the north by two main passages i.e. Mona Passage and the Anegrada Passages. The other passages between the islands of the Lesser Antilles are significantly narrower, with relatively the same threshold depth of the Anegada Passage (Parr, 1937). In the southern region of the Caribbean Sea, a fairly uniform continental Shelf extends about 60 Nm from the northern coast of Venezuela, sloping gradually from the delta lowlands, forming a nearly right angle with Tobago in the corner (Gade, 1961). On the Eastern side of Trinidad the Shelf is irregular and shallow, and on the northern side the initial slope is steep plunging to more than 50m with a nearly horizontal platform extending north. The slope then falls steeply from about 200m to more than 2000m, where the islands north of Tobago have no significant Continental Shelf (Gade, 1961).

Table 1

2.2.2 Atmospheric Forcing

The upper level circulation in the IAS is influenced by the Trade Winds, which are best established in the summer. In the southern IAS along the northern coast of South America, the variability of the Inter-tropical Convergence Zone (ITCZ) influences the atmospheric forcing of coastal waters as it migrates meridionally on a seasonal basis (Moores and Maul, 1998). The ITCZ experiences maximum and minimum zonal wind stress as well as patterns of cyclonic and anticyclonic wind stress curl, resulting in seasonal variations in the coastal, open ocean up welling and directions of coastal flows along the IAS coasts (Moores *et al*, 2000). The northern IAS is under the influence of the westerlies in the winter season, with weekly Northers. These Northers penetrate progressively further south, generating transient shelf circulation and cool shelf waters. In storm conditions the wind can exceeds the average 4N m^{-2} to almost 2 orders of magnitude greater and could substantially contribute to intensive localized mixing and open ocean upwelling.

2.2.3 River Forcing

Major discharge influence in the Region is from the Amazon, Orinoco, Magdalena, Mississippi and Rio Grande rivers (Muller-Karger, 1993). Runoff from these rivers has substantial influence on the upper level salinity, nutrients, biogeochemical and ecological properties. The Magdalena River in Colombia discharges directly into the Caribbean Sea and its plumes has been observed to extend to Jamaica. The Amazon River most strongly influences the region in winter and spring and it has been suggested that its discharge is on the increase (Gentry and Lopez-Parodi, 1980). The plumes become embedded in the Guiana current in the rainy season, meandering north and then west at Barbados (Muller-Karger, 1993; Froelich *et al*, 1978). During June to January most of its flow is towards Africa in the NBC retroflection. The Orinoco River plumes influence the IAS all year round and its plumes engulf the islands of the southern Lesser Antilles, at times extending across the Caribbean Sea to Puerto Rico. The Mississippi river plumes have been observed to flow to the west in the northern Gulf of Mexico. When the Gulf Loop Current penetrates far enough north, some of the discharged water, especially under periods of eastward winds is entrained into the Loop Current and transported into the Straits of Florida (Moores and Maul,1998).

2.2.4 Stratification

Surface waters from the Tropical Atlantic Ocean has an average temperature (**T**) of ≈ 28°C and salinity (**S**) ≈ 36 ppt., and flows through the Antilles Passages and the Straits of Florida, maintaining almost the same general **T**/**S** properties throughout, except during extreme winters. In the summer the IAS has large zones with surface temperatures in excess of 28°C consistent with “warm pools”. Tropical cyclonic developments may occur producing strong air-sea interaction. Stratification of the water column below the surface shows three distinct deepwater layers. The Sub Tropical Underwater (STW), the Western North Atlantic Central Water (WNACW), and the Intermediate Water (AAIW) (Table 1). The temperature and salinity of the deepwater in the Caribbean Sea has been found to have a very resilient relationship, exhibiting remarkably uniform bottom water with respect to **T**/**S**, but there is limited knowledge with respect to the dynamic role of the DWBC and the IAS (Moores and Maul, 1998).

3. WATER CIRCULATION MODELS

In general terms a model is a simplified representation of some aspect of the real world, which happens to interest an investigator (Huggett, 1993). Models as tools, should be robust, effective and easy to understand and use, yet complex enough to be representative of the system being studied (Anderson and Burt, 1985). Modelling water circulation is based on a conceptual understanding of ocean dynamics, which result from the complex interaction of the atmospheric and oceanic subsystems. These subsystems induce circulation cycles of various scales that need to be parameterised. The assumptions applied to the system state, relations and dynamics are important considerations in configuring the causative variables in the model environment. Therefore, conceptually the objective is to calculate the velocity of a fluid held in a three-dimensional container with a free surface considering the internal and external forces acting on the fluid (Carey, 1995).

3.1 Model Architecture

Water circulation models are often based on independent architectures to mimic reality (Cartwright, 1999; Carey, 1995). One type of architecture is based entirely on utilizing dynamic equations, shape and bathymetry of the domain, and parameters of elasticity and friction and the form of the primary potential (Primitive equation)(Figure 3). The non-linearity of the equations, the complex geometry of the ocean, unknown boundary conditions and the use of various assumptions make the equations difficult to solve and validation is required. Approximations such as the hydrostatic, Boussinesq or Quasi-geostrophic can be employed at the risk of their modelling deficiencies. This architecture may be guilty of placing too much reliance on approximate mathematical equations and arbitrary parameters and requires long calculations in finite resolution. Currently friction values applied are large and do not allow the non-linear terms to play a realistic role, instead they are suppressed, leading to underestimation of velocity and transport values of currents. Small friction values lead to an accumulation of energy and non-linear computational instability may arise (Pond and Pickard, 1983). Finer resolution is required to reduce suppression of the non-linear terms.

