Physical Oceanography in Canada, 1995-1998: A Review for the International Union of Geodesy and Geophysics

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PHYSICAL OCEANOGRAPHY IN CANADA, 1995-1998: A REVIEW FOR THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

by

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ABSTRACT

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This report summarizes physical oceanographic research in Canada for the period of 1995 to 1998. It was prepared for the Canadian National Committee for the International Union of Geodesy and Geophysics (CNC/IUGG) and the International Association for the Physical Sciences of the Ocean (IAPSO), and was presented at the 22nd General Assembly of the IUGG at the University of Birmingham, United Kingdom, July 19-31, 1999. Contributions are grouped according to the following geographic regions or generic topics: Coastal Atlantic, Coastal Pacific, Arctic Ocean, Labrador Sea, Pacific Ocean, St. Lawrence River and Gulf, Regional Seas, Turbulence and Mixing, and Ocean Circulation and Modelling. A comprehensive list of references and internet homepage addresses is included for readers wishing further details.

Keywords: review, physical oceanography, Canada

RÉSUMÉ

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Ce rapport reprend les principaux travaux en océanographie physique effectués au Canada entre 1995 et 1998. Il a été préparé à l'intention du comité national canadien pour l'union géodésique et géophysique internationale (CNC / UGGI), ainsi qu'à l'intention de l'association internationale des sciences physiques de l'océan (AISPO). Le rapport a été déposé lors de la 22ième assemblée générale de l'UGGI tenue à l'université de Birmingham, au Royaume Uni, du 19 au 31 juillet 1999. Les contributions sont regroupées selon les régions géographiques ou selon les sujets généraux suivant: la côte Atlantique, la côte Pacifique, l'océan Arctique, l'océan Pacifique, la mer du Labrador, le système du Saint-Laurent, turbulence et mélange, circulation océanique et modélisation. Nous avons inclus une liste détaillée de références ainsi qu'une liste de sites internet pour les lecteurs qui désireraient obtenir des détails supplémentaires.

Mots clefs: revue, océanographie physique, Canada

INTRODUCTION

During the years 1995-98, the focus for physical oceanographic research in Canada maintained many of the same directions that began in 1991-94 and were outlined in the previous IUGG report (Gratton, 1995). In the Department of Fisheries and Oceans (DFO) government laboratories, an emphasis on studies linking physical and biological oceanography continued to grow, with salmon being the primary focus on the West Coast and cod being the focus on the East Coast. Investigations looking at the paths of contaminants in the environment, the effects of climate change, and integrated coastal management (a combination of "hard" and "soft" science) also gained in prominence. In academic institutes, significant efforts continued on national and international multidisciplinary programs such as global climate change, ecosystem dynamics, large-scale ocean circulation, sea-ice interactions, etc. The "bloom" in numerical circulation models (both coastal and basin-scale), coupled atmosphere-ocean models, ice models and remote sensing studies also continued. In general, large, fully integrated, multidisciplinary teams and studies became more prolific.

Though we do not cover the details of physical oceanographic research in Canada in this short report, we have attempted to highlight contributions within specific geographic regions and among generic topics. The classifications were the Coastal Atlantic, Coastal Pacific, Arctic Ocean, Labrador Sea, Pacific Ocean, St. Lawrence River and Gulf, Regional Seas, Turbulence and Mixing, and Ocean Circulation and Modelling. Extensive information on the research carried out at Canadian universities and government laboratories is now generally available through Internet Homepages. A list of relevant addresses is included in Appendix 1 and it is recommended that interested readers either refer to these pages, or our publication list, for further details on specific research. Finally, although our goal was to include all research between 1995 and 1998, it is possible that we may have missed some significant contributions. We apologize to the relevant scientists if this has occurred.

COASTAL ATLANTIC STUDIES

The breadth of physical oceanographic research for Atlantic coastal regions expanded during the period 1995-98, with increased demands for applications to problems pertaining to fisheries, ecosystems, climate variability, aquaculture, oil and gas development, emergency response and water quality. Increased emphasis was placed on circulation modelling, historical data analysis and interpretation, remote sensing and interdisciplinary applications, while field measurement programs were carried out at a reduced level compared to previous periods. Research programs involved participation in international and national programs like GLOBEC (Global Ocean Ecosystem Dynamics), interdepartmental government activities like PERD (Panel for Energy Research and

Development), and collaborative projects with universities, industry and provincial governments.

