Climate Change and Aquaculture: Literature Review

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Climate Change and Aquaculture: Pacific workshop

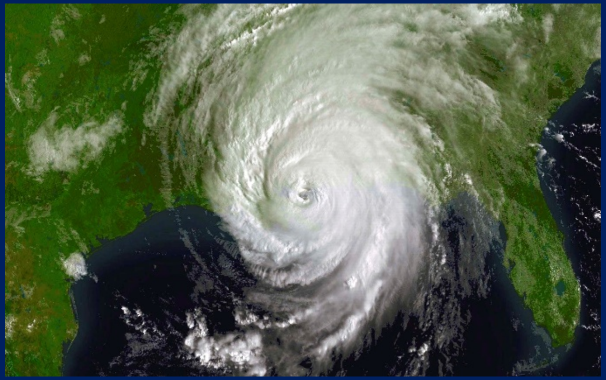
Coast Discovery Inn

Campbell River, British Columbia, Canada

24 June 2015

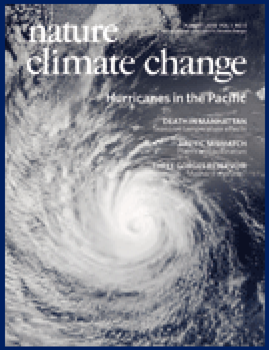
Introduction

- Climate change - most pressing environmental concern of our era
- Climate change current and predicted conditions are likely to affect all aspects of human lives
- Global reliance on aquaculture = food security + dietary preferences + increasing population
- Global wild fisheries landings are predicted to decrease 10% by 2050; aquaculture is expected to meet anticipated demand (Barange et al., 2014).



NOAA

Introduction



- Research on climate change has grown exponentially, with many new journals dedicated exclusively to the subject

- Climate change research on aquaculture is still relatively new → more on some aspects than others

- A 'big picture' may require additional data gathering approaches:
  - Extrapolation of effects from fisheries and feral species research
  - Industry reports
  - Comparisons with terrestrial agriculture
  - International assessment initiatives

- This presentation is intended to review climate change and aquaculture from a global perspective, while workshop sessions and break-out groups will have a regional focus

Introduction

This presentation will explore:

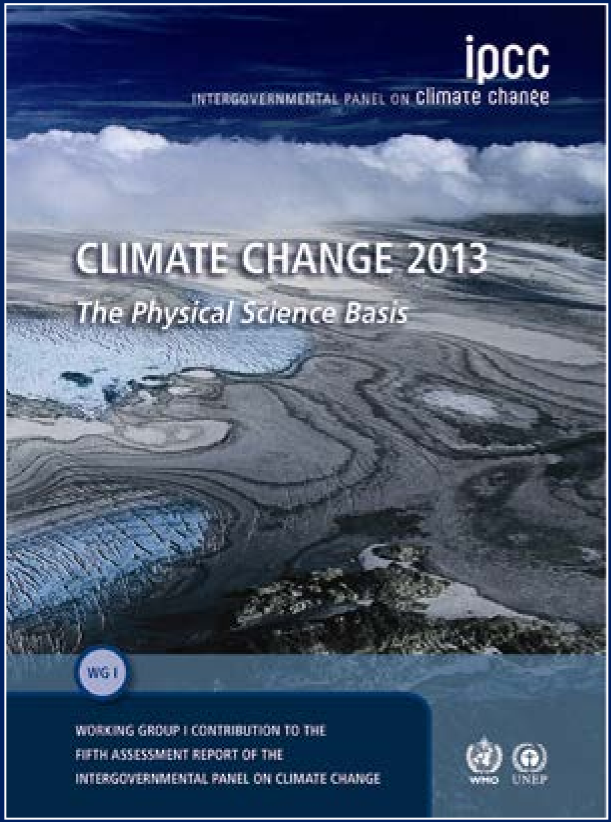
1. Physical effects
2. Biological response
3. Trends?
4. Mitigation potential

PHYSICAL EFFECTS

Photo by Environment Canada

IPCC Assessment Report

- Intergovernmental Panel on Climate Change (IPCC) leading international body for the assessment of climate change
- Established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO)
- Main activity every 6-7 years is Assessment Reports of the state of knowledge on Climate Change
- Recently (October 2013) the IPCC released its 5th Assessment Report (AR5)
- Produced by over 600 contributing authors from 32 countries



IPCC (AR5) summary of oceans, highly simplified

- The oceans have become a sink for 93% of the earth's additional energy inventory (between 1971-2010)
- Sea level rise: thermal expansion of seawater and glacier melting are considered the dominant contributors (mean 0.19m increase in mean sea level from 1901 to 2010)
- Evidence of increased stratification, size of oxygen minima zones and wave heights
- Anthropogenic CO_2 has caused a gradual decrease in pH, by 0.1 (≈ 26%) since the beginning of the industrial era

Physical Effects: Sea Level Rise

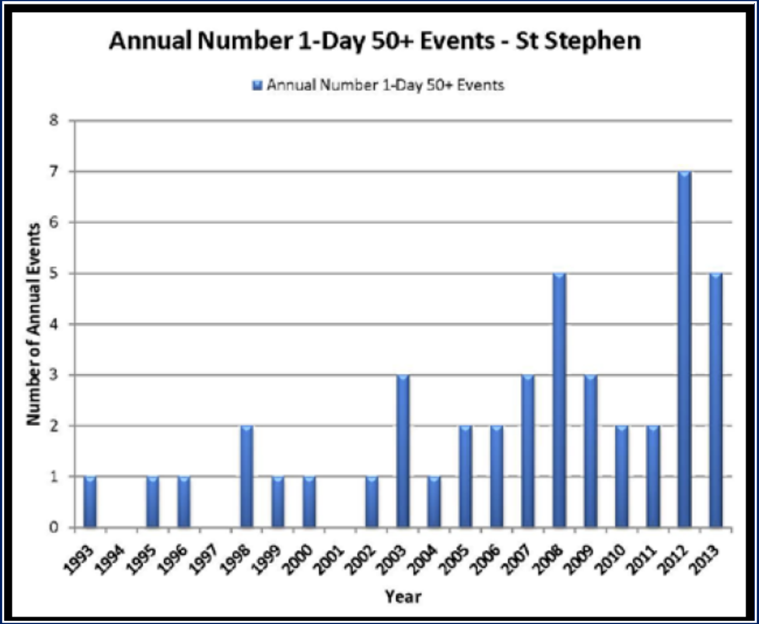
- Global mean sea level rise of 1.2 ± 0.2mm per year between 1901 to 1990, and almost 3 times that (3.0 ± 0.7mm yr^{-1}) between 1993 to 2010 (Hay et al. 2015)
- Thermal expansion accounts for 30-55% of the global mean sea level rise, and glaciers for 13 to 35% (Rye et al. 2014)
- Sea-level rise is not expected to be the same everywhere – hot spots e.g. American Atlantic 3-4 times higher (1950 to 2009, Sallenger et al. 2012)
- Sea-level rise can also be affected by:
  - El Niño Southern Oscillations (Cazenave et al. 2014)
  - Pacific Decadal Oscillation (Mantua et al. 1997)
  - Pacific Gyre Oscillation (Di Lorenzo et al. 2008)
  - Variations in sea surface temperature, causing local convergences of water masses and resulting in higher sea levels (King et al. 2011)
  - Collapse of the Antarctic-ice sheet (not expected until 2100?)

Physical Effects: Storm Potential

- **Wind intensification** – likely greater at higher latitudes (Sydeman et al 2014), possibly linked to stronger warming trends in polar rather than equatorial regions (Baumann et al. 2013)
- There is **low confidence of any trend of tropical storm** frequency or intensity in any ocean basin, although there is robust evidence for an increase in the most intense tropical cyclones in the North Atlantic basin since the 1970s (Rhein et al., 2013).
- **Increased occurrences of tropical cyclones** in the Caribbean and landfall Typhoons are expected in some areas (East Asia), but changes to hurricanes are uncertain (Stocker et al., 2013).
- There is some evidence (**medium confidence**) that **wind stress has increased** in areas such as the Southern Ocean and that average winter wave heights have increased in the North Atlantic (since the 1950s) with a reported trend of 20cm per decade (Rhein et al., 2013).

Physical Effects: Flood and Storm Potential

- Most aquaculture is located in water bodies, on coastal lands and almost always near a water source → **potential flood plain**
- Sea level rise can impede river discharge to the sea = **longer flood periods** and larger inundation areas (Nguyen et al., 2014)
- **Fish kills** from floods are mainly due to low oxygen in flood waters (Idris et al., 2014) and mortalities often associated with pond culture (Bell et al., 2010)
- There is strong evidence that the frequency and intensity of **heavy precipitation events** has increased in some continents such as Europe and North America and less precipitation and in other regions such as Southern Europe and central America (IPCC, 2013)



Annual number of days that precipitation was 50mm or greater, including snow water equivalent and rain combined, at the St. Stephen airport (Daigle 2014)

Physical Effects: Flood and Storm Potential

- **Storms** can be devastating to coastal aquaculture operations (Luening 2013)
- **High winds and waves** destroy structures used for coastal aquaculture such as embankments, pond dikes, sluice gates, hatcheries, electricity poles and rearing structures (Rahman and Hossain 2012)
- **Large-scale escape** events form sea-cages are correlated with storm events (Jensen et al. 2010)
- **Inaccessibility** to damaged cages due to ongoing weather severity (Dodd 2011)
- A 2010 Mexican experience illustrates the extreme potential for storm damage. Three storm events caused flooding and structural damage, **reducing the annual tilapia production by 80 percent** due to the devastation of 1200 uninsured farms; the pre-2010 production level has yet to return (Reid and Jackson, 2014)


TENENEXPAN


LAS GOLONDRINAS, BOCA DEL RIO


LA CONQUISTA, PASO DE OVEJAS

Photos courtesy of Diego Esteban Platas Rosado

Physical Effects: Internet Search of 'Fish Hatchery and Flood'


Lanesboro fish hatchery scrambles to recover from flooding

Story | Comments | Image (2) | Print | Font Size:

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Posted: Wednesday, June 26, 2013 9:37 am | Updated: 10:14 am, Wed Jun 26, 2013.

Marion Renault, mrenault@postbulletin.com

Scott Jacobson / sjacobson@postbulletin.com

Its crew is tearing out carpeting and cleaning mud from its offices, but the Lanesboro State Fish Hatchery has bigger fish to fry.