Another type of architecture employs the inverse dynamic theory in which the solution is based on using in situ or satellite altimetry measurements (Data Assimilation) (Figure 3). The profile of the height of the satellite above the mean sea surface is then used to relate the surface fields to the three-dimensional model fields of temperature, T, or salinity, S (Thompson *et al*, 1992; Ezer and Mellor, 1994). Vertically integrated nonlinear primitive equations for horizontal momentum and mass conservation are solved using mass transport per unit width as the dependent variable. The use of altimetry data facilitates the comparison of the sea surface height (SSH) generated by the model with data obtained from the satellite. Assimilation scheme errors consist of errors in the correlation factors and in the optimal interpolation (Ezer and Mellor, 1994). Although rapid consecutive radar pulses improve the accuracy of the satellite measurements, the absorption of data noise into the solution remains an issue. Ezer and Mellor (1994) have suggested that the SSH and SST data obtained by satellite only provide surface information and are spatially incomplete, being derived from specified satellite tracks and requiring the absence of cloud cover. The measured surface elevation response varies slowly in deepwater and can be approximated well by this method. In shallow Shelf waters however, it results in rapid variations, impairing its applicability in coastal areas (Cartwright, 1999). While it is typical in most model eddy resolving scheme for modelled eddies to be more diffuse and have a shorter lifetime that observed in reality, assimilation of altimeter data into the model partially corrects this model deficiency. The assimilation is able to constrain the model so it can produce some of the observed mesoscale variability, but Ezer and Mellor (1994) have suggested that significant differences are found between the nowcast and the analysis fields.

3.2 Resolution Considerations

The interplay between intense mesoscale eddies resulting from non-linearity in field acceleration and frictional shears associated with depth require the sophisticated measurement techniques and the finer resolution of a 3-dimensional numerical model (Pond and Pickard, 1983).

Water circulation models are often described based on their vertical structure (Figure 3). Models can be layered-oriented, vertical-level or sigma-level (bottom following models), where the vertical resolution is based on the degree of vertical structure the model supports. This has a direct impact on the ocean layer dynamics that can be modelled. Models that are Layer-oriented require the selected layers to remain thicker than a specified threshold thickness (usually 40-50m) everywhere within the model to prevent surfacing of the layer interfaces, which make the model computationally inefficient. Bottom topography is also not allowed to intersect any layer interface (Frantantoni *et al*, 2000). This often results in a vertical structure that is not representative of reality and reduces the models vertical resolution capabilities in the upper ocean if realistic subsurface topography is used. Some other contemporary layer-oriented models allow zero-thickness layers anywhere within the domain, but at significant computational expense (Frantantoni *et al*, 2000). Vertical-levels models facilitate a higher vertical resolution,

Figure 3

and a high resolution turbulent boundary layer facilitates the modelling of shallow seas where maximum density gradients exist. Haney (1991) has identified that models that utilize sigma (σ) coordinates can however introduce large truncation errors into the model near steep topography and due to “hydrostatic inconsistency” associated with the σ-coordinate system.

Truncation errors are distributed throughout the water column resulting in the creation of erroneous geostrophic currents parallel to the isobaths. These errors can have significant implications over the continental rise and slope. Haney (1991) further identifies that the errors are particularly sensitive to the number of vertical layers utilized in the model and estimates that based on the number of levels a false geostrophic current at the sea surface of the order $5m^{-1} \approx$ 10-levels; $1.2m^{-1} \approx$ 20-levels; and $1cm^{-1} \approx \geq$ 30-levels is created. He suggests that for many problems a false geostrophic current of this magnitude would be a serious error and that due to the complex nature of the pressure gradient error the horizontal and vertical resolution should be chosen not only to accommodate the particular ocean problem, but also to satisfy the hydrostatic consistency condition.

Currently horizontal grid resolutions of 5km to 100km grid or 1/12 - 1/4° degrees latitude have been achieved for the IAS. The grid construction is generally a finite difference β(beta)-plane approximation for the tangent plane, since it successfully accommodates latitude variations of tens of degrees, between mid-latitudes and the Equator, making it most suitable for the IAS (Pond and Pickard, 1983). While finite difference constructions produce good approximations when the velocity varies in a smooth linear manner it creates false serrations and vorticity if a straight coastline lies 45° to the cells. New developments in finite element constructions utilizing triangles of varying sizes have been found to approximate bathymetry dynamics better. The grid resolution determines the size of the phenomena that can be modelled and the time step that can be employed. Low resolution results in broader weaker currents then observed in reality and cannot facilitate the modelling of mesoscale eddies. High resolution however, requires smaller time steps to maintain computational stability. Doubling of the resolution results in a sixteen fold increase in computational time and storage (Pond and Pickard, 1983). Depending on the computational needs of the model, array, parallel or single processor processing is applied. Better computational stability is achieved utilizing an implicit time integration scheme, as opposed to an explicit scheme, but high-speed computer power is required. Relaxation methods can be employed to reduce processing time, facilitating larger time steps.