Advances in continental shelf physics included: the description of the predominant influence of the subpolar Labrador Current system on the NW Atlantic shelf (e.g. Loder et al. 1998); the description and understanding of interannual hydrographic variability on the NW Atlantic shelf (e.g. Drinkwater 1996; Umoh et al. 1995; Colbourne and Mertz, 1998); the numerical modelling of seasonal circulation (e.g. Han et al. 1997; Tang et al. 1996), particularly its predominant baroclinic component (e.g. Hannah et al. 1996); the description and modelling of current variability on the Newfoundland and Scotian Shelves (e.g. deTracey et al. 1996; Greenberg et al. 1997; Petrie and Buckley 1996); the description of turbulent mixing on Georges Bank (e.g. Horne et al. 1996; Yoshida and Oakey 1996); the numerical modelling of benthic boundary layer dispersion (Hannah et al. 1998); methodologies for data assimilation in ocean circulation models (Xu 1998); and improved descriptions of shelf tides from altimetry data (Han et al. 1996). Field programs (P. Smith, D. Gilbert, and collaborators) were carried out into seasonal circulation variability in the Laurentian Channel and Cabot Strait region, interannual circulation variability in the Northeast Channel and Georges Bank region, and near-surface drift on the Scotian Shelf. Hydrographic sampling of the Halifax and other cross-shelf sections on the Scotian Shelf was increased in 1997 and 1998, as part of GLOBEC (A. Herman and collaborators) and an Atlantic Zonal Monitoring program.

During this period, studies of circulation and dispersion in coastal embayments have increased, in support of aquaculture, water quality evaluations and engineering developments. Emphases have included current measurements and circulation modelling in Passamaquoddy Bay, New Brunswick (F. Page, D. Greenberg), and field studies in the Bras d'Or Lakes and Country Harbour, Nova Scotia (G. Bugden, B. Petrie) and Bay d'Espoir, Newfoundland (J. Helbig).

Efforts to better document the interannual to interdecadal variability of physical properties in shelf waters off Eastern Canada led to several publications (e.g. Colbourne et al., 1997; Drinkwater, 1996; Gilbert and Pettigrew, 1997; Prinsenberg et al., 1997). The monitoring program over the Canadian eastern shelf waters has also been reviewed in detail and a significant program is being mounted to improve our capacity to understand and detect climate changes (Therriault, et. al. 1998).

At Dalhousie University, Thompson and colleagues focussed their research on the development of an assimilating operational circulation model for the Scotian Shelf (Thompson and Sheng, 1997; Griffin and Thompson, 1996; Dowd and Thompson, 1997; Sheng and Thompson, 1996). Although this model is presently forced by winds and coastal sea-levels, preliminary tests with another model capable of simulating the complete three-dimensional circulation have been carried out.

Both Tony Bowen and Alex Hay of Dalhousie have participated in near-shore dynamic experiments at Queensland Beach N.S., Duck, North Carolina (Hay and Bowen, 1998), and at the wave research flume at the National Research Council in Ottawa . Their research encompasses edge wave trapping (Bryan and Bowen, 1996), shoaling and breaking waves (Doering and Bowen, 1995), and sediment transport (Sheng and Hay, 1995).

At Memorial University, Brad de Young and colleagues have carried out both observational (de Young et al., 1995) and modelling studies (Mathieu and de Young, 1995) along the Newfoundland and Labrador continental shelves, while Len Zedel has focussed his research on acoustical techniques (Zedel et al., 1996a) and applications (Zedel et al., 1996b).

