WITH LAKES IN MIND:
A REVIEW OF THE SCIENTIFIC CONTRIBUTIONS OF
T.J. SIMONS (1939-1987)

by

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EXECUTIVE SUMMARY

This paper was written as an introductory review to a collection of reprints of the scientific contributions of T.J. (Joe) Simons (1939-1987). The collection was published as a memorial to Simons by the National Water Research Institute. The review provides a chronologically-ordered summary of his work. Initially trained as a meteorologist in the Netherlands, Simons pursued graduate studies in numerical atmospheric modelling at Colorado State University before joining the Canada Centre for Inland Waters in 1969. At CCIW, Simons applied the techniques of numerical weather prediction to the study of lake circulations. His development and thorough testing of numerical models of large-lake circulation, based on data from the 1972 International Field Year on the Great Lakes (IFYGL) was internationally recognized and he was granted the Chandler-Misner award of the International Association for Great Lakes Research two years in a row. He led a small group of colleagues in pioneering research into the possibilities of lake systems modelling, interfacing the circulation model with biochemical models. He resisted the temptation to promote this work as the ultimate management tool, choosing instead the more conservative approach of using models to synthesisze and to test knowledge across disciplines. His caution was amply justified and Simons'reputation for thoroughly trustworthy work remains intact. His careful and often critical appraisal of the possibilities amd limitations of lake systems modelling won him a third Chandler-Misner award. Recognizing that the IFYGL data was insufficient to study the wave-like features of large-scale circulations in a deep lake with sloping bottoms, Simons designed and led a circulation experiment in 1982-83 that provided essential information. He discovered and subsequently explained a persistent residual circulation in Lake Ontario rendered most visible by a strong eastward flow along the south shore of the lake. The transport of this flow is of the order of 10 times the discharge of the Niagara River, and it has a significant effect on the distribution of contaminants entering the Lake from the Niagara River. Simons also made valuable contributions the the understanding of circulation in shallow lakes in his work on Lake St. Clair. He did pioneering work on the interfacing of atmospheric models with water circulation models. All of his work brought enormous credit to the Institute he served. He will be missed as a tough-minded and extremely capable scientist, as a teacher, a friend, a husband, and as a father.

RÉSUMÉ

Le présent article a été rédigé en introduction à une collection de tirés à part des articles de T.J. (Joe) Simons (1939-1987). Cette collection a été publiée à la mémoire de M. Simons par l'Institut national de recherche sur les eaux. L'article passe en revue ses travaux par ordre chronologique et en donne un aperçu. Ayant d'abord acquis une formation de météorologiste aux Pays-Bas, M. Simons a poursuivi des études supérieures en modélisation atmosphérique numérique au Colorado State University avant de joindre les rangs du Centre canadien des eaux intérieures en 1969. M. Simons a alors appliqué la technique de prédiction numérique de la température à l'étude de la circulation dans les lacs. Ses travaux de mise au point et de vérification systématique des modèles numériques de circulation dans les lacs de grande dimension, à partir des données de l'Année internationale d'étude des Grands lacs, lui ont acquis une réputation internationale et lui ont valu le prix Chandler-Misner de l'Association internationale de recherche sur les Grands lacs deux années de suite. Il a dirigé une petite équipe de recherche qui a effectué des travaux de pionnier dans le

domaine de la modélisation des lacs, en associant des modèles biochimiques aux modèles de circulation. Il a résisté à la tentation de présenter ces travaux comme étant l'outil idéal de gestion; il a plutôt adopté une attitude plus conservatrice en utilisant les modèles pour acquérir et vérifier des connaissances dans plusieurs disciplines. Ses réserves étaient pleinement justifiées et sa réputation de chercheur systématique et fiable est restée intacte. Son évaluation approfondie et souvent critique des possibilités et des limitations de la modélisation des lacs lui a valu un troisième prix Chandler-Misner. Réalisant que les données de l'Année internationale d'étude des Grands lacs étaient insuffisantes pour étudier les propriétés ondulatoires des types de circulation sur une grande échelle dans un lac profond aux fonds inclinés, Simons a conçu et exécuté en 1982-1983 une expérience de circulation qui lui a fourni des données essentielles. Il a découvert et expliqué par la suite un type de circulation résiduelle persistante dans le lac Ontario qui se manifeste surtout par un fort courant en direction est le long de la rive sud du lac. Ce courant correspond à environ 10 fois le débit de la rivière Niagara à son embouchure et a un effet significatif sur la distribution des contaminants qui pénètrent dans le lac à cet endroit.

Simons a également a apporté une contribution significative à la compréhension du type de circulation dans les lacs peu profonds grâce à ses travaux sur le lac St. Clair. Il a été l'un des premiers à associer des modèles atmosphériques et des modèles de circulation d'eau. Tous ses travaux ont conféré une solide réputation à l'Institut où il a oeuvré. Ses qualités en tant que chercheur rigoureux et extrêmement talentueux, de professeur, d'ami, d'époux et de père feront regretter son absence.

ACKNOWLEDGEMENTS

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WITH LAKES IN MIND -
- A REVIEW OF THE SCIENTIFIC CONTRIBUTIONS OF T.J. SIMONS: 1939-1987

On April 4, 1987, with the death of Theodore Johannes (Joe) Simons, the Great Lakes scientific community lost an exceptional researcher. Unlike that of many talented and able people, Simons' work maintained a lifelong coherence and focus that resulted in a substantial, thorough, and essentially complete achievement. Had he lived, there is no doubt that he would have continued to produce the excellent work for which he was justly renowned. His close colleagues will remember, that as the end approached, Joe drew comfort from the knowledge that he had travelled well and far enough for one lifetime. In celebration of his achievement and the fine example he set to us, his colleagues and fellow scientists, we offer this assessment of the scientific contributions of T.J. Simons.

In this review we have chosen to focus on those contributions that we feel to have been of exceptional merit or pivotal in his development as a scientist. A gifted communicator, Simons wrote for many audiences; all of his papers are constructed with exceptional clarity and economy of style, the more remarkable since English was not his mother language. A full list of Simons' publications is appended. Bracketed numbers in this text refer to the numbered list; a separate list of references is included for other work cited.

Among Simons' papers were a set of loose-leaf binders containing handwritten notes from his undergraduate university career in Holland. Meticulously organized and beautifully laid out, they are eloquent testimony to the thorough and well-prepared approach so characteristic of the man. Doodles and other evidence of distraction are few. Here and there, the name "Marleen", that of his wife of 25 years, appears in the margins as indications of a commitment to life that he in no way lacked. His early training was thorough and he mastered it.

RESEARCH IN METEOROLOGY: 1966-1972

After serving as a Meteorological Officer with the Royal Dutch Air Force (1), Simons enrolled in a postgraduate program at the Colorado State

University in Fort Collins under the supervision of F. Baer. Here he met D.B. Rao, a former student of G.W. Platzman, with whom he was to collaborate on many meteorological and limnological projects. He completed his Ph.D. in 1970 with a dissertation title, "The non-linear dynamics of cyclone waves" (4,10). The themes of Simons' work in this period are numerical hydrodynamical methods (5), finite amplitude or nonlinear effects in geophysical fluid motions (5,10,13), and the dynamic effects of stratification, notably baroclinic instability (3,6,7,12).