3.3 Boundary conditions

Operational constraints must be applied in model generation to facilitate the solution of the dynamic equations and maintain stability of the system. These boundary conditions include specifications for the geometric boundaries, and constraints on water movement. Determining what value to specify for the boundary condition can be problematic (Moores and Maul, 1998). Class II forcing which is of particular concern to the IAS is sensitive to the initial state since they affect the model transformation of all fields (Thompson *et al*, 1992). Velocity components are required at the boundaries based on a combination of the parameters, S, T, P, D, wind stress and frictional and topographic influences. Most models use an eddy-resolving scheme, where constant eddy viscosity and diffusivity terms are specified for the different spatial components to relate the frictional effects to the calculated large-scale velocity. The terms prescribed can induce model instability if a balance is not maintained between the vertical and horizontal diffusivity values (Holland and Line (1975); Schmitz and Holland (1983). The inclusion of slip boundary conditions can be imposed to facilitate the use of smaller friction values, but these can eliminate certain phenomena from the possible solution. Inaccurate consideration of these terms can also lead to erroneous solutions i.e. producing downwellings where upwellings should occur. The frictional effects greatly impact calculations in Shelf seas.

3.4 Configuration and External Forcing

Models can be executed in a hydrodynamic configuration in which a barotrophic scheme is employed and the model is forced by a combination of monthly climatological wind stress at the surface and steady imposed mass fluxes at partially open zonal boundaries. While good for modelling deepwater where the water is generally stationary, the inclusion of bottom topography in barotrophic schemes can result in over estimation of the topographic steering affects, significantly affecting transport and mixing calculations (Pond and Pickard, 1983). Currently the most widely used values are those established by Hellerman and Rosenstein (1983). This wind climatology scheme has been found to produce the most reasonable low-latitude results (Frantantoni *et al*, 2000). These values are currently being revised to improve accuracies associated with transport calculations. Currently there is rapid transition of the drag coefficient resulting in over and under estimations. The values specified by Saunders (1976), while providing better spatial resolution, does not accommodate seasonal variations of the position of the maximum curl. Hybrid schemes, which use contributions from different calculations, are also utilized (Murphy *et al*, 1999).

Alternatively, a model can incorporate thermodynamic equations in a baroclinic scheme facilitating the inclusion of thermohaline forcing. Diapycnal mixing schemes are used to remove static instability associated with instability in the density field. Temperature and salinity values are applied at lateral boundaries and for the interior, at prescribed depths, based on the vertical structure utilized. The density gradients described by the non-linear relationship of these parameters and pressure (in a non-hydrostatic mode) are used to deduce circulation and facilitate eddy identification. This scheme is good for modelling the pycnocline layer where maximum density gradients result in fast currents. The inclusion of bottom topography results in more enhanced currents as deep current terms interact with the bottom slopes (Holland, 1973). Hybrid models generally utilize mode-splitting to accommodate treatment of both modes in separate sub-systems. In this configuration T, S and wind forcing are applied, and currents caused by non-uniform atmospheric pressure developed by steady-state cyclones and anticyclones, can be modelled.

3.5 Bathymetry/Topography Considerations

The inclusion of bottom topography is an important consideration, since it affects the amplitude of the velocity field, affecting mixing and transport. The speed of the current increases flowing around headlands, passing through a restriction in a channel or in passing from deeper to shallower water, resulting in more pronounced variations in currents. The effects being influenced by the size of the island, the presence or absence of a continental shelf, the steepness of the bottom slope, and the speed and vertical structure of the ambient flow impinging on the island (Bowden, 1983). These effects can be larger than those induced by the wind-stress curl and tidal elevations in some regions, but their full impact on circulation is still virtually unknown (Holland, 1973). NRL/NLOM model experiments in the IAS have shown that errors in the geometric boundaries can result in unrealistic flow paths and mean transport estimations (Willems, 1994). In low resolution models smoothing of the topography is often required to reduce energy generation on small scales that the model cannot resolve (Murphy *et al*, 1999). Poor consideration of the inflow to, and out flow from the Region, in addition to other open boundary conditions have resulted in limited success in early model development (Moores and

Maul, 1993). Inputs from the larger-scale flow such as the DWBC and the cross-equatorial flow from the South Atlantic (13Sv) need to be included to obtain a realistic Gulf Stream path and eliminate “overshooting” and inaccurate transport which occurs in Gulf Stream models.