At the Northwest Atlantic Fisheries Centre, Jim Helbig and Pierre Pepin have carried out a series of field experiments and numerical simulations to study the spatial and temporal structure of ichthyoplankton distributions over the continental shelf and in coastal embayments, as well as how physical processes affect ichthyoplankton survival, and the estimation of population size (Pepin et.al., 1995; Pepin and Helbig, 1997; Helbig and Pepin, 1998a,b). In addition, both short range and long range high frequency radar have been evaluated for their application to fisheries related processes (Hickey, et. al., 1996). Long range radar is being used to study the spatial structure of inertial currents over the Grand Banks.

Eugene Colbourne is focusing on ocean climate variability on the Newfoundland and Labrador Shelves from historical data and through ongoing monitoring activities (Colbourne et al., 1994; Colbourne et al., 1997; Colbourne and Mertz, 1998). Emphasis is placed on determining and understanding environmental effects on the fisheries (Rose et al., 1995; Shelton et al., 1999; Colbourne et al., 1997; Dawe et al., 1999; Parsons et al., 1998). Additionally, Colbourne with Ken Drinkwater at BIO and Denis Gilbert at IML are investigating the contributions of local atmospheric heat flux, advection and shelf ice cover to recent climatic variability in the Canadian Atlantic Continental Shelves.

COASTAL PACIFIC STUDIES

Numerous modelling studies were carried out between 1995 and 1998 along the Pacific coast of Canada. Barotropic tides were simulated for the inner waters of Juan de Fuca Strait and the southern Strait of Georgia (Foreman et al., 1995) and western continental margin of Vancouver Island (Foreman and Thomson, 1997) while both barotropic and baroclinic tides were represented for the northern coastal waters (Cummins and Oey, 1997). Generation mechanisms for the Vancouver Island Coastal Current were investigated (Pal and Holloway, 1996; Masson and Cummins, 1999) and background buoyancy currents were simulated diagnostically for Dixon Entrance (Ballantyne et al, 1996) and the western continental margin of Vancouver Island (Foreman and Thomson, 1997). Drifter observations were used to determine surface currents (Crawford et al., 1998a,b) along the north coast of British Columbia and compared with model results, and

TOPEX/POSEIDON altimetry was combined with coastal tide gauge data to calculate seasonal surface elevations and flows (Foreman et al. 1998).

A two-dimensional numerical model (using the level 2.5 Mellor-Yamada turbulence closure scheme) was used to successfully simulate the complex circulation of Knight Inlet (Stacey et al., 1995). The circulation was influenced significantly by the winds, the tides and fresh-water runoff. More recently, closer examination of the near-surface (as shallow as 2m deep) observations of velocity from Knight Inlet has shown that the near-surface circulation can be better simulated by specifying the flux of turbulent kinetic energy (in the Mellor-Yamada scheme) at the air-sea interface, instead of using the more standard boundary condition whereby the turbulent kinetic energy itself is specified.

Several long-term current meter moorings were maintained along the Vancouver Island shelf as part of the La Pérouse Bank and GLOBEC programs. The vertical shears from one of these locations were used as an alternative to the Bakun Index to determine the start of the upwelling and downwelling seasons (Thomson and Ware, 1996). The final set of observations taken as part of the North Coast PERD program (which ended in 1995) whose mandate was to study surface currents in the event of future hydrocarbon exploration was summarized by Crawford et al. (1995).

Numerous other (unrelated) studies were also carried out in the coastal regions of British Columbia. Allen and colleagues studied the role of canyons (Allen, 1996; Chen and Allen, 1996), escarpments (Allen and Hsieh, 1997), and seamounts (Shore and Allen, 1996) in modifying shelf and tidal flows. Cummins (1995) and Li and Cummins (1998) examined bores and solitons, Mihaly et al. (1998) found evidence of nonlinear interactions between inertial and semi-diurnal internal waves, Gower (1996) compared wind/wave data measured by the TOPEX/POSEIDON satellite with those from offshore buoys, Masson (1996) studied wave-current interactions in strong tidal currents off Cape St. James, Hsieh and Thomson (1995) studied wind-induced upwelling along the west coast of North America, and Ott and Garrett (1998) looked at the frictional estuarine circulation in Juan de Fuca Strait.