At 6 a.m. Sunday, workers got a call from hatchery supervisor Pat Schmidt saying that the water had risen 40 inches after Saturday's flooding.

Lanesboro State fish hatchery flood, Lanesboro, Minnesota, June 2013 (postbulletin)

Bellvue-Watson fish hatchery flood, Colorado, September 2013 (fox31 Denver)

Belize coast, Hurricane Richard damage, October 2010 (ANA 2012)

Oak Bay hatchery flood, New Brunswick, December 2010 (St. Croix Courier)

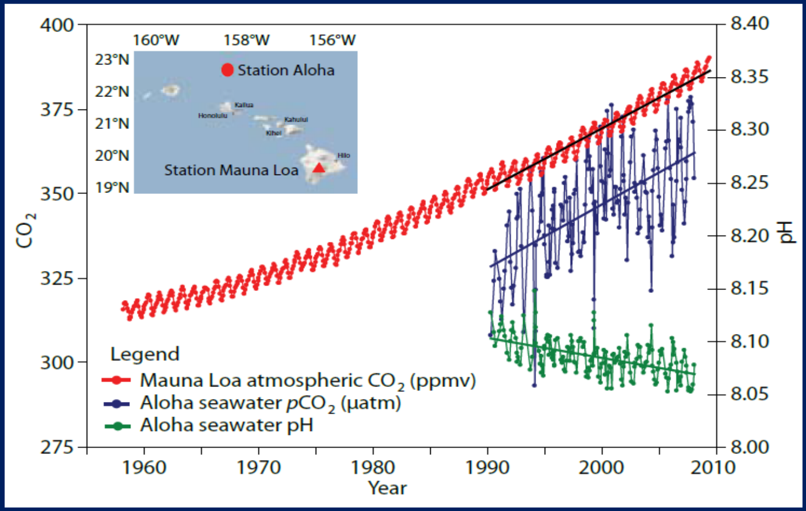
Bow habitat station fish hatchery flood, Alberta, June 2013 (worldpress)

White River National Fish Hatchery flood (Hurricane Irene), Vermont, August 2011 (flickr)

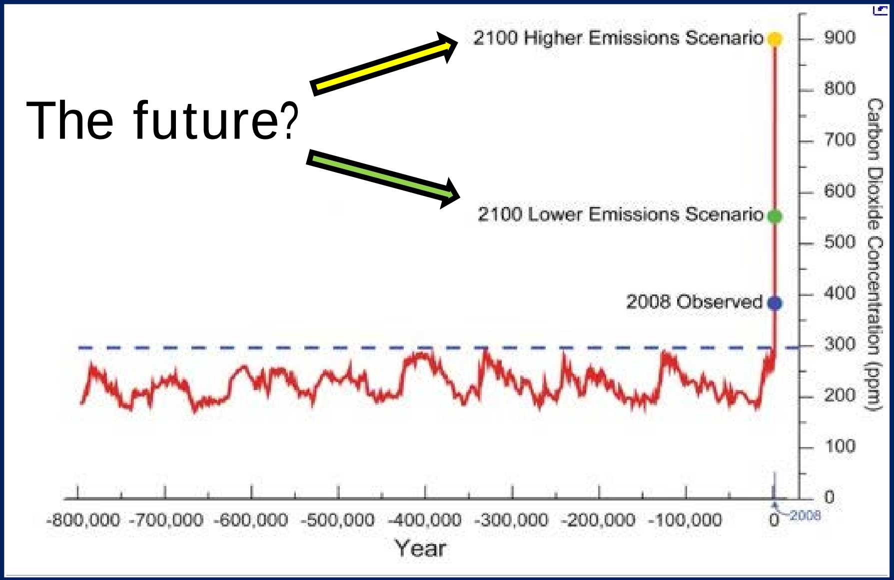
Physical Effects: Ocean Acidification

- Anthropogenic carbon dioxide ↑
- Buffering ocean capacity ↓
- Increase hydrogen ions =

↓ ocean pH = acidification



Feely et al., 2009. Oceanography 22 (4): 36-47



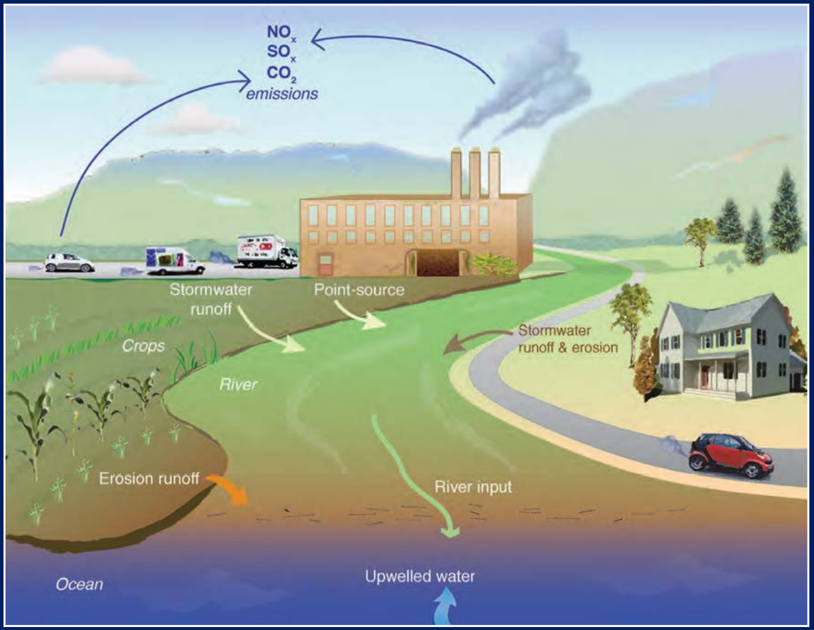
800,000 years ago to 2008

Ocean pH declined by 0.1 unit since industrial revolution (Orr et al., 2005) and expected decrease by another 0.5 unit by end of 2100 (IPCC projections)

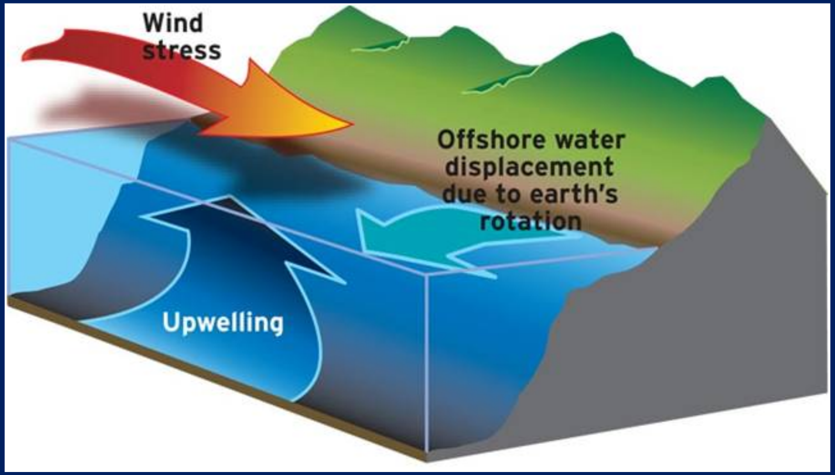
Dewey and Feely

Ocean Acidification – Global and local scale

- **Open ocean vs coastal areas**
- **Local inputs** can increase levels of pCO_2 (Waldbusser et al., 2011)
- Upwelling increasing pCO_2 rich waters in coastal areas (Cooley et al., 2009, Feely et al., 2012)



Kelly et al., 2011. Science, 332(6033): 1036.



NOAA.gov

- River inputs (Salisbury et al., 2008) and watershed changes (Dove & Samut, 2007; Green et al., 2009, Salisbury et al., 2008)
- Eutrophication (Cai et al., 2011)