4. MODELLING ISSUE IN THE CARIBBEAN

In general, model validation in the IAS is based on how well they have characterized the major features of the Gulf Stream System and how well SSH generated by the model compare with those obtained from satellite altimetry data. Spatial and temporal variability of the mixed layer depths and Largrangian particle trajectories and rates have received limited validation in the past. Chosen models for use in the IAS must fulfil a number of constraints including;

1. Model configuration must be aligned to the general characteristic and seasonal variations experienced in the IAS.
2. Filtering techniques used must be able to isolate the slowly changing average large-scale circulation, from the rapid small-scale movements of random nature with appropriate paramatization (section 2.1).
3. Must give consideration to the inflow and outflow of large and regional-scale processes to resolve issues of open boundary conditions as they relate to the IAS.
4. Must allow for the initial condition to be selected with care, since imbalances can create wave motions that can swamp the true field and destroy a forecast over certain time scales (Thompson *et al*, 1992).
5. Must allow for the influence of the islands and the irregular bottom topography, which can steer the flow must be analysed to provide estimates of its contribution to circulation and mixing (Bowden, 1983) (Section 2.2.1).
6. The model domain must include coastal, Shelf and non-Shelf Seas, and have the capability to accommodate islands and mesoscale and basin scale phenomena brought about by the combination of various forces (section 2.2.2-2.2.4).
7. Must accommodate transport trajectory, volumes, mixing and flushing rates of various contaminants.
8. Must model the surface layer and some aspects of the pyconocline based on the dispersion properties of various contaminants.

4.1 An Examination of the suitability of Models for IAS

There are approximately ten numerical water circulation models developed for use in the entire IAS (Moores *et al*, 2000). This examination focuses on the applicability of two leading models to the prescribed application (Moores *et al* 2000). They utilize different architectures and have been partially validated for the IAS general circulation and mesoscale variability. They have also been used to explore regional mesoscale eddy dynamics and transport and trajectory.

4.1.1 Princeton Ocean Model (IAS- POM)

The POM model is a primitive equation, free surface, estuarine and coastal prognostic ocean circulation model (Blumberg and Mellor, 1987). It accommodates a grid resolution of 20x20km in the horizontal and addresses mesoscale phenomena of the order 1-100km in length, and tidal variations on a 30-day time scales, depending on basin size and grid resolution. It is a sigma (σ)-level model and has substantial vertical resolution in the surface boundary layer. It can accommodate 21-sigma levels in the vertical facilitating mixed layer dynamics. Mode-splitting is applied for the separate solution of volume transport and vertical velocity. The model is thermohaline forced and utilizes Hellerman-Rosenstein climatological monthly winds and Levitus climatological mean open boundary conditions. It can model coastal regions from the 20m isobath and is capable of modelling coastal upwelling and horizontal advective processes associated with tide and storm surge modelling within reasonable computational time. The prognostic variables are temperature, salinity, turbulence kinetic energy, and turbulence mesoscale, and the sophisticated Mellor-Yamada level 21/2 turbulence closure scheme is employed to provide vertical mixing parameters. The general circulation and mesoscale variability has been partially validated for the IAS. Currently exploratory research is being executed to validate regional mesoscale eddy dynamics and Lagrangian particle pathways and rates. A major advantage of this model is that it includes an ecosystem submodel (nutrient-phytoplankton-zooplankton-detritus). Inclusion of data assimilation will facilitate further validation issues (Moores *et al*, 2000).

4.1.2 NRL/NLOM

The NRL/NLOM is a layer-oriented model, which can be employed in a reduced gravity thermodymanic or purely hydrodynamic mode (Hurlbert and Towsend, 1994). The thermodynamic mode contains more accurate stratification than the hydrodynamic mode. Murphy *et al*, (1999) has demonstrated that in studies executed for the IAS the thermodynamic simulation produced a more accurate representation of the return flow of the global thermohaline circulation, which effects the mean transport through the Lesser Antilles. It is modular in nature and can be set up in several different configurations i.e. as a regional, basin or global model, linear or non-linear, wind-forced only or port-forced only or both, with or without surface thermal forcing, with or without data assimilation. The model boundary conditions are kinematic and no slip at solid boundaries. It employs inverse dynamic theory, utilizing SSTs and SSHs to deduce the pressure gradients and solve for resulting circulation. Nudging and statistical techniques are applied to assimilate TOPEX/POSEIDON and ERS-2 satellite altimetry SSH to facilitate comparison with model SSHs. It is layer-oriented, and has been employed at 1/4° resolution in the horizontal and supports six vertical layers. In general the vertical layer thickness is usually 40-50m everywhere in the model domain and bottom topography is confined to the lowest level (Murphy *et al*, 1999). This makes the model computationally more efficient than models that do not utilize these restrictions. It utilizes meteorological forcing in a hybrid scheme in which the Hellerman and Rosenstein stress values drive the long-term temporal mean, while the variability is driven by the European Centre for Medium-Range Weather Forecasts (ECMWF). Wind forcing data from the Fleet Numerical Meteorological and Oceanography Centre, Naval Operational Global Atmospheric Prediction System is also utilized in some model configurations. The subsurface temperature and salinity structure is obtained using the method of Carnes *et al*, (1996) in which the correlation between dynamic height and coefficients of empirical orthogonal functions (EOF) of observed vertical temperature profiles are employed. It can forecast for all classes on the basin scale, but the primary emphasis is on Class II forcing (Thompson *et al*, 1992). The model includes realistic coastline geometry, based on ETOP05 with modifications from Youtsey, (1993), and the coastline boundary is limited to the 200m isobath, some extension into shallow water can be achieved by an analysis method (Moores *et al*, 2000). Partial validation of the general circulation and mesoscale variability of the IAS has been executed. Validation of Lagrangian particle pathways and rates are still to be executed. Operational testing are ongoing on an upgrade, which utilizes a grid resolution of 1/16° and includes a mixed layer and SST as well as an Ekman layer for surface currents. The governing equations are solved in the frequency domain as opposed to the time domain, often leading to significantly smaller computational effort.