Most of the above themes come together in two papers, the first entitled, "The nonlinear dynamics of cyclone waves" (10) and the second, "On the theory of atmospheric development" (11). Simons points out that any zonal air flow derived from atmospheric data is unstable for a range of cyclone-scale waves (10) and poses the question as to why one atmospheric disturbance, and not another, should develop into a mature cyclone when both appear equally unstable. Early work on stability problems adopts a normal mode or spectral approach, based on the linearized equations of motion. Unstable wave modes possess complex-valued phase speeds, characteristic of initial exponential growth. In the first paper, a precis of his doctoral dissertation, the consequences of the unstable waves reaching finite amplitude are explored. It is shown that energy from the baroclinically unstable waves is fed into the mean zonal flow, bringing their growth to a halt. This process does not reduce the instability of the mean zonal flow from the viewpoint of the customary linear analysis. The second paper (11) explores the sensitivity of the intrinsically unstable baroclinic flow to the shape of the initial disturbing perturbation by an initial value analysis. The problem is simplified in such a way as to eliminate the interactions of the growing disturbance with the mean flow, a topic that was studied in the first paper. The second paper demonstrates that wave growth depends on the shape of the initial perturbation as much as on its wavelength. Both papers demonstrate Simons' talent for revealing simplification. Without losing sight of a phenomenon's eventual interaction with a host of other effects, Simons sought to isolate the principal effects one at a time. Both papers make a judicious and carefully tested use of numerical techniques. This early meteorological work, significant in its own right, by its themes, approaches, and techniques, flows directly into his subsequent limnological work.

DEVELOPMENT OF NUMERICAL HYDRODYNAMICAL MODELS OF LARGE LAKES: 1969-1972

After joining the Canada Centre for Inland Waters in 1969, Simons pursued the development of numerical hyrodynamical models of the circulation of large lakes. His development was systematic, dealing first with the circulations of unstratified, homogeneous basins, a situation typical of winter conditions, before addressing the more complicated stratified circulations occurring in summer. These studies were presented at the 1971 and 1972 Annual Great Lakes Conferences (8,14). For his 1972 paper, Simons received the 1972 Chandler-Misener Award conferred by the International Association for Great Lakes Research. A quote from the introduction to the first study (8) demonstrates a firm grasp of the essentials of the problem:

> "... The problem of computing the water circulation and temperature stratification of a lake is a boundary-initial value problem not unlike the forecasting of the weather. Thus the models require a specification of the boundary conditions including the shore configuration and depth contours together with the initial values of the flow parameters. However, much of the behaviour of the lake is a direct consequence of the external forces such as wind stress and atmospheric pressure, which may tend to reduce the effects of the initial conditions to a large extent. At the same time, it has been well established that the mass circulation of the lake is governed by the topography of the basin. This means that the boundary value aspect of the present problem is more accentuated than, for instance, in numerical weather prediction...."

Recognizing that the annual stratification cycle of the Great Lakes could be represented by a homogeneous water column, and at other times by a water column divided into two or more distinct layers with moving interfaces and a smoothly-varying structure, Simons developed a layered model that could accommodate all these conditions (14).

> "The model equations of the layered system have been derived by vertical integration over each layer without specifying the character of the interfaces. In principle, the model allows for rigid horizontal levels, rigid sloping permeable interfaces, moving material interfaces, or any combination of these. The character of the interfaces is formally eliminated from the equations of motion and the thermal energy equation by defining a new vertical velocity relative to the interfaces. With the Boussinesq approximation, the continuity equation

integrated over each layer makes it possible to compute either this relative vertical velocity or the vertical displacement of a material interface...."

The technical details of the model development are summarized in a thorough report (14). Simons' stated goal was to build a general circulation model that conserved essential quantities such as mass and momentum and kinetic energy despite limited spatial resolution, that avoided spurious diffusion and other effects due to the careless treatment of sloping boundaries, that employed conservative and reliable numerical techniques, but remained flexible in the specification of sub-grid scale processes, horizontal resolution, and vertical structure of the water column. The wide-spread use of Simons' algorithm is a testimonial to its thorough craftsmanship.

VERIFICATION OF THE NUMERICAL HYDRODYNAMICAL MODEL WITH DATA FROM THE INTERNATIONAL FIELD YEAR ON THE GREAT LAKES: 1972-1976

Data from the basin-wide experiments undertaken during the International Field Year on the Great Lakes (April, 1972 to June, 1973) provided an opportunity to test the hydrodynamic model. Simons published four papers on this topic during the period 1973-76 (21,24,33). The first of these earned him the Chandler-Misener Award for the second consecutive year. The other three papers (21,24,33) form a connected suite and will be discussed next.

True to Simons' one-step-at-a-time approach, the first paper in this sequence (21) deals with the situation of a homogeneous water column using a model with fixed but permeable interfaces. A central problem of modelling the circulation of lakes is the lack of clear separation between the scales of mean motion and those of turbulence. The separation in his model is dictated by the choice of grid resolution. A major goal of the verification program is to examine the consequences of such arbitrary choices. Simons chose to model the vertical transfer of momentum through the specification of the stresses at the interfaces. Rather than run the entire model repeatedly in order to select the best value for the stress coefficients and other parameters, simpler, one-dimensional diagnostic models were employed. A vertical diffusion coefficient was used to relate the vertical flux of momentum to the velocity shear between layers. The vertical diffusion coefficients must also depend on stratification, the velocity shears, as well as on the evolution of the wind stress. In effect, the lake is considered to possess a "memory" of past wind events.

Rather than deriving correlation coefficients between observed and computed currents as an assessment of model performance (an automatic technique that is unconcerned with the physical processes involved), the time-series of currents were filtered to isolate specific frequency bands and then displayed graphically. Three-day time averages of currents were used to study the spatial distribution of low frequency motions. In addition, a low frequency band free of inertial period motions was isolated by employing a symmetrical filter with roll-off periods between 24 and 18 hours in order to compare the temporal behaviour of observed and simulated low frequency motions. Inertial period motion was studied specifically using the residual of the above filter.

The tropical storm, Agnes, passed to the southeast of the Great Lakes between June 22 and 24, 1972, providing an exceptionally strong meteorological input. The storm arrived just as the lake was entering full stratification. Because the density contrasts were still weak, internal pressure gradients remained insignificant. Stratification did however exert a significant effect on the distribution of vertical diffusion. Of particular interest are the reversals of low-frequency current from eastward to westward along the the north shore of Lake Ontario that occur after the storm. The reversal propagates from eastward to westward at a speed of the order of 0.5 m/s and is simulated qualitatively by the model. Although this speed is typical for long internal waves, the motion is observed to be barotropic (21):

> "The phenomenon is obviously related to the principle of conservation of potential vorticity and the meandering return flow... Looking at the circulation from the viewpoint of topographic Rossby waves over the gently sloping bottom on the northern half of the lake, one would compute a westward movement of the system; ..."