Complex issue to measure and predict OA impacts

IPCC (WR5) projection of ocean salinity and temperature

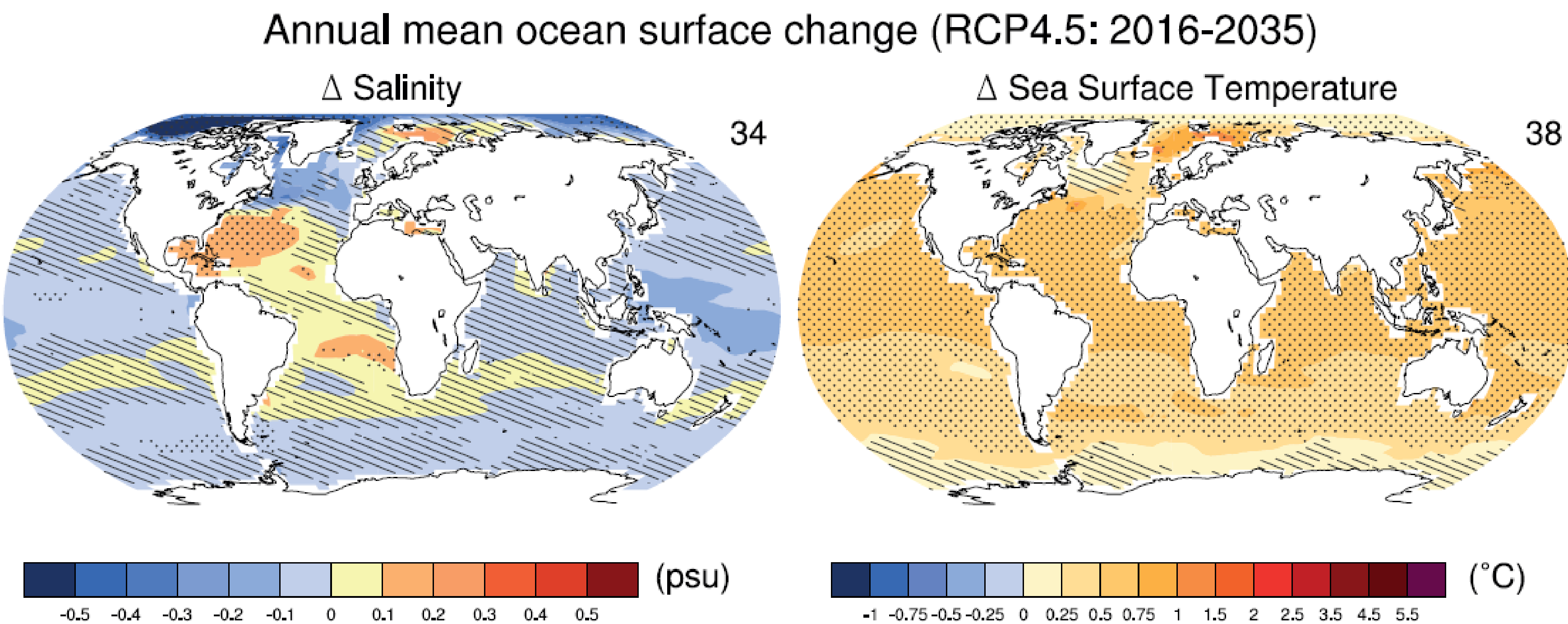
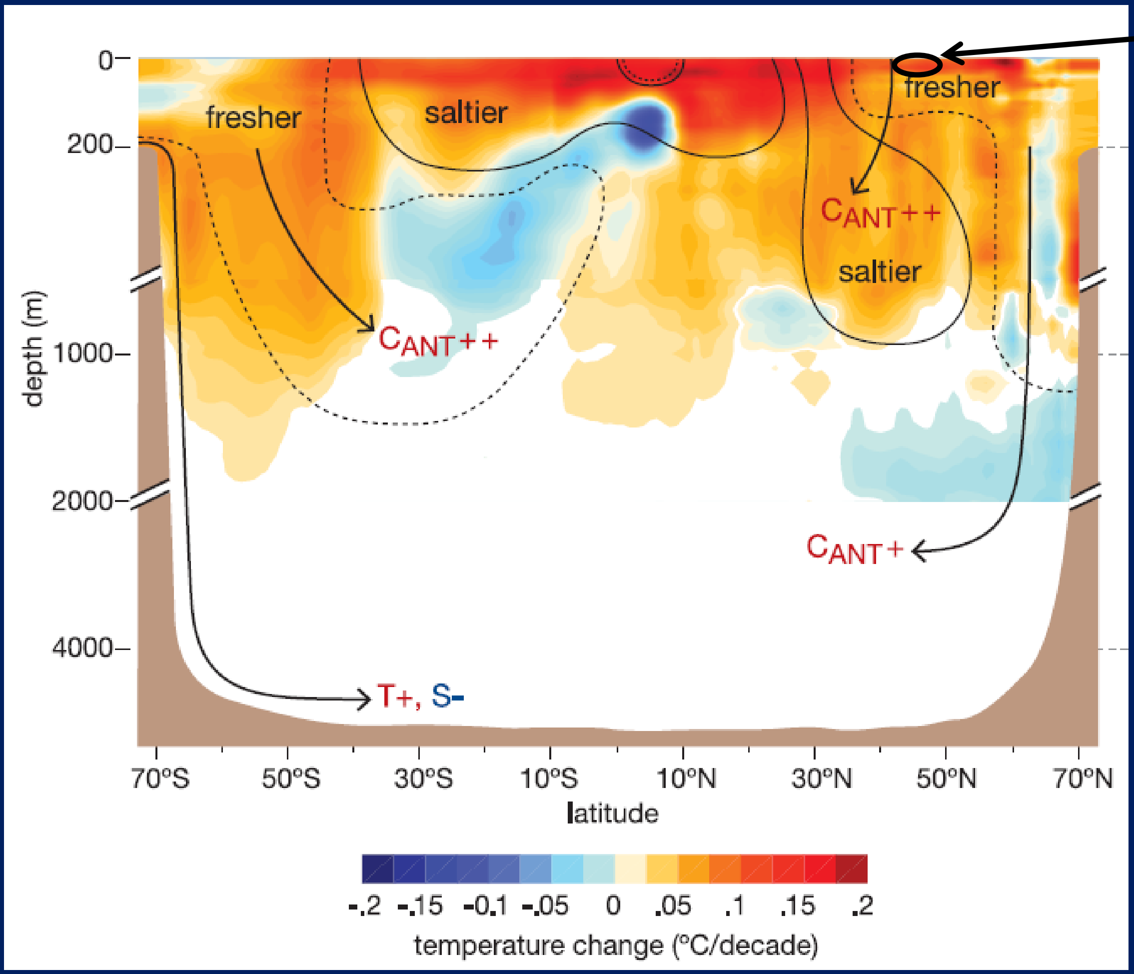


Figure 11.20 | CMIP5 multi-model ensemble mean of projected changes in sea surface temperature (right panel; °C) and sea surface salinity (left panel; practical salinity units) for 2016–2035 relative to 1986–2005 under RCP4.5. The number of CMIP5 models used is indicated in the upper right corner. Hatching and stippling as in Figure 11.10.

- Coastal waters off Canada's east and west coasts, are projected to increase an average of 1°C over the next 20-30 years
- More uncertainty, near-shore and at regional scales

IPCC (WR5) summary of oceans

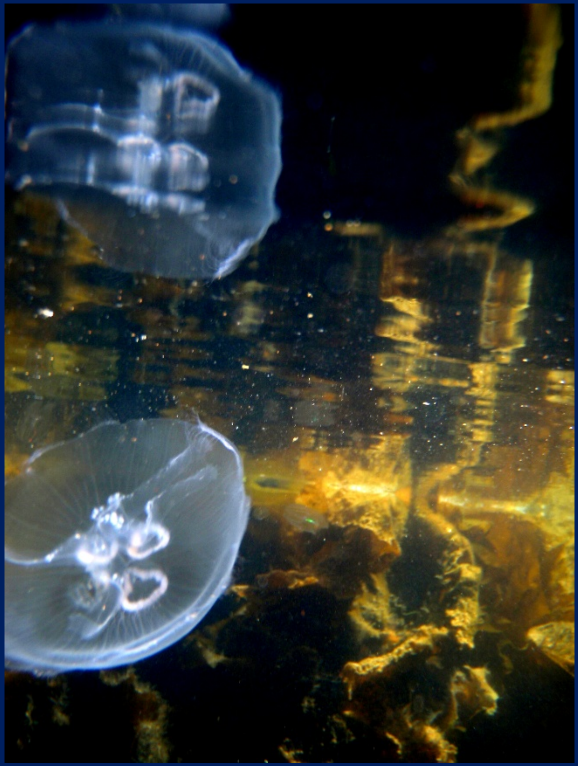


Atlantic Canada location and aquaculture depth

Summary of observed changes in zonal averages of global ocean properties.

Temperature trends (°C per decade) are indicated in color (red = warming, blue = cooling); salinity trends are indicated by contour lines (dashed = fresher; solid = saltier) for the upper 2000 m of the water column (50-year trends from data set of Durack and Wijffels (2010); trends significant at >90% confidence are shown).

BIOLOGICAL RESPONSE



Photos by GK Reid

Biological Response: Impacts on Primary Productivity, Algae and Food Webs

- Micro and macro algae account for **50% of global primary productivity** (Longhurst et al.1995) and account **~50% of the global carbon biogenic fixation** (Field et al., 1998)
- Phytoplankton responds rapidly to environmental change in due to their short generation times, sensitivity to temperature and advection of organisms within water masses (Beaugrand 2009), and are good indicators of climate change (Hays et al. 2005)
- Global sea-surface **temperature increase** is likely to **decreases phytoplankton abundance** in tropical and mid-latitude regions, while **increasing in in higher latitude regions** → tropical areas typically nutrient limited, whereas polar areas are light limited (Richardson and Schoeman 2004, Doney 2006)
- Changes in circulation, nutrient upwelling, salinity and sea level have caused many **warm-water species to expand their ranges** towards the poles, pushing cold-water algal species more northward (Hallegraeff 2010)

Biological Response: Algal Culture

- There are about 37 separate algal species or species groups cultivated in 33 countries, with a total harvest of 23.8 million tonnes (wet weight) with about 9 million MT for human consumption (FAO 2014)

- **Macro-algal species** which are currently CO_2 limited are **expected to benefit** from increases in atmospheric CO_2 and sea surface temperatures more than species which are already CO_2 saturated (Beardall et al., 1998)

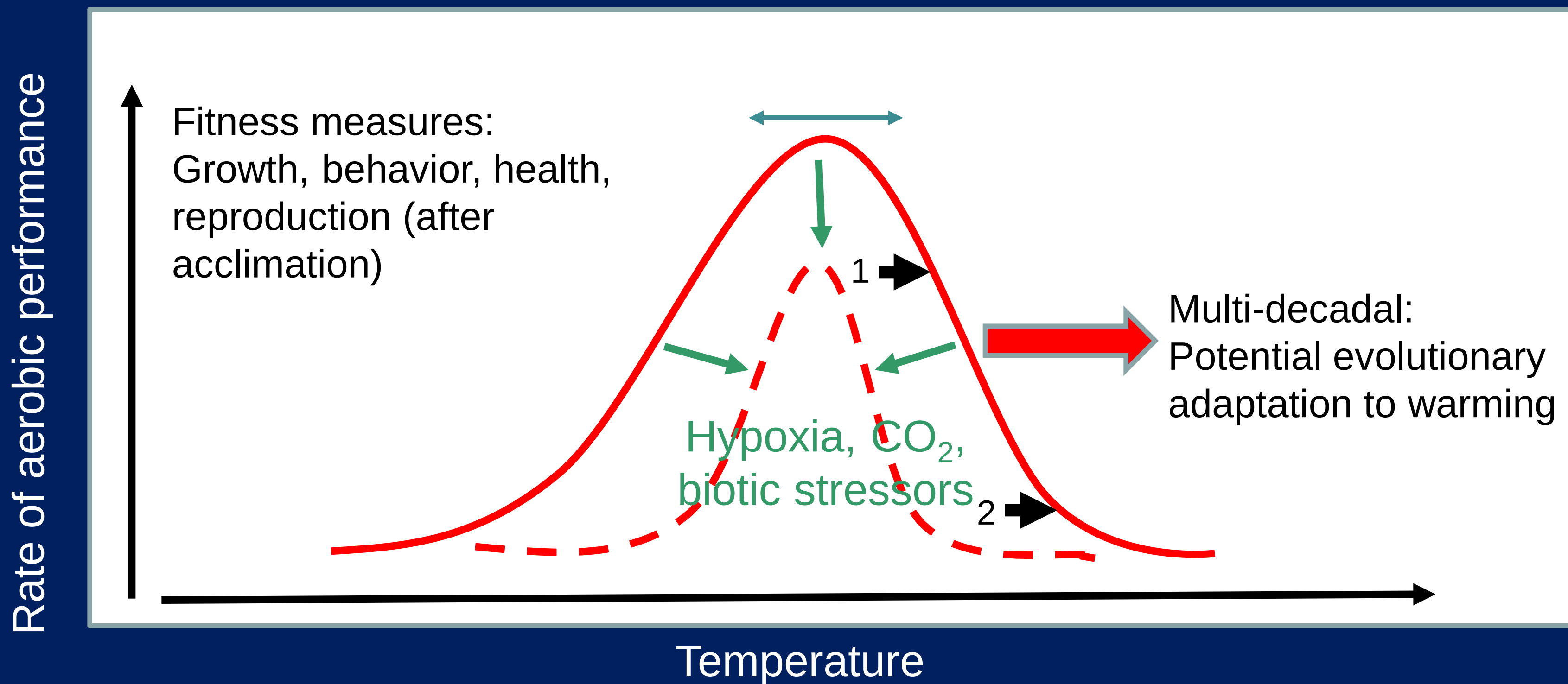
- Also, elevated temperatures **are likely to increase macro-algal recruitment**, but only to a point, as high temperatures have also shown to increase consumption of macro-algae by grazers (Lotze and Worm, 2002)