4.1.3 Evaluation

The IAS-POM and the NRL/NLOM utilize different architectures (see sections 3.1, 4.1.1, and 4.1.2), which are affected by the model environment in different ways.

- **IAS Characteristics and Prescribed Application**

Based on the characteristics of the IAS modelling for the prescribed application requires the modelling of Shelf seas as well as deep basins and steep sloping island seamounts. As outlined in section 4.1.1, IAS-POM utilizes sigma (σ) coordinates at specified σ-levels, while the NRL/NLOM model is a layer-oriented model with specified layer thickness. This is one of the major differences between the IAS-POM and the NRL/NLOM model. The vertical scheme utilized is sensitive to the topographic features in the model domain. The POM model due to its high vertical resolution is suitable for coastal (20m isobath) and Shelf Seas, but uncertainty in errors introduced near steep topography present limitations in a region such as the IAS. The vertical resolution of the layer-oriented NRL/NLOM models is lower than that of the POM. The model domain starts at the 200m isobath and confines the bottom topography to the lowest layer, eliminating Shelf Seas from model solution. It does however has an advantage over the σ-level models in modelling deep ocean, since they do not suffer from the excessive vertical diffusion (Frantantoni *et al*, 2000).

- **Water Circulation and Contaminant Transport**

As previously identified in section1, contaminants can be introduced from both land and ocean based sources and can travel to distant locations based on the water circulation experienced and the nature of the contaminant. The regional circulation experienced is influenced by atmospheric forcing, topography, stratification and inputs from river run-off. The nature of a contaminant introduced into the region, prescribes the layer of interest in the water column. In the case of substances that float on the surface or become emulsified, suspended or mixed in the upper surface layer, deep ocean modelling is of limited importance. Essential the application requires the modelling of both the surface and pycnocline layer.

- **Modelling**

Both models facilitate 3-dimensional processing, transport computations, a basin scale domain and have been applied to the IAS in the past with good replication of the Gulf Stream flow. Results with respect to Lagragian particle transport are still to be determined (Moores, *et al*, 2000). The NRL/NLOM model can run more efficiently than the POM model, requiring less storage space and shorter run time. Both models can be wind and or density driven. In both cases the accuracy of the parameters applied will impact on model performance. The POM model places considerable reliance on approximate mathematical equations with arbitrary parameters, while the altimetry measurements utilized in the NRL/NLOM model can compromise the accuracy of the solution by the introduction of data noise. Validation of basin-scale models for mesoscale predictions is complicated by insufficient verification data to test the closure scheme. Model/data comparisons should include the deep eddy-kinetic-energy field, comparison of sea surface height variability with altimetry and large-scale transport measurements (Thompson *et al*, 1992; Hallock *et al*,1989).

5. CONCLUSION

The Intra-American Seas (IAS) consists of a number of small islands. The population centres, industrial activities as well as a number of unique and fragile ecosystems often co-exist within the coastal zones. The IAS provides a transport medium for any contaminants introduced by accidental spillage, unregulated dumping and river discharge. These contaminants represent a potential threat to sustainability of these systems. Therefore, it is important to identify the processes that contribute to the characteristics of water circulation in the Region. This paper examined the effects of seasonal and inter-annual variations in tidal regimes, currents, air and sea surface temperatures in addition to bathymetry. All of these factors found to be potentially contributing to the observed circulation and dispersion of water contents. The identified processes were then used to evaluate the POM and the NRL/NOLM water circulation models for the IAS.

The research concludes that ultimately a combination of the capabilities of the two models is required to optimally represent the model domain and facilitate the modelling of mesoscale phenomena. Although the POM model is not the best choice for modelling deep ocean circulation due in part to its susceptibility to errors near steep topography, its capabilities in coastal and Shelf Seas is a particular benefit to the application. In addition, the POM model includes a ecosystem sub-model (nutrient-phytoplankton-zooplankton-detritus), which is an added advantage in a region such as the IAS with extensive coastal regions, which provide habitats for numerous unique flora and fauna. This sub-model can facilitate impact assessments and management of potential contaminant transport. While it is suggested that the NRL/NOLM model is more efficient than the POM model its benefits are less applicable to the coastal applications. The optimum situation could involve the execution of both models, utilizing results from NRL/NLOM model to fuel the deep ocean modelling of the POM model.