Study of inertial period motions in both the lake and the model showed that the model underestimated their amplitude, and that the observed rotation is faster than the computed oscillation in the western basin. The upper layer was always observed to be 180 degrees out of phase with respect to the lower layer, and the level of phase reversal was substantially below the thermocline level in summer. Simons noted that for frequencies less than the inertial rotation, the model current speeds were altered by changing diffusion (both horizontal and vertical) coefficients, but directions were unaffected. On the other hand, the computed inertial oscillations were very sensitive to model parameters. Simons concludes:

> "The results presented here indicate that further model improvements hinge on a better understanding of the vertical pathways of momentum and energy in the lake. Comparisons of observed and computed currents for various frequency bands lead to the conclusion that conventional formulations of the air-water interactions are not able to add sufficient kinetic energy to the lake. Oscillations close to the local inertial frequency are important features of the lake circulation, even in the absence of stratification, and their amplitudes are dominated by vertical momentum fluxes."

The second verification paper (24) deals with simulations of water circulations and temperature changes during the month of August, when the lake is stratified. The combined complexity of modelling baroclinic circulations and predicting long-term temperature changes as functions of surface fluxes of heat and momentum give this study particular interest. In keeping with his general philosophy that more insight can be gained from a creative simplification of a problem than from an uncritical frontal attack, Simons focussed on the intermediate time scales and he studied the advective changes of temperature associated with current and upwelling patterns, making no attempt to include thermocline formation or entrainment. He analysed the period August 1-15, 1972, an interval that included a strong, but short-lived storm on August 9. General agreement between observed and modelled water level changes is taken as evidence that the model wind stress is correctly sized (Fig. 1).

In order to study the dynamic effects of stratification, the model was run both with and without thermal structure, using the same parameterization for vertical momentum fluxes that was employed in the previous study. The two solutions appear similar during the storm of August 9-10, but the model simulations that include stratification appear to be the more realistic after the storm, particularly on the north shore of the basin. Although the computed stratified circulation is different from the homogeneous circulation, it is barotropic in character; Simons points out that the vertical shear, and hence the baroclinicity of the solution

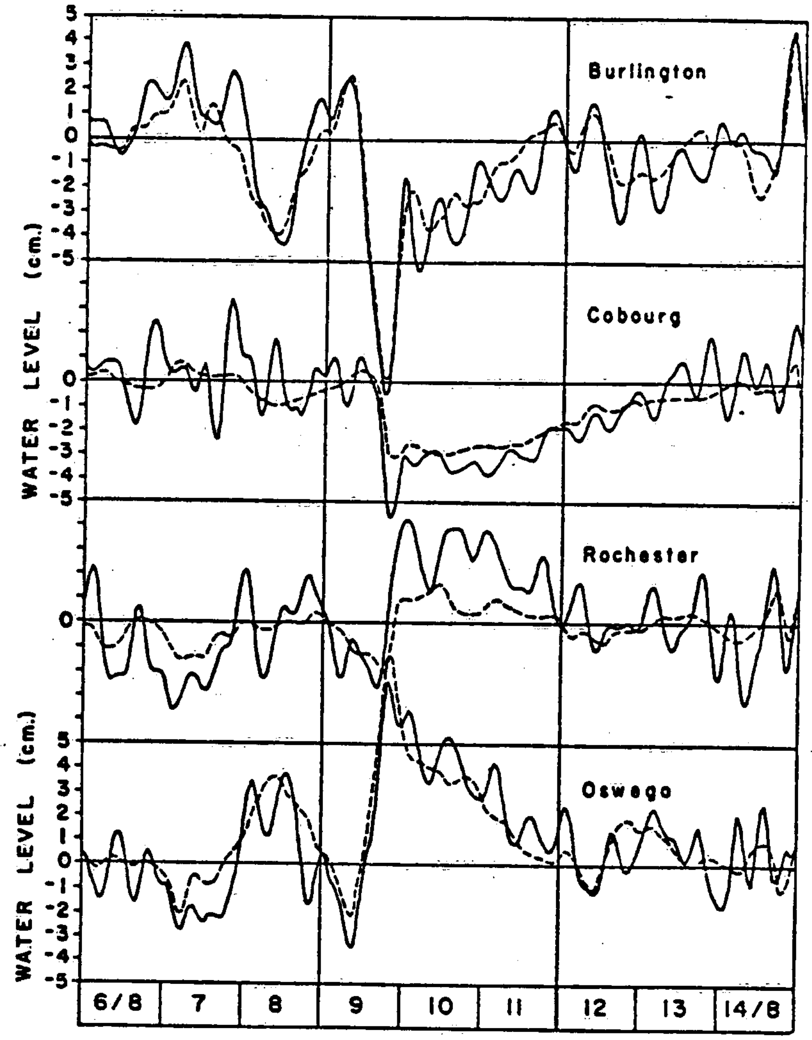

FIG. 1. Observed (solid lines) and computed (dashed lines) water levels in four stations on the shore of Lake Ontario. All time series were filtered to remove periods <5 h. (Reprinted by permission of J. Phys. Oceanogr. 1975, 5: 101; Reference (24).)

is controlled by the vertical diffusion parameter. Coupling terms in the model make it difficult in practice to distinguish between barotropic and baroclinic effects. In particular, a westward propagating current reversal occurring after the August 9 storm might be taken as evidence of an internal Kelvin wave (baroclinic phenomenon) or a topographic Rossby wave (barotropic phenomenon) since their propagation speeds are similar. Simons' interpretation favours the latter. Vertically integrated transports computed by the stratified model for the period following the storm of August 9 exhibit a pattern that is very similar to that of a two-cell rotational mode for an idealized basin, with a correct period as well (approximately eight days). A major conclusion of the study is that theoretical models based on a separation of baroclinic and barotropic flow components for time scales greater than the inertial period are of limited application.

The simulation of long-term heat transports as a test of (1) parameterizations of turbulent fluxes and, (2) the model's ability to handle similarly calculated transports of dissolved and suspended materials is described in the third paper in this series (33). Here, the three-dimensional hydrodynamic model was run continuously for the 1972 Field Year and the results stored for later application to a heat transport model. Internal pressure gradients calculated from a thermal structure that was interpolated between weekly heat content surveys were supplied as inputs to the hydrodynamical model. Vertical circulations tend to be over-estimated in the model because the crude simulation of the temperature structure reduces the gravitational restoring force. Nevertheless, baroclinic effects are probably more accurately estimated in this fashion than with a prognostic thermal structure model with large cumulative errors. The two most critical parameters in the model are surface stress and vertical diffusion of momentum. In the model runs, the aerodynamic drag coefficient was set to a constant value of 0.0024, which from subsequent studies of lake setup may be slightly too large. Vertical mixing coefficients are demonstrably sensitive to environmental conditions, and the parameterization of the vertical diffusivity event must be ammended to reflect this.

