Lake Physics to Ecosystem Services
Forel and the Origins of Limnology

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Slide Lecture Notes: Slide 48 onwards

ASLO

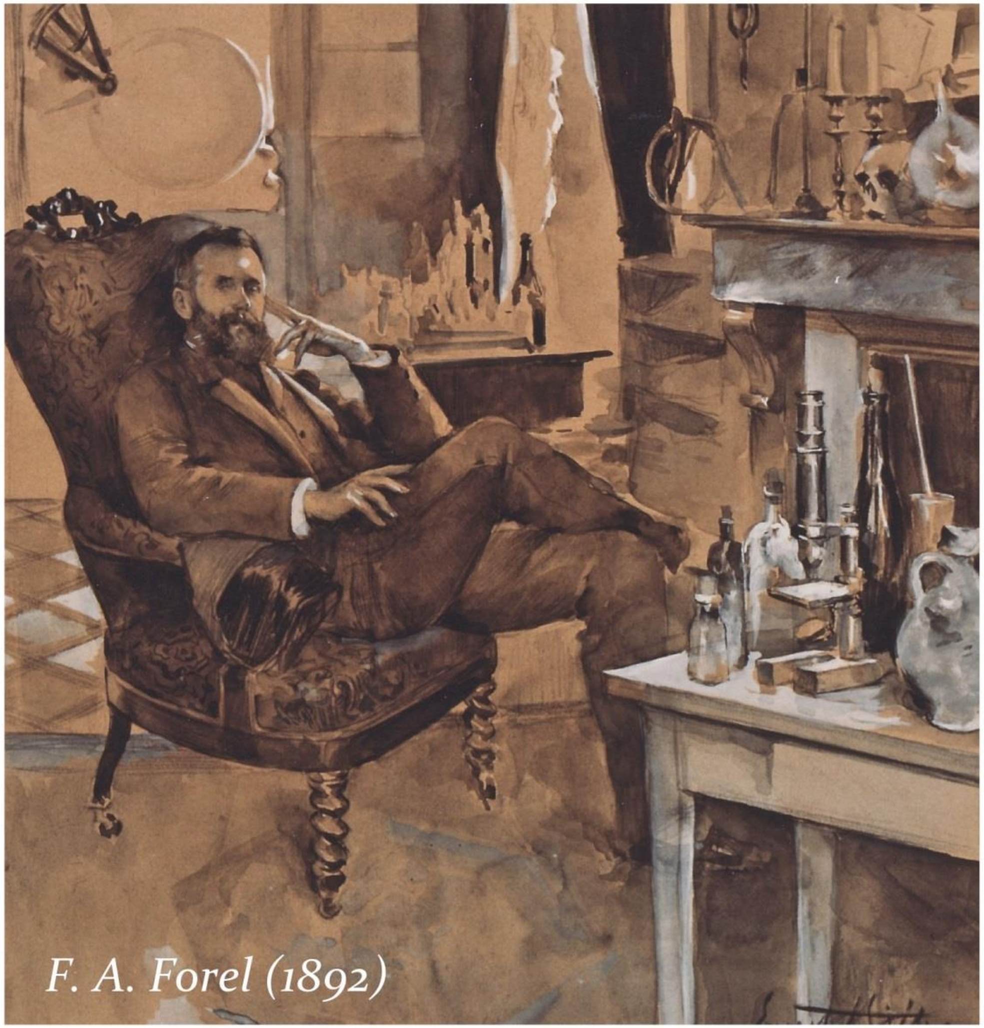
François Forel's New Science

In his study and lab on the shores of *Lake Geneva, Switzerland*, Professor Forel wrestled with the question of what he should call his new science: *Lake physics* and *chemistry*… but also *biology* and *people*…

Lake Science, in the broadest sense: everything about lakes and especially the way each branch of knowledge informs the other.

Maybe it was Geography – but wasn't that more about land?

Perhaps it was Oceanography?



F. A. Forel (1892)

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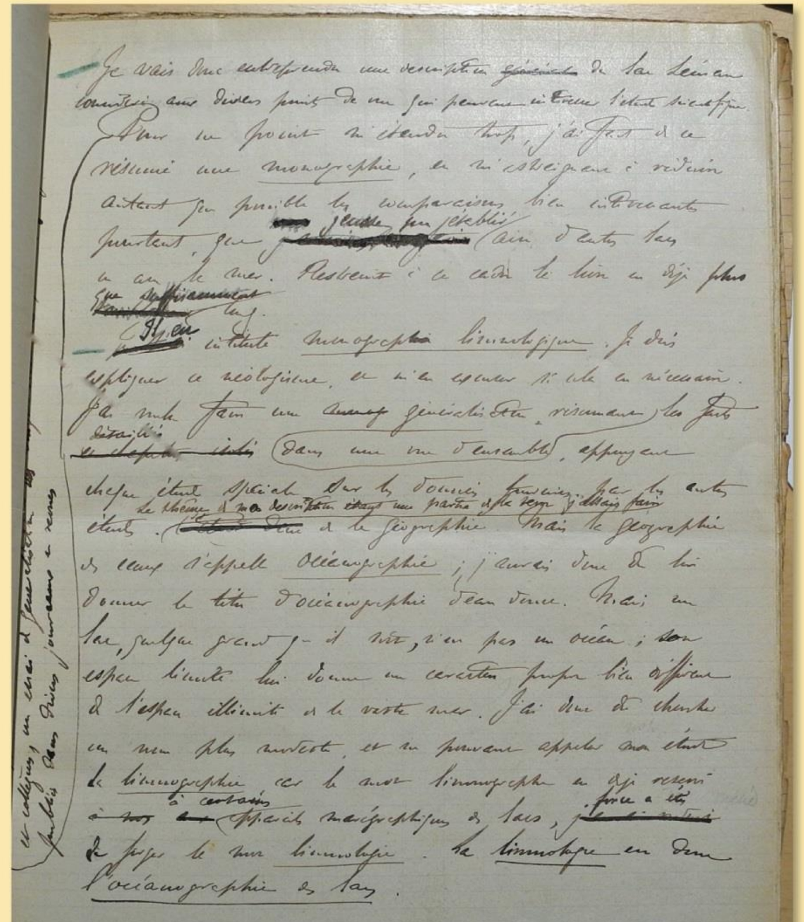
François Forel's New Science

"I wanted to achieve a generalization, an overview of all the detailed facts, …each specialized study… supported by the data from other studies"

"The theme is part of the land…
… geography?
… oceanography?"

"I am forced to forge a new word: ***Limnology***"

"Limnology is thus the ***oceanography of lakes***"



limnos: *lake;* **logos**: *study*

W.F. Vincent & C. Bertola

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Where did limnology come from?

- From the 17th century onwards, there was increasing interest in **freshwater biology**, stimulated by Leeuwenhoek's discovery of microscopic ***animalcules*** (micro-invertebrates & motile protists, such as ciliates) in **lake and pond water**.
- **Natural history**, the study of biology and geology, was a popular subject for scholars with broad interests, including those trained as medical doctors; for example, **Ernst Haeckel** who coined the word '**ecology**' in 1866.
- **Oceanography**, considered a branch of geography, developed rapidly in the 18th century with studies of ocean currents, and in the 19th century with marine research expeditions, notably the ***Challenger Expedition***, 1872 to 1876.

lensonleeuwenhoek.net/content/overview-lens-leeuwenhoek

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François Forel: Beginnings

Born: 2 February 1841 in the Swiss town of Morges, 16 km from Lausanne, 40 km from the city of Geneva, on the shores of Lake Geneva.

Family: His father, *François Forel* (1765-1865) was a respected magistrate, naturalist and historian; his cousins included *Alexis Forel* (1852-1922; chemist/engraver) and *August Forel* (1848-1931; zoologist, psychiatrist)

Schooling: Morges (*College de Morges*), and then later in Geneva (*Gymnase de Genève*) followed by university studies at Geneva (*Académie de Genève*; Bachelor of Arts and Bachelor of Physical and Natural Sciences).

Postgraduate studies: left Switzerland to study medicine and natural history at the *Académie de Montpellier* for 2 years. Continued his medical studies in Paris; then moved to the *University of Würzburg*, graduating Doctor of Medicine at the age of 24, in July 1865.

Return to Morges: In 1867, after 11 years away; Lecturer, then Professor of Anatomy at *Académie de Lausanne* (today the *University of Lausanne*).

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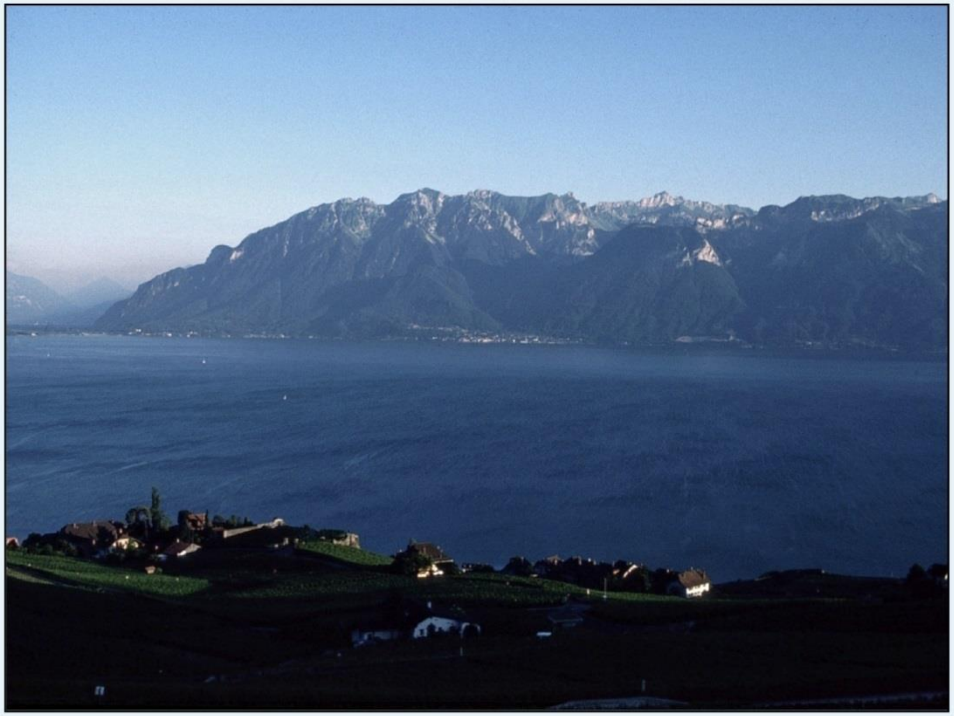
François Forel: Beginnings

Like all young scientists, Forel had to make a **decision on how to orient his career**. One option would be to focus on his teaching subjects: "**anatomy, histology and physiology**".

But this would mean trying to establish his place in a world of scholars who were better prepared and set up for such research.



He was attracted to another more exciting possibility: "**Or instead to take for my laboratory and my aquarium this lake, which was offering me its mysteries and beckoning me to study them**".

Forel seized this opportunity, with "**a fairly clear sense of the career that had taken hold of me**". (Forel 1912)

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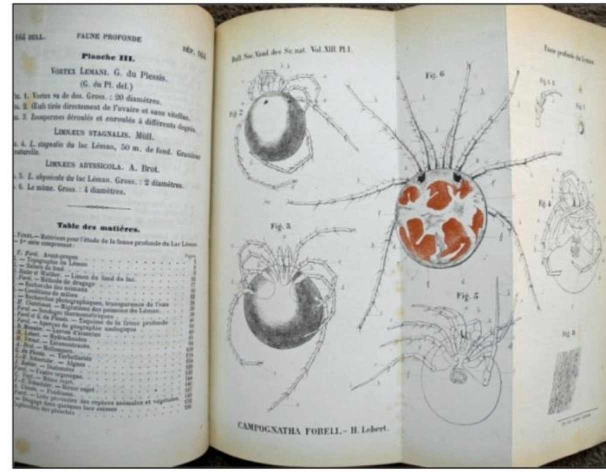
François Forel: Two main projects

In these **early years back in Morges**, Forel identified many potential topics for limnological research. But there were two that immediately captured his imagination:

- **Observing some lake sediment** off Morges, he discovered a live nematode, that led him to hypothesize that lakes contained a community of deep-living, benthic animals.

- **Observing the flow of water** into and out of the harbor at Morges, he discovered a reciprocating flow that he hypothesized was linked in some way to the surface seiches in the lake.

These two discoveries were pivotal in the development of his career, and in his new science that included biological as well as physical studies.



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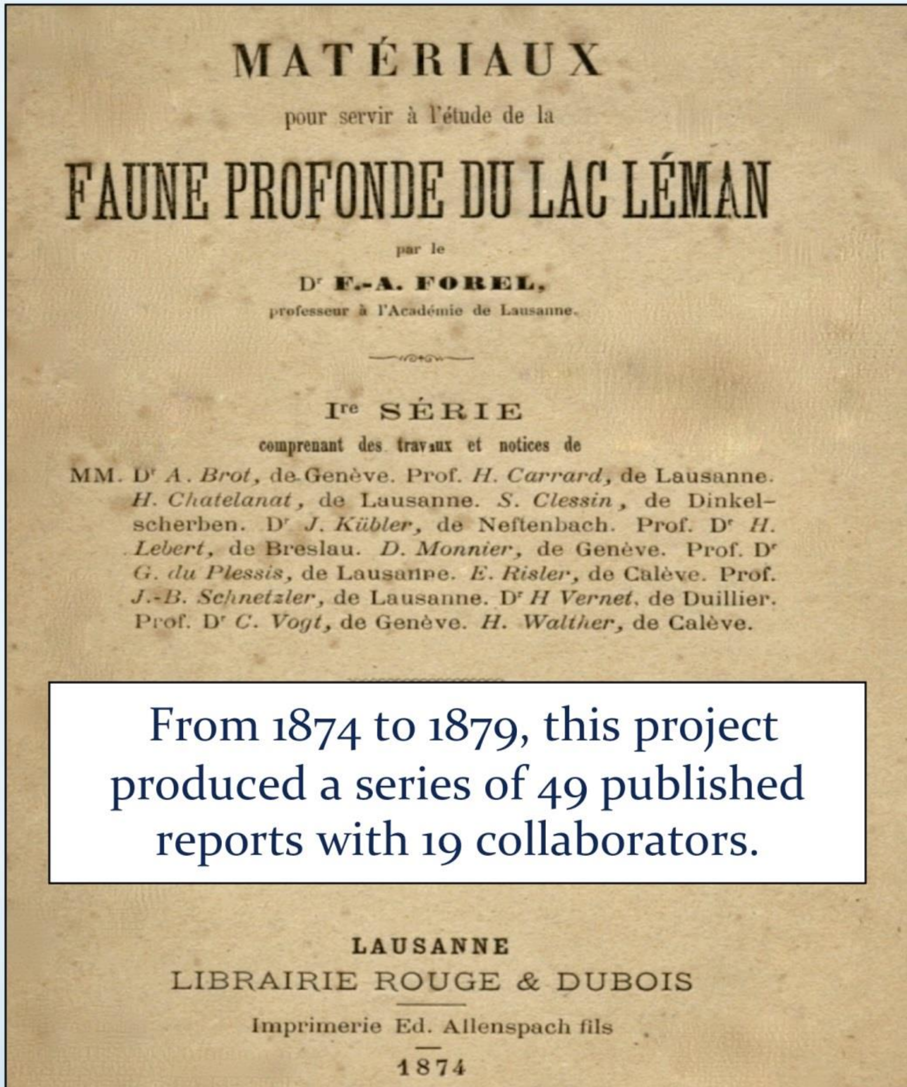
Benthic animals: life to 300 m depth



MATÉRIAUX

pour servir à l'étude de la

FAUNE PROFONDE DU LAC LÉMAN

par le

Dr F.-A. FOREL,

professeur à l'Académie de Lausanne.

Ire SÉRIE

comprenant des travaux et notices de

MM. Dr *A. Brot*, de Genève. Prof. *H. Carrard*, de Lausanne. *H. Chatelanat*, de Lausanne. *S. Clessin*, de Dinkelscherben. Dr *J. Kübler*, de Neftenbach. Prof. Dr *H. Lebert*, de Breslau. *D. Monnier*, de Genève. Prof. Dr *G. du Plessis*, de Lausanne. *E. Risler*, de Calève. Prof. *J.-B. Schnetzler*, de Lausanne. Dr *H Vernet*, de Duillier. Prof. Dr *C. Vogt*, de Genève. *H. Walther*, de Calève.

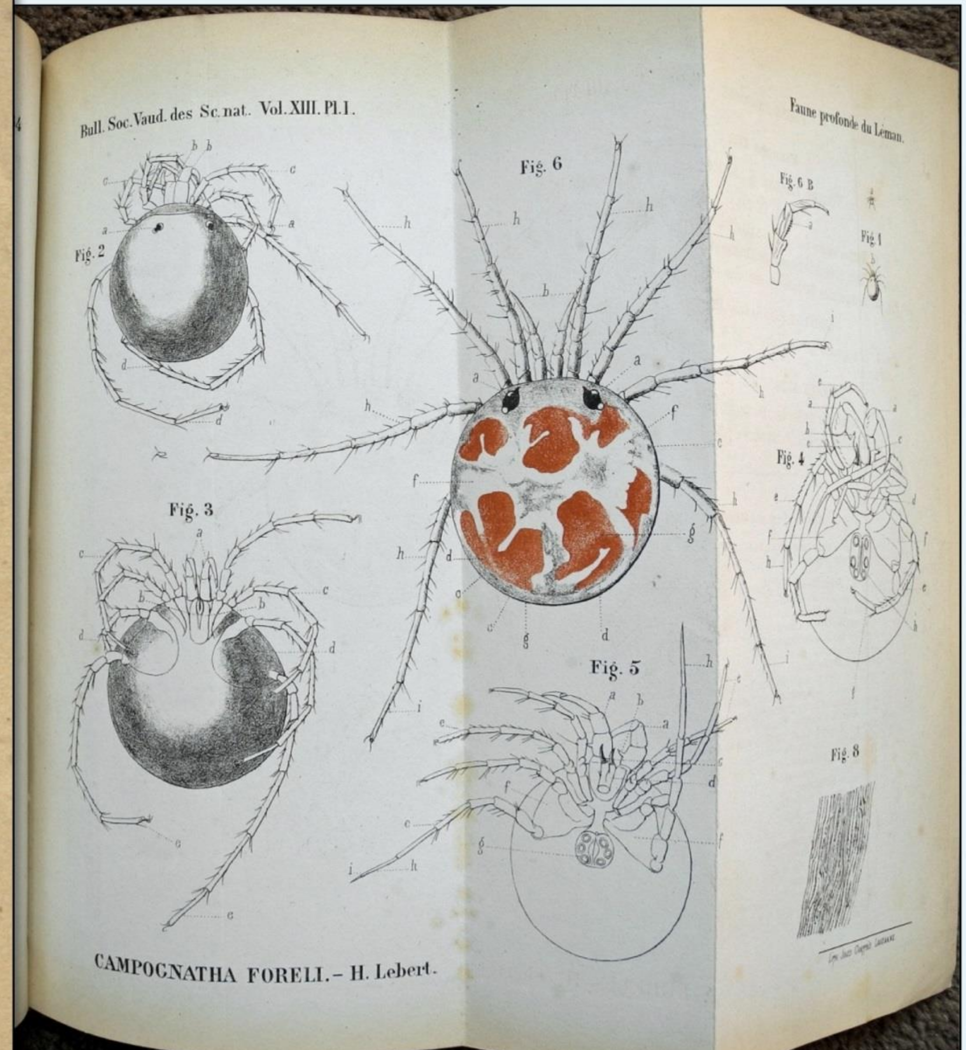
LAUSANNE

LIBRAIRIE ROUGE & DUBOIS

Imprimerie Ed. Allenspach fils

1874

From 1874 to 1879, this project produced a series of 49 published reports with 19 collaborators.