ARCTIC OCEAN STUDIES

As a major Canadian contribution to the international Arctic Climate System Study (ACSYS), a field and modeling program for the Canadian Archipelago investigated the importance of heat and freshwater fluxes through the Archipelago to the heat and freshwater budgets of the Arctic Ocean and its outflows to the North Atlantic. The international Climate Variability and Predictability program (CLIVAR) also identified the determination of the flow of Arctic Ocean Surface water into Baffin Bay and Labrador Sea as an important component to research foci on the North Atlantic Oscillation and the Atlantic Thermohaline Circulation. The program also contributed the NOW (Northwater project) with mooring instrumentation and ice beacons.

Field activities involved mooring instrumentation development and mooring deployment in each of the major passages in order to define the seasonal variability of the heat and freshwater transports through these passages and is being coordinated with DFO of Pacific region. The data will be used to validate models of the Arctic Ocean circulation and the flow through the Archipelago to provide a tool to estimate what changes various global warming scenarios might bring to the oceanographic conditions in the Canadian Arctic itself and to North Atlantic. A finite element model of the Arctic Channels is being used in collaboration with researchers from DFO Pacific Region.

Canadian scientists participated in two international expeditions organized under the Arctic Climate System Study (ACSYS): a major expedition in 1996 on board the German icebreaker, Polarstern, in the Nansen, Amundsen, and Makarov basins of the Arctic Ocean, and a shorter one in 1997 on board CCGS Louis S. St-Laurent in the Canada Basin and in the Canadian Archipelago. These expeditions, together with data from earlier ones, showed the Arctic Ocean circulation to be much more complicated than had previously been suggested. These data also greatly increased our understanding of the processes that affect water mass characteristics (Rudels et al., 1994; Jones et al., 1995; Rudels et al., 1996; Jones et al., 1997; Carmack et al., 1997; Swift et al, 1997; Anderson et al., 1999). Also from these data, Jones et al. (1998) were able to delineate the separate distributions of waters of Pacific and Atlantic origin as they flowed through and out of the Arctic Ocean (Jones et al., 1998). The Bedford Institute of Oceanography (BIO) Arctic climate program addressed questions of carbon and carbon budgets in the context of climate change that could result from emissions of fossil fuel carbon (Anderson et al., 1998a). All of these programs were collaborative, carried out with partners in Sweden, Germany, U.S.A., and other Canadian laboratories.

Continuing work by scientists from the Institute of Ocean Sciences (IOS) also produced several interesting findings in the Arctic. Observations taken in a trans-Arctic expedition in 1993 led by Carmack and colleagues (Carmack et al.1997, 1995; Jones et al., 1995) found temperatures much warmer than expected. Based on time series of almost twenty years Melling (1998) also found evidence of changes in the Canada Basin of the Arctic Ocean. Detailed studies around the Mackenzie Canyon found evidence of upwelling, internal Kelvin waves (Carmack and Kulikov, 1998), and flow variability (Kulokov et al, 1998). Numerous studies were carried out by Melling on ice pack development, motion, and its effects (Melling, 1998; Galloway and Melling, 1997; Melling and Reidel, 1996a, 1996b, 1995) while Holloway and colleagues modelled the spreading of contaminants (Nazarenko et al., 1997).

Numerous Arctic studies were also carried out by Lawrence Mysak and colleagues at McGill University. Mysak and Venegas (1998) and Slonosky et al. (1997) looked at interannual and decadal oscillations based on atmosphere-ice-ocean interactions, Tremblay and Mysak (1997) modelled sea ice as a granular material, Wang et al. (1994a,b) modelled circulation and sea-ice cover in Hudson Bay, Ingram et al. (1996) studied the impact of fresh water on the southeastern Hudson Bay coastal ecosystem under seasonal sea ice, Holland et al. (1995) simulated the sea-ice cover in the Northern

Greenland Sea, and Mysak et al. (1996) studied sea-ice extent in Hudson Bay, Baffin Bay, and the Labrador Sea during three simultaneous NAO (North Atlantic Oscillation) and ENSO events.