The transport of heat from the north to the south shore in summer was greatly exaggerated in the simulations, probably because of the intense vertical circulations that developed in the model in a plane perpendicular to the prevailing wind (Fig. 2). The excessive Ekman drift of the

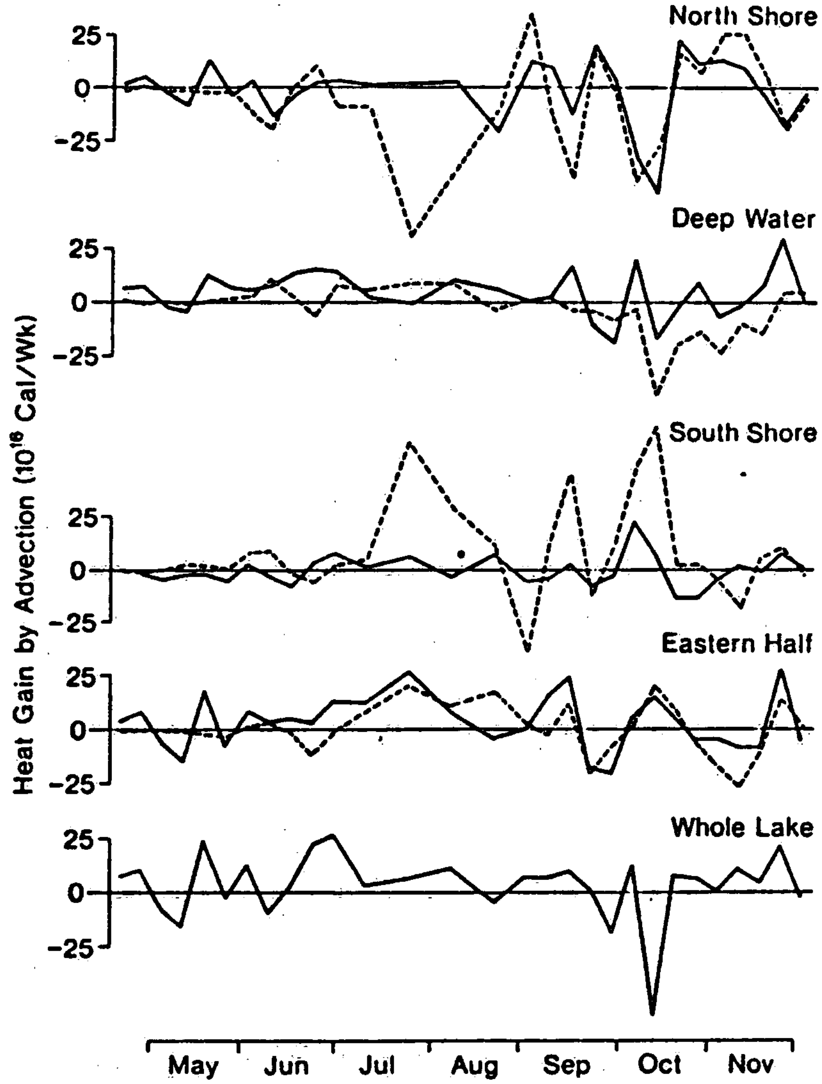

FIG. 2. Measured (solid lines) and computed (dashed lines) heat gains by advection for north shore, mid-lake, south shore, and eastern half of Lake Ontario during 1972. Bottom graph represents the difference between observed heat changes and surface fluxes for the whole lake as a measure of observational error. (Reprinted by permission of J. Phys. Oceanogr. 1976, 6: 376; Reference (33).)

model appears to have been a result of low vertical resolution that reduces the effective "stiffness" of the model towards vertical displacement, the same phenomenon described earlier. During the fall season, it was shown that horizontal transport of heat makes important contributions to the heat budget of lake zones and the model simulated these reasonably well. It was also apparent that the model grid was too coarse to resolve the south shore flow patterns. There is a limit to the useful refinement of this approach since it is also shown that the observational errors in heat fluxes are comparable to weekly changes in heat storage.

These detailed model verifications are perhaps the most thorough undertaken at that time. They achieve far more than the assessment of model performance, being particularly rich in physical insights, while being accomplished with a refreshing economy of means. A significant direction emerges from this work that Simons pursued in subsequent dynamical studies, that of the combined effects of stratification and topography.

LAKE SYSTEMS MODELLING: 1974-1982

From the early stages of the model development, Simons' concerns extended beyond the narrowly physical and technical to envisage the hydrodynamic model as the framework of a synthesis of limnological disciplines in support of water quality issues. Quoting from his Great Lakes Conference paper of 1972 (14):

> "The ultimate goal of the current numerical modelling program at CCIW is to design a general water quality model for the whole Great Lakes Basin. A program of this scope calls for the cooperative effort of a wide variety of scientific disciplines ranging from hydrology and hydrodynamics to chemistry and biology. With regard to this interaction of disciplines, it is apparent that the primary objective of the hydrodynamical modelling program is to enable scientists to compute the three-dimensional temperature distributions and water transports insofar as they affect the various water quality parameters. Thus in addition to the purely hydrodynamical aspects of the modelling program, an important problem is to consider the transport of dissolved or suspended material associated with the computed currents in the lakes..."

In 1972, using the computed currents in Lake Ontario as input to an advection-diffusion model of material transport, Simons (14) simulated the movements of a conservative dissolved substance released into the Niagara River. This initiative drew the attention of many water quality modellers. At this time several water quality models had been developed elsewhere in order to study the problem of eutrophication, models that placed strong emphasis on biological and chemical transformation (Thomann et al., 1974) and on the biological food chain (Parker, 1973), but these did not consider the effects of physical transports.

A series of water quality models incorporating physics, chemistry, and biology were then developed (28,30,37) during the period 1973-75. By this time, Simons had now assembled a small team of modellers in support of what he called the Environmental Simulation Program (its carefully chosen acronym, ESP, providing a glimpse of Joe's wry humour).

Simons acquired the computer code of the Lake1 model from R. Thomann of the Manhattan College, N.Y. This model was intended to allow for many input and output variables and was considered rather lengthy (about a box of cards). By extracting the essence of the model (equations and formulations), Simons reduced the program to a small deck, nick-named the "simple Simons" by his co-workers. This program became a subroutine dealing with the temporal changes of eight biological and chemical variables and is used routinely at Manhattan College as a teaching aid. The subroutine was applied to each of the four layers in twenty-one horizontal segments chosen to represent Lake Ontario in three dimensions. The hydrodynamical model calculated the transport of the eight constitutents among these compartments. Indeed, this linkage of physical and biochemical processes was the most comprehensive at that time. Early results were published in 1976 (37) in a paper for which he was again awarded the Chandler-Misener prize by the International Association of Great Lakes Research. This landmark paper is a careful assessment of the strengths and weaknesses of integrated lake systems modelling.

Referring to both vertical and horizontal variability in large lakes, Simons (37) outlined the main goal of the 1976 paper:

> "It is clear that individual layers and zones of a natural water body cannot be expected to behave independently from one another for any length of time. In effect, horizontal and vertical transport and dispersion mechanisms will lead to interaction of different volume elements. The question then arises whether such coupling effects can produce significant

modifications between local physical and biochemical parameters. The answer to this question is of fundamental interest with regard to observational programs as well as simulation studies of the aquatic environment."

Simons emphasizes that the model serves primarily as a diagnosis of observations rather than a prognosis of future events. This attitude permeates most of Simons' modelling work at a time when system modelling was widely promoted (and eagerly awaited) as a management tool.

In a section of the paper devoted to exchange processes among lake volume elements, Simons touches on one of the conundrums of lake systems modelling, that of distinguishing local biochemical transformations from those induced by water transports. Assuming that the physical mechanisms are better understood than biochemical rate processes, the kinetic interactions appear as residuals after all other changes to local concentrations have been taken into account. At all times, therefore, the accuracy of estimates of biochemical processes are bounded by the accuracy with which the physical exchange processes are known.