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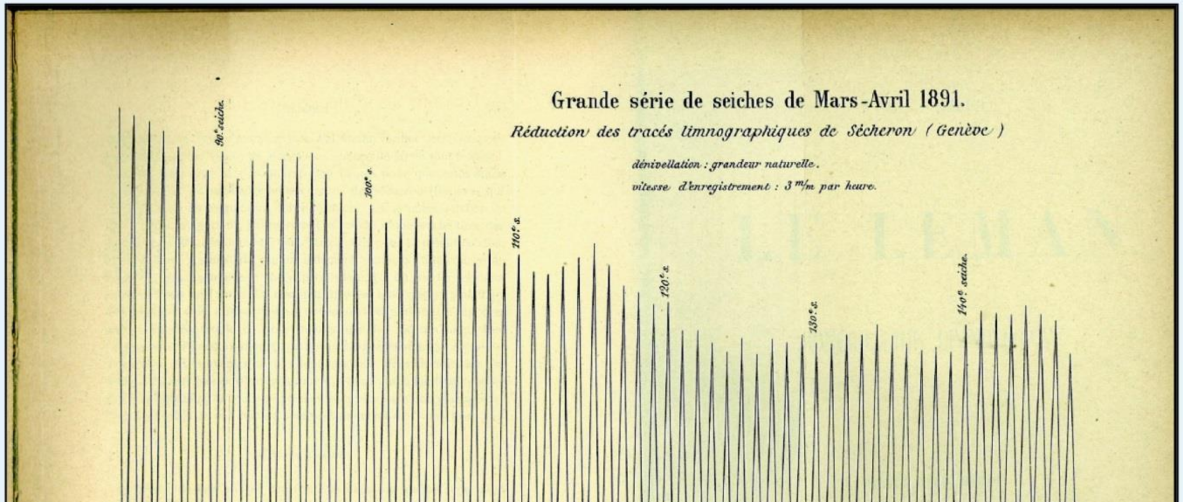
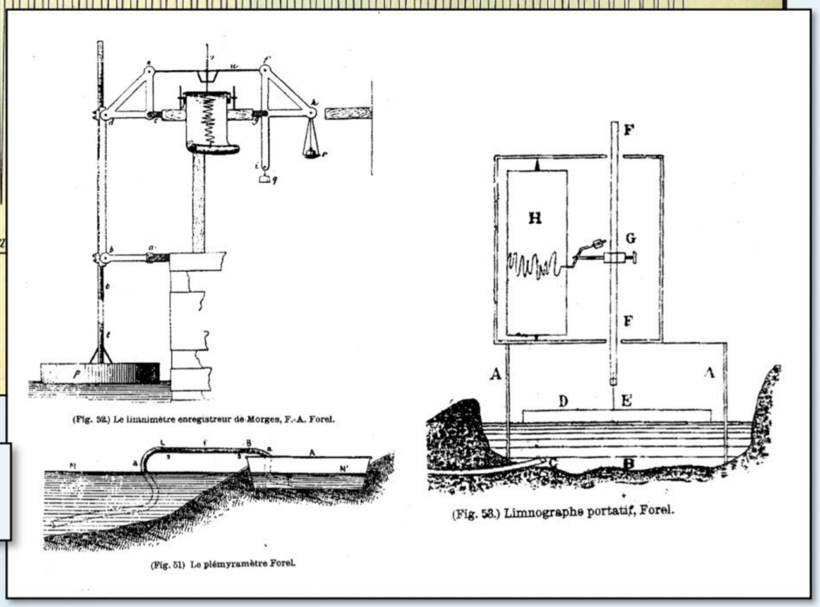
Seiches: Standing waves





$$t = L/\sqrt{(g\ z)}$$

Forel concluded that the **periodic rise and fall in lake level** was related to wind events, that gave rise to standing waves at the scale of the lake basin.

He developed and applied **new technologies** to study seiches:

* a portable 'limnograph'

* an installed system for continuous monitoring

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Both studies illustrate Forel's talents and strategies for success in research

- Deep curiosity and intuition about the natural world.
- Experienced great pleasure in asking questions and proposing hypotheses
- Enormous capacity to collect and synthesize information.
- Carefully observed the environment and obtained large quantities of new data.
- Developed new technologies and approaches – ***limnograph.***
- Devised experimental tests of his ideas – ***lab and field experiments.***
- Talked about, shared and published his findings - he was a prolific correspondent, with a global network of contacts.

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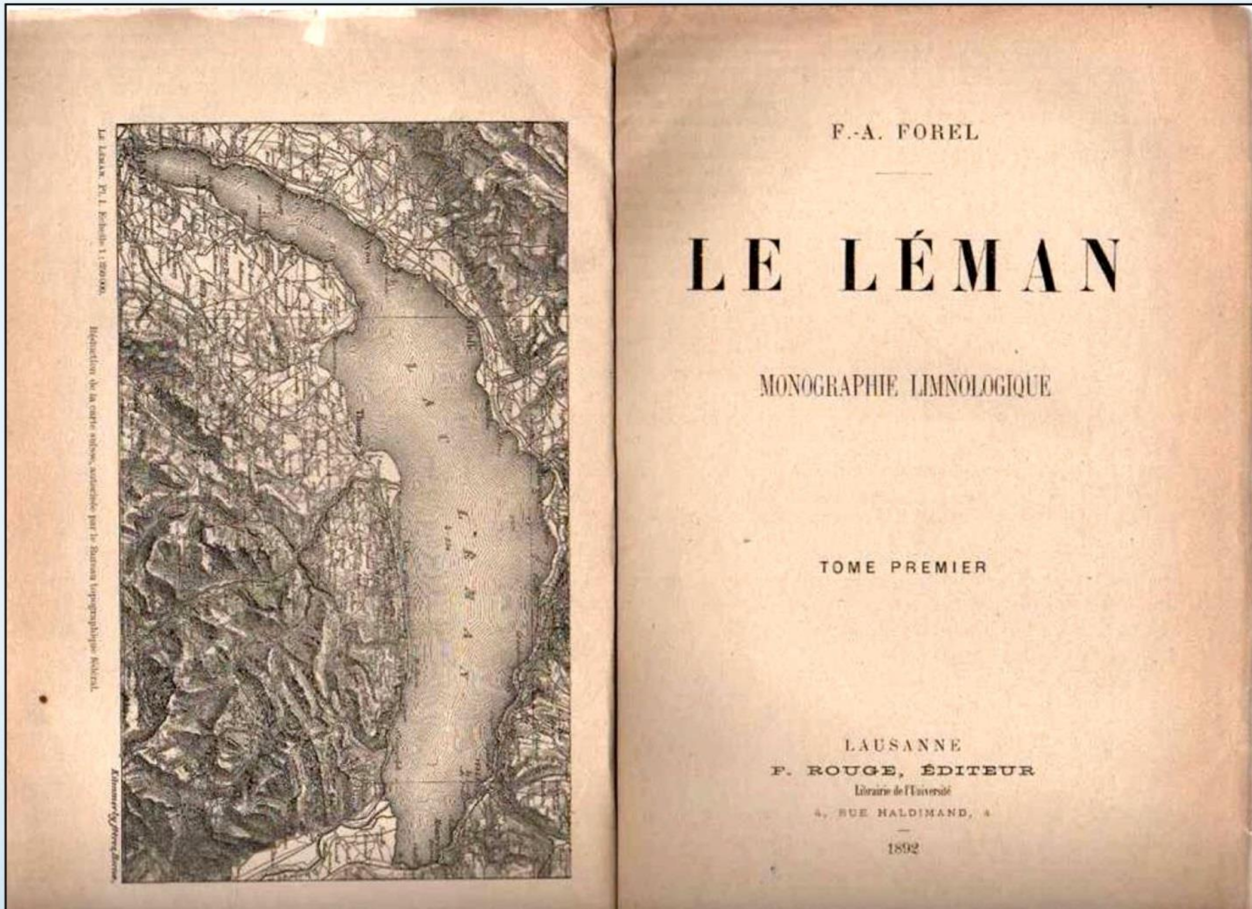
Limnological Monograph, Vol. I, Aug. 1892

All of these abilities came together in his founding of the new integrative science, which he called 'Limnology' and explicitly defined in the Preface to Vol. I of his 3-volume ***"Lake Geneva - Limnological Monograph"***



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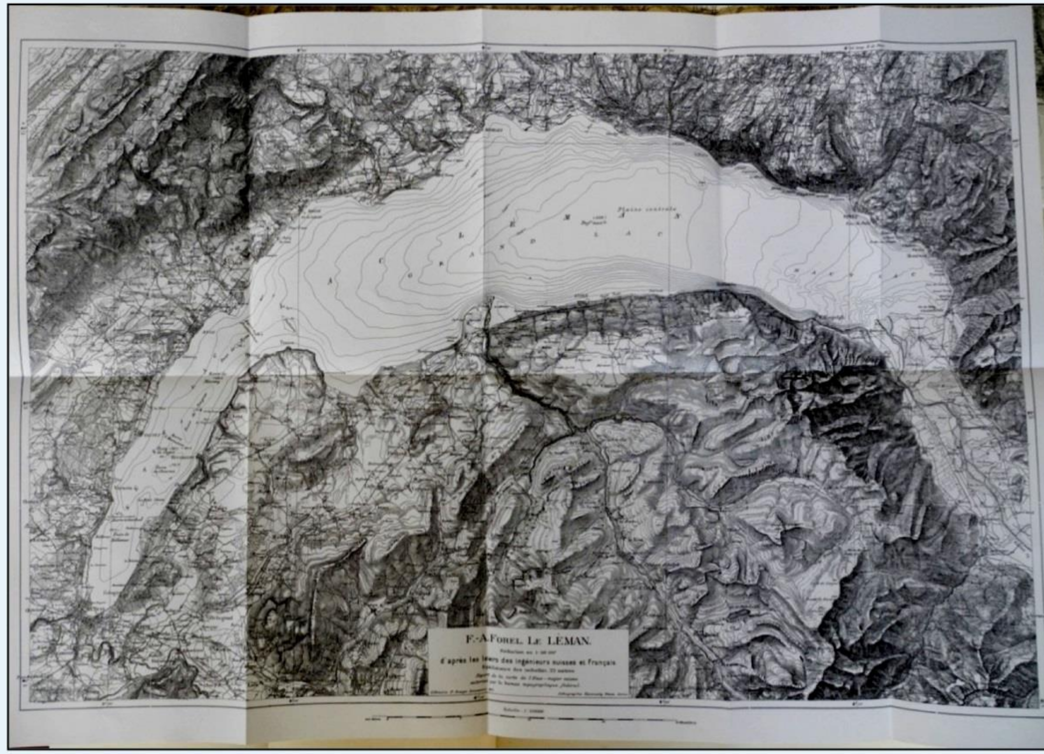
Limnological Monograph, Vol. I, Aug. 1892

Volume 1
- Defined limnology
- Geographic setting
- Shore & sediments
- Geology - origin
- Climatology
- Hydrology
- Bathymetric map
  (as a fold-out insert)



The treatise was aimed toward many types of readers:

*Fellow scientists, but also other readers interested in “**an explanation of natural features that they are intrigued by or admire,**” the people who live around the lake “**for whom the vast water mass of Lake Geneva is an ocean that intervenes in so many aspects of their individual lives and society,**” and the boatmen and fishermen “**who live on the lake, who live from the lake, and who hold the precise knowledge and methods for their professional activities". (p.XI).***

W.F. Vincent & C. Bertola
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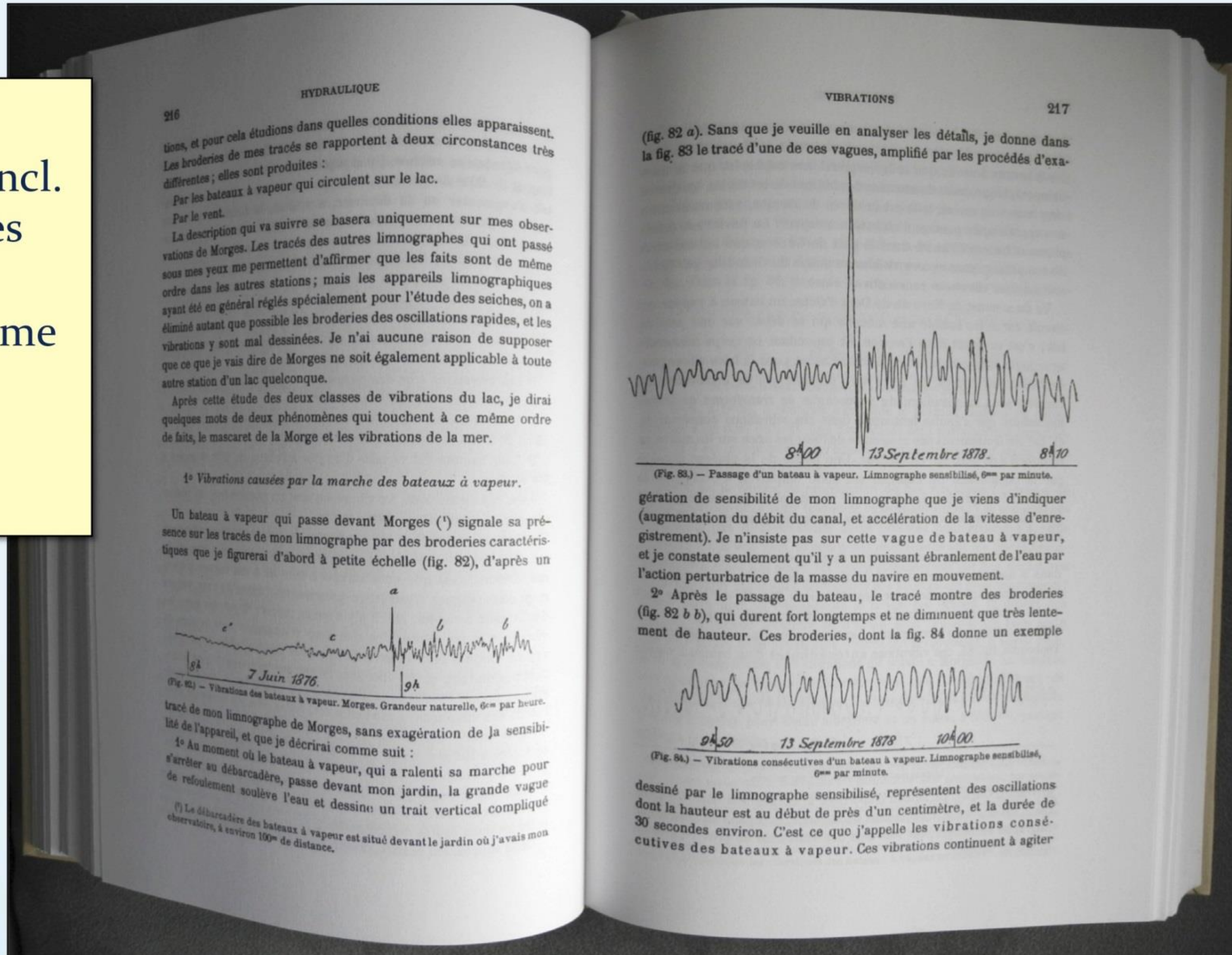
Limnological Monograph, Vol. II, 1895

Volume 2

- Hydraulics, incl. seiches, waves and currents
- Thermal regime
- Optics
- Acoustics
- Chemistry



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tions, et pour cela étudions dans quelles conditions elles apparaissent. Les broderies de mes tracés se rapportent à deux circonstances très différentes ; elles sont produites :

Par les bateaux à vapeur qui circulent sur le lac.

Par le vent.

La description qui va suivre se basera uniquement sur mes observations de Morges. Les tracés des autres limnographes qui ont passé sous mes yeux me permettent d'affirmer que les faits sont de même ordre dans les autres stations ; mais les appareils limnographiques ayant été en général réglés spécialement pour l'étude des seiches, on a éliminé autant que possible les broderies des oscillations rapides, et les vibrations y sont mal dessinées. Je n'ai aucune raison de supposer que ce que je vais dire de Morges ne soit également applicable à toute autre station d'un lac quelconque.

Après cette étude des deux classes de vibrations du lac, je dirai quelques mots de deux phénomènes qui touchent à ce même ordre de faits, le mascaret de la Morge et les vibrations de la mer.

1° *Vibrations causées par la marche des bateaux à vapeur.*

Un bateau à vapeur qui passe devant Morges ([1]) signale sa présence sur les tracés de mon limnographe par des broderies caractéristiques que je figurerai d'abord à petite échelle (fig. 82), d'après un

(Fig. 82.) — Vibrations des bateaux à vapeur. Morges. Grandeur naturelle, 6cm par heure.

tracé de mon limnographe de Morges, sans exagération de la sensibilité de l'appareil, et que je décrirai comme suit :

1° Au moment où le bateau à vapeur, qui a ralenti sa marche pour s'arrêter au débarcadère, passe devant mon jardin, la grande vague de refoulement soulève l'eau et dessine un trait vertical compliqué

([1]) Le débarcadère des bateaux à vapeur est situé devant le jardin où j'avais mon observatoire, à environ 100m de distance.

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(fig. 82 *a*). Sans que je veuille en analyser les détails, je donne dans la fig. 83 le tracé d'une de ces vagues, amplifié par les procédés d'exa-

(Fig. 83.) — Passage d'un bateau à vapeur. Limnographe sensibilisé, 6mm par minute.

gération de sensibilité de mon limnographe que je viens d'indiquer (augmentation du débit du canal, et accélération de la vitesse d'enregistrement). Je n'insiste pas sur cette vague de bateau à vapeur, et je constate seulement qu'il y a un puissant ébranlement de l'eau par l'action perturbatrice de la masse du navire en mouvement.