In 1995, Rick Marsden of the Royal Military College (RMC) organized an investigation of internal solibores under land-fast ice near Resolute, NWT. This program was an extension of the 1992 SARES study and had two objectives. First, the influence of internal waves on turbulence production was observed using turbulence probes operated by L. Padman of Oregon State University (OSU). Second, a three element ADCP array was established using instruments provided by RMC, OSU and McGill Universities. The objective was to extend the work of Marsden et al. (1995) to improve the resolution of internal wave directional spectra. Marsden was also involved in the 1998 North Water Polynya (NOW) project. An AVHRR data downlink station was deployed at Alert, NWT approximately 300 km north of the study area on Ellesmere Island. Over 1300 NOAA-12 images were obtained during the period 1 Apr to 1 Aug. Of these, approximately 350 had cloud-free views of the polynya. Turbulence measurements of wind speed and direction and air-sea temperature and humidity differences were and taken during May and June. The data will be used to examine the effect of varying ice concentrations on the turbulent transfer coefficients and will be used in combination with radiation measurements to be compared to the IR imagery.

DFO, McGill University, and INRS-Océanologie were involved in the international Northwater project (NOW) aiming at the understanding of the arctic polynya located in northern Baffin Bay. A major field experiment took place in 1997 and 1998. The Maurice Lamontagne Institute (MLI) contribution to this program included the determination of chlorophyll concentrations using remote sensing (P. Larouche), the measurement of optical properties within the polynya, and the measurement of vertical mixing rates through analysis of microstructure.

Regional atmospheric climate models under development in Canada and elsewhere (e.g., SMHI in Sweden) now aim at coupling coastal ocean models to downscale global climate change scenarios to regional scales. Coastal ocean models can now reproduce, to some extent, the coupled evolution of the ocean and the sea ice cover over seasons and years (Saucier and Dionne, 1998). From previous so-called diagnostic models, wherein the stratification was assumed constant and the baroclinic circulation derived, numerous applications now have temperature and salinity fields evolving through advanced turbulence closure and advection schemes, and under detailed atmospheric conditions.

LABRADOR SEA STUDIES

As a Canadian contribution to WOCE (World Ocean Climate Experiment) and CLIVAR, a field and modeling program for the Labrador Sea investigated the importance of heat and freshwater fluxes of the pack ice and coastal shelf water along the Canadian east coast on the oceanographic properties of the Labrador Sea and the North Atlantic.

Instrumentation (ice beacons, moorings and Helicopter-borne sensors) were used to quantify the areal pack ice fluxes flowing south along the Canadian east coast determined from remotely-sensed data (RADARSAT imagery). Cross-shelf heat and freshwater fluxes determined from observations and simulated by coupled ice-ocean models were found to be important to the oceanographic properties of the Labrador Sea (vertical mixing). Ice-ocean models developed and calibrated against observations were used for both real-time short-term ice ocean forecasts and for long-term predictions of ice and ocean climate changes due to global warming.

In each of these years DFO continued its WOCE commitment to occupy the AR7W CTD section across the Labrador Sea each in the early summer. In the fall of 1996 and spring of 1997 larger scale surveys were completed in the region as a contribution to the WOCE basin scale program focusing on the Atlantic Ocean. Under a joint program with the University of Washington a mooring has been maintained near the OWS Bravo position since 1994 to monitor the velocity, temperature and salinity.

ST. LAWRENCE RIVER AND GULF STUDIES

Ice–ocean instrumentation is being developed to quantify the ice signatures seen in remotely-sensed imagery for the improvement of the safety and efficiency of the marine transportation and offshore developments of the Gulf of St. Lawrence. Ice beacon and helicopter-sensors are being designed and tested to deliver real-time data set to the Canadian Coast Guard and the Canadian Ice Service which in turn will provide ice breaking service and ice information to marine industry. All ice data is being used to better our understanding of ocean-ice-atmospheric interaction processes in the Gulf for uses in both ice forecasting and research in the variability of ocean parameters and their affects on fish and mammal stocks.