This matter comes into particular focus in a discussion of the settling term. Separate budgets were calculated for total phosphorus and total nitrogen in the Lake Ontario model compartments. After both vertical and horizontal exchanges had been accounted for, the residual changes were ascribed to sedimentation. The apparent settling velocity of phosphorus across the 10 m level, vertical transport of phosphorus calculated from the observed phosphorus profile, and the water movements determined by the hydrodynamic model come close to balancing the phosphorus budget. On the other hand, while the nitrogen budget for the upper layer also implies a downward flux of nitrogen across the 10 m level, the net mass transport is directed upwards. The residual settling term that must be invoked to balance the nitrogen budget is large. Simons points out that a simple model formulation of settling in the form of particulate organic material with a constant nitrogen/phosphorus ratio is not tenable. He resists the temptation to include an artificial mechanism in the model until the actual process responsible for this effect is known. While settling rates can in principle be determined for each model variable and model compartment, the potential errors are large and a horizontally uniform settling coefficient, equal to the arithmetic means of values derived from the nitrogen and phosphorus budgets is used instead.

While recognizing that a discussion of plankton physiology is beyond the scope of the paper, Simons feels obliged to check that the formulation chosen to represent photosynthesis is not contradicted by the actual observations. A formula proposed by Steele (1965) is used to account for the effects of light intensity and a simple empirical formula of the Monod type accounts for the nutrient limitation effect (DiToro et al., 1971). Simons reports a high correlation between observed and computed photosynthetic rates over a wide range of conditions in Lake Ontario and he points out that variations in primary productivity can be largely accounted for by adjustment of physical parameters.

In order to evaluate effects of spatial variations of environmental conditions, computations were carried out for a horizontally mixed lake as well as for the horizontally segmented lake. The effects of horizontal transports were studied by running a horizontally segmented model both with and without the horizontal transports. In all cases, a four-layer vertical structure (interfaces at 10, 20, and 40 m depths) was employed. From the results obtained with the model, Simons concluded that the relative effects of water transports, vertical mixing associated with the stratification cycle, and spatial variations of environmental conditions are all comparable, and that a segmented large lake model that did not include large-scale water circulations would be inappropriate. Vertical mixing processes are of prime importance in spring and early summer, but large-scale horizontal transports dominate during the the stormy fall season. In answering the question as to whether the response of a large lake can be simulated by horizontally uniform models, Simons concludes that the horizontally-averaged results from a segmented model do not differ significantly from the results of a horizontally well-mixed model. This is a consequence of the dominant influence of vertical stratification.

Simons made no attempt to assess the overall performance of the model; he instead addressed the sensitivity of the model to various environmental effects. By virtue of the observed differences between the nitrogen and phosphorus budgets of the upper layer mentioned above, and the compromises adopted in the model formulation, the model over-estimates phosphorus concentrations in the upper layers. It is concluded that the exact relationships between plankton growth and nutrient availability remain to be determined, and indeed the diagnostic role of the model is particularly valuable here as a guide to profitable future research.

Simons' continuing interest in water quality modelling is expressed in several publications (35,36,46,50,53,56) spanning at least a decade. Faced with pressures to develop predictive lake models going beyond what he felt to be both reliable and verifiable, Simons, aided by a team of ten scientists, undertook a major review of water quality simulation using the unique Lake Ontario data base. The project took two years of careful work. Published in 1979, (46), the 220 page document, "Assessment of Water Quality Simulation Capability for Lake Ontario", soon became a landmark. The essence of this report, a cautioning against inferences based on the results of current models, was published in a densely-argued paper in the February, 1980 issue of Water Resources Research (49) by Simons and Lam. The main question posed by this paper is whether long-term trends in water quality that are associated with net loading and sedimentation and that happen over time scales comparable to the hydraulic retention time of the basin, can be studied independently of the much larger seasonal changes in water quality parameters controlled by surface radiation, temperature, and vertical exchanges. In view of the seasonal nature of, say, the net loss of phosphorus by sedimentation, a detailed "process model" may be required; but there is however no guarantee that such a model, even if it successfully reproduced seasonal variations, would correctly simulate the long-term trends, i.e., establish whether or not the system is in long-term (steady-state) balance with the loadings.

Starting with a simple two-component phosphorus model of Lake Ontario, a mass balance diagnosis was used to quantify the rate processes. Important conclusions of this analysis are that (a) the results are strongly affected by the vertical resolution of the model (two versus three layers) and (b) model uncertainty is large because of the limited knowledge of sub-thermocline uptake of phosphorus. In a second phase of the study, the foregoing mass balance investigation is used as a basis for the parameterization of the rate processes, and the corresponding rate coefficients are determined by optimization techniques. It is found that an acceptable periodic seasonal simulation can be obtained with a wide variety of model structures and parameter values but in order to do so, it must be assumed that the lake is in equilibrium with the inputs at time scales longer than seasonal. Predicting the lake's response by rerunning such a model with time-varying inputs may be inappropriate.

A lakewide budget model or input-output model such as the one developed by Vollenweider (1975) was considered. Two major shortcomings were identified; the net sedimentation term is not usually directly proportional to the total nutrient concentration (it may be a function of the organic component and thus subject to large seasonal variations), not to mention the further complications of sediment resuspension or internal loading under anoxic conditions; such a model cannot represent the important spatial heterogeneity such as the crucial summer stratification. Increasing the number of components or compartments allows a more flexible simulation but with the serious cost of additional processes and parameters. Comparison of a two-layer with a three-layer box model led Simons and his colleagues to conclude that there is substantial uptake of soluble reactive phosphorus in the intermediate layer.

> "It does not appear useful to predict the response of a lake to changing phosphorus loadings by dynamical models unless processes such as sub-thermocline phosphorus uptake are fully understood and simulated. After all, it is the ability to simulate this type of process that sets a dynamic model apart from simple static considerations. It is not enough for a model to simulate that soluble reactive phosphorus drops to a value of 2 µg/L in summer, the question is how it gets to that point."

In discussing parameter estimates, Simons and Lam (49) discuss the problem of mathematically representing the process of nutrient limitation on primary productivity. They propose two methods, the first, a conventional formulation where gross primary productivity is a function of soluble reactive phosphorus (SRP) but keeping regeneration independent of SRP. The second formulation assumes that gross production is independent of SRP concentration but that nutrient regeneration depends on it, i.e., low nutrient concentrations do not inhibit primary production but rather increase recycling rates. The authors show that acceptable simulations can be obtained with either formulation, despite their marked conceptual difference. This situation is analogous to the successful fitting of experimental data to two mathematically different curves, a parabola and a logarithmic function, say, that resemble one another over a limited range of the independent variable.