2° Après le passage du bateau, le tracé montre des broderies (fig. 82 *b b*), qui durent fort longtemps et ne diminuent que très lentement de hauteur. Ces broderies, dont la fig. 84 donne un exemple

(Fig. 84.) — Vibrations consécutives d'un bateau à vapeur. Limnographe sensibilisé, 6mm par minute.

dessiné par le limnographe sensibilisé, représentent des oscillations dont la hauteur est au début de près d'un centimètre, et la durée de 30 secondes environ. C'est ce que j'appelle les vibrations consécutives des bateaux à vapeur. Ces vibrations continuent à agiter

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Many types of currents in the lake:

1. The transport from inflows to outflow
   "The lake is simply an enlarged river"

2. Thermal convection – autumnal cooling.

3. Wind-induced currents – plus upwelling

4. Atmospheric pressure effects

5. Seiche-induced currents

Inflow density currents (classified in 1 above)

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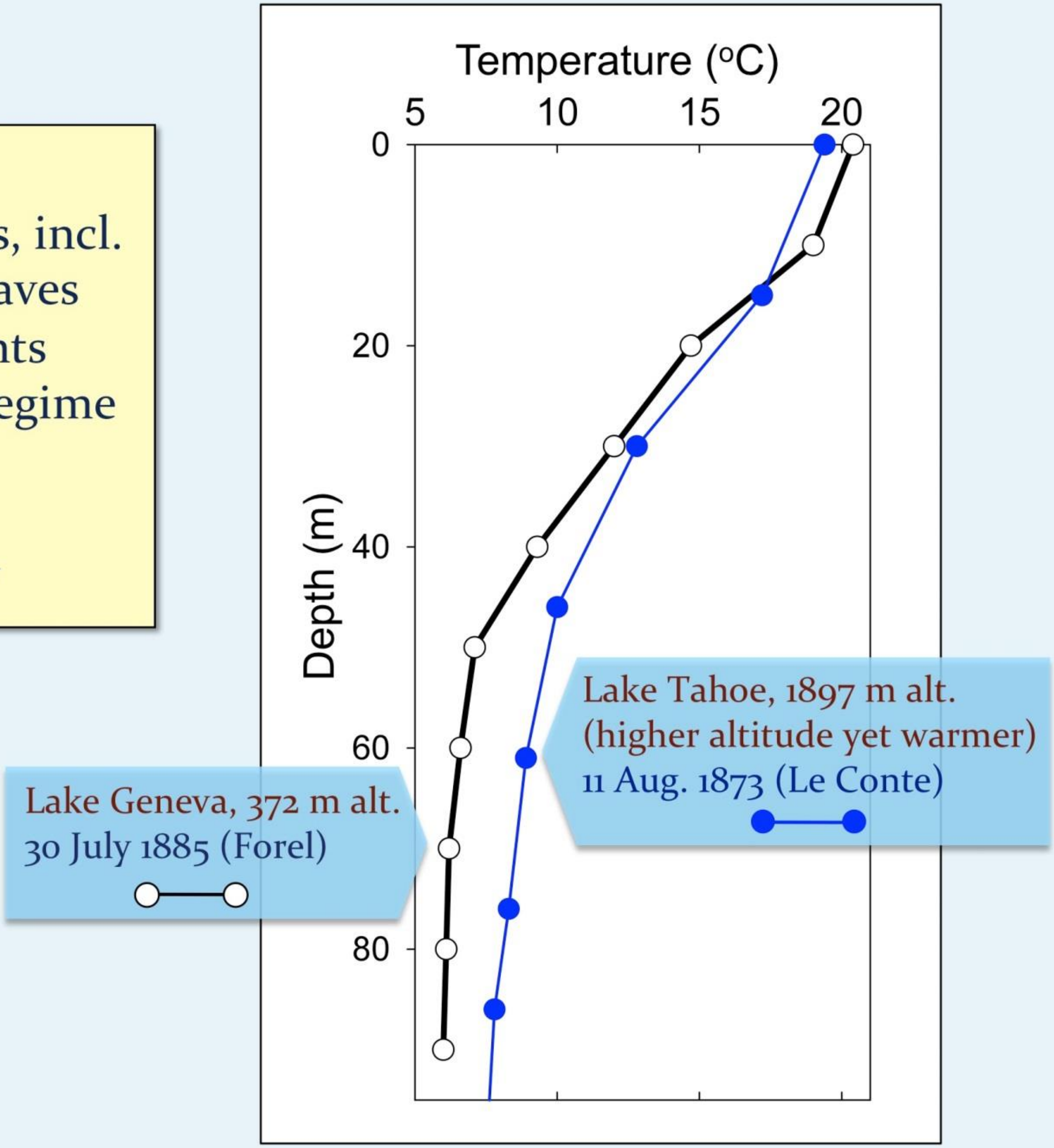

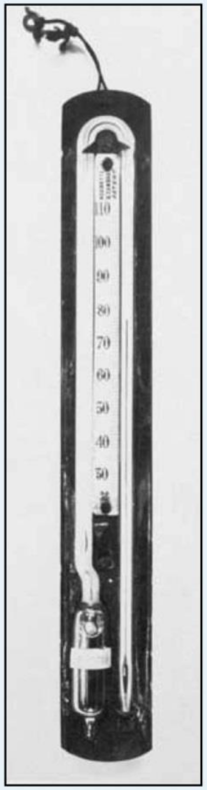

Deep-sea reversing thermometer (Negretti & Zambra)

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Google

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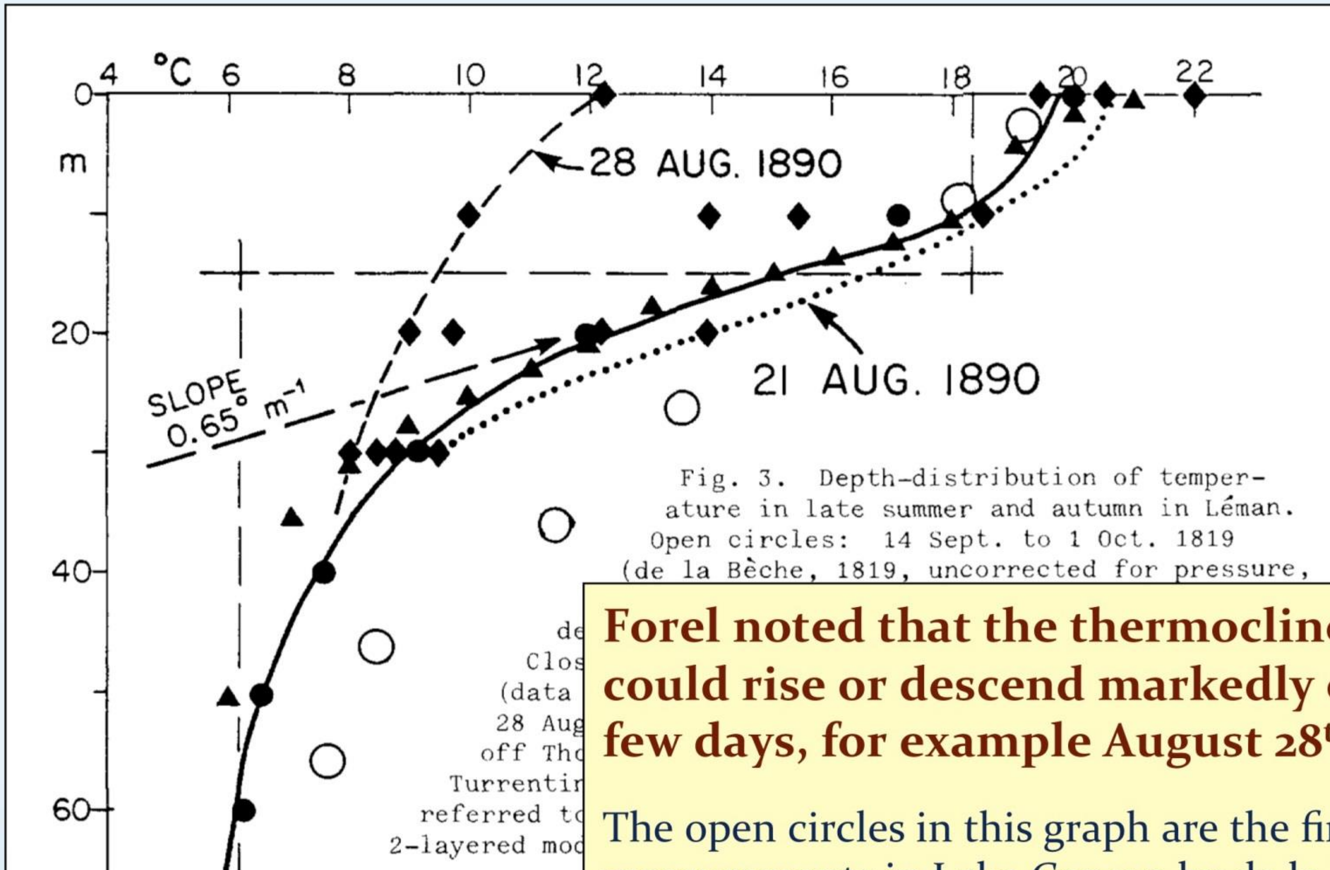
Seiches beneath the surface of the lake:
Evidence of internal waves



Forel noted that the thermocline of Lake Geneva could rise or descend markedly over the space of a few days, for example August 28th versus 21st, 1890.

The open circles in this graph are the first temperature measurements in Lake Geneva by de la Bèche (1819), perhaps the first temperature profile for any lake. This figure, with additional profiles shown here for Lake Geneva during late summer, is from Mortimer (1979).

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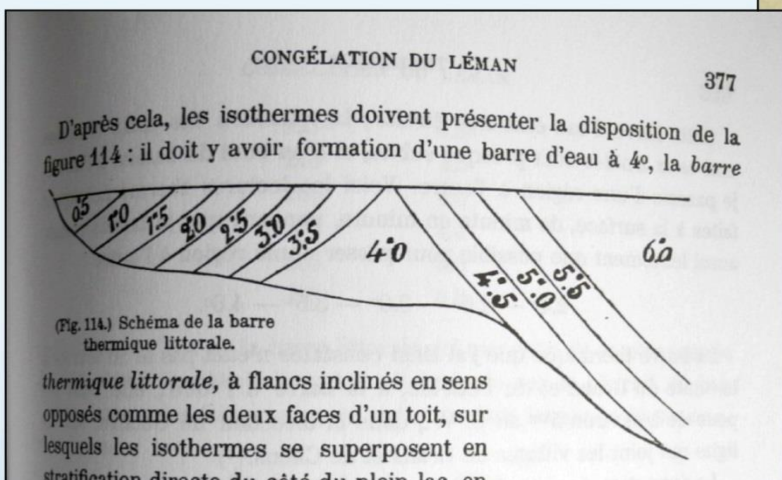
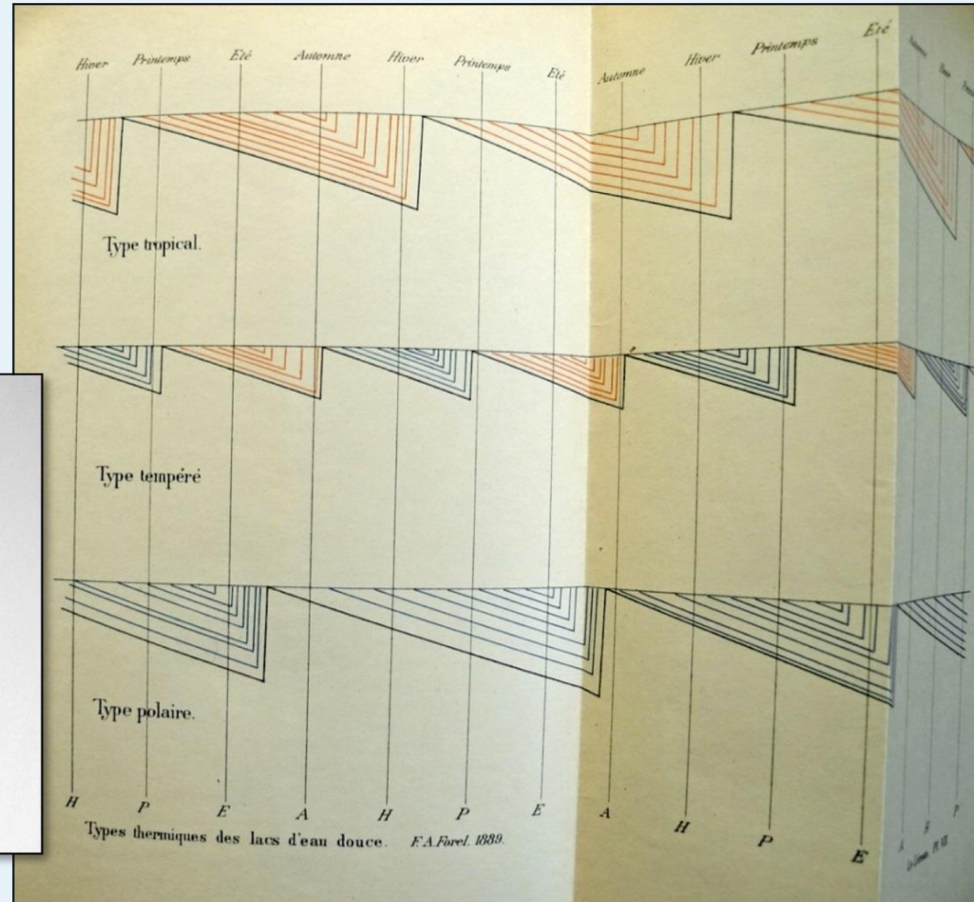


D'après cela, les isothermes doivent présenter la disposition de la figure 114 : il doit y avoir formation d'une barre d'eau à 4°, la *barre*

(Fig. 114.) Schéma de la barre thermique littorale.

thermique littorale, à flancs inclinés en sens opposés comme les deux faces d'un toit, sur lesquels les isothermes se superposent en stratification directe du côté du plein lac, en

Classification of lakes: based on their annual cycle of stratification and mixing



Hypolimnetic variations in temperature

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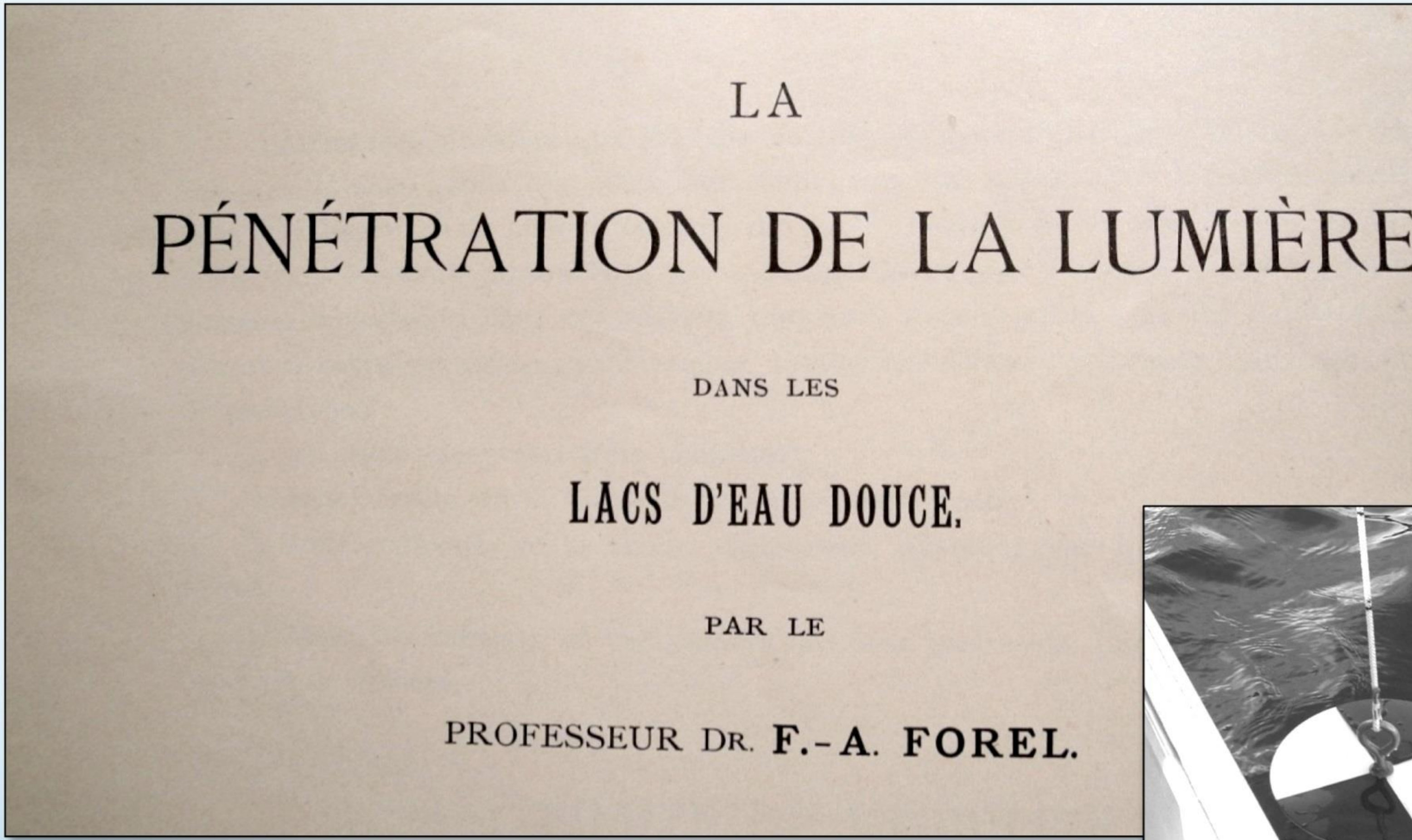
Forel was fascinated by all aspects of the interplay between light and lake water.


LA

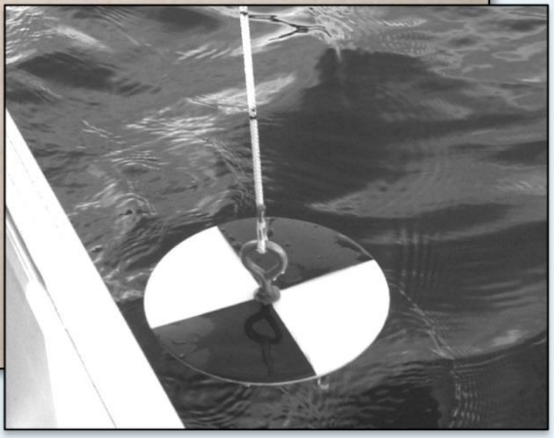
PÉNÉTRATION DE LA LUMIÈRE

DANS LES

LACS D'EAU DOUCE.

PAR LE

PROFESSEUR DR. F.-A. FOREL.



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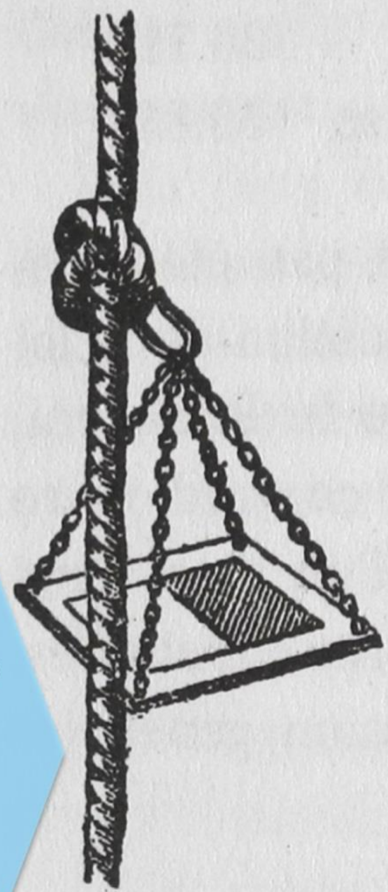
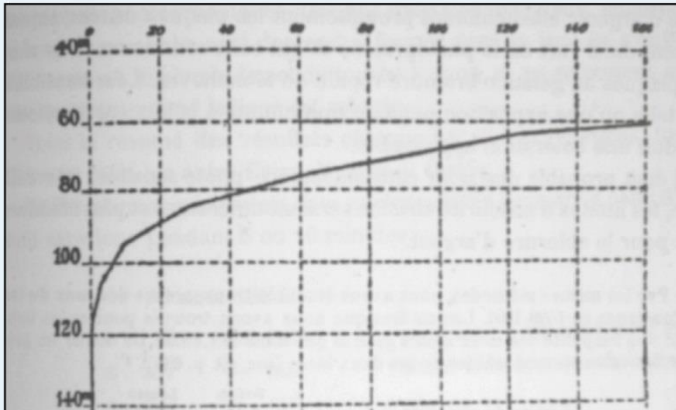


(Fig. 116.) Appareil photographique Forel.