In the St. Lawrence Estuary-Gulf region, Savenkoff et al. (1997) recorded the passage of a fresh water pulse (for the first time) and described its impact on the onset of the spring bloom. Marsden and Gratton (1998) were the first to show conclusively that winds move surface water upstream along the north shore and contribute to the formation of pulses at the head of the Laurentian Channel. P. Galbraith has been surveying a grid of CTD stations in early March since 1996. The survey measures the depth, temperatures and salinity of the surface convection layer formed by brine rejection (up to 100m) and the near surface nutrients available for the upcoming spring bloom.Work is also being done (D. Gilbert) to determine whether climatic effects could have played a role in the collapse of the cod fishery in the Gulf of St. Lawrence in the early 1990’s. The region’s contribution to the GLOBEC program (B. Zakarjian, Y. Gratton, and J. Runge) consists of the development of a set of 2D and 3D numerical models for assessing the impact of physical processes on the abundance and distribution of zooplankton in the Gulf of St. Lawrence and the Scotian Shelf. El-Sabh et al. (1999) continued to stress the importance of proper coastal management.

Numerous models have been developed for hindcasts in all or parts of the St. Lawrence River and Gulf (Gan et al., 1995; Chasse et al., 1998) However, following the steps taken in operational meteorology for some years, models are also being used routinely to forecast currents (Saucier et al., 1999), water levels, waves, or sea ice. These fields are needed for various applications such as: surface current charts for navigation, search and rescue planning, oil spill trajectory modelling (Lefaivre et al., 1997; Guerrier et al. 1997), water levels for under-keel clearance in shallow channels, storm surges for coastal flooding, and sea-ice for navigation. Canadian laboratories are now continuously updated with near real-time observations for the weather, sea-ice, water levels, sea-surface temperature and salinity, and other remote sensing observations. Currents are still missing from these real-time observations but they should become available in the next few years.

The years 1995-98 saw the launch of OCTS and SeaWiFS, two satellite sensors aimed at observing global ocean colour. DFO is participating in an international network of receiving stations by operating antennas at Halifax, Mont-Joli, Victoria, and Resolute Bay. These stations give DFO a new window on Canada's three surrounding oceans .To complement the space observation of ocean colour and correctly interpret the data, a major field program was started at Maurice Lamontagne Institute (MLI) to validate ocean colour data in the optically complex St. Lawrence estuary and gulf (Larouche, 1998).

PACIFIC OCEAN STUDIES

A series of drifters released as part of WOCE studies at IOS revealed evidence of inertial currents (Thomson et al., 1998), eddies (Thomson et al.,1997), and diurnal shelf waves (Rabinovich and Thomson, 1998). WOCE sampling lines were also carried out from Dutch Harbor, Alaska to American Samoa (Whitney and Barwell-Clarke, 1997) and in the Sea of Okhotsk (Whitney and Quenneville, 1997; Freeland et al., 1998; Wong et al., 1998). An analysis of long time series from Station P by Freeland et al (1997) found a shallowing of the winter mixed layer in the Northeast Pacific and related these changes to lower productivity. A composite of satellite photos along the rim of the Gulf of Alaska showed numerous unstable eddies (Thomson and Gower, 1998). Collaborative ongoing studies with geophysicists and biologists along the Juan de Fuca Ridge revealed the importance of hydrothermal vents in warming the surrounding waters (Thomson et al, 1995; Baker et al., 1995). Gargett (1997) proposed a mechanism underlying decadal fluctuations in North Pacific salmon stocks.

An extensive observational program was initiated at IOS to monitor changes in the water properties, circulation, and ecosystem during the 1997-98 El Niño. Notable changes were surface temperature anomalies of up to five degrees, sea surface elevation anomalies of approximately 30 cm, and significant increases in the number of mackerel and hake along the Vancouver Island shelf. Publications documenting these, and other significant features, are in preparation.

At the University of British Columbia, neural network models were developed as nonlinear extensions of classical multivariate methods (such as regression, principal component analysis and canonical correlation analysis), and used for nonlinear data analysis and prediction. Currently, there are about a dozen operational El Niño prediction models in the world, including one Canadian effort-- the UBC neural network model (Hsieh and Tang, 1998; Tangang et al., 1998). A connection has also been made between neural network models and dynamic models under variational data assimilation. Variational data assimilation has also been applied to simple equatorial coupled atmosphere-ocean models (Lu and Hsieh, 1998).