In the final section of the paper, Simons and Lam discuss the prospects for long-term model predictions and point to the crucial question of how to determine whether Lake Ontario is in a state of dynamic balance with loadings. Inaccuracies in the data base combined with the large inter-annual fluctuations in weather are such that ten or more years of data must be collected before trends are apparent in a lake like Lake Ontario. Given that the model rate coefficients depend on assumptions concerning model periodicity on annual time scales, attempts to short circuit the trend evaluation with models risk being completely circular. Nevertheless, one can attempt to fit observed long-term responses extending in time over at least the hydraulic retention period. The authors experiment with the long-term response of both "simple" and "complicated" models. For a given "original" loading the rate coefficients are chosen to yield the observed amplitude of the annual solution. Then, holding the rate coefficients constant and changing the load, the models run until a new equilibrium is established. These results are compared with the sensitivity of the model to changes in rate parameters with the loading held constant. A 10% change in the coefficients for nutrient regeneration, for example, well within the uncertainty associated with such a coefficient in the first place produces a drastic change in equilibrium. Of course such a change could be offset by another "adjustment" in reestablishing a periodic solution to the original loadings but such fiddling is not productive of insight. The authors state (49):

> "It is also evident that these problems are compounded, rather than alleviated, by more sophisticated models, at least until our scientific understanding of the various process catches up with our modelling capability."

It is worth recalling that systems modelling became popular in the mid-sixties to early seventies, a period crowned, if that is the word, by the first visits to the moon. Nothing, it seemed at that time, was beyond computation. Simons' great contribution was to test systems modelling in a thorough and objective fashion, searching always for the basis under which it becomes a legitimate and valuable activity. He resisted the temptation to sell modelling to whoever would buy, and in his hands, as this review attests, it became a powerful technique for the quantitative evaluation of scientific understanding.

CIRCULATION MODELS OF LAKES AND INLAND SEAS; A MONOGRAPH: 1980

From 1979 through 1986, Simons pursued the goal of explaining the large-scale, wind-driven circulation of closed basins, returning to some of the themes of his earlier meteorological work. To those unfamiliar with the subject, the problem may seem relatively simple, but in fact, the concepts necessary to physical insight are both difficult and subtle. The literature of the past century on geophysical fluid mechanics is rich and varied and the subject continues to challenge the best of minds. A full explanation of the circulation patterns of closed basins requires an understanding of the interaction of different scales of motion, the effects of variable bottom topography, stratification, and the earth's rotation, in combination as well as singly. Formally, the relationships can be described in the differential equations of fluid mechanics that express material continuity and the balance of forces and accelerations at a point, but the integration of these equations to yield comprehensible velocity and density fields is not easy. By the late seventies, when Simons was beginning the culminating phase of his work, he had developed and refined efficient techniques for the numerical integration of the basic differential equations. This is a substantial achievement in itself. But Simons' interest was not in the tools alone, but rather what they could show, and his particular genius lay in the selection of simple yet powerful illustrative examples and experiments by which he clarified and confirmed his insights.

Simons began this work with a thorough review of existing geophysical fluid dynamic theory and numerical modelling techniques. This work was published in 1980 as a monograph entitled, "Circulation Models of Lakes and Inland Seas" (48). The first paragraph of the preface reads:

> "The purpose of this monograph is to summarize current understanding of large-scale water circulations in lakes and inland seas, and to outline the methodologies by which this understanding has been acquired and, undoubtedly, will be enlarged in future years. More specifically, this review is intended to provide the necessary background for analysis and simulation of material transports in large natural basins, as required by investigators of water quality problems and other ecological concerns."

In terms of Simons' own work, it is the first sentence of the above paragraph that applies, but Simons also felt a strong responsibility to be an effective teacher. Throughout the book, and indeed through all his scientific writing, Simons declares from the beginning that the final result is an interaction of many causes and factors, but searches always for a suite of examples, beginning with the simplest, that isolate the effects of the various causes. The creativity of such a synthesis is not to be denied, and while Simons articulated many of the major themes of the review in his earlier work, their refined exposition alongside elegant examples drawn from the work of other investigators amplifies considerably the power of their insights. For a review of this monograph see LeBlond (1981).

BASIN-SCALE CIRCULATION IN LAKE ONTARIO; NEW EXPERIMENTAL EVIDENCE

A theme common to much of Simons' work in geophysical fluid dynamics is the study of the effects of variable bottom topography and stratification. The best available data, that resulting from the 1972 International Field Year program, with its spatially uniform network of current meters, did not adequately resolve the transition between nearshore and offshore responses, nor did it lend itself to studies of alongshore propagation of wave-like features associated with both variable topography and stratification. Under Simons' leadership, an ambitious field program was undertaken from the late spring of 1982 to the early spring of 1983. Instruments were concentrated on a transverse section of Lake Ontario from Port Hope, Ontario to Point Breeze, New York, and along the north shore of the lake both east and west of the transect. The careful prior groundwork, the resulting clear and achieveable experimental aims, the substantial material and technical resources of the Institute, and the insightful and timely analysis, mark this undertaking as a model of how to organize and execute large-scale experiments.

A paper published in early 1983 entitled, "Resonant topographic response of nearshore currents to wind forcing" (63) provides a model of the anticipated low-frequency response to wind forcing of an unstratified basin of variable depth. Simons claims that an appropriate model is based on the low frequency, non-divergent flow component that includes the possibility of propagating "topography waves" and is forced by wind.

> "... Such forced wave models can explain peaks in current spectra at frequencies different from those in the wind spectra and time lags between response and forcing depending on frequency (see, e.g., Clarke, 1977). It should be noted, however, that differences in the results from forced-wave models and simple momentum-balance models may be much less spectacular in the time domain than in the frequency domain...."

The governing equations are the linearized, hydrostatic, vertically integrated equations for homogeneous water without horizontal diffusion and with constant Coriolis parameter. The rigid-lid approximation is employed, eliminating the divergent component of flow, and a simplifed version of Ekman's formulation for bottom friction is employed. This parameterization tends to augment the bottom friction in water shallower than the Ekman depth ($\sqrt{2\nu/f}$). The equations are solved in spectral form; the current response is expressed per unit wind stress as an amplitude and phase angle with respect to the forcing wind.

The simple model of a progressive atmospheric wave of fixed length and shore-parallel winds moving along an infinitely long, straight shelf is used to demonstrate the effects of bottom friction and variable shelf width. The solutions are the well-known topographic shelf waves propagating with the shore on the right; all the cross-shore shelf modes of the same wavelength as the wind will be generated. Whenever the phase speed of the atmospheric disturbance becomes equal to the phase speed of one of the normal wave modes, resonance occurs. In the frequency response, the vehicle Simons chose for analysis, resonance is characterized by a peak in the amplitude function and a shift in phase from current leading wind to current lagging wind as the frequency shifts from lower to higher than resonant. The effect of friction is to reduce the contribution of the higher mode, long period waves; the first cross-shelf mode is dominant. The peak of the amplitude response shows a shift from longer to shorter periods when approaching the shore. The effect of variable shelf width is explored by first computing the response for a shelf of 20 km width and one of 40 km width and then allowing the width to vary between the two widths sinusoidally with distance along the shelf. The wavelength of the variation is taken to be 400 km, roughly the perimeter of Lake Ontario on the assumption that the wavelength applicable to a closed basin is determined by the circumference of the basin rather than the much larger scale of the atmospheric forcing. For the straight shelves, the resonant periods are longer and the response smaller for the narrow shelf than for the wide one. For the variable shelf width, the frequency response varies along the shore but the range of variation is much smaller than the difference between the solutions for the two straight shelves of maximum and minimum width.