TEMPERATURE

Biological Response: Temperature

- **Direct effects**: Growth, immune function, osmoregulation, pathogen life-cycles, predator range shifts, reproductive cues, larval survival, diet digestibility, gene expression, metabolic rate, enzyme functionality, and behavior
- **Indirect effects:** on the environment, such as gas saturation, pH, and stratification
- Marine animals have a temperature range of optimal aerobic fitness; as the edge of this range is approached, fitness measures such as growth, health and behaviour are detrimentally effected (Pörtner, 2008)
- **Combined effects:** plus environmental and biotic stressors will reduce the temperature range of aerobic performance
  - operating at thermal limit + small increase in temperature = issue
  - add external stressor = reduce thermal limit

Biological Response: Aerobic fitness of marine animals and ambient temperature



Arrow 1. Animals functioning near the boundary of their "thermal window", but at high residual levels of aerobic performance

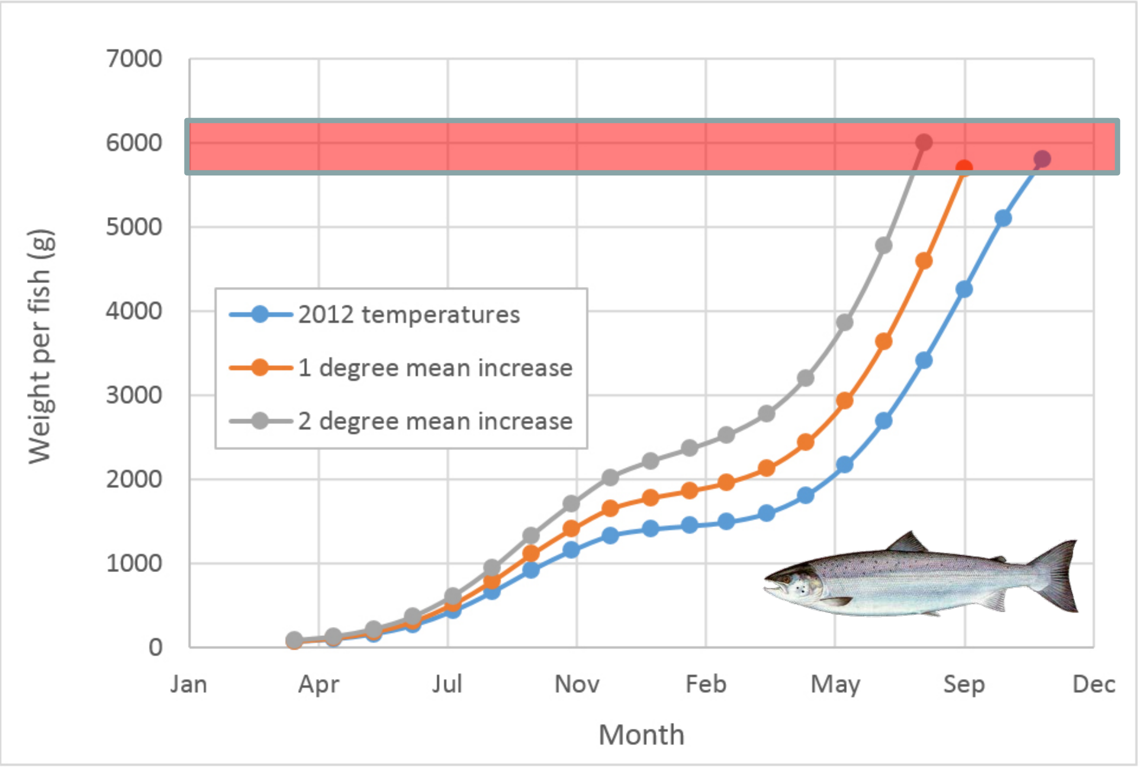
Arrow 2: Tolerance of marginal conditions for a longer time than those at lower levels of aerobic performance

Adapted from Denman et al. (2011) and Pörtner (2010)

Effect of 1-2°C increase on Atlantic salmon production using a predictive TGC

How does an annual mean increase of 1 to 2°C affect Atlantic salmon growth?

- Using an Thermal Growth Coefficient (TGC) of 0.300, which is representative of a present day cultured Atlantic salmon in eastern Canada
- Using mean monthly temperatures collected in Passamaquoddy Bay (Lander and Robinson 2011) as a baseline
- **An increase of 1°C, increases time to market by approximately 2 months, with a 2°C raise increasing time to market by 3 months**



- TGC based on historical performance of growth at temperature days (temp * days), so sub-optimal temperature regimens already embodied in measure

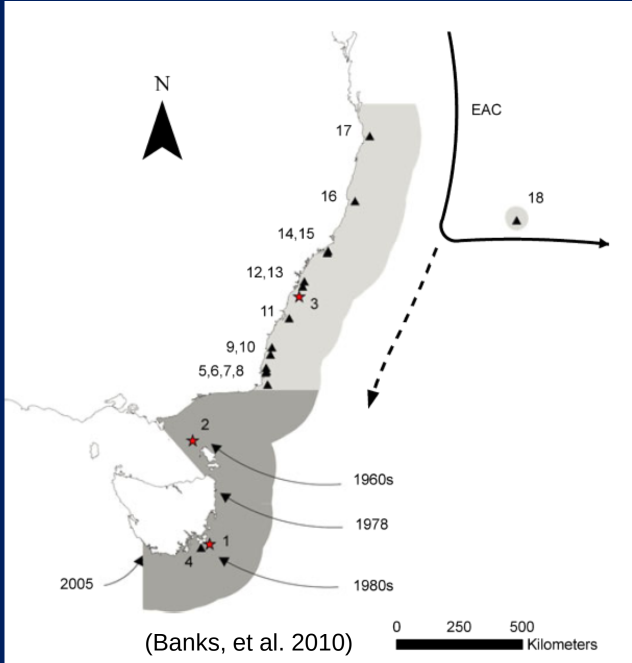
Biological Response: Confounding Effects of Temperature

Detriment (within ranges tested)	**Benefit** (within ranges tested)
• Warmer temperatures in Patagonia reservoirs have **caused lack of ovulation, reduced spawning and larval survival of cultured rainbow trout** (Baez et al. 2011)	• Warmer temperatures in Patagonia reservoirs **have increased growth** (> 2 kg) to market size (Baez et al. 2011)
• Maximum summer water temperatures in Lake Huron, Canada have recently been **sub-optimal for trout culture** (ANA 2013)	• At least one farm has reported in **improved harvest weight by 10-20%** (ANA 2013)
• Increased winter water temperatures are projected to **accelerate the growth rate** of four abalone species in Australia (Russel et al. 2012)	• Projected summer temperatures are expected to cause a **10-fold increase in juvenile abalone mortality** (Russel et al. 2012)

Shifts in distribution range

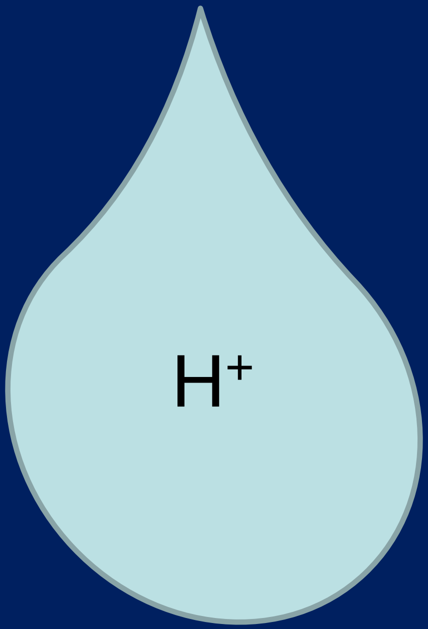
- **Range change** influence predation, disease potential, food supply for extractive species and shellfish ‘seed collection’ (e.g. spat)
- In general, climate warming is predicted to drive species ranges northwards in the northern hemisphere and southwards in the southern hemisphere (Gianguzza et al. 2011)
- **Opportunistic species** that are limited only by developmental temperature, will show ‘early-response’ to range shifts

- Example: barrens-forming sea urchin, *Centrostephanus rodgersii*, off the coast of Australia, where genetic investigations (via microsatellites) have confirmed its rapidly expanding range is one population (Banks et al. 2010)
- Marine larval period influences dispersal distance; **increased temperature can decrease the duration** of non-motlile stage, influencing population connectivity, community structure, and regional-to-global scale patterns of biodiversity (O'Connor et al. 2007)