REGIONAL SEA STUDIES

Not all physical oceanographic research in Canada focussed on Canadian waters. Chris Garrett and colleagues at the University of Victoria carried out studies in the Red Sea and Gulf of Thailand. The former includes water mass formation (Garrett et al., 1995), the heat and freshwater budgets (Tragou et al., 1998), and the thermohaline circulation (Tragou and Garrett, 1997), while the latter looked at the salt and heat budgets (Stansfield and Garrett, 1997). El-Sabh et al. (1997) reviewed the oceanography of reverse estuaries, with emphasis on the Mediterranean Sea and the Red Sea.

TURBULENCE AND MIXING STUDIES

Farmer and colleagues made wide use of acoustical techniques to study a variety of ocean processes. These include Langmuir circulation (Farmer et al., 1998; Plueddemann et al, 1996; Farmer and Li, 1995), breaking waves (Farmer and Gemmrich, 1996), fish detection (Ye and Farmer, 1996; Trevorrow and Claytor, 1998), sea-ice processes (Menemenlis and Farmer, 1995; Xie and Farmer, 1995), tidal fronts (Farmer et al., 1995), air-sea interactions (Farmer, 1997), internal solitary waves (Trevorrow, 1998), bubbles (Vagle et al., 1996), ocean wave directions (Trevorrow, 1995) and estuarine mixing (Pawlowicz and Farmer, 1998). Additional Langmuir circulation studies were also carried by Li and colleagues (Li et al., 1995; Li and Garrett, 1995, 1997) and Tandon and Leibovich (1995a, 1995b), while mixing was studied in tidal fronts by Gargett and Moum (1995). The role of turbulence in transporting heat and salt was studied by Merryfield et al. (1998) while and overview of techniques and theories for observing turbulence was published by Gargett (1997). Cummins and Foreman (1998) demonstrated numerically the importance of bottom mixing in generating circulation around a submarine bank.

Significant advances in the understanding the roles of mixing and turbulence have been made by Dan Kelley, Barry Ruddick, and colleagues at Dalhousie University. Kelley focussed his attention on double-diffusion and its parameterization (May and Kelley, 1997), methods for identifying overturns in CTD profiles, and diapycnal mixing (Kelley and Van Scoy, 1998). Ruddick also studied diapycnal and isopycnal mixing via the North Atlantic Tracer Release Experiment (Ruddick et al., 1997), thermohaline intrusions that seem to be driven by vertical double-diffusive fluxes (Walsh and Ruddick, 1997, 1995), and the thermohaline circulation (Ruddick and Zhang, 1996).

Rolf Lueck and colleagues at the University of Victoria also carried out numerous turbulence and mixing investigations. Topographically induced mixing was studied around Cobb Seamount (Lueck and Mudge, 1997), turbulent dissipation and shear were studied in the Mediterranean outflow plume (Johnson et al., 1995), and the logarithmic boundary layer (Lueck and Yu, 1997), mean flow, shear, and turbulence (Yu and Lueck, 1997a, 1997b) were studied in Cordova Channel.

OCEAN CIRCULATION AND MODELLING STUDIES

Holloway and colleagues continued their investigations in the role of topography stress in ocean circulation (Holloway and Sou, 1996; Holloway, 1996; Sou et al., 1996; Holloway et al, 1995). In the context of quasi-geostrophic models, these studies included the effects of stratification on inviscid equilibria (Merryfield, 1998), eddy fluxes and topographic links (Merryfield and Holloway, 1998), and testing statistical theory (Merryfield and Holloway, 1996). Cummins (1995) also looked at angular momentum balances in quasi-geostrophic models.

Richard Greatbatch of Dalhousie University carried out a variety of modelling studies related to climate change. These included global, basin (Greatbatch et al., 1996), and shelf circulation (Greatbatch et al., 1995); mesoscale eddy transport parameterizations; and variability on time scales of days to several decades (Greatbatch and Peterson, 1996; Greatbatch and Zhang, 1995).