While maintaining the simplicity of a straight shelf model, insight into the response of a closed basin to a uniform wind may be obtained by considering the case of a standing atmospheric wave of length equal to the perimeter of the basin. The comparison will be valid to the extent that the effects of boundary curvature in the closed basin can be neglected. Comparison with a solution for a circular basin of parabolic cross-section shows this to be the case. The phase lag between the response and the local forcing now depends on the alongshore position. From the circular basin model, the alongshore variation of amplitude and phase of the response to a uniform wind of a frequency close to that of the first azimuthal wave in the basin reveals a very important distinction between nearshore and offshore zones:

> "... It is apparent that the offshore current is governed by resonant wave propagation with constant amplitude and linear phase change alongshore. On the other hand, the nearshore response appears as a standing wave with a slight counterclockwise shift of the current maxima similar to the steady-state solution (Birchfield, 1973). In terms of alongshore phase propagation, the nearshore current exhibits an alongshore variation somewhat similar to the amplitude variation of the forcing with large apparent phase speeds occurring at the location of maximum alongshore wind. Hence even at resonance, the nearshore phase propagation observed under conditions of standing atmospheric wave forcing cannot be related to free shelf wave propagation."

As a final example, the model is extended to idealized elongated basins with variable shelf widths forced by a uniform wind directed along the main axis of the basin. The resonant wave response moves more slowly along the straight portion of the coast and along the narrow shelves.

In examining the momentum balance it is shown that the topographic wave solution is quasi-geostrophic; the pressure gradient and Coriolis terms are in near balance. For this reason, a simple local momentum balance with wind stress and bottom friction can give better results than a more complete model if the bottom friction is manipulated to obtain the best fit to local observations, thereby yielding the apparently correct answer for the wrong reasons.

With the observations from the 1982/83 experiment, Simons was able to confirm many of the conclusions of the previous theoretical study on forced topographic waves in the following paper (65). The energy spectra of the currents showed that low frequency variations at all stations were aligned with the local bathymetry. Knowing from model studies that nearshore current fluctuations are induced by the alongshore wind component, Simons deals only with the alongshore components of wind and current. Lagged cross-covariances between alongshore components of wind stress and currents measured along the north shore of the basin show a westward increase in phase as anticipated from the earlier model studies. Spectral transfer functions between wind and currents in the frequency domain confirm this result. In addition the anticipated westward decrease in resonant frequency of the topographic response along the north shore of the lake due to variable bottom topography is observed.

For practical reasons it may often be useful to construct empirical relations between the wind stress and current in the form of impulse functions. In view of the topographic wave model, the impulse functions must be determined locally. Because of the losses due to friction, it is found unneccessary to extend the convolution integral over more than 20 days. It was determined that inaccuracies in the determination of wind stress contributed substantially to the residual variance. Based on the alongshore component of wind alone, these empirically determined models can account for about 75% of the variance of the observed currents.

The closely spaced measurements made in 1982/83 along the north-south transect of Lake Ontario are suitable for a more thorough evaluation of numerical model performance than had been possible previously. As a check on the adequacy of the sampling, the net transport through this section was estimated from an interpolation of the measurements and found to conserve mass accurately. The ability of numerical models to simulate the observed distribution of transport in the cross-section at a variety of time scales is the major focus of this paper. Standard techniques are employed, and care is taken to ensure that the models conserve energy in the absence of friction.

Experiments with the spatial resolution of the models were performed with an idealized circular basin for simplicity so that only the radial spatial dimension need be considered. The (linear) numerical models were checked against established inviscid analytical solutions for a parabolic cross-section (Birchfield and Hickie, 1977; Birchfield, 1967, 1973). Introducing topography that represented the steep southern shore of Lake Ontario, and including friction, it was found that the grid interval must be reduced to less than 1 km, a few percent of the distance over which the bottom slopes. It was also found that a rigid-lid model required smaller grid spacing than a free surface model for comparable accuracy, but that for low bottom friction, the free surface model tended to overestimate topographic current oscillations in deep water. This last effect could lead to serious error when solutions are averaged over long periods of time.

Short-term model performance is studied by comparing the response of the model and the real lake to a finite wind impulse. For the real lake, this response is determined locally and empirically from simultaneously observed winds and currents. Very long-term currents with periods longer than 40 days are filtered out of the observations. Both the model-derived and empirical impulse functions agree well near the north shore and in deep water but agree poorly where the water depths are close to the cross-sectional mean (100 m), a depth that other studies (Bennett, 1974) show to be the location of null points in the mean circulation. When the impulse solutions are extended in the time domain it is seen that good agreement is obtained initially and again after a period of five days or so (when currents are small), but is poor in the time interval between three and five days after the impulse. This finding is in agreement with earlier results ((65); Schwab, 1983).

Long-term circulations with periods greater than a month are examined next:

> "A striking feature of the observations is the belt of strong eastward currents extending from the south shore to well beyond the mean depth contour. In contrast to the north shore currents, the south shore current and the deep lake return flow show no clear correlation with the wind variations."

Linear models prove incapable of simulating the long-term features on the south shore and in deep water, even when lateral diffusion is added to remove the small-scale features. It turns out that both nonlinear terms in the momentum equation and lateral diffusion are required to obtain reasonable simulation of these features (Fig. 3).

A final paper in the sequence devoted to the circulation of unstratified water bodies examines in detail the heretofore neglected nonlinear models (75). Simons points out that the linear models, while adequate for simulations lasting over perhaps a month, fail over seasonal time scales as