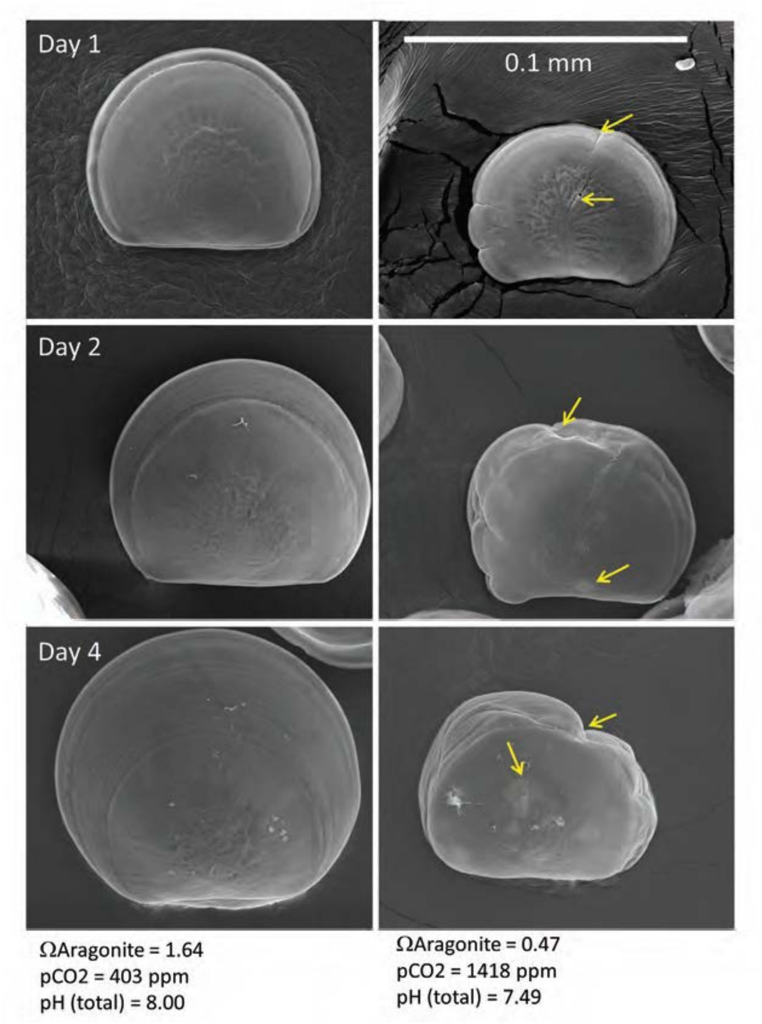


(Banks, et al. 2010)

OCEAN ACIDIFICATION



Biological impacts of Ocean Acidification

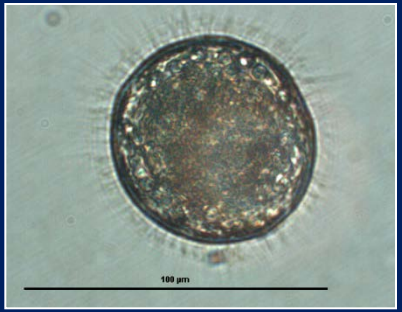


- Major problem for organisms with calcium carbonate shells e.g. shellfish (Gazeau et al., 2013 review)
- Severe impact on larvae
  - Shell deformities
  - Slow growth
  - Poor metamorphic success
- Massive impact on hatchery production (Pacific Northwest) (Ekstrom et al., 2015)
  - Estimated nearly $110 million USD, jeopardized directly or indirectly 3,200 jobs
- Impact on aquaculture and wild populations long-term?

Brunner / Waldbusser, 2012. Washington State Blue Ribbon Panel Report

Calcium carbonate forms and life stage development

<u>Saturation states (Ω) of calcium carbonate</u> ($CaCO_3$) in seawater are used as a proxy for the ease in which calcifying biota such as bivalves can deposit calcium carbonate (Fabry et al., 2008; Feely et al., 2009; Feely et al., 2004; Millero, 2007)



amorphous → aragonite → calcite

most sensitive to OA → less sensitive to OA

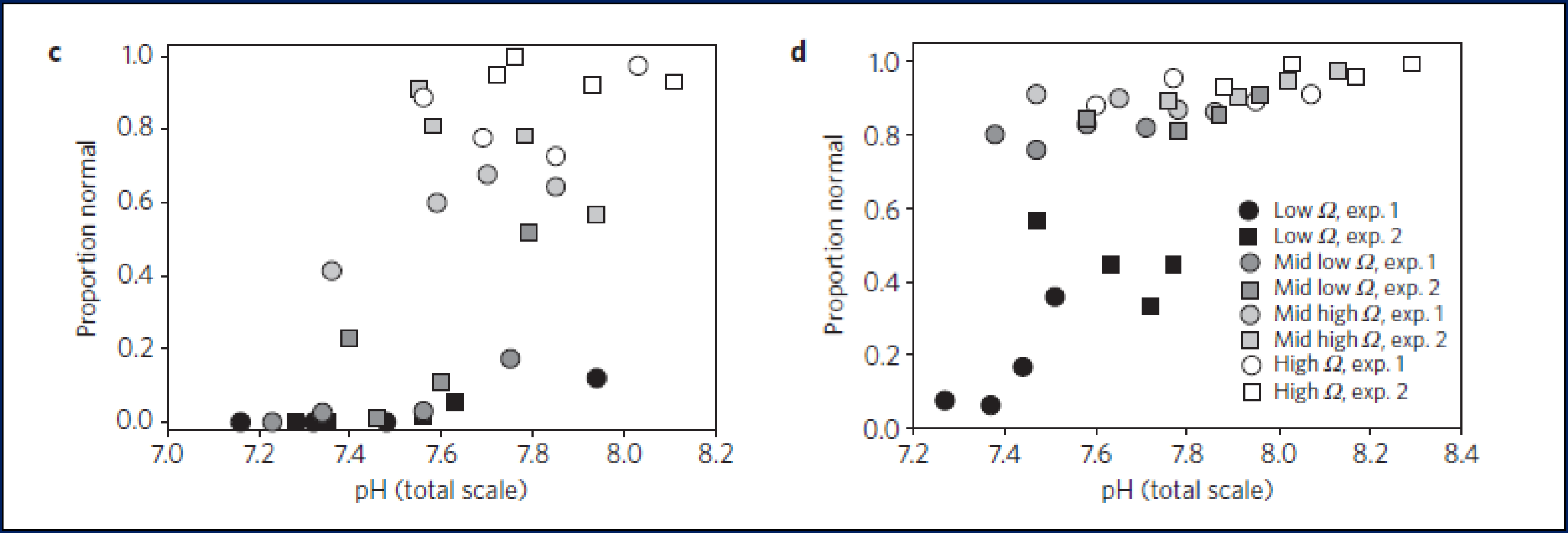
- OA **<u>decreases the biological availability</u>** of calcium carbonate forms for shells
- Energy expenditure is higher under OA conditions in early sensitive stages = **<u>mortalities and deformities</u>**

Images Gurney-Smith

Ocean Acidification: Effects to Shellfish

- Local invasions and extinctions (Doney et al., 2012)
- Problem in hatchery production (WA State Blue Ribbon Panel, 2012) or wild seed recruitment
- Loss of ecosystem services (Cooley and Doney, 2009; Feely, et al., 2012, Newell, 2004)
- Significant reduction in aquaculture production and economic stability – adaption potential (Sanford & Kelly, 2011)
- High mortalities in larvae sensitive to calcium carbonate saturation states (Gazeau et al., 2013)
- Multifactorial impacts, including temperature and predator / competitor ranges (Gazeau et al., 2013)

pH not measure of OA impact



Mussels (Mytilus galloprovincialis)

Pacific oysters (Crassostrea gigas)

Waldbusser et al., 2014 Nature Climate Change

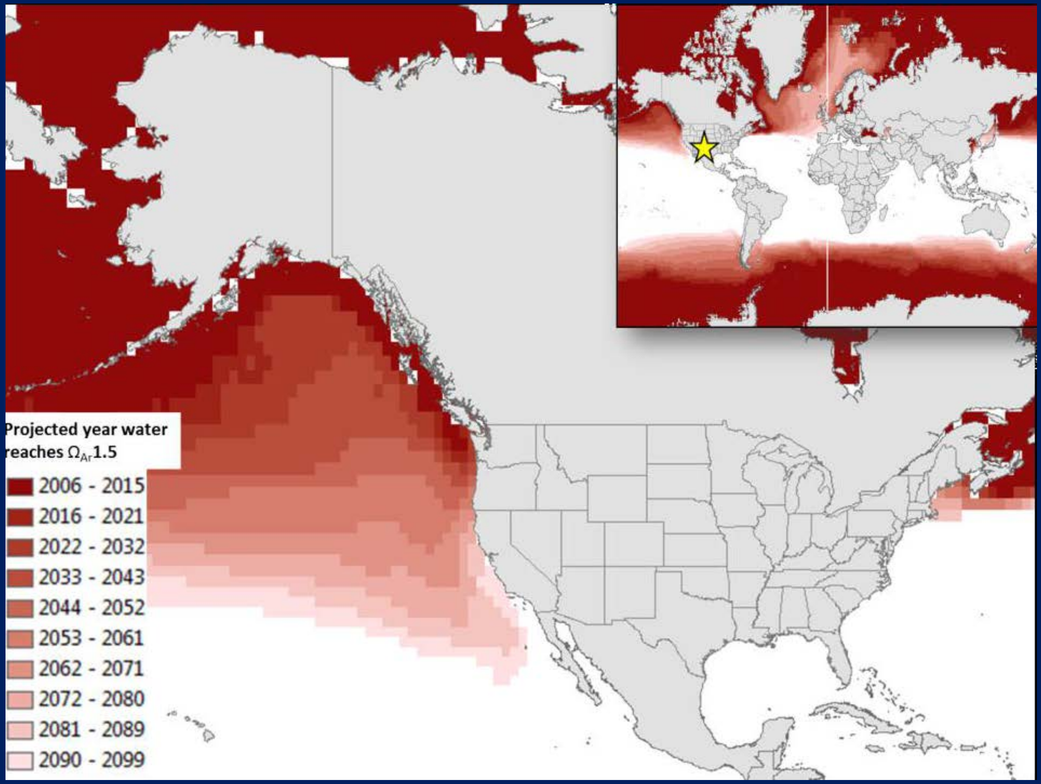
- Previously thought pH was definitive measure
- Decoupling of pH and biological impact
- Aragonite form of calcium carbonate used by shellfish larvae

Calcium carbonate key variable to measure for biological studies

Projections of chronically stressful surface seawater (Ωa =1.5)

Overall system vulnerability[1] is function of

- Marine **ecosystem exposure**
- **Social vulnerability** (market value and jobs)
- **Adaptive capacity** (scientific support + political capacity + diversification potential)