Mysak and colleagues at McGill University studied large-scale air-sea interactions in the South Atlantic (Venegas et al., 1996, 1998), modelled the warm cretaceous climate (Schmidt and Mysak, 1996), and studied the stability and variability of the thermohaline circulation (Schmidt and Mysak, 1996; Bjornsson et al., 1997). Charles Lin (also McGill) studied coupled atmosphere-ocean models, convective adjustment in ocean models, and with Daniel Le Roux developed finite element semi-Lagrangian ocean circulation models (Le Roux et al., 1997, 1998). Also a member of the McGill group, David Straub studied Southern Ocean dynamics and the behaviour of ocean models when the Reynolds number becomes large (Straub, 1996, 1998).

Several theoretical studies related to ocean circulation were carried out by Chris Garrett and colleagues. Tandon and Garrett (1995, 1996) looked at geostrophic adjustment and restratification in a mixed layer and the parameterization mesoscale eddies respectively, while Zahariev and Garrett (1997) studied an apparent buoyancy flux associated with the nonlinearity in the equation of state.

Andrew Weaver and colleagues at the University of Victoria have been very prolific in their ocean modelling studies. In addition to numerous numerical sensitivity studies and the development of improved numerical methods, highlights of their research include investigations of the ocean conveyor belt (Weaver, 1995), the summer mean circulation in the western North Atlantic (Reynaud et al., 1995), intedecadal variability in the subpolar North Atlantic (Wohlleben and Weaver, 1995), the seasonal cycle and variability in the North Pacific (Myers and Weaver, 1996), sea surface temperature/evaporation effects on the thermohaline circulation (Hughes and Weaver, 1996), the Gulf Stream separation from North America (Myers et al., 1996), paleoclimatic effects on closing the the Isthmus of Panama (Murdock et al., 1997), meltwater implications for the Younger-Dryas period (Fanning and Weaver, 1997), carbon dioxide and ice sheet effects on the last glacial maximum (Weaver et al., 1998), and past lesson and future policies related to global climate change (Weaver and Green, 1998).

SUMMARY

In summary, the period of 1995-98 saw many advances in various aspects of physical oceanography in Canada. We have highlighted research in nine geographic regions or specific topics and refer interested readers to the following lists of references and internet homepages (Appendix 1) for further details.

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APPENDIX 1: INTERNET ADDRESSES FOR FURTHER INFORMATION

1. Department of Fisheries and Oceans Laboratories :
   i) Institute of Ocean Sciences, Sidney, British Columbia : http://www.pac.dfo-mpo.gc.ca/sci/Pages/osap.htm
   ii) Bedford Institute of Oceanography, Dartmouth, Nova Scotia: http://www.mar.dfo-mpo.gc.ca/science/ocean/welcome.html
   iii) Maurice Lamontagne Institute, Mont Joli, Québec: http://www.qc.dfo-mpo.gc.ca/iml/en/intro.htm
   iv) Northwest Atlantic Fisheries Centre, St. John’s, Newfoundland: http://sunny.nwafc.nf.ca:81/index.html

2. Universities :
   i) School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia : http://ceor.seos.uvic.ca/seos/research.html
   ii) Department of Earth and Ocean Science, University of British Columbia, Vancouver, British Columbia : http://www.eos.ubc.ca/research/research.html
   iii) Department of Oceanography, Dalhousie University, Halifax, Nova Scotia: http://www.phys.ocean.dal.ca/phys-ocean.html
   iv) Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Québec : http://www.meteo.mcgill.ca/fac.html
   v) Department d’Océanographie, Université de Québec à Rimouski, Rimouski, Québec : http://www.uqar.uquebec.ca/uqar/brochure.htm
   vi) Department of Physics, Royal Military College, Kingston, Ontario : http://www.rmc.ca/academic/physics/www/acad.htm
   vii) Department of Physics, Memorial University of Newfoundland, St. John’s, Newfoundland : http://www.physics.mun.ca/Ocean/physocean.html