Photochemically active radiation as a function of depth



(Fig. 117.) Courbe de la pénétration de la lumière dans le lac (effet photographique) 5 mars 1888.

In 1888, every 2 months: incubated at 10 m intervals to 115 m, from sunset to sunset (3.5 km off Morges) and converted to seconds of equivalent surface exposure

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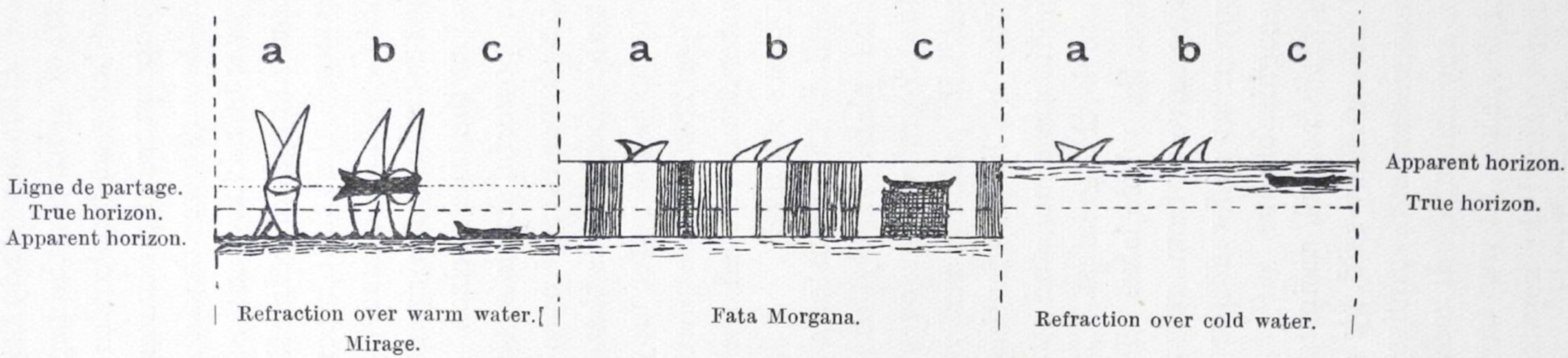
Limnological Monograph, Vol. II, 1895

Optical phenomena at the lake surface

XV.—The **Fata Morgana.** By Professor **F. A. Forel,**
Morges, Switzerland.

"Among optical phenomena which originate over the surface of water there is one so ill-defined and ill-observed as to be still mysterious; till now it has received no valid explanation. The Italians call it the Fata Morgana." (Forel 1912).



a and *b*, vessels beyond the circle of the horizon ; *c*, boat within the circle. Fata Morgana shifts from right to left.

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What controls lake color?

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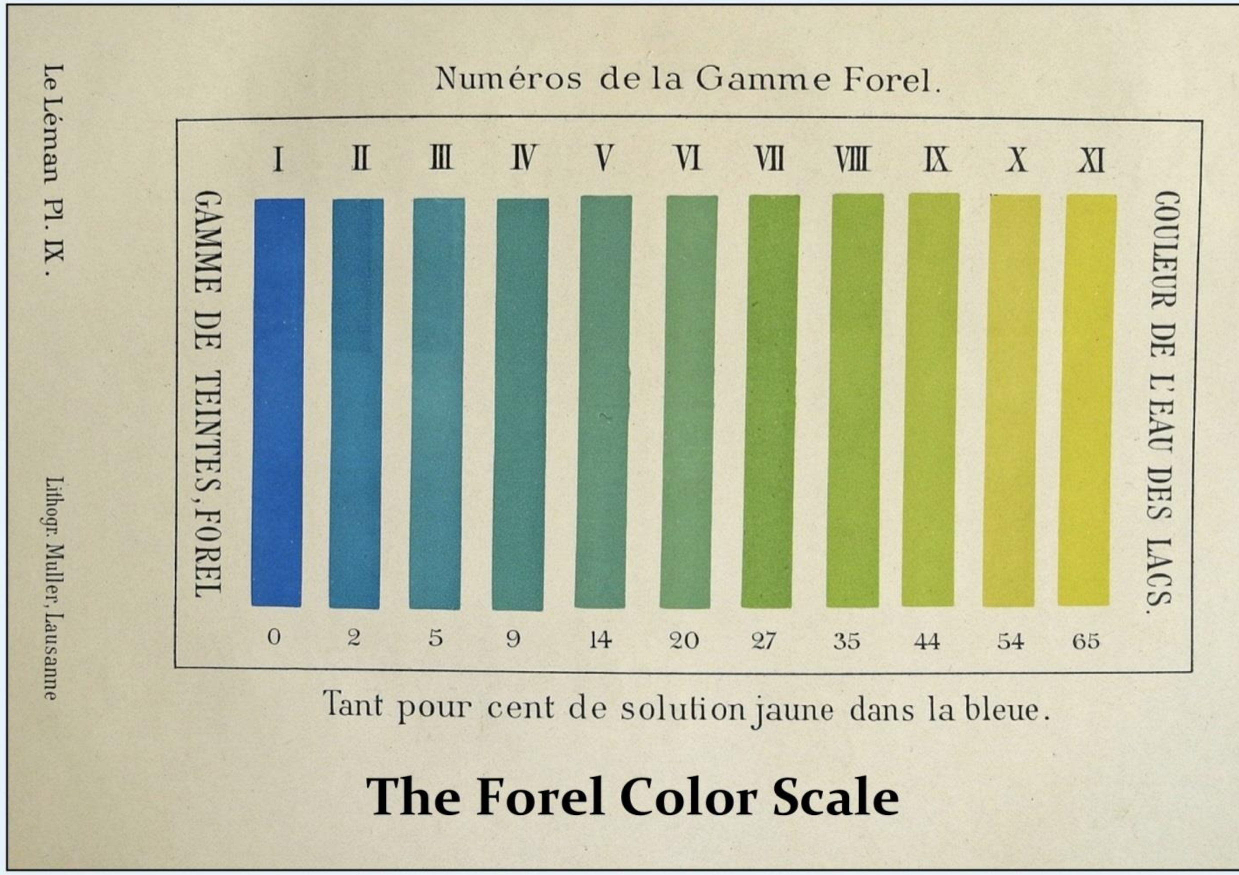
Importance of CDOM:

Forel added fine-filtered swamp water to a 6 m viewing tube and concluded that dissolved humic substances cause the greenness of the water.



The Forel Color Scale

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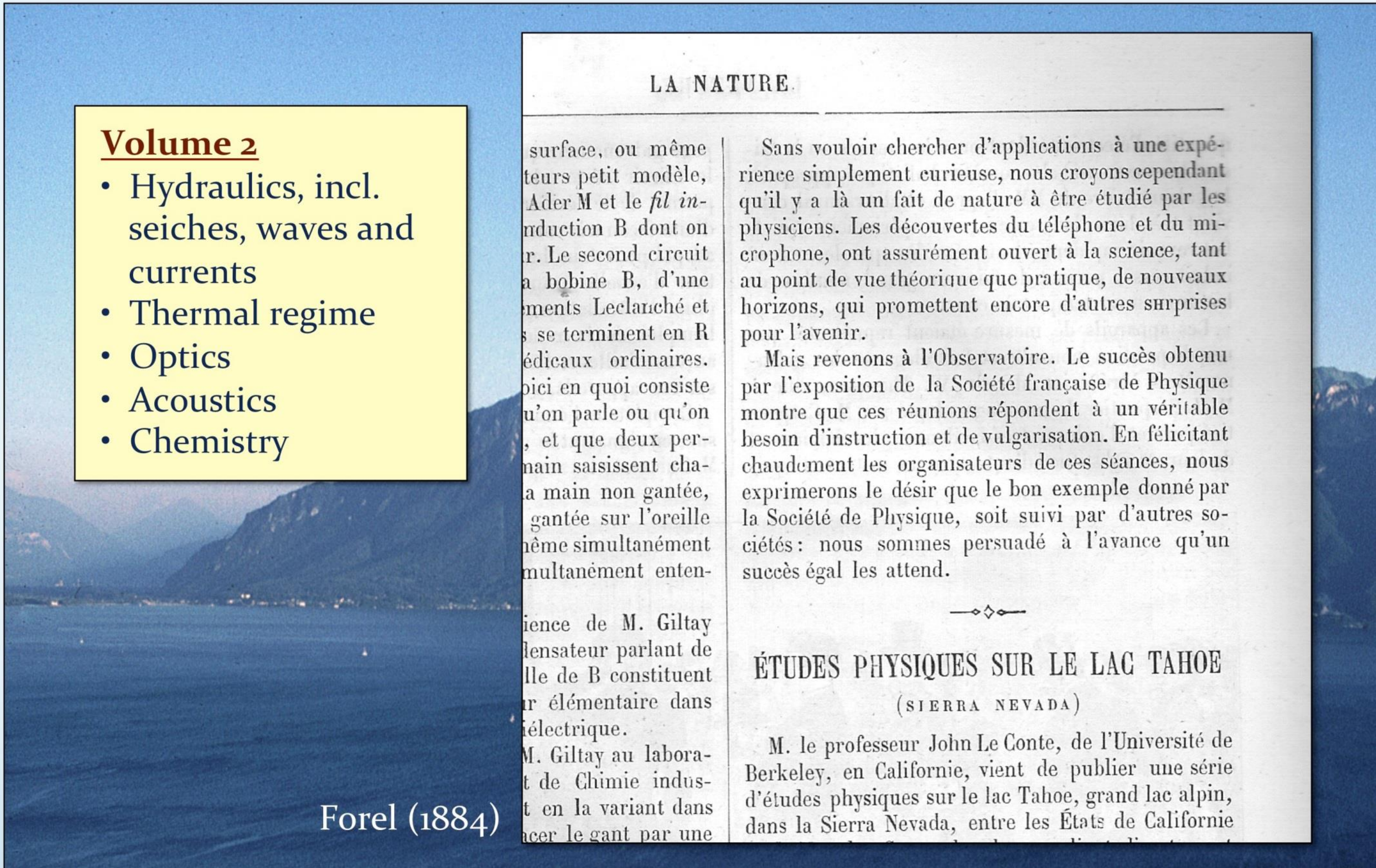

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- Chemistry

LA NATURE

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Sans vouloir chercher d'applications à une expérience simplement curieuse, nous croyons cependant qu'il y a là un fait de nature à être étudié par les physiciens. Les découvertes du téléphone et du microphone, ont assurément ouvert à la science, tant au point de vue théorique que pratique, de nouveaux horizons, qui promettent encore d'autres surprises pour l'avenir.

Mais revenons à l'Observatoire. Le succès obtenu par l'exposition de la Société française de Physique montre que ces réunions répondent à un véritable besoin d'instruction et de vulgarisation. En félicitant chaudement les organisateurs de ces séances, nous exprimerons le désir que le bon exemple donné par la Société de Physique, soit suivi par d'autres sociétés : nous sommes persuadé à l'avance qu'un succès égal les attend.

ÉTUDES PHYSIQUES SUR LE LAC TAHOE

(SIERRA NEVADA)

M. le professeur John Le Conte, de l'Université de Berkeley, en Californie, vient de publier une série d'études physiques sur le lac Tahoe, grand lac alpin, dans la Sierra Nevada, entre les États de Californie

Forel (1884)

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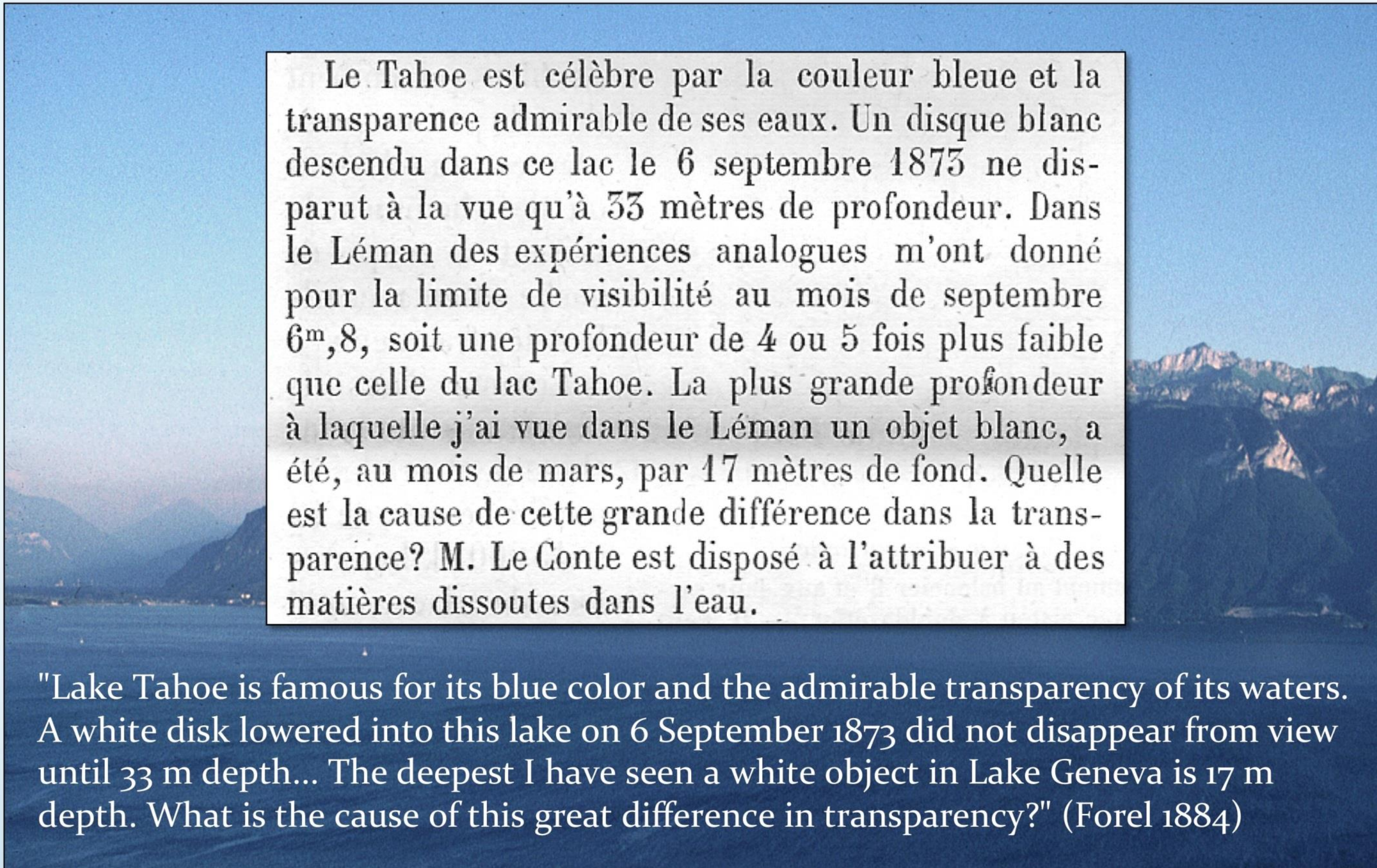
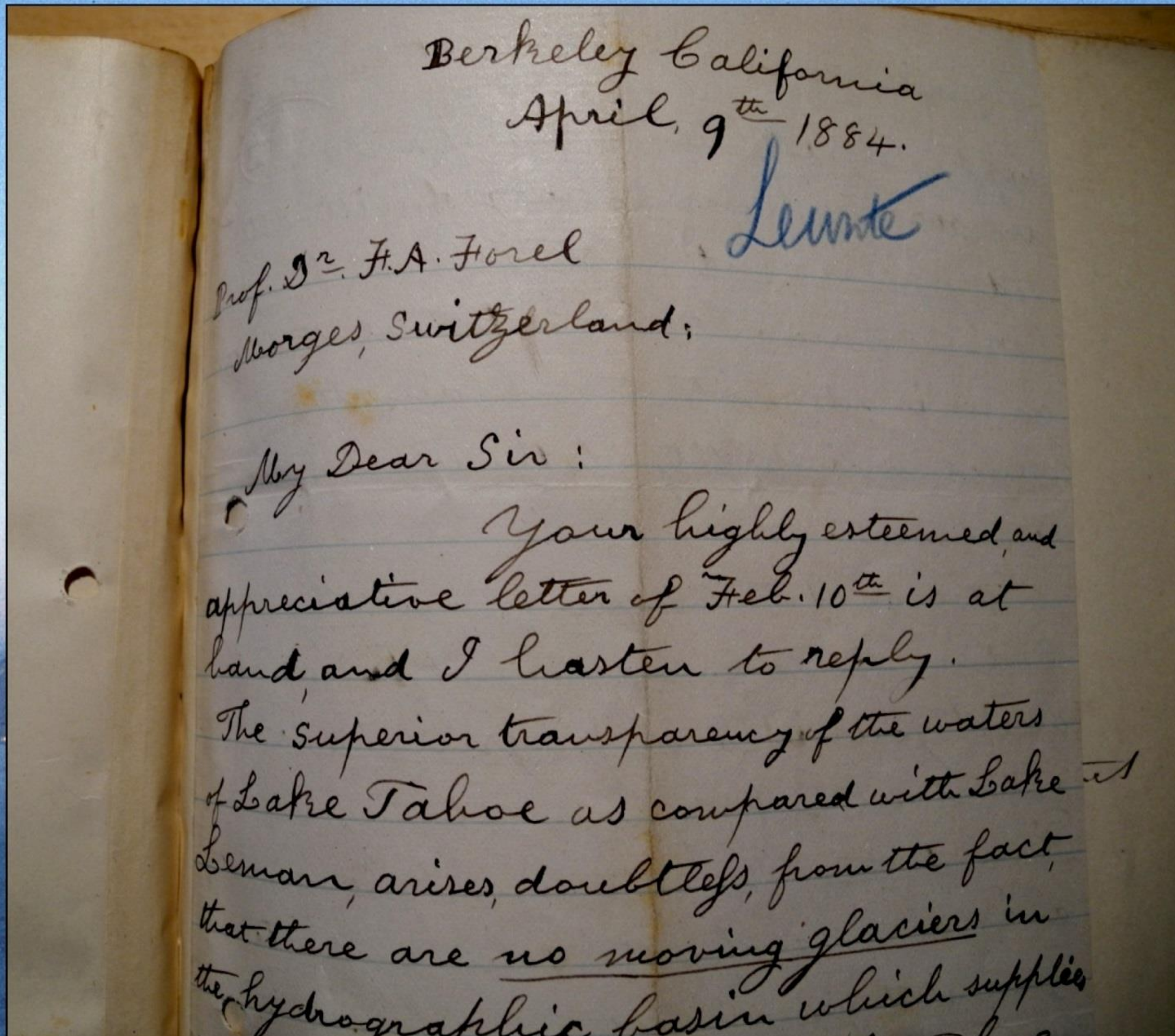


Le Tahoe est célèbre par la couleur bleue et la transparence admirable de ses eaux. Un disque blanc descendu dans ce lac le 6 septembre 1873 ne disparut à la vue qu'à 33 mètres de profondeur. Dans le Léman des expériences analogues m'ont donné pour la limite de visibilité au mois de septembre 6^{m},8, soit une profondeur de 4 ou 5 fois plus faible que celle du lac Tahoe. La plus grande profondeur à laquelle j'ai vue dans le Léman un objet blanc, a été, au mois de mars, par 17 mètres de fond. Quelle est la cause de cette grande différence dans la transparence? M. Le Conte est disposé à l'attribuer à des matières dissoutes dans l'eau.