[1]*Ekstrom et al, 2015. Nature Climate Change* 2508
Scenario RCP 8.5

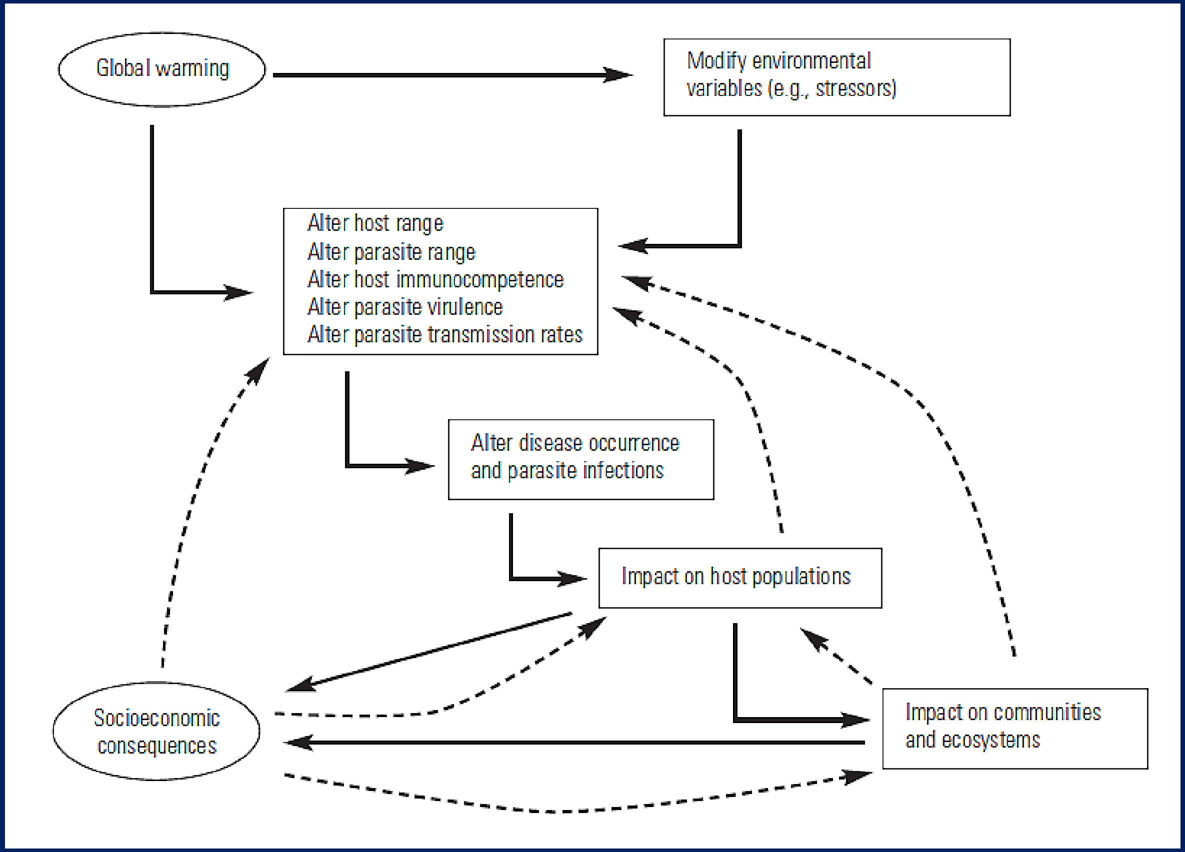
PATHOGEN AND DISEASE POTENTIAL

Pathogen and Disease Potential: Introduction

- The **effects of climate change on the health** of both cultured shellfish and finfish is **extremely complex** and to date there have been only a handful of studies published
- Much of the available research focuses on climate change stressors on parasitic infection, but this is still very little compared to the terrestrial realm (Karvonen et al., 2010)
- Accelerating changes in environmental factors, together with anthropogenic translocation of hosts and parasites, act together to produce **hard-to-predict disease outcomes** in freshwater and marine systems (Adlard *et al.* 2015)

Pathogen and Disease Potential: Aquatic Parasites and Hosts

- Effects will cascade up, leading to impacts on host populations, communities and ecosystems
- Effects will be modified by interactions with other stressors and environmental variables
- Effects on populations, communities and ecosystems will 'feed back' onto hosts and their parasites (dashed lines)



Schematic: global warming effects on marine and aquatic parasites and hosts (Marcogliese 2008)

Pathogen and Disease Potential: Life Cycles, Fecundity and Transmission

- Increased sea temperatures could **affect transmission of parasites** and pathogens through:
  1. **Direct enhancement** of parasite/pathogen metabolic rate, increased transmission stages, improved parasite/pathogen survivability, faster disease spread (Karvonen et al., 2010)
  2. **Indirectly**, via effects on the host with respect to distribution, behavior, physiology and mortality (Callaway et al., 2012)
  3. **Reducing immune functionality** of the host

- While there is the potential for increased disease prevalence from one or a combination of these factors, there is also the **potential for decrease** (Karvonen et al., 2010).

- The more complicated the life cycle (host number and parasitic stages), the greater the chances parasites and pathogens will be impacted by climate changes (Overstreet, 1993)

Pathogen and Disease Potential

- At the **lower latitudes**, disease progresses more rapidly and **results in higher cumulative mortality** and tropical countries suffer proportionally greater losses in aquaculture during disease outbreaks and have less time to mitigate losses (Leung and Bates 2013)
- An important consideration for the assessment of health impacts is the potential for climate change mediated effects to **translocate hosts and vectors** that may facilitate disease emergence (Zell et al., 2008)
- Increasing temperatures have provided a conducive environment for nonindigenous marine pathogens introduced by storms
  - This effect has been linked to mass urchin mortalities in Nova Scotia, due to tropical cyclone-mediated introduction of amoebic disease (Scheibling and Lauzon-Guay, 2010)

Elevated Temperature and Infection Potential: Examples

Increased infection potential (within tested ranges)	**No effect** (within tested ranges)
• ***Vibrio* sp. in Pacific oysters,** *Crassostrea gigasoysters* (Wendling and Wegner, 2013). • Furunculosis (*Aeromonas salmonicida*) infection of lake fish in Northern Quebec (Tam et al., 2011). • Dermo disease *(Perkinsus marinus)* in the eastern oyster, *Crassostrea virginica* (Cook et al., 1998) • E**arlier onset of sea-lice infection** (Boxaspen and Næss, 2000, Stien et al., 2005, ANA 2014)	• **Cold-water disease** (*Flavobacterium psychrophilum)* in salmonids (Harvell et al., 2002). • Low water temperature viruses: Viral hemorrhagic septicemia virus (VHSV), **infectious haematopoietic necrosis (IHN)**, *Oncorhynchus masou* virus (OMV) (Callaway et al. 2013) • Tape worm infection in juvenile Sockeye salmon (Bentley and Burgner, 2011).

Impaired immune response	**No effect** (within tested ranges)
• The clam, *Chamelea gallina*, haemocyte count (Matozzo et al., 2012) • The sea urchin, *Lytechinus variegatus*, decrease in the phagocytic indices (Branco et al., 2013).	• The mussel, *Mytilus galloprovincialis* (Matozzo et al., 2012). • The sea urchin *Echinometra lucunter* (Branco et al., 2013).

Pathogen and Disease Potential: 'Contamination'

- Under heavy rainfall (or snow meltwater) tertiary sewage treatment can be bypassed, **discharging contaminated effluent** in a raw or highly contaminated state
- After human outbreaks of norovirus, the Shellfish Association of Great Britain has seen an **increase in the number of incidents** of norovirus associated with bivalve shellfish (Pickerell, 2010).

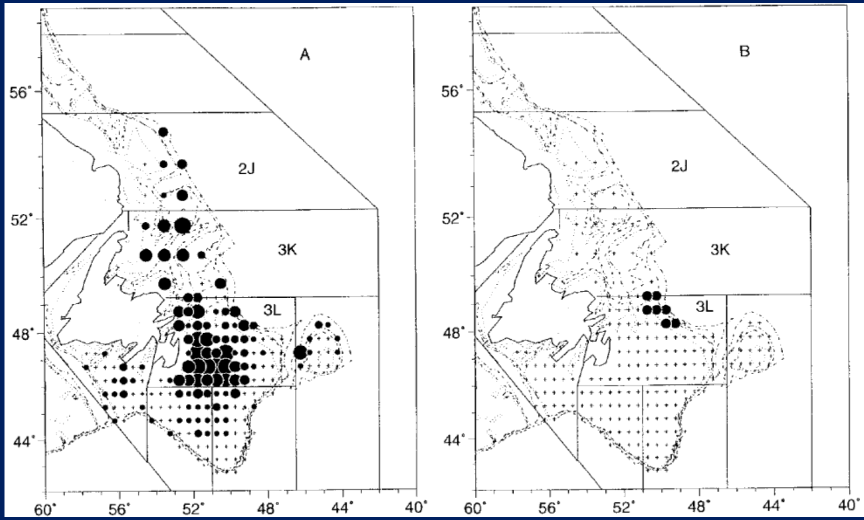
(Cornelisen et al., 2011)

- A moderate flood event in Tasman Bay, New Zealand, resulted in a shallow low-salinity plume delivering elevated concentrators of Enterococci (E. coli) and Enterococci concentrations to a major shellfish production area resulting in ruminant **faecal contamination** in shellfish 6 km off-shore (Cornelisen et al., 2011)
- **Salinity intrusion** is already causing serious problems with freshwater prawn production in coastal Bangladesh, with increasing salinity linked to viral and bacterial infections (Ahmed 2013)

GENETICS

Biological Response: Genetics

- All cultured species originate from wild progenitors and in the case of modern commercial aquaculture, many species have only **recently been domesticated**
- Examining genetic response of feral species and populations to climate change may provide some insight for **aquaculture management**
- The effects of climate change on population genetics are **difficult to isolate from other ongoing human influences** such as overfishing, which cause changes in age structure, reproduction and a reduction in genetic diversity or variability