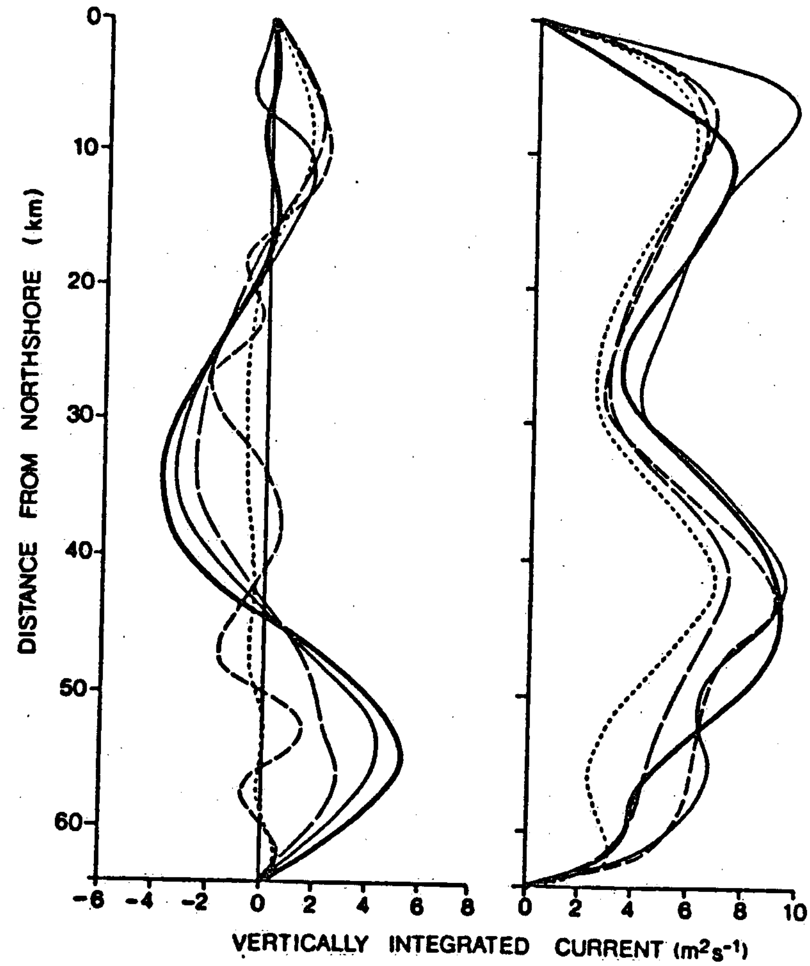

FIG. 3. Long-term means (left) and standard deviations in time (right) of vertically integrated currents for cross-section of Fig. 1 from 4 November 1982 to 23 March 1983. Heavy solid line: observed; dashes: free-surface model without diffusion; dots: free-surface model with horizontal diffusion coefficient of 25 m^2 s^{-1}; long dashes: nonlinear free-surface model with diffusion; thin solid line: nonlinear rigid lid model with 2.5 km grid and diffusion of 5 m^2 s^{-1}. (Reprinted by permission of J. Phys. Oceanogr. 1985, 15: 1202; Reference (72).)

exemplified during the 1982/83 observation period, because the wind stress averaged over that season nearly vanishes. The nonlinear response, small on a day-to-day basis, is persistent and it produces a sizeable residual circulation consisting of a single cyclonic gyre with current reversal occurring near the maximum depth of the lake rather than the two gyre pattern predicted by the linear model with friction. Simons addresses the question of whether the 1982/83 result is typical by comparing the modelled linear and nonlinear responses during the unstratified season to 10 years of climatological wind data.

A circular basin is chosen for the computational simplicity it confers and for ease of comparison with previously established analytical solutions. The governing equations are the vertically averaged hydrostatic equations of motion for a homogeneous basin transformed into the familiar vorticity/stream function equation. The rigid-lid approximation is invoked. Successive approximation approach is used to establish the nonlinear effects wherein the solution to lowest order is that of the linearized equations and nonlinear corrections are subsequently added, starting with the largest. This problem has many parallels with the atmospheric modelling undertaken by Simons at the beginning of his career (10). In the present case, the principal nonlinear contribution turns out to be a circular vortex forced by the self-interaction of the linear solution for the first azimuthal wavenumber. More accurate solutions permit a feedback between the low order solution and the circular vortex. The ratio of nonlinear to linear mean seasonal circulations will tend to be proportional to the ratio of the standard deviation to the mean of the atmospheric forcing and will depend on the spectrum of wind forcing. The frequency dependence of the nonlinear response is similar to the linear topographic response to wind (75) with resonance characteristics in certain frequency bands determined by the topography of the basin and bottom friction. Despite interannual variations in wind forcing, the one-way transport of the circular vortex exceeds that of the wave in all cases. Averaged over the 10 years of observations, the vortex transport is almost three times as large as the wave transport computed from linear models. Conventional linear models are therefore unsuitable for computing seasonal mean circulations in homogeneous lakes. The discovery and subsequent explanation of the long-term homogeneous flow with its persistent band of strong eastward current along the south shore of Lake Ontario is one of Simons' major research results. The implications of this finding for the distribution of contaminants in the lake have been explored by Murthy, Simons, and Lam (76,77).

Data from the summer of 1982 provide a beautifully documented view of coastal upwelling and Kelvin wave propagation (86). Temperature data from current meters and thermistor strings placed in the transverse and alongshore sections are interpolated to provide daily averaged distributions. From these distributions, the accompanying current meter data, aided by the theory of wind-induced upwelling developed by Bennett (1973), Bennett and Lindstrom (1977), Csanady and Scott (1974), and Clarke (1977), an upwelling sequence is tracked and explained. This paper, written for non-physicists,is a fine example of lucid explanation that minimizes technical jargon.

The major results of the fruitful 1982/83 Lake Ontario experiments are summarized in an unpublished report by Simons and Schertzer (69) entitled "The circulation of Lake Ontario during the summer of 1982 and the winter of 1982/83" and prepared in 1985. Some of the results appearing in the open literature have been reviewed above. Others, notably a detailed study of upwelling models, including the important and inevitable coupling between the barotropic and baroclinic modes, await distillation into journal publications. Even in "rough" form this report demands a wide readership and, together with the 1980 monograph, constitutes a most thorough exposition of the observation and theory of large lake circulations.

GENERAL CIRCULATION MODELLING: 1980-1985

An area of Simons' research which is perhaps less well known is his work on the coupling of an ocean model with an atmospheric general circulation model (AGCM). In 1980 Simons initiated a collaborative project with G.J. Boer of the Canadian Climate Centre (Atmospheric Environment Service) with the aim of developing a simple ocean model suitable for coupling with the Canadian AGCM. Such coupling is essential in many atmospheric circulation studies where the induced variations of the sea surface temperatures (SST) must be included. Simons adopted a simple approach to model the upper surface of the ocean to provide SST for use in the AGCM. He developed a heat balance model (essentially a one-dimensional thermodynamic model for the upper ocean) that reacts to the total downward heat exchange between the atmosphere and the ocean. In this simple model, Ekman pumping and large-scale horizontal tranports are parameterized through a residual term which is derived to ensure that the model returns to the observed seasonal variation of SST on average when driven with the observed surface heat flux. A turbulence closure scheme is employed for the vertical diffusion which is based on the local surface wind stress (51). He then proceeded to test this model from AGCM simulated data in non-interacting modes, i.e., so that the ocean model SST's are not fed back to the AGCM. Some problems were identified, especially relating to the formulation of the turbulence closure scheme in terms of the AGCM stresses (52). Simons never actually succeeded in running this ocean model interactively with the AGCM, but his pioneering work paved the route to subsequent attempts at coupling ocean models of various kinds with the AGCM (Carrieres, 1985).

Weakened physically by illness, Joe continued to produce incisive work until only a few weeks before his death. His last work was part of an international study on Lake St. Clair (78 through 84). In his study of the circulation of Lake St. Clair (79) he observed that the wind-driven component of the current was remarkably insensitive to the speed of the forcing wind. He simulated this behaviour by allowing the effective vertical eddy viscosity in his model to increase with the wind speed. In shallow Lake St. Clair this phenomenon may be a consequence of bottom turbulence generated by surface wave orbital motions. Simons' discovery has resulted in a follow-up measurement campaign. Through the modelling studies he was led to re-examine the shallow water Ekman problem (81). He was able to make a convincing simulation of sediment resuspension in Lake St. Clair, a process that must be considered in mapping the distribution and fate of persistent organic contaminants in that lake (80).

To sum up, we wish to record that Joe's substantial formal contributions to environmental science that we have just reviewed are only a part of his total legacy. His powers of concentration and dedicated work habits were legendary and they continue to inspire his colleagues. He was not gregarious by nature but he gave freely of his time to colleagues. While his advice might be astringent, it was usually correct. He could be ferocious in defence of anyone whom he felt to be the victim of an injustice. Many will remember him as an encouraging teacher and guide. We know that he cared deeply for his wife, Marleen, and his two children, Irene and Eric. We all miss a tough-minded and extremely capable colleague. In reviewing this unfortunately abridged but remarkable career it is enough to say that Joe's life was one of fulfilled promise.

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