"Lake Tahoe is famous for its blue color and the admirable transparency of its waters. A white disk lowered into this lake on 6 September 1873 did not disappear from view until 33 m depth... The deepest I have seen a white object in Lake Geneva is 17 m depth. What is the cause of this great difference in transparency?" (Forel 1884)

W.F. Vincent & C. Bertola
doi:10:4319/lol.2014.wvincent.cbertola.8

Correspondence from John Le Conte, University of California



Berkeley California
April, 9th 1884.

Leconte

Prof. Dr. F.A. Forel
Morges, Switzerland:

My Dear Sir:

Your highly esteemed and appreciative letter of Feb. 10th is at hand, and I hasten to reply.
The superior transparency of the waters of Lake Tahoe as compared with Lake Leman, arises, doubtless, from the fact, that there are no moving glaciers in the hydrographic basin which supplies

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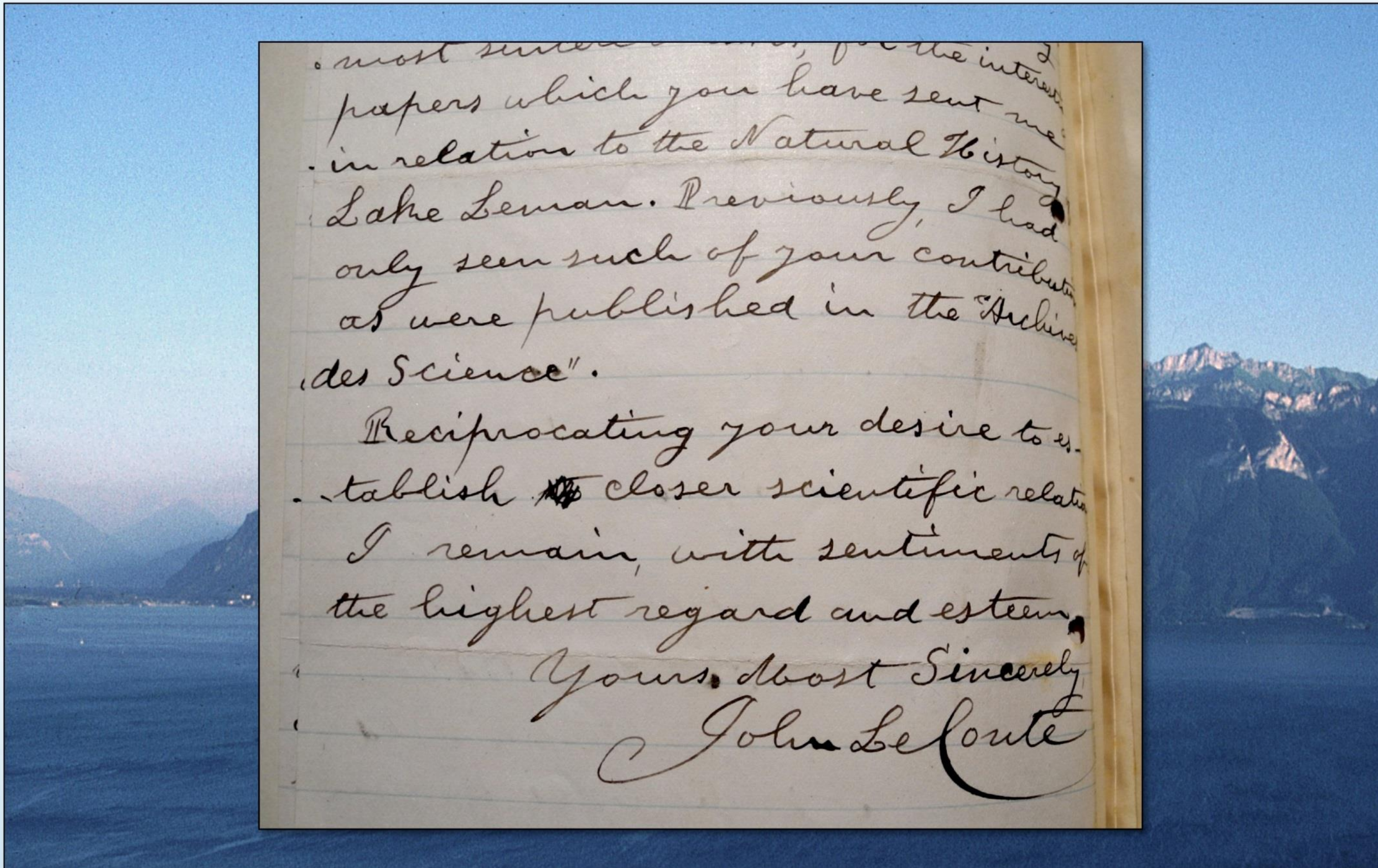
ASLO

Correspondence from John Le Conte, University of California



most sincere thanks, for the interesting
papers which you have sent me
in relation to the Natural History
Lake Leman. Previously, I had
only seen such of your contributions
as were published in the "Archives
des Science".

Reciprocating your desire to es-
-tablish closer scientific relations
I remain, with sentiments of
the highest regard and esteem,

Yours Most Sincerely
John Le Conte

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Biogeochemistry

Volume 2

- Hydraulics, incl. seiches, waves and currents
- Thermal regime
- Optics
- Acoustics
- Chemistry

Dissolved organic carbon: "What is the nature of these organic materials in the lake water? This question has not been sufficiently studied".

Deep water oxygen: 7.08 cm^3 L^{-1} at 300 m, Nov. 1880

"**The sulfate concentration of 64 mg [L^{-1}]… is considerable… is due to the presence of gypsum in many valleys of the watershed**".

Forel realized that a lake cannot be considered a closed system: "*Rather, it **communicates with the rest of the world**, via its constant exchange of gases with the **overlying atmosphere**, via its **outflow** of water carrying away dissolved and non-dissolved substances, and via its **tributaries** that deliver new materials into the lake*" (Forel 1891, p.3).

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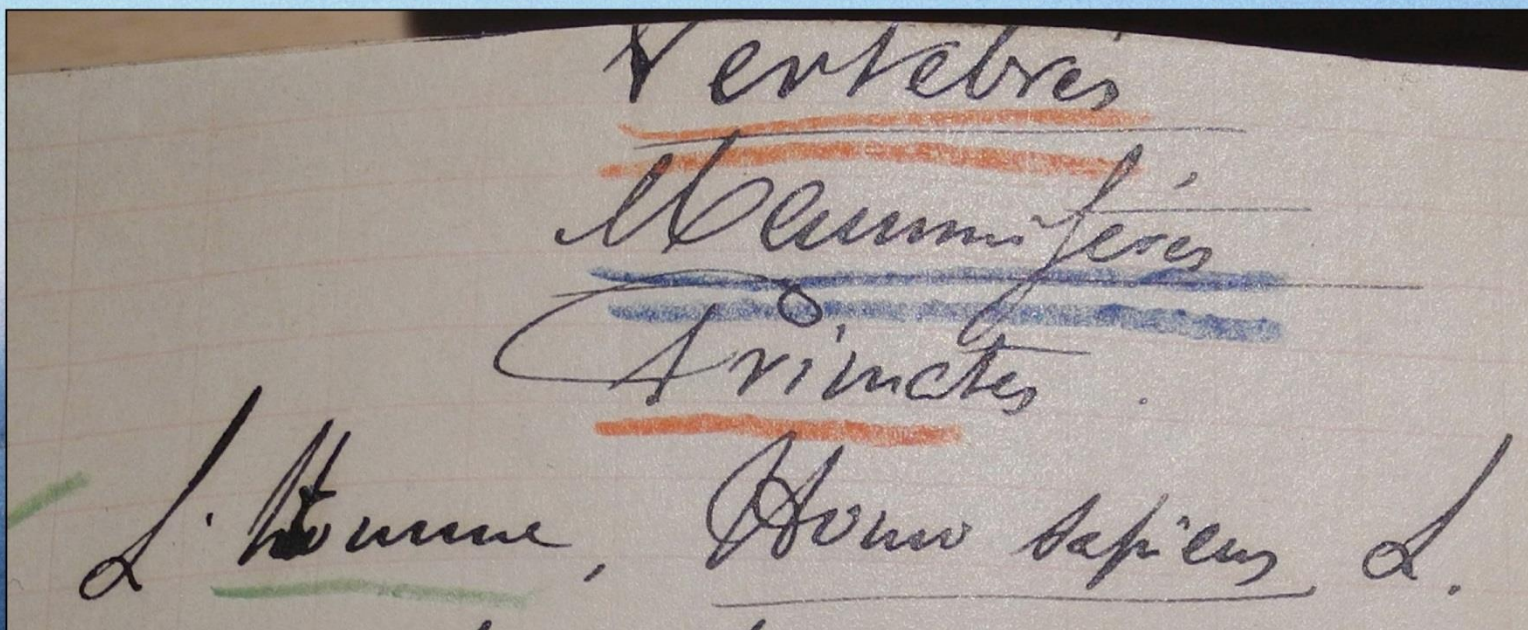
In Volume 3, Forel listed the animals and plants of Lake Geneva. The species he started with was:

Man, *Homo sapiens* L.



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The biota of Lake Geneva

VERTEBRATES
MAMMALS
Primates

Man, *Homo sapiens* L., is not an essentially aquatic species… but his activities make him an erratic species in the fauna of the lake.

"Man exerts, more than any other animal, a powerful influence on the natural environment and all living things around him".
Forel (1904) Le Léman, v.3, p.24

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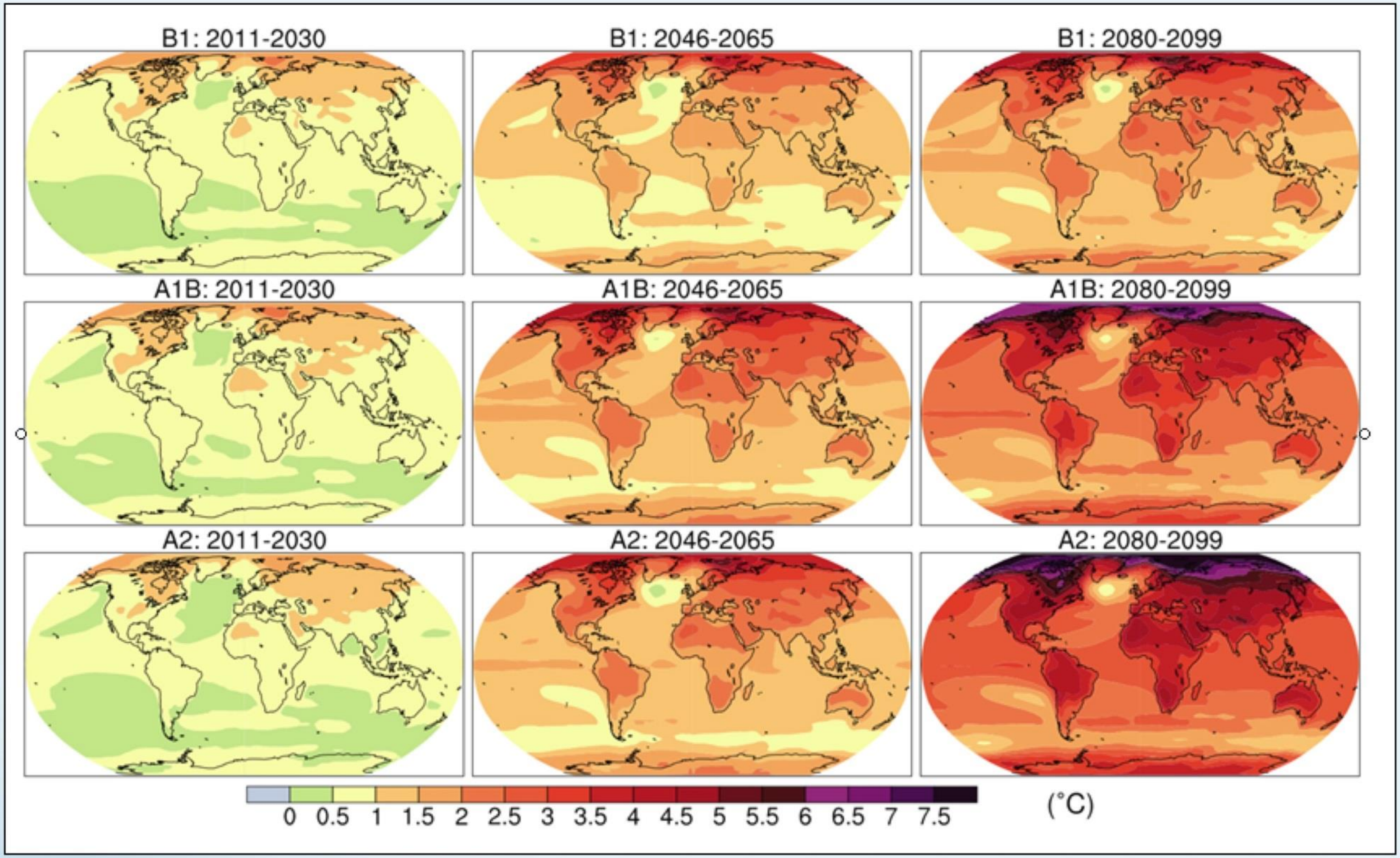
Global climate change



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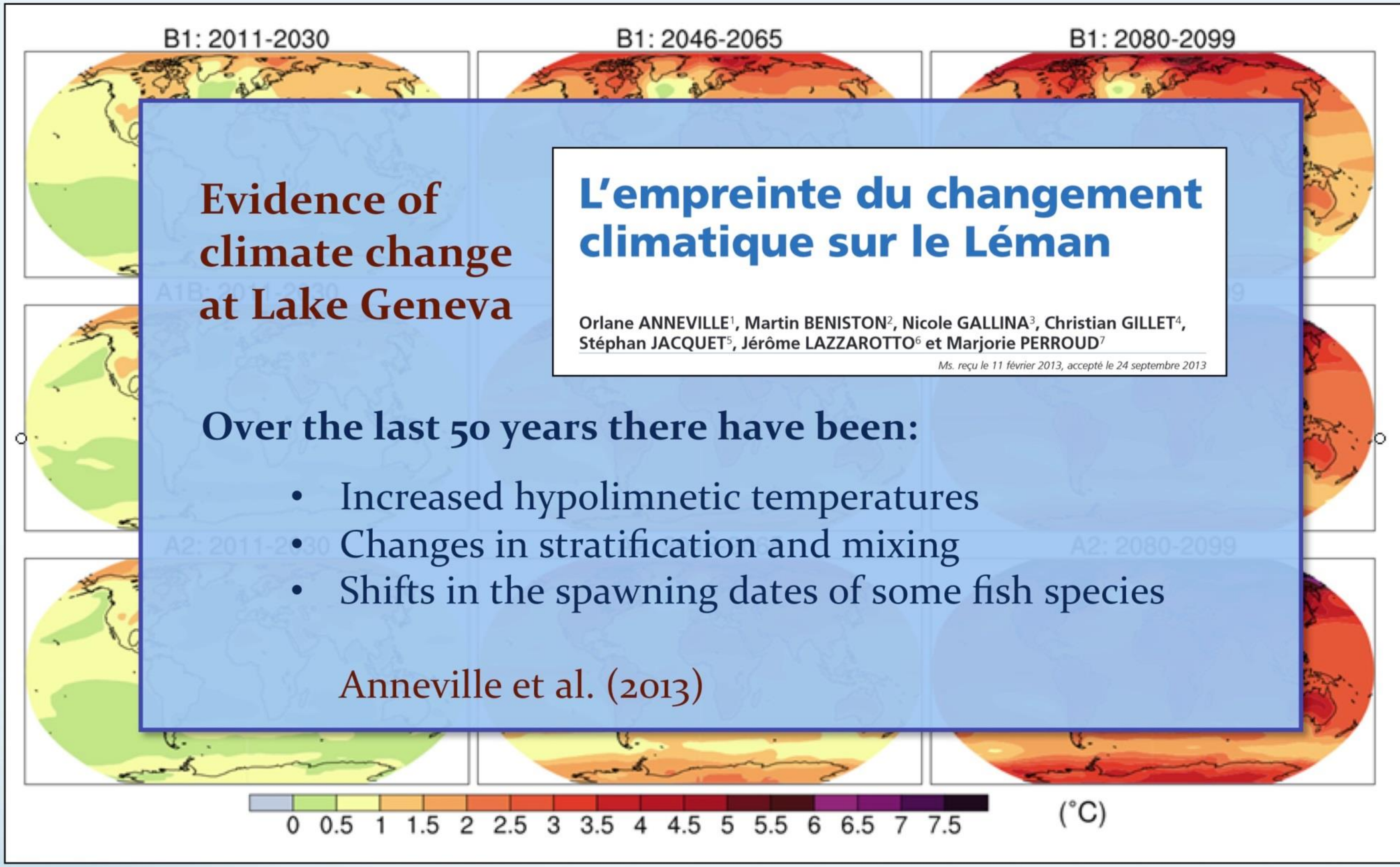


Evidence of climate change at Lake Geneva

L'empreinte du changement climatique sur le Léman

Orlane ANNEVILLE[1], Martin BENISTON[2], Nicole GALLINA[3], Christian GILLET[4], Stéphan JACQUET[5], Jérôme LAZZAROTTO[6] et Marjorie PERROUD[7]

Ms. reçu le 11 février 2013, accepté le 24 septembre 2013

Over the last 50 years there have been:

- Increased hypolimnetic temperatures
- Changes in stratification and mixing
- Shifts in the spawning dates of some fish species

Anneville et al. (2013)

Invasive species

Forel and associates collecting aquatic macrophytes

He observed the plant *Elodea canadensis* with great concern when it entered the lake as an invasive species.

Cygnus olor L.

Detailed observations on many animals, including the Geneva swans, introduced 1837:

"Although of very little intelligence, swans can have strong passions and even show signs of corruption that are truly deplorable".

doi:10:4319/lol.2014.wvincent.cbertola.8

Limnological Monograph, Vol. III, 1904

Microbes, Detritus and Carbon Cycles

“No serious analysis, to my knowledge, has indicated any lake water completely free of microbes” (vol 3, p 360).