Regardless of the model used the impact of seasonal variations on local tidal regimes, currents, meteorological conditions and their potential impact on velocity, trajectory, vertical mixing rates, thermal balances and associated flushing rates also need to be evaluated in the context of mitigation. Model results need to be validated by appropriate methods to facilitate the identification of a valid prediction system for the IAS. A valid circulation model in conjunction with an inventory of potentially vulnerable habitats in the Caribbean will facilitate the determination of high-risk areas. Knowledge in this area will aid marine management and policy development through operational oceanography.

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Figures

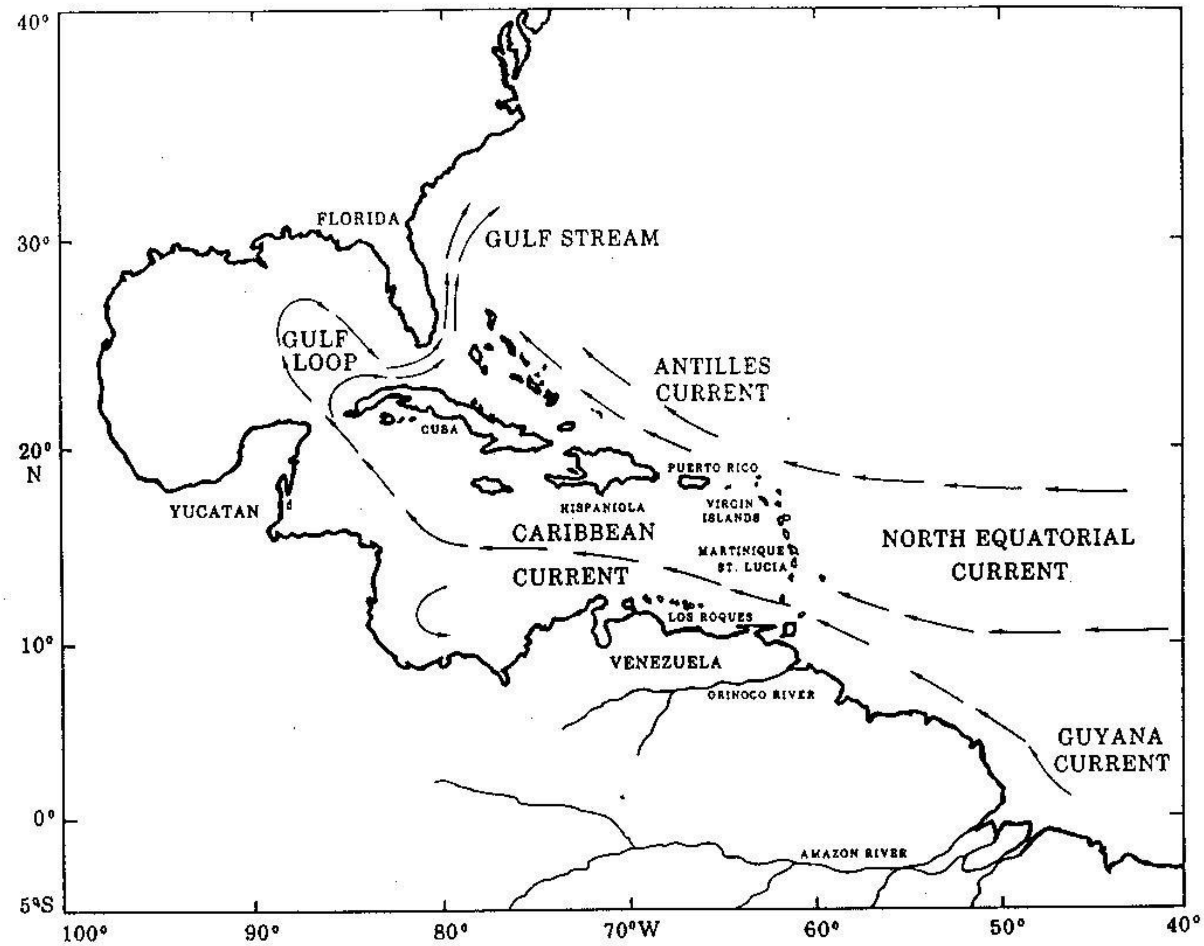

Figure 1a. Schematic Caribbean circulation drawn from pilot charts [After, Duncan *et al*, 1982]