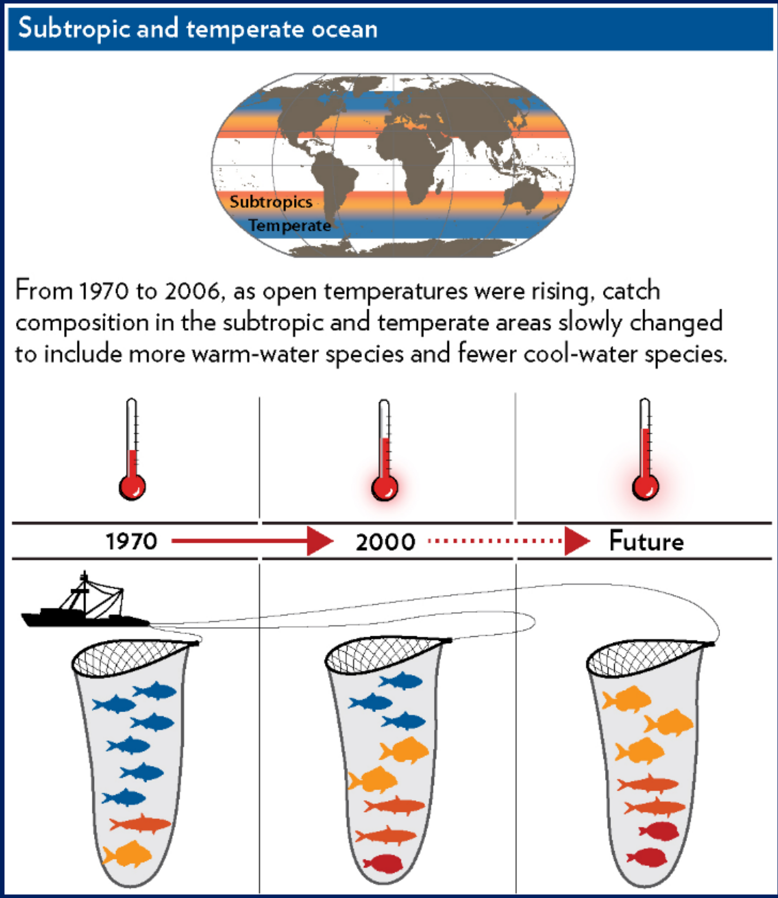
Erosion of spawning components and severe range contraction in northern cod stock complex of NAFO Divisions 2J3KL. A) Location of spawning stocks during the period 1948-1992, B) Location of spawning cod during the period 1990-1993. (Figure copied with permission from Frank and Brickman, in press, and originally adapted from Hutchings *et al.*, 1993 (A) and deYoung and Rose 1993 (B)).

(Kenchington, 2001)

Biological Response: Genetics

Climate changes will affect aquatic species by altering geographic ranges and distribution, which in turn alter:

1. Population dynamics,
2. Effective population sizes (average **number of organisms** contributing genes to succeeding generations),
3. Genetic diversity (**genetic variability**),
4. Gene flow (**genetic transfer or exchange** of genes from one population of the same species to another resulting in change in gene frequencies),
5. **Genetic drift** (random fluctuations in gene frequencies),
6. Mutation
7. Selection



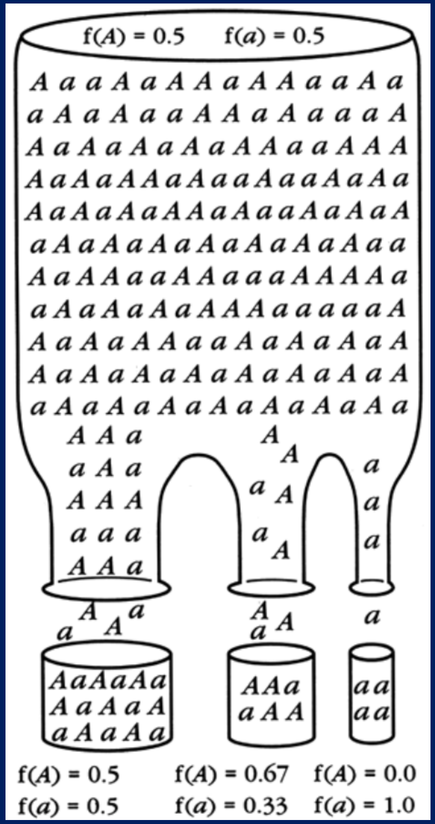
(Cheung et al. 2013)

Biological Response: Genetics

- Genetic variability is one means that enables species to respond to environmental change and this **variability can promote adaptability** in a changing climate through gene expression (variation we can see/measure) and gene regulation.

- However, typical broodstock selection **decreases** variability in production, aiming to increase growth rate, improve survival, and often disease resistance

- Appropriate genetic variability in a broodstock may shield some effects of climate change through better tolerance of inconstant environments (e.g., large temperature fluctuations)



Effects of bottlenecks on gene frequency. (FAO 1999)

Genetics: Adaptation Potential

- A challenge of predicting the outcome of climate change stressors, is unknowns around the capacity of short-term adaption, or epigenetic expression
- Some fish development is considered highly ‘plastic’, with flexibility of developmental pathways, depending on environmental conditions
- Many broodstock selected traits are **polygenic**; a specific phenotype (what we see/measure) is dependent on the interaction of numerous genes, rather than one or a few genes
- This underlying compilation of genes interact to result in phenotypes (gene expression, gene regulation) and may enable aquatic organisms to be **somewhat ‘plastic**’ in their responses to climate changes especially if those changes are gradual (e.g., larval fish, Pitmann et al. 2013)
- Such responses are supported in the literature with cultured and feral species

Genetics: Adaptation Potential

- **Family variation** in response to stressors has been recorded for Rainbow trout (Weber and Silverstein 2007), Atlantic cod (Hori et al., 2012)

- **Multiple generation cultured** Arctic charr are better adapted to higher temperature growth compared to the offspring (F1 generation) of wild charr (Siikavuopio et al. 2013)

- **Substantial phenotypic variation** related to thermal and oxygen tolerance between 41 families of Atlantic has been reported (Anttila et al. 2013)

- Zambonino-Infante et al. (2013), suggested an irreversible plastic response to warmer larval rearing temperatures of the Common sole, which allowed **adaptive regulation** of metabolic rates and/or oxygen demand with long-lasting effects

TRENDS AND MITIGATION POTENTIAL

Trends?

- Multiple stressors will occur simultaneously and have the potential for **positive or negative interaction**
- Response to climate change stressors between related species, and even between populations of the same species is **not universal**
- Evidence to date, suggests different **adaptive responses** (short-term) are a function of 'plasticity' or epigenetic expression
- In many species successful adaptation is a function of parental or early life-stage exposure to stressors
- Magnitude of threat a function of region, culture method and species

Mitigation: Nutrition

Ocean acidification

- Under elevated CO_2, shell dissolution of *M. edulis* reduced with high food availability (Melzner et al. 2011)
- Benthic stages of *M. edulis* can tolerate high ambient pCO_2 when food supply is abundant (Thomsen et al. 2013)
- Echinoderms such as the urchin *P. lividus*, have also responded to diet augmentation to modulate the Mg/Ca ratio to improve adaption to acidification (Asnaghi et al. 2014)

Temperature extremes

- Increasing dietary protein under elevated temperatures improved blood serum immune parameters (antioxidant enzymes, expression of the heat shock protein genes) for juvenile mirror carp (Huang et al. 2014)
- Propolis, a antioxidant resinous hive product collected by honeybees improved sea-bass resistance to low-temperature stress (Šegvić-Bubić et al. 2013)
- Bioenergetic factorial models for some species like rainbow trout (2014) and barramundi (Glencross and Bermudes 2012) can estimate optional digestible protein and energy requirements under elevated temperatures

Mitigation: Nutrition

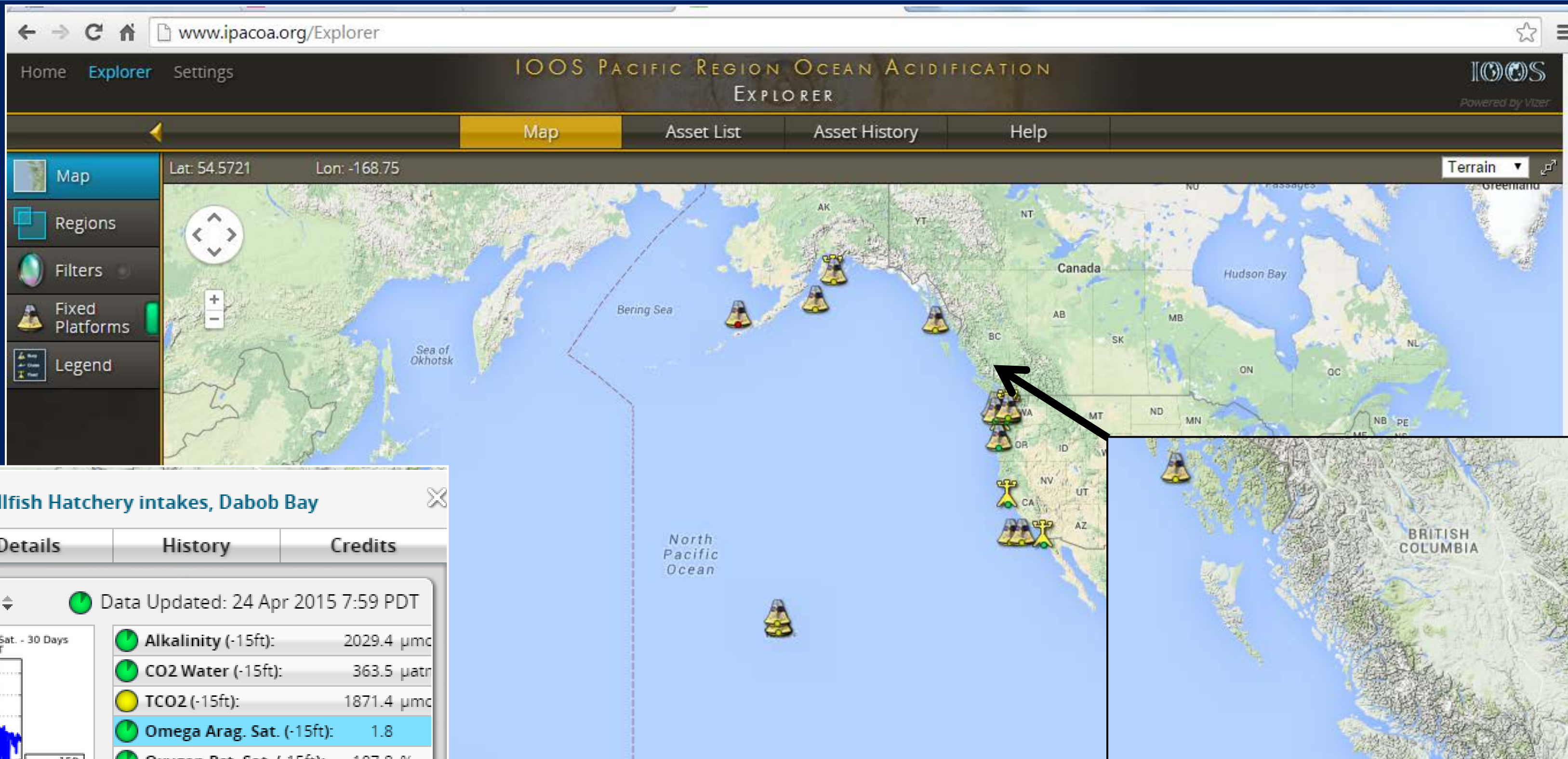
- Diet is one of the **'low hanging fruit'** in the tool box of climate mitigation approaches for fed aquaculture
- Skretting (Norway) has been investigating whether **feed formulation** can be used to reduce the impacts of rising seawater temperatures, since 2011
- Dietary control will be a greater challenge for species that extract their diet from the ambient environment
- Culture practices such as Integrated Multi-Trophic Aquaculture may provide diet augmentation opportunities through increased organic and dissolved nutrient availability (Reid et al. 2013)
- **Rearing systems** which enable greater environmental control (e.g. land-based) could enable more dietary control of extractive species