En second lieu, et c’est là un point très important, tout microbe n’est pas nécessairement malsain, bien au contraire ; l’immense majorité de ces petits êtres sont parfaitement innocents.

"Secondly, and this is a very important point, all microbes are not necessarily unhealthy. To the contrary, in fact: the immense majority of these minute life forms are completely harmless."

Importance of **detrital processing by benthic animals** for the food web and carbon cycle of a lake: “They live like the scavengers of our cities, like the dogs of Constantinople, on the left-overs from the table of others"

Geosystem and Ecosystem Services

Bronze Age stilt villages on the lake

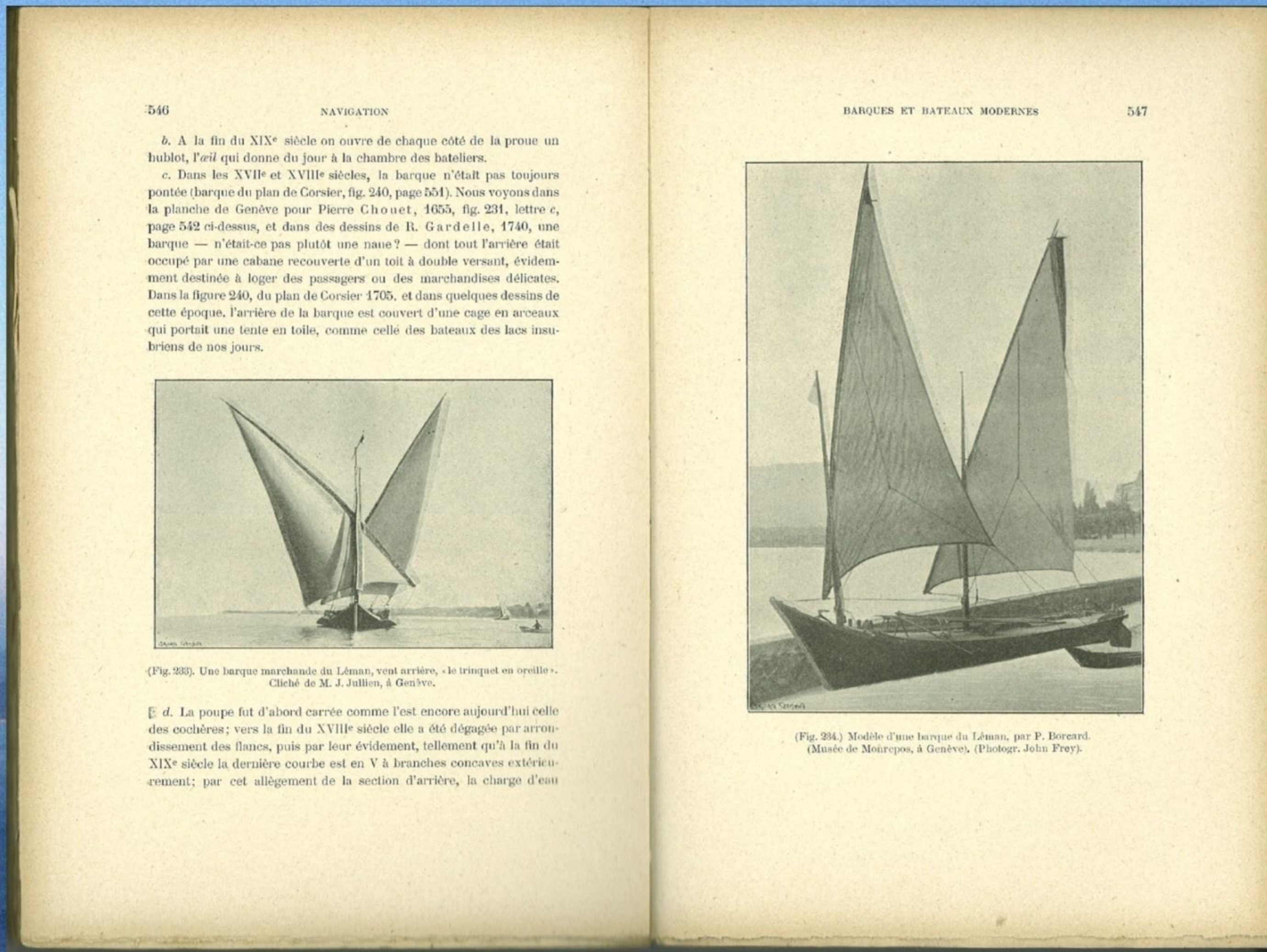
Reconstruction of a prehistoric stilt village at Lake Constance, Germany

photo: Dietmar Straile

- washing
- transport by boat
- Fisheries
- drinking water
- sanitation, waste disposal
- warm lake effect in winter
- cool lake effect in summer
- aesthetics of the lake
- flood protection
- protection of food from animal pests

doi:10:4319/lol.2014.wvincent.cbertola.8

Limnological Monograph, Vol. III, 1904


546 NAVIGATION

b. A la fin du XIX^e^ siècle on ouvre de chaque côté de la proue un hublot, l'*œil* qui donne du jour à la chambre des bateliers.

c. Dans les XVII^e^ et XVIII^e^ siècles, la barque n'était pas toujours pontée (barque du plan de Corsier, fig. 240, page 551). Nous voyons dans la planche de Genève pour Pierre Chouet, 1655, fig. 231, lettre *c*, page 542 ci-dessus, et dans des dessins de R. Gardelle, 1740, une barque — n'était-ce pas plutôt une naue? — dont tout l'arrière était occupé par une cabane recouverte d'un toit à double versant, évidemment destinée à loger des passagers ou des marchandises délicates. Dans la figure 240, du plan de Corsier 1705, et dans quelques dessins de cette époque, l'arrière de la barque est couvert d'une cage en arceaux qui portait une tente en toile, comme celle des bateaux des lacs insubriens de nos jours.

(Fig. 233). Une barque marchande du Léman, vent arrière, « le trinquet en oreille ». Cliché de M. J. Jullien, à Genève.

d. La poupe fut d'abord carrée comme l'est encore aujourd'hui celle des cochères; vers la fin du XVIII^e^ siècle elle a été dégagée par arrondissement des flancs, puis par leur évidement, tellement qu'à la fin du XIX^e^ siècle la dernière courbe est en V à branches concaves extérieurement; par cet allègement de la section d'arrière, la charge d'eau

BARQUES ET BATEAUX MODERNES 547

(Fig. 234.) Modèle d'une barque du Léman, par P. Borcard. (Musée de Monrepos, à Genève). (Photogr. John Frey).

Ecosystem Services

W.F. Vincent & C. Bertola

doi:10:4319/lol.2014.wvincent.cbertola.8

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Limnological Monograph, Vol. III, 1904

		Tonnes.	Hommes.
1666	Barques d'Ouchy	50	—
1667	Barques	60 à 70	—
—	Coursières	6 à 12	—
1691	Barque à Panchaud, Morges	—	400
1697	La *Grangère*, Vevey	67	200
—	Barque à 16 rameurs, de Vevey	54	160
—	Galiotte de Vevey	20	60
1702	Corsières de St-Gingolph	53	—
1720	Bateaux de Vevey	45 à 90	—
—	Coursières de Vevey	13 à 34	—
1778	Barques	120	—
—	Barquettes	30	—
1791	Barques	68 à 104	—
—	Brigantins	22 à 41	—
1900	Grandes Barques	100 à 190	—
—	Cochères	20 à 40	—
—	Bateaux à vapeur *Cygne, Mouette*	87	250
—	— — *Helvétie, Léman*	200	800
—	— — *Suisse*	322	1200

2° La *Cochère*, barque de faibles dimensions de 20 à 40 tonneaux de port, non pontée, sauf à l'avant, où est le *carcagnou* des bateliers, deux bancs entre les mâts, sans appoustis, sans naviot de service. Elle a la même voilure que la barque; elle est armée de deux avirons moteurs à tribord-avant et d'un aviron recteur à bâbord-arrière.

Dans quelques cochères de construction récente le pont de la proue a été avancé vers l'arrière jusqu'au mât grand voilier. Le banc qui, dans les anciennes cochères, était entre les deux mâts, a été supprimé.

Le nom de *cochère* vient-il de coche d'eau, barque faisant le service des voyageurs? ou bien est-ce une déformation du mot corsaire que nous avons vu (p. 523) désigner certaines barques de notre lac? Je n'en sais rien et je n'ose vraiment pas me lancer dans une discussion d'étymologie, quand je vois l'excellent Littré faire venir le coche d'eau, le bateau à voyageurs, du mot latin *concha* et le coche de terre, la voiture à voyageurs, du mot hongrois *kotczy*. Cette science des dérivations de mots est évidemment un terrain trop dangereux pour un naturaliste.

3° Le *bateau* de pêche, bateau plat de même forme en petit que la barque, ou plutôt que la cochère, de 6 à 8m de longueur, de 2m de largeur, sans pont, avec 2 ou 3 avirons à tribord-avant, et une rame rectrice à bâbord-arrière, sans gouvernail; un réservoir à poisson sous l'un des bancs de l'avant. (Fig. 241.)

(Fig. 241). Bateau de pêche du Léman, d'après un tableau de F. Bocion.

4° La *liquette*, petit bachot à fond plat transversalement, concave d'avant en arrière, à bords évasés de 30cm de hauteur, rétréci et taillé en carré aux deux extrémités (1). Un banc et une paire de rames.

5° Le *noie-chrétien*, réduction de la liquette.

Ces deux derniers types, liquette et noie-chrétien, ont presque disparu actuellement.

Outre ces types indigènes, les constructeurs ont introduit les bateaux en usage dans d'autres eaux en les adaptant aux conditions de notre lac. Yachts de tous gréements, canots, péniches (2) de chasse, de course, de promenade, yoles, skiffs, etc.

(1) Les noms locaux de Genève sont différents de ceux du reste du lac. La *liquette* y est un petit bateau de pêche à proue pointue; le bachot à avant carré y est appelé *canardière*.

(2) Le mot péniche est appliqué sur notre lac à un canot léger marchant à rames ou à voiles. On ne lui connaît pas l'acception qu'il a sur les canaux et les rivières de France, lourd chaland de fort tonnage pour le transport des marchandises. La première péniche a été construite sur le Léman en 1854, d'après les plans de l'ingénieur Eugène de Morsier, à son retour de Marseille.

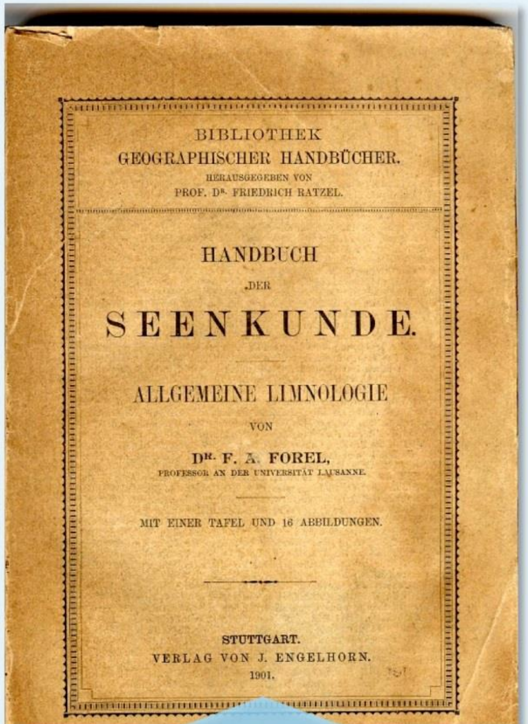
Culture, Economics & Management of the Lake Geneva Ecosystem

W.F. Vincent & C. Bertola

doi:10:4319/lol.2014.wvincent.cbertola.8

ASLO

Forel's limnology: Broad legacy


BIBLIOTHEK
GEOGRAPHISCHER HANDBÜCHER.
HERAUSGEGEBEN VON
PROF. Dr. FRIEDRICH RATZEL.

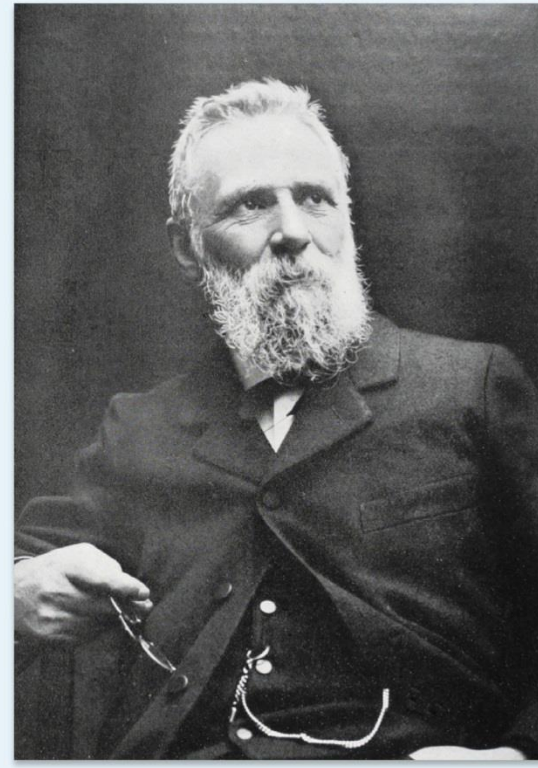
HANDBUCH
DER
SEENKUNDE.

ALLGEMEINE LIMNOLOGIE
VON
Dr. F. A. FOREL,
PROFESSOR AN DER UNIVERSITÄT LAUSANNE.

MIT EINER TAFEL UND 16 ABBILDUNGEN.

STUTTGART.
VERLAG VON J. ENGELHORN.
1901.

Institut F-A. Forel



1901: first textbook in **"Lake Science - General Limnology"**

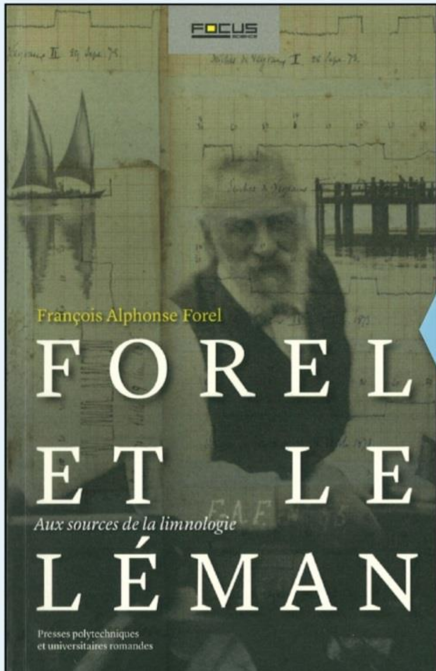
"Father of Limnology" (Needham 1916)

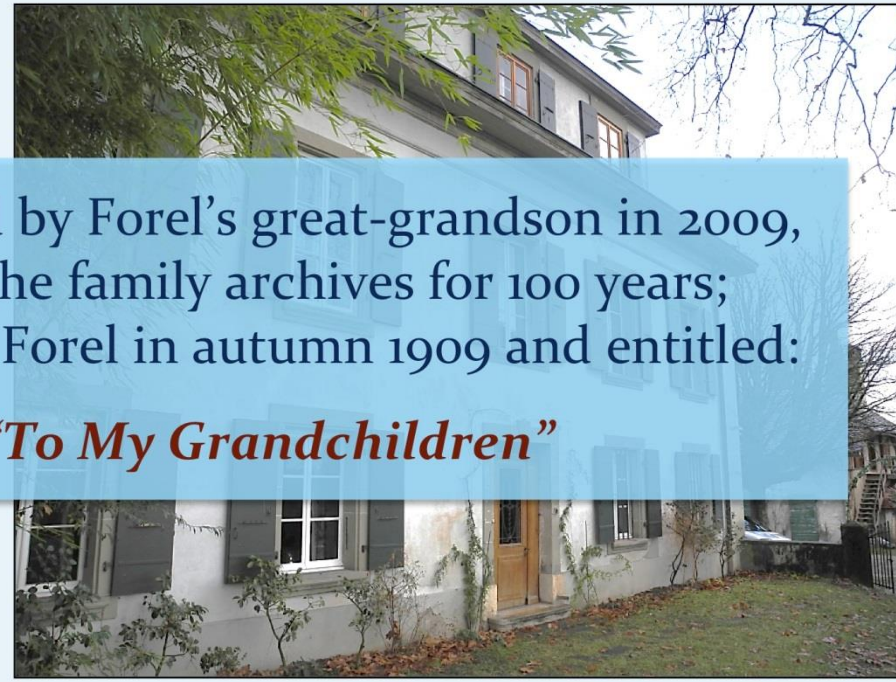
First Vice-President of the ***International Earthquake Commission***: *Rossi-Forel scale*, precursor to the Richter scale
- Earthquake-induced seiches

First President of the ***International Glaciological Commission***
Mount Forel - eastern Greenland
Forel Glacier - west Antarctica

W.F. Vincent & C. Bertola
doi:10:4319/lol.2014.wvincent.cbertola.8
ASLO

Forel's Lost Manuscript





Discovered by Forel's great-grandson in 2009, lost in the family archives for 100 years; written by Forel in autumn 1909 and entitled:

"To My Grandchildren"

"If you ask me how I spent my life, I will try to explain myself to you … Naturalist by heart and by profession, I devoted my life to the search for truth in the natural sciences; sometimes finding it, I believe."

This autobiography with commentaries by contemporary limnologists was published in the original French in December 2012 (Forel 2012).

Limnology: After Forel

Limnology continued to develop rapidly over the 20th century

Thienemann, August Friedrich (Germany, 1882-1960)
Published extensively on aquatic insect ecology and lake classification.
In 1922, co-founded with **Einar Naumann** (Sweden, 1891-1934) the ***International Association for Theoretical and Applied Limnology* (SIL)** devoted to the study of inland waters.

Edward A. Birge (USA, 1851-1950).
With colleague **Chancey Juday** (USA, 1871-1944), undertook influential limnological studies on Lake Mendota.

G. Evelyn Hutchinson (USA, 1903-1991).
Contributed many seminal ideas in limnology and evolutionary ecology. Perhaps inspired by Forel's monograph, Hutchinson wrote his own encyclopedic three volume limnological treatise (a 4th volume was published posthumously) that initiated the modern era of limnology.

doi:10:4319/lol.2014.wvincent.cbertola.8

Limnology: After Forel

Limnological societies were founded:

- The ***Limnological Society of America*** (co-founded by Juday) merged with the Oceanographic Society of the Pacific in 1948 to create **ASLO**, now known as the ***Association for the Sciences of Limnology and Oceanography***.
- The ASLO journal ***"Limnology and Oceanography"*** began in 1956.

In addition to representation in **SIL**, many other countries also developed their own limnological societies; e.g., the ***Japanese Society of Limnology*** (founded in 1931); the ***Society of Canadian Limnologists*** (SCL); the ***Iberian Society of Limnology;*** the ***Australian Society of Limnology***; the ***German Limnological Society***; the ***Polish Limnological Society***; the ***Czech Limnological Society***; and the ***Italian Society for Oceanology and Limnology.***

International Society of Limnology

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Conclusions

François Forel made many lasting contributions to our understanding of aquatic ecosystems and how to study them:

In founding the science of ***"limnology"***, Forel drew attention to the interconnectedness of all aspects of lakes.