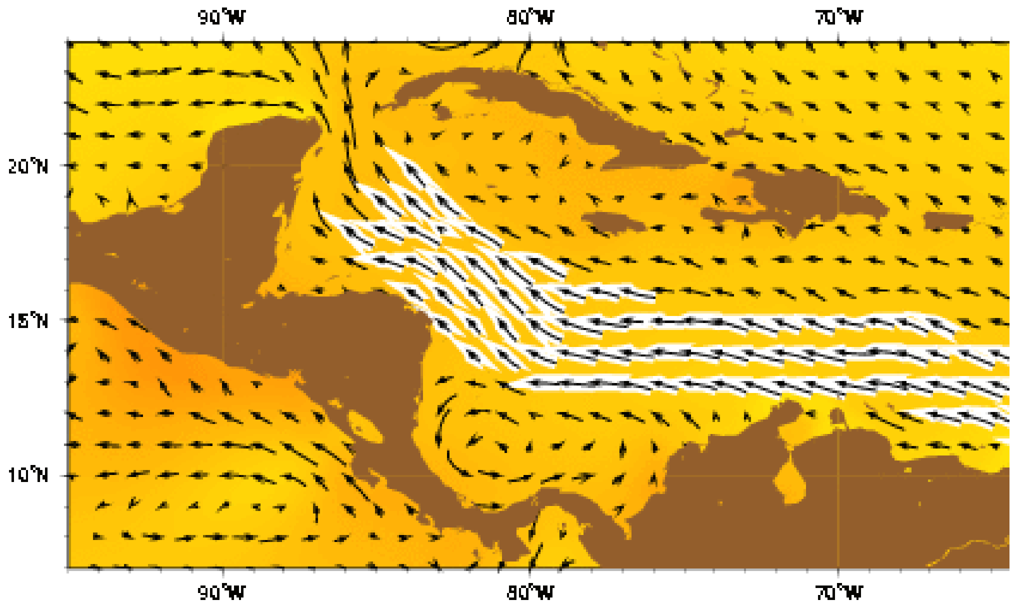

Figure 1b. Detailed Caribbean circulation. The Caribbean Current transports significant amounts of water north-westward through the Caribbean Sea and into the Gulf of Mexico, via the Yucatan Current. The source water for the Caribbean Current is from the equatorial Atlantic Ocean via the North Equatorial, North Brazil, and Guyana Currents. The counter-clockwise circulation of the Columbia-Panama Gyre is evident off-shore of southern Central America (Nicaragua, Costa Rica, and Panama) and northern Colombia (Gyory *et. al*, 2004).

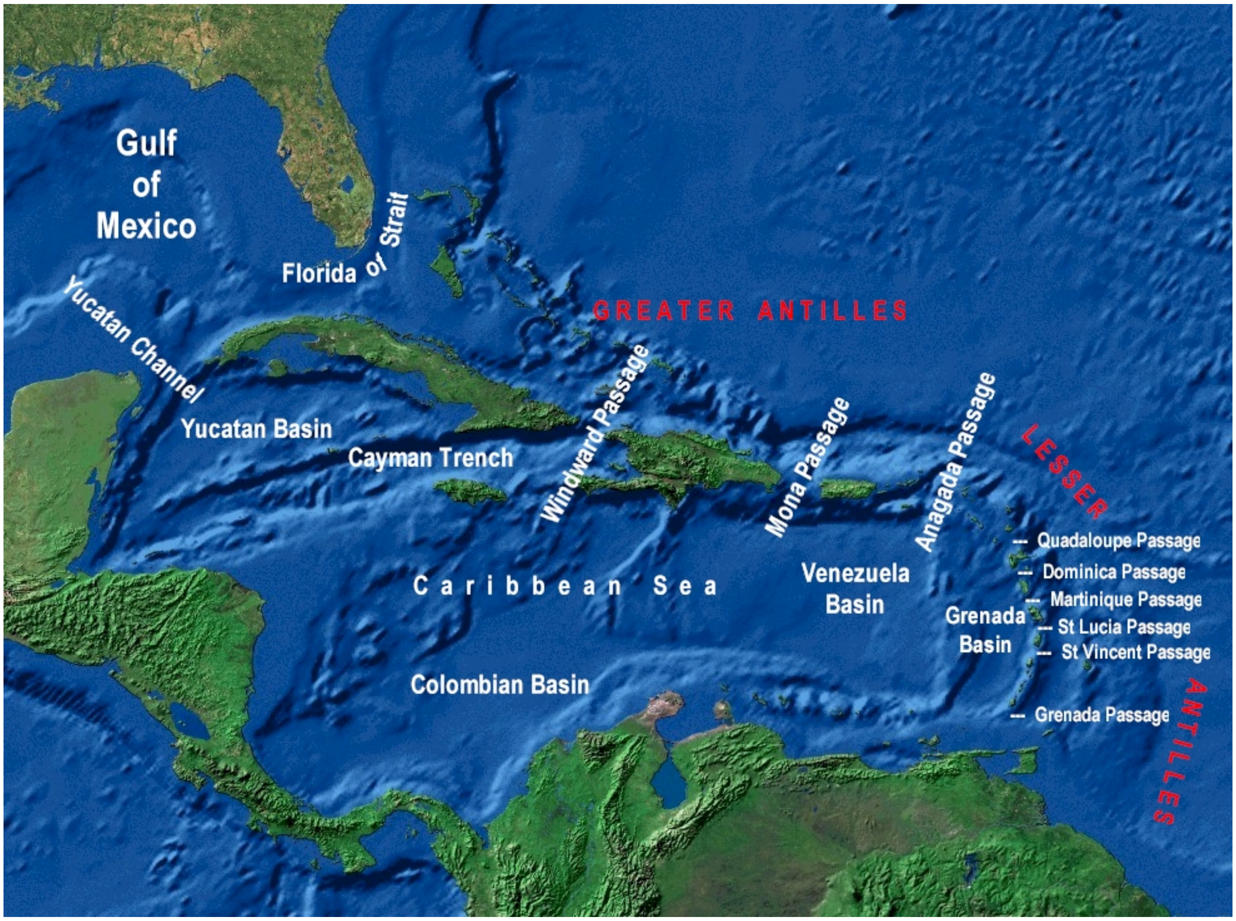

Figure 2. Topographic Illustration of the IAS (Compiled from ESRI Global Imagery, 1998).