His career provides many compelling examples of the power of networking, collaboration and synthesis.

He described how humans are a component part of lake ecosystems and he drew attention to the value of lake ecosystem services, and our inadvertent power to degrade the environment.

He made a myriad of specific contributions - from ***morphometry*** and lake physics to food webs, microbes and ***the carbon cycle***.

His perspective on lakes as coupled physical-chemical-biological-human systems is highly relevant to the "***limnology of global change***".

W.F. Vincent & C. Bertola
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Acknowledgments

Thank you to:

The Forel Family and the ***Lake Geneva Museum Documentation Centre*** for access to unpublished material.

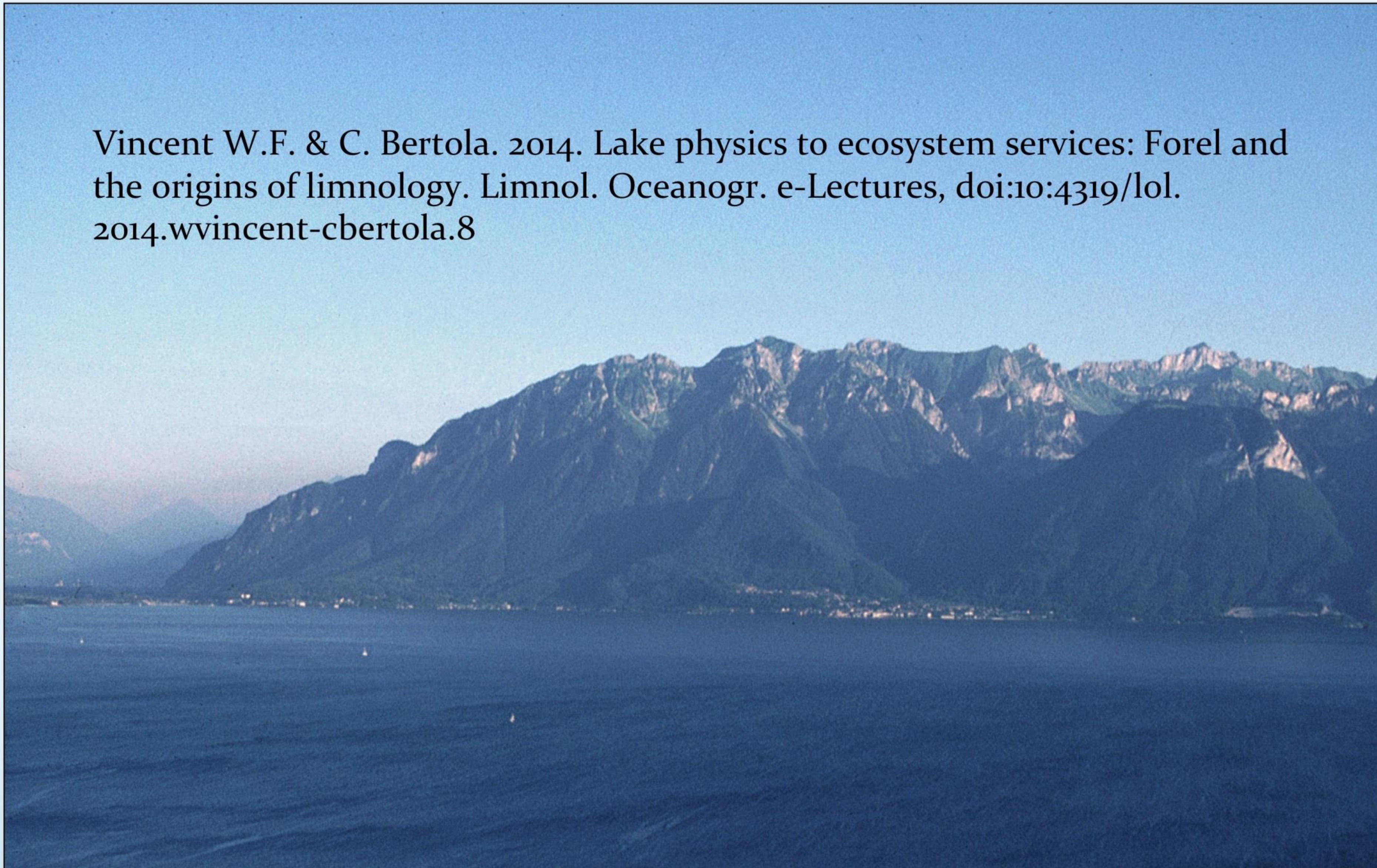
Carlos Duarte, John Dolan, Michio Kumagai, John Downing and Irene Gregory-Eaves for their encouragement of this 'voyage of discovery' of Forel.

All participants in the ***ASLO-Japan Special Session*** commemorating François A. Forel, 1841-1912.

We thank **François D.C. Forel** for reviewing this lecture, and for the support and encouragement also by **Jacqueline Porret-Forel**.

Photographs of the Forel manuscripts and other material, and translations from Forel's original texts are by the authors, unless otherwise noted.

Citation information



Vincent W.F. & C. Bertola. 2014. Lake physics to ecosystem services: Forel and the origins of limnology. Limnol. Oceanogr. e-Lectures, doi:10:4319/lol.2014.wvincent-cbertola.8

Lake Physics to Ecosystem Services: Forel and the Origins of Limnology

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Carinne Bertola (Musée du Léman, CH-1260 Nyon, Switzerland)

<u>Lecture Notes</u>

- **SLIDE 1**
  Lake Physics to Ecosystem Services: Forel and the Origins of Limnology
  Warwick Vincent
  Département de biologie & Centre d'études nordiques (CEN)
  Université Laval, Québec, QC G1V 0A6, Canada
  and
  Carinne Bertola
  Musée du Léman, CH-1260 Nyon, Switzerland

  e-lecture
  Received February 2014, revised version accepted June 2014
  doi:10:4319/lol.2014.wvincent.cbertola.8

  Photo: Lake Geneva looking south from its northern shore.

- **SLIDE 2**
  In the late 19th century on the shores of Lake Geneva, which lies on the border of France and Switzerland, François A. Forel wrestled with the question of what to call his new lake science. Forel was a professor in the medical faculty at the 'Academy of Lausanne', where he taught anatomy and physiology. However his true passion was the ecology of lakes, especially Lake Geneva, known in French as Lac Léman. Here this water color painting by Ernest Biéler (reproduced courtesy of the Forel family) shows his study and laboratory at his home near Morges, Switzerland.

  "His research encompassed all aspects of the lake, from its morphometry, sediments, underwater light and mixing patterns, to its microbial, plant and animal ecology. He observed that the environmental characteristics of the lake were all closely interrelated, and he saw the lake as a system that was intimately tied to its surrounding catchment. As a doctor of medicine and the son of a local jurist and historian, he also identified the lake as a precious resource for the health and well being of the many people who lived around it in the past and present, and he quantified the lake fishing economy in a way that foreshadowed the modern concept of ecosystem services." (Vincent and Bertola 2012).

Pronunciation guide:
François Forel: Frohn–**swa** Fore- **rell**;
Lausanne: **Loh**-zahn;
Lac Léman: lahk **Leh**-mohn**;**
Morges: Mor-zjh (-ge as in beige)
(consult also: http://www.forvo.com/)

- **SLIDE 3**
  Forel's research interests on the lake were simply too broad to classify within any specialised subject area, and there were problems trying to insert it into any existing integrative discipline: "I wanted to achieve a generalisation, an overview of all the detailed facts, where each specialised study would be supported by the data from other studies. The theme of my description being partly terrestrial, this subject might be considered Geography. But the geography of waters is called Oceanography; I could therefore call the discipline *Freshwater Oceanography*. But a lake, no matter how large it might be, is not an ocean; the limited expanse gives each lake its own proper character that is very different from the unlimited expanse of the vast ocean." Forel went on to explain that this lack of fit to any existing discipline forced him to create a new word for a new discipline: "...it is necessary to forge the word *limnology*. *Limnology* is thus *the oceanography of lakes*." (Forel 1892, p.VI).

- **SLIDE 4**
  Limnology has its origins in the development of the natural sciences, and the advent of new technologies to study the environment. From the 17th century onwards, there was increasing interest in freshwater biology, stimulated by Leeuwenhoek's invention of the microscope and discovery of minute 'animalcules' in lake and pond water: micro-invertebrates such as rotifers ("wheel animalcules") and motile protists ("infusoria") such as ciliates. 'Natural history', the study of biology and geology, was a popular subject for scholars with broad interests, including those trained as medical doctors; for example Ernst Haeckel who coined the word 'ecology' in 1866. 'Oceanography', considered a branch of geography, developed rapidly in the 18th century with studies of ocean currents, and in the 19th century with marine research expeditions, notably the Challenger Expedition. This latter expedition, organized by the Royal Society of London, was

undertaken from 1872 to 1876 with the ship HMS Challenger, which travelled more than 125,000 km to survey the physical, chemical and biological properties of the World Ocean, with emphasis on the deep seafloor (http://aquarium.ucsd.edu/Education/Learning_Resources/Challenger/science.php).

- **SLIDE 5**

  Forel grew up and spent most of his career in the French-speaking part of Switzerland. He was born 2 February 1841 in the Swiss town of Morges, 16 km from Lausanne, 40 km from the city of Geneva, on the shores of Lake Geneva. His family had a diverse range of professional and scholarly interests. His father, François Forel (1765-1865) was a respected magistrate, naturalist and historian. His cousins included Alexis Forel (1852-1922; chemist/engraver) and August Forel (1848-1931) a celebrated zoologist and psychiatrist (Forel 1937).

  Forel's schooling began in Morges (College de Morges), and then later in Geneva (Gymnase de Genève) followed by university studies at Geneva (Académie de Genève; Bachelor of Arts and Bachelor of Physical and Natural Sciences). He left Switzerland to study medicine and natural history at the Académie de Montpellier in France for 2 years. After continuing his medical studies in Paris, he then moved to the University of Würzburg, graduating Doctor of Medicine at the age of 24, in July 1865.

  Forel returned to Morges in 1867, after 11 years away; he became a Lecturer, then Professor of Anatomy at Académie de Lausanne (today the 'University of Lausanne').

  Further biographical details including anecdotes about his schooling are given in Forel (2012).

- **SLIDE 6**

  When Forel returned to Morges, like all young scientists, he had to make a decision on how to orient his career. One option would be to focus on his teaching subjects: "anatomy, histology and physiology". But this would mean trying to establish his place in a world of scholars who were better prepared and set up for such research.

  Instead he turned to the lake; "Or instead to take for my laboratory and my aquarium this lake, which was offering me its mysteries and beckoning me to study them". Forel seized this opportunity, with "a fairly clear sense of the career that had taken hold of me" (Forel 1912).

- **SLIDE 7**
  In these early years back in Morges, Forel identified many potential topics for limnological research. But there were two that immediately captured his imagination.

  Examining under the microscope the characteristics of some lake sediment that he had sampled offshore from the family home at Morges, Forel was astonished to discover a small invertebrate, a nematode that was moving among the particles. This accidental discovery led him to hypothesize that lakes contain a community of deep-living, benthic animals.

  Observing the flow of water into and out of a harbor entrance at Morges, Forel discovered a reciprocating flow that he hypothesized was linked in some way to the surface seiches in the lake.

  These two discoveries were pivotal in the development of his career, and in his new science that included biological as well as physical studies.

- **SLIDE 8**
  His work showed that diverse species of animals occurred in the sediments, even to 300 m, the deepest abyssal region of the lake. This was the start of a remarkably successful long term project. Rather than keeping the samples and discoveries to himself, Forel made the early decision to work collaboratively with specialists on different animal phyla. From 1874 to 1879, this project produced a series of 49 published reports with 19 collaborators and later culminated in his 1884 publication "La faune profonde des lacs Suisses" (The Deep Fauna of Swiss Lakes). This volume has sections on physical and chemical limnology, and descriptions of several large lakes of the world.

- **SLIDE 9**
  Forel concluded that the periodic rise and fall of lake level, well known locally as 'seiches' (perhaps because the upper littoral zone would become 'sèche', French for 'dry', when the level dropped), were the result of standing waves propagating throughout the lake. His first paper on this subject was published in 1873, and he continued to amass data from his own observations and from other sources around the world. He constructed a series of automated instruments (called limnographs) that could obtain a continuous record of lake level. These devices followed the design of tide gauges used by oceanographers, but unlike the marine versions at the time, they could resolve mm-level fluctuations in water level, and even picked up the vibrations of steam ships passing many km away.

Over the subsequent 20 years, Forel worked with many colleagues at Lake Geneva, Lake Constance and elsewhere to define the properties of surface seiches, and he corresponded on this subject with scientists around the world. Always the great networker, he sought out the mathematical expertise that he needed to develop a quantitative theory of seiches. One of his contacts at the University of Leipzig passed on to him a treatise published in 1828 by a family member, a mathematician by the name of J-R Merian who had applied Lagrangian analysis to the problem of water movement in a rectangular tank. Forel transformed and applied this equation to lake basins, and found that he could estimate the average depth of the lake based on the period (t) of the seiche. In a letter to Forel dated 6 October 1876, Professor William Thomson, better known as Lord Kelvin, showed how the Merian-Forel formula could be simplified for the condition that lake depth (z) is very small relative to lake length (L), to produce the elegant approximation: $t = L/\sqrt{(g\,z)}$.

- **SLIDE 10**

  Forel's success as a researcher was the combined result of many attributes:

  His deep curiosity and intuition about the natural world; his great pleasure in asking questions and proposing hypotheses; his enormous capacity to collect and synthesize information; his ability to carefully observe the environment and obtain large quantities of new data; his development of new technologies and approaches such as the limnograph; and his ability to devise experimental tests of his ideas, in both the laboratory and the lake. Most importantly, he talked about, shared and published his findings. Forel was a superb communicator: a prolific correspondent, with a global network of contacts. He would have loved Email!

- **SLIDE 11**

  All of these abilities came together in his founding of a new integrative science, which he called 'Limnology'. Forel had used this word earlier in his career, for example in his 1886 publication "Program for limnological studies of subalpine lakes". But it was in the Preface to Vol. I of his 3-volume treatise on Lake Geneva entitled "Limnological Monograph" that he explicitly defined this new discipline (Forel 1892).

- **SLIDE 12**

  In this first volume, Forel then went to describe the physical setting of Lake Geneva: its geographic position, shores, sediments, geology including the origin of the lake, local climatology, and hydrology. This volume also included a new bathymetric map of the lake based on a synthesis of thousands of soundings from his own work, and also from others, notably from the renowned French limnologist André Delebecque.

  The book was aimed toward many types of reader: Fellow scientists of course, but also other readers interested in "an explanation of natural features that they are intrigued by or admire", the people who live around the lake "for whom the vast water mass of Lake Geneva is an ocean that intervenes in so many aspects of their individual lives and society”, and the boatmen and fishermen “who live on the lake, who live from the lake, and who hold the precise knowledge and methods for their professional activities” (p.XI).

- **SLIDE 13**
  The second volume was published in 1895 and covered hydraulics, including his favorite subject – seiches - as well as wave and currents, the thermal regime of the lake, optics, acoustics and lakewater chemistry.

- **SLIDE 14**
  Forel described how there were many types of currents in the lake:
  1. Overall transport from the inflows to the outflow
     “The lake is simply an enlarged river”.
  2. Thermal convection – autumnal cooling.
  3. Wind-induced currents – plus upwelling
  4. Atmospheric pressure effects
  5. Seiche induced currents

  He classified inflowing density currents in category-1, and realized that these might explain the curiously low bottom temperatures of Lake Geneva by comparison with other lakes at a higher altitude.

- **SLIDE 15**
  With a reversing thermometer, Forel was able to obtain dozens of vertical profiles of temperature of the lake. The summer profile resembled that of Lake Tahoe, obtained by Professor John Le Conte, one of his many correspondents. But the hypolimnetic water temperatures were lower, possible reflecting the cold glacial waters of the upper Rhone which enter the eastern end of the lake and then plunge to the bottom as a result of the colder temperatures and the high sediment load from the glaciers.

- **SLIDES 16-20**
  This series of satellite images from Google Earth shows the origin of the upper Rhone River with its grey-colored sediments (‘glacial flour’) from the glaciers that feed it, and its entry into Lake Geneva, where it disappears from view a little offshore as a plunging density current that then flows along the bottom of the lake.

- **SLIDE 21**
  Forel noted that the thermocline of Lake Geneva could rise or descend markedly over the space of a few days, for example August 28th versus 21st, 1890. However, he erroneously attributed thermocline tilting to the mixing of more dense water, for example from the Rhone at the western end of the lake (Forel 1895, p.354). In fact the evidence and theory from Scotland of internal waves (Wedderburn and Williams 1911) came late in his career, and he was reluctant to accept the possibility of internal seiching, now well known in Lake Geneva. But as Mortimer (1979) notes, these discoveries were all connected: "F. A. Forel's classic seiche investigations on Léman led directly to E. M. Wedderburn's pioneering studies of internal seiches in Scottish lakes and, in turn, to theoretical and experimental advances elsewhere, including the Great Lakes of North America."

- **SLIDE 22**
  Comparing the seasonal temperature profiles with other lakes led Forel to develop a classification system based on stratification regimes – lakes that stratify in winter under the ice (which he called 'polar lakes'), lakes that stratify only in summer (which he called 'tropical lakes'), and lakes that have both periods of stratification. Hutchinson (1957) later acknowledged and adopted Forel's approach, but introduced a more logical terminology based on the timing and frequency of full water column mixing each year: cold monomictic, warm monomictic, dimictic, etc.

- **SLIDE 23**
  Forel was fascinated by all aspects of the interplay between light and lake water. To quantify the clarity of fresh waters, he established a standard protocol for the use of the Secchi disk, a white circular plate that had been invented by Priest Angelo Secchi to measure the transparency of the Mediterranean Sea. It was extensively tested by Forel in Lake Geneva as early as 1874 (Forel 1895, p. 410), only a few years after its publication (Secchi 1866). He then applied his standardized Secchi disk method to describe the seasonal dynamics of lake water transparency, showing the variations from around 15 m in winter to around 5 m in summer.
  Photo: A black and white Secchi disk being lowered over the side of a boat.

- **SLIDE 24**
  He also developed a number of novel approaches in hydrologic optics, including an *in situ* method based on photographic plates to measure photochemically active radiation,
  (details in Vincent 2012a).

- **SLIDE 25**
  Forel was also interested in optical phenomena at the lake surface, including reflection and mirages, including the Fairy Morgan (Fata Morgana) phenomenon that has intrigued ocean sailors for centuries (Forel 1912). The Fata Morgana is a mirage caused by thermal gradients in the atmosphere, and it appears as a dark narrow bar above the horizon. It was named after the Fairy Queen Morgan, an enchantress who appears in the legends of King Arthur. The story goes that she created these 'fairy castles' in the air to lure sailors inshore, onto the rocks and to their deaths. These mirages are apparent during periods of thermal air inversion at Lake Geneva.