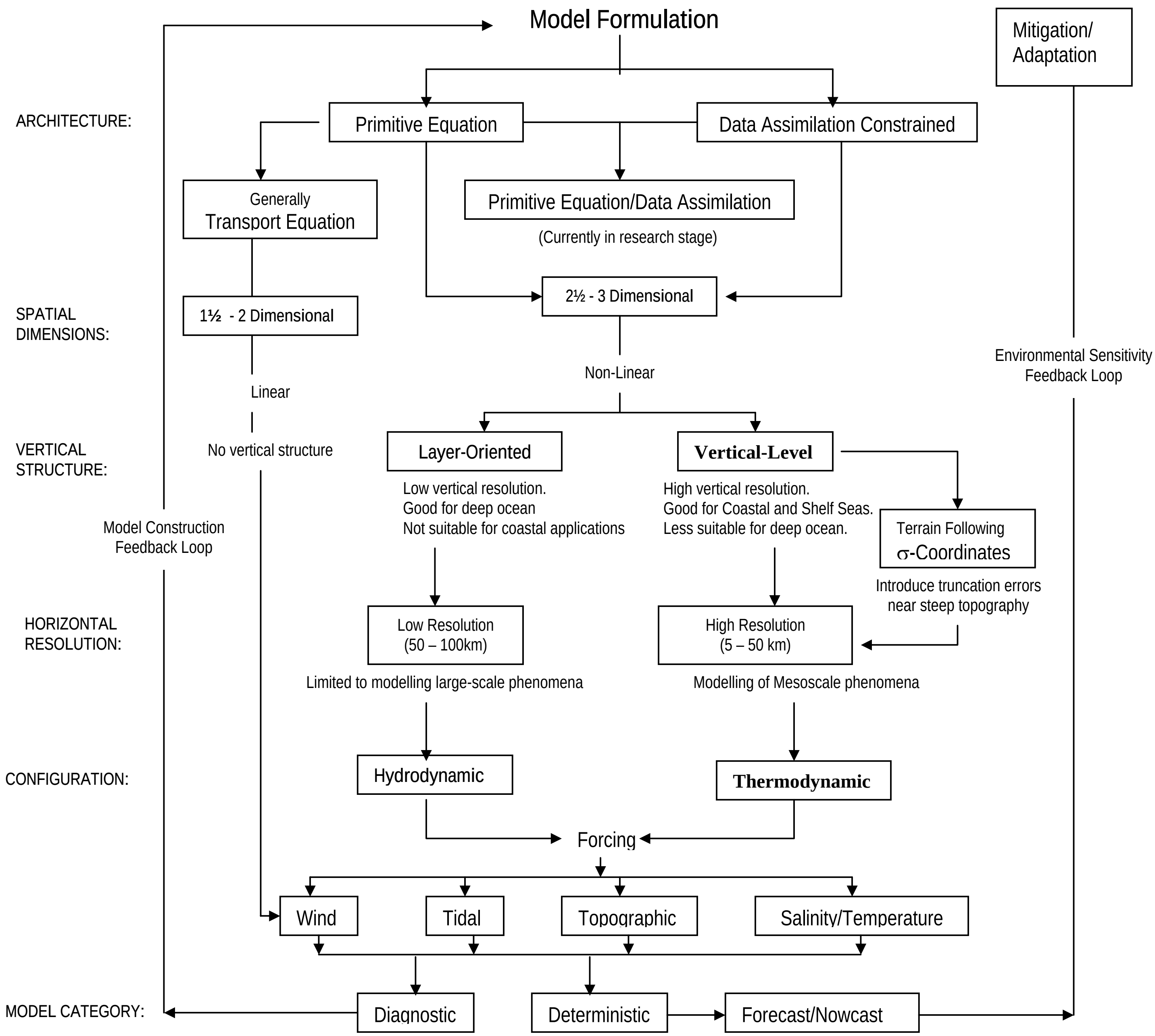

Figure 3. Schematic of Model Formulation Process

Tables

Table 1. Bathymetric Summary of the IAS (After Macpherson, 1984)

Seas	**Approx. Threshold** Depth (Metres)		
Cayman Sea	2500		
Caribbean Sea	2000		
Gulf of Mexico			
Cayman Trench	6000		
Honduras/Jamaica Ridge	700		
Passages	**Approx. Threshold Depth** (m)		**Width** (Km)
WindWard	1830--2012		72
Mona	550		97
Anegada	1830--2012		86
Layers	**Approx. Depth** (m)	**Temp.** (°C)	**Salinity** (ppt)
Surface	0-200	28	36
Sub Tropical Under Water (STUW)	200	22	36.7 (affected by riverine input)
Western North Atlantic Central Water (WNACW)	200-500	8-20	35.2-36.3
Atntarctic Intermediate Water (AAIW)	700	7	34.8
Deepwater	> 1000m	4	35