  Forel (1912) compared different types of mirages, and began his paper:
  "Among optical phenomena which originate over the surface of water there is one so ill-defined and ill-observed as to be still mysterious; till now it has received no valid explanation. The Italians call it the Fata Morgana."

- **SLIDE 26**
  He asked the question: what determines the color of lakes? He developed a color scale for lakes, and determined experimentally that colored dissolved organic matter (CDOM) could give rise to the green coloration of Lake Geneva's coastal waters receiving inflows from wetland areas.

- **SLIDES 27-30**
  Forel was intrigued by the extreme clarity and deep blue color of Lake Tahoe, California-Nevada, USA, that had been reported on by John Le Conte, a professor of physics and limnologist who served as president of the University of California. Forel wrote to Le Conte about Lake Tahoe's 'blueness', and diverse other subjects. Below is a full transcript of the reply letter to Forel from Le Conte, held at the Lake Geneva Documentation Centre, Lake Geneva Museum (Musée du Léman), Nyon, Switzerland:

Berkeley California

April 9th 1884

Prof. Dr. F.A. Forel
Morges, Switzerland.

My Dear Sir :

Your highly esteemed and appreciative letter of Feb 10th is at hand, and I hasten to reply.

The superior transparency of the waters of Lake Tahoe as compared with Lake Leman, arises, doubtless, from the fact, that there are no moving glaciers in the hydrographic basin which supplies water to the affluents of Lake Tahoe. The masses of snow which remain all the year in some of the deep gorges which furrow the sides of the surrounding amphitheatre of mountain peaks which environ this lake, never assume the character of true glaciers; they remain in the condition of névé. Consequently, the sub-glacial streams which supply the affluents of Lake Tahoe are not so heavily charged with attenuated glacial mud, as those which supply Lake Leman. It seems to me, that this cause is adequate to explain the difference in limpidity of the waters of these two Lakes.

With regard to the question "Why the Bodies of the Drowned do not Rise", I accept your idea of pressure as an important supplement to my explanation of this phenomenon. It is evidently a vera causa; for the volume of the generated gases must be modified by the greater or less pressure to which they are subjected, and consequently the buoyancy must be correspondingly modified.

In relation to the "Seiches" of Lake Tahoe, it is very difficult to secure trust-worthy observations by any resident on its shores. Scientific men can only make short summer visits to it ; not long enough to furnish satisfactory results. I shall endeavor, however, to establish one of your self-registering instruments at Capt. McKinney's house on the western margin.

I agree with you that the deep-water fauna of this Lake is a most inviting field of research and discovery for the rising generation of American naturalists. But in as much as such investigations require protracted residence on the shores of the Lake, and the application of more or less expensive appliances, it is difficult to find an investigator. Surrounded as you are with all the adjuncts of an old civilization, it is difficult for you to appreciate the conditions of our new and undeveloped civilization. The overwhelming influence of the commercial spirit, almost paralyzes the genuine seeker after truth. The worship of gold inspires all classes of society; and the true scientific spirit is consequently stifled.

I beg leave to return you my most sincere thanks, for the interesting papers which you have sent me in relation to the Natural History of Lake Leman. Previously, I had only seen such of your contributions as were published in the "Archives des Sciences".

Reciprocating your desire to establish closer scientific relations, I remain, with sentiments of the highest regard and esteem,

Yours Most Sincerely,
John Le Conte

- **SLIDE 31**
  Forel's interests included a wide range of biogeochemical topics, including the organic carbon pools of lakes. He observed that the concentrations of dissolved organic carbon in Lake Geneva were low but variable, perhaps associated with variations in rainfall and

runoff, and he posed the question, highly relevant to research in limnology and oceanography today: “What is the nature of these organic materials in the lake water? This question has not been sufficiently studied” (Forel 1895, p. 616).

He compiled dissolved gas measurements from Lake Geneva. For example, on the sampling date of 30 November 1880, the lake was still stratified, but well oxygenated even at the bottom. He reported a value of 7.08 cm^3 O_2 L^{-1} at 300 m depth (Forel 1895, p. 622), establishing an important baseline value for gauging change in Lake Geneva during its period of rapid eutrophication in the 20^{th} century.

Today we view lakes as landscape features that are intimately coupled to their surrounding watersheds, and Forel provided some of the first evidence of this. In the chapter “Dissolved materials in the water of the lake” he linked lake chemistry to catchment properties, for example: “The sulfate concentration of 64 mg [L^{-1}], chalk sulfate in particular, is considerable. It is due to the presence of gypsum in many valleys of the watershed, in particular in the large valley of the Rhone…” (Forel 1895, p.608).

On the same theme, Forel emphasized that a lake cannot be considered a closed system: "Rather, it communicates with the rest of the world, via its constant exchange of gases with the overlying atmosphere, via its outflow of water carrying away dissolved and non-dissolved substances, and via its tributaries that deliver new materials into the lake" (Forel 1891, p.3).

- **SLIDE 32**
  Forel published Volume 3 of his monograph in May 1904. From his childhood onwards, Forel was acutely aware of the significance of Lake Geneva to the people who lived around it, including for the many generations of his own family who lived at Morges. In his development of the new science of limnology, Forel made it clear that human activities, past and present, were part of the structure and functioning of lacustrine systems. In this third volume he lists the aquatic and semi-aquatic biota of the lake ecosystem. At the top of the list, his first species was *Homo sapiens.*

- **SLIDE 33**
  <u>Vertebrates</u>
  MAMMALS,
  PRIMATES:
  Man, *Homo sapiens* L., is not an essentially aquatic species, but has become so by way of his activities; the calling of fishermen, sailors, ... etc results in many such people living a semi-lacustrine life, making mankind almost an erratic species of the lake fauna.” (Forel 1904, p. 26). Forel goes on to note that humankind also has negative impacts on the lake waters: “he builds ports and quays, he channels the inflows, he dams the outflow, he discharges into the lake the products of his factories, the sewers of his villages, the ashes of his steam

boats etc. All of these actions modify the lake environment, and directly or indirectly impact on the biological functions of its inhabitants. Mankind exerts a more powerful effect than any other animal on Nature and its inhabitants" (Forel 1904, p. 26).

- **SLIDE 34**
  Forel's perspective is especially relevant to the challenges we face associated with climate warming in the Anthropocene. If he were here today, Forel would likely encourage us to pay close attention to the role of humans in the biosphere, and to understand the human presence as a component part of all aquatic ecosystems. Today we consider lakes as integrators as well as sentinels of global change (Williamson et al. 2009).

- **SLIDE 35**
  There is evidence that climate change is already having effects on the Lake Geneva ecosystem, with records over the last five decades indicating increases in hypolimnetic water temperature (but with large year-to-year variations), changes in mixing and stratification, and shifts in the spawning dates of some fish species, including whitefish (*Coregonus lavaretus*). Details are given in Anneville et al. (2013), and the title of their article shown in French on the top right of this slide "L'empreinte du changement climatique sur le Léman" translates as "The footprint of climate change on Lake Geneva".

- **SLIDE 36**
  Volume 3 of the Forel monograph (Forel 1904) presented a detailed compendium of information about the plant and animal species of Lake Geneva, including invasive species. For example, he observed the plant *Elodea canadensis* with great concern when it entered the lake as an invasive species. He also described the introduction and rapid expansion of mute swans on the lake and reports, with notes on their phenotypic variation and sexual behaviour: "Although of very little intelligence, swans can have strong passions and even show signs of corruption that are truly deplorable." (Forel 1904, p. 38).

- **SLIDE 37**
  Forel recognized the importance of microbes in the lake, and their critical role in carbon and nutrient cycling. "No serious analysis, to my knowledge, has indicated any lake water completely free of microbes" (Forel 1904, p 360). He pointed out that the bacterial population size is especially high in the surficial sediments, in rivers, in waste water, and parts of the lake near sewage outfalls, with lowest concentrations in the offshore pelagic zone. He separated the bacteria into functional groups, and underscored the essential role that they play in the carbon cycle of lake ecosystems through the degradation ("putrefaction") of organic materials.

Earlier in Volume 2, Forel had noted that even clean natural waters contain microbes, and he cautioned the reader not to be alarmed about this: “Secondly, and this is a very important point, all microbes are not necessarily unhealthy. Much to the contrary, the immense majority of these minute beings are completely harmless” (Forel 1894, p. 637).

Forel embraced the Forbes (1887) metaphor of ‘lakes as microcosms’ in the sense that different communities of organisms play different, interconnected roles in the ecology of the lake, with benthic invertebrates working alongside microbes in the processing of detritus: “In this microcosm that is Lake Geneva, what is the specific role, or in other words, the function or value or place in Nature, of the organisms associated with each of the diverse biological communities that we recognize? The role of the deep fauna is simple. The little animals that comprise this community use the residues and debris that fall from the upper layers to the lower layers, into the deep waters of the lake. These little beings, obscure and modest, are workers in their way: they feed, they excrete, they reproduce. They live like the scavengers of our cities, like the dogs of Constantinople, on the left-overs from the table of others; they collect everything that falls to the bottom of the lake.” (Forel 1904, p. 381).

Decades later, Raymond Lindeman (1941) praised Forel for providing “a brilliant exposition of the general nature of food cycles that will serve even today as an introductory account of trophic relationships”.

- **SLIDE 38**

In Volume 3, Forel introduced the concept known today as ‘geosystem and ecosystem services’ and the benefits to human society provided by the ‘natural infrastructure’ of lakes, although of course did not use these modern terms. He first described the evidence of neolithic villages along the shores of Lake Geneva and other European lakes, thousands of years ago, which his father (an amateur archeologist and historian) had first introduced him to in his youth. The houses were built on raised pilings or stilts, the remains of which are still visible today. Forel suggested that these villages extended out over the lake, which was the popular view at the time. More recent evidence suggests that the buildings were mostly away from the lake edge, but built on these raised foundations to prevent periodic flooding that would be associated with the fluctuating lake levels.

Forel outlined many of the services that the lake would have provided to these early lake shore residents.

Photo: Reconstruction of a Bronze Age stilt village on Lake Constance, Germany, similar to the type surmised from the archaeological remains at Lake Geneva (photocredit: Dietmar Straile, Limnological Institute, University of Konstanz, reproduced by permission).

- **SLIDE 39**

In the final sections of Volume III, Forel (1904) detailed two aspects of Lake Geneva's geo/ecosystem services in quantitative economic terms: ship transport and commercial fishing. He described the long history of navigation on the lake, from the canoes of the stilt villagers to naval vessels, merchant barques, fishing boats and the arrival of steam ships. Forel presented a compilation of the commercial steamship tonnage at the time and its passenger capacity, and to illustrate the commercial value of these activities he reported that the steamship company CGN based out of Lausanne had receipts for passenger and freight services in 1901 that totaled 1.24 million Swiss Francs.

- **SLIDE 40**

Forel described how several fish species (notably lake trout, Arctic char, whitefish, carp, pike and perch) had been part of the diet of lake residents from prehistoric times onwards. He compiled data for the fishery at the time estimating that some 1200 fisherman worked on the lake, and that the fishery generated retail sales of around 1.5 million Swiss Francs per year. He hastened to add that this was a very rough estimate: "Not necessary to emphasize the vagueness and elasticity of this number" (Forel 1904, p. 650). This may be the first quantitative estimate of a 'lake ecosystem service'.

- **SLIDE 41**

In 1901, Forel produced the first textbook on limnology, which he wrote, as always, in his native French language. This was then translated (by a friend and colleague) and published in German. It was not until 15 years later that the first English textbook of limnology appeared (Needham and Lloyd 1916), and in this volume, James G. Needham (1888-1957), Professor of Limnology at Cornell University, refers to Forel as "the Father of Limnology".

Forel's contributions were numerous (a publication list of 288 titles was published with his obituary; Egerton 1962) and diverse, including many publications on glaciology and seismology (including co-authorship of an earthquake magnitude scale, and correspondence with colleagues in Japan and Australia about how earthquakes may induce seiches in lakes).

At the commemoration ceremony for Forel and the unveiling of a special medallion, two years after his death in 1914, Paul-Louis Mercanton noted: "François A. Forel was a great naturalist, his name was known everywhere and for such diverse reasons that many a scholar outside Switzerland thought that there must exist several François Forels" (p.39).

François Forel has been honored in many ways. In recognition of his glaciological contributions, two geographical features are named after him: one in the High Arctic (Greenland), and the other in Antarctica.

The Institute F-A Forel was founded in his name at the University of Geneva in 1980. This limnological institute is renowned for its multidisciplinary studies on lakes (website: www.unige.ch/forel).

- **SLIDE 42**
  A remarkable discovery was made in 2009. In the attic of the ancestral home near Morges (shown in the right hand photo), Forel's great-grandson, François D.C. Forel, discovered an unpublished manuscript that was lost in the family archives for 100 years, written by Forel in autumn1909. It was entitled "To My Grandchildren" and began *"If you ask me how I spent my life, I will try to explain myself to you... I devoted my life to the search for truth in the natural sciences; sometimes attaining it, I believe."* This autobiography with commentaries by contemporary limnologists was published in the original French in December 2012 (Forel 2012).

- **SLIDE 43**
  Subsequent to Forel, over the course of the 20th century, limnology as a science achieved broad interest and support, and developed rapidly.

  Several major figures, influenced by Forel, included:

  August Friedrich Thienemann (Germany, 1882-1960), who directed the Biological Station at Plön and published extensively on chironomid ecology and lake classification. In 1922, Thienemann and Einar Naumann (from Sweden, 1891-1934) founded the International Association for Theoretical and Applied Limnology (SIL) devoted to the study of inland waters.

Edward A. Birge (USA, 1851-1950), with Chancey Juday (USA, 1871-1944), undertook influential limnological studies on Lake Mendota.

G. Evelyn Hutchinson (USA, 1903-1991) contributed many seminal ideas in limnology and evolutionary ecology. Perhaps inspired by Forel's 3-volume monograph, Hutchinson wrote his own encyclopedic 3-volume limnological monograph (a 4th volume was published posthumously), beginning with Hutchinson (1957). This treatise established the foundation for modern limnology.

The most detailed limnological text since that time, encompassing flowing waters as well as lakes, is by Robert G. Wetzel (Wetzel 2001). A comprehensive, 3-volume encyclopedia covering limnology in its broadest sense has been compiled and edited by Gene E. Likens (Likens 2009).

A brief history of limnology is given in many limnological text books, for example Horne and Goldman (1994), Kalff (2002) and Dodson (2005). More detailed accounts have been published by Elster (1974), Steleanu (1989) and Egerton (2014).

- **SLIDE 44**
  Many limnological societies developed around the world in the 20th century. The Limnological Society of America (co-founded by Juday) merged with the Oceanographic Society of the Pacific in 1948 to create ASLO, now known as the 'Association for the Sciences of Limnology and Oceanography'.

  The flagship ASLO journal 'Limnology and Oceanography' was founded in 1956.

  Freshwater scientists in many other countries also founded national limnological societies, as well as participated in SIL.

- **SLIDE 45**
  François Forel made many lasting contributions to our understanding of aquatic ecosystems and how to study them:

  In founding the science of 'limnology' he drew attention to the interconnectedness of all aspects of lakes

  His career provides many compelling examples of the power of networking, collaboration and synthesis

  In contrast to the view of 'Man against Nature', Forel described how humans are a component part of lake ecosystems. He drew attention to the value of lake ecosystem services such as fisheries, drinking water, transport and aesthetics, and our capacity to inadvertently disrupt those services by severely degrading the aquatic environment.

  He made a myriad of specific contributions – from morphometry and lake physics to the food webs, microbes and the freshwater carbon cycle.

His perspective on lakes as coupled physical-chemical-biological-human systems is highly relevant to understanding the effects of climate warming and other planetary scale effects on lakes, and it sets the path toward an integrative ‘limnology of global change’ that is needed to address our many challenges ahead.

- **SLIDE 46**
We thank the Forel Family and the *Lake Geneva Museum Documentation Centre* for access to unpublished material; Carlos Duarte, John Dolan, Michio Kumagai, John Downing and Irene Gregory-Eaves for their encouragement of this ‘voyage of discovery’ to learn more about Forel; all participants in the *ASLO-Japan Special Session* commemorating François A. Forel, 1841-1912 (Vincent 2013); and François D. C. Forel (great-grandson of F. A. Forel) and Jacqueline Porret-Forel (granddaughter of F .A. Forel) for enjoyable discussions and for their continuous support and encouragement of this project.

We thank Jason Emmett for technical editing of the lecture, and the editors and anonymous referees for their helpful feedback and suggestions. Photographs of the Forel manuscripts and other material, and translations from Forel’s original texts are by the authors, unless otherwise acknowledged in the slide notes.

- **SLIDE 47**
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Warwick F. Vincent is a professor of biology at Laval University (Université Laval) in Quebec City, Canada, where he is also Scientific Director of the Center for Northern Studies (CEN) and Canada Research Chair in aquatic ecosystem studies. Warwick grew up in New Zealand, and graduated BSc (hons) in botany and cell biology at the University of Auckland. He obtained his PhD in ecology at the University of California, Davis, under the supervision of Professor Charles R. Goldman, and then undertook postdoctoral studies at the Freshwater Biological Association in the English Lake District. He worked as a research scientist on lake and oceanographic projects in New Zealand, Field Director at Lake Titicaca, Peru-Bolivia, visiting professor at the University of Kyoto and the Lake Biwa Environmental Research Institute, Japan, and as a researcher on Antarctic, and more recently Arctic, aquatic ecosystems. In 1990, he moved from the Lake Taupo Research Laboratory, New Zealand, to Laval University, Québec, where he learned French in order to teach limnology and oceanography in French Canada. One of the unforeseen benefits was that he became able to read Forel's 3-volume treatise on limnology, published only in French, and to appreciate the remarkable scope and depth of Forel's insights into lake ecosystem science. This ultimately brought him to Lake Geneva to learn more about Forel and the origins of limnology.

Carinne Bertola is Project Coordinator at the Lake Geneva Museum (Musée du Léman) at Nyon, Switzerland. Carinne grew up in Nyon, on the shores of Lake Geneva, and at an early age developed an interest in the social sciences. She obtained her Masters degree in sociology at the University of Geneva, and her PhD in museum science at the National Museum of Natural History (Musée national d'histoire naturelle) in Paris, France. Her first contact with the work of François Forel was in 1997 when the Forel family donated many original documents to the Lake Geneva Museum Documentation Centre, including his handwritten drafts of the 3-volume monograph. She has worked with scholars from around the world interested in Forel, including Dr. Yukiko Kada, former Deputy Director of the Lake Biwa Museum, and currently Governor of Shiga Prefecture, Japan. Carinne has produced many publications on the history, science and culture of Lake Geneva, including her edited volume "Bertola, C., C. Goumand and J.F. Rubin [eds.] 1999. Découvrir le Léman: 100 ans après François-Alphonse Forel [Discover Lake Geneva : 100 Years after François-Alfonse Forel]. Editions Slatkine, Geneva, 922 pp; and Bertola, C. 2009. Léman Maniac [Crazy about Lake Geneva], Éditions Glénat, Nyon, 189 pp.