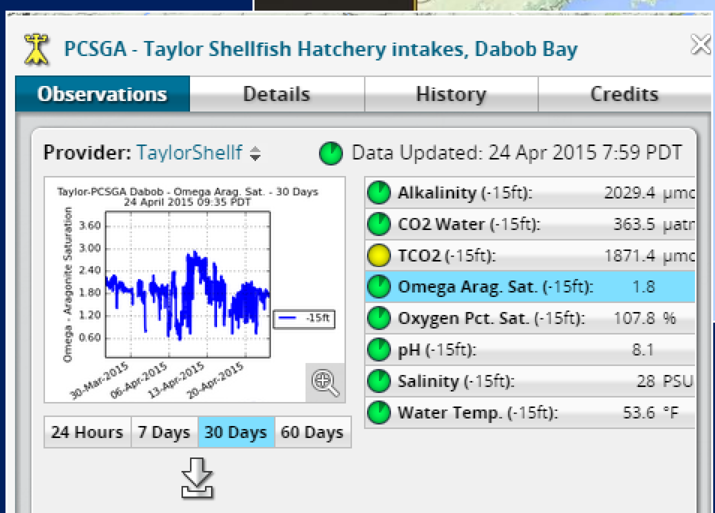
Mitigation: Monitoring, Early Warning and Prediction

Real-time monitoring

- Real-time monitoring can alert famers to the presence of deleterious conditions that may not be obvious until the onset of behavioral or clinical symptoms
- Common practice for oxygen and temperature, but recent developments have greatly expanded monitoring breath and capability
- Recent developments in microsensor technology enable shellfish heat rates to be monitored as a means to monitor animal response to environmental and biological stressors (Reid and Jackson, 2014).
- Ocean condition monitoring networks like the Integrated Ocean Observing System (IOOS) allow aquaculturists to track pH and other crucial water quality parameters in real-time → some monitoring stations are even located at shellfish farms with the data publically available online (http://www.ioos.noaa.gov/)

Pacific Coast OA monitoring





Online searchable sites and equipment all along Pacific coast (no sites in Canada)

Near real-time data for hatchery operators for <u>informed decision-making</u> (e.g. aragonite saturations)

UNB · Vancouver Island University · NSERC CRSNG · Huntsman Ocean Sciences Océaniques · New Brunswick Nouveau Brunswick Canada · NSERC Canadian Integrated Multi-Trophic Aquaculture Network / Réseau canadien d'aquaculture multitrophique intégrée du CRSNG · Fisheries and Oceans Canada / Pêches et Océans Canada

Mitigation: Monitoring, Early Warning and Prediction

Early Warning

- Early warning of acute, deleterious events such as storms, flooding, CO_2 influx or water temperature extremes, can provide a window to **enable management response**
- Xu and Zhang (2014) developed a GIS-based meteorological information system for aquaculturists in Zhanjiang, China, which **warns farmers of pending weather extremes**
- In Australia, the Predictive Ocean Atmosphere Model for Australia (POAMA), can provide **several months warning** of adverse salmon culture temperatures (Spillman and Hobday, 2014)
- **Early warning strategies** have had some success; avoiding the use of low aragonite saturated waters when strong upwelling conditions occur, have enabled the significant restoration of oyster hatchery production (Barton et al., 2012)

Mitigation: Monitoring and Prediction of Infection

- **Routine monitoring** for serious and potentially reoccurring infection is a common aquaculture health management protocol in developed regions
- Example: the web-based management program Fish-iTrends, maintains an evidence-based-epidemiological sea-lice database, that tracks temporal and spatial trends of regional salmon farm infection to provide decision support for treatment options (Hammell, 2014; Harris, 2015) → provides a wealth of temperature data
- At the global scale however, **disease outbreaks often go unreported**, standardized reporting of aquaculture-based epizootics and conditions surrounding outbreaks is lacking, and required to **formulate adaptation strategies to climate extremes** (Leung and Bates, 2013)

Geographic distribution and severity of published disease outbreaks in aquaculture systems. (a) Locations of aquaculture-based disease events included in the Leung and Bates, (2013) study for fish and invertebrates.

Mitigation: Management and Engineering Solutions

- The simplest, adaption strategies are based around management and husbandry practices and these are often proceeded by **engineering solutions**
- Protection against floods, will be a combination of management strategies and age old engineering approaches such as **increasing dike or embankment capacity**
- Flood-response management strategies are routine in regions with **predictable seasonal flooding**; In Malaysian flood prone areas, fish are harvested prior to floods (Idris et al., 2014) and water levels in ponds are dropped prior to flooding in Taiwan (Chang et al. 2013)
- Backup generators are common in land-based facilities to ensure aeration during power failures, but under extreme conditions where tanks may be destroyed or overtopped, fish evacuation may be necessary (Dodd 2011)
- Protection of land-based aquaculture facilities from land erosion and storm surges can be facilitated with appropriate natural barriers; restoration of reefs and coastal vegetation is reported to have the greatest potential to protect coastal communities from sea level rise and storm surges (Arkema et al. 2013)

Mitigation: Management and Engineering Solutions

- Uncertainties of climate change extremes have introduced additional considerations for the **design of aquaculture facilities** (Alvarez-Lajonchère and Pérez-Roa, 2012)
- The **storm Intensity-duration-frequency** (IDF) curves used by engineers to guide design specifications, are changing with the climate and specifications are currently being updated for new scenarios (Liew et al., 2014)
- Failure of cages during storm events prompts redesign efforts regardless (Can and Tuan, 2012).
- Recent interest in off-shore aquaculture (Shainee et al., 2013) and submersible finfish (Shainee et al., 2014) and shellfish (Kim et al., 2014) systems has helped to **develop technology for extreme conditions**

NOAA

Mitigation: Management and Engineering Solutions

- Choosing farm locations less impacted by climate change effects is one obvious mitigation strategy
- Some shellfish hatcheries have already moved to less acidic waters (Welch 2012).
- GIS tools have long been used to select good aquaculture locations (Hossain et al. 2007, Hossain and Das 2010, Mamat et al. 2014, Nath et al. 2000, Perez et al. 2005, Radiarta et al. 2008) and recently used to identify areas less threatened by climate change stressors (Handisyde et al. 2008, Hossain and Das 2010, Khan et al. 2012)
- A potential complicating factor with the strategy of relocation to areas of optimal water quality, is that conditions may not be optimal for all life stages
- Báez et al. (2011) experiences with rainbow trout, suggests the fastest growth rates occur at temperatures which are detrimental to reproductive performance and have advocated separate site locations for broodstock and grow out

Mitigation: Management and Engineering Solutions

In some circumstances, direct mitigation of the localized environment may be possible

- For infaunal species in detrimental sediment saturation states, **sediment buffering** using crushed shell can increase the alkalinity, pH and aragonite saturation states of the sediment and decrease shell dissolution and / or promote larval recruitment (Green et al., 2009), with reported success (ANA 2012)

An inability to mitigate the environment may require the creation of an artificial one

- Rearing strategies which enable environmental control to either protect sensitive life stages from environmental stressors or promote adaptive responses
- Such strategies may require water quality control through either recirculation approaches (Timmons et al., 2002) or strategic water intake to avoid periodic stressors such as CO_2 upwelling (Barton et al., 2012).

Mitigation: Genetics and Biotechnology

- Suggest adaptive potential to climate change stressors through epigenetic responses for certain fish (Pittman et al., 2013) and invertebrates (Sanford and Kelly, 2011), but there are many knowledge gaps
- **Adaptive capacity** of marine populations to ocean acidification is largely unknown; few studies have considered acclimation times of more than a few months (Doney et al., 2009; Gazeau et al., 2013; Harley et al., 2006; Kurihara et al., 2007; Thomsen et al., 2010).
- 'Plastic responses' particularly in early life stages suggest greater environmental control during early rearing may help direct epigenetic responses, and hatcheries are already well positioned to do this
- Not suggesting leaving mitigation up to 'mother nature'

Mitigation: Genetics and Biotechnology

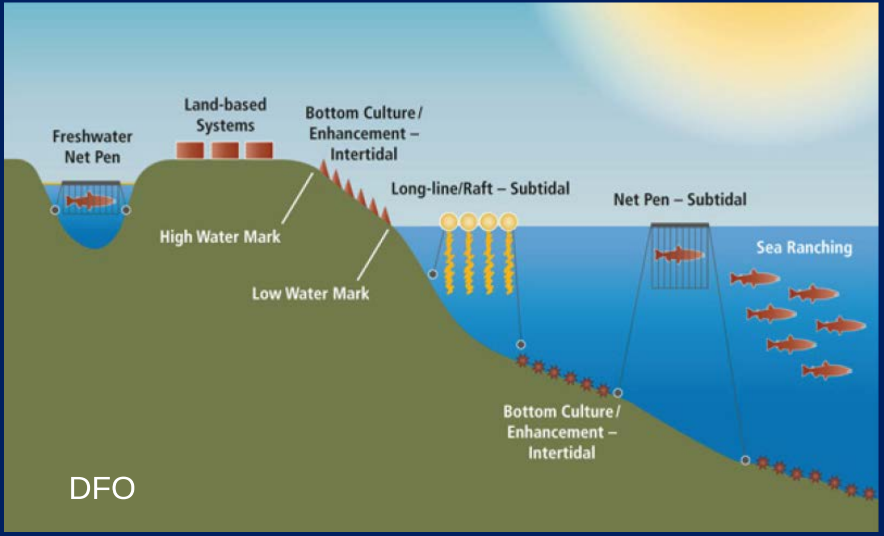
- There is the potential for selective breeding
  - Significantly differing sensitivities to elevated pCO_2 conditions in wild and selectively bred populations of the Sydney rock oyster (Parker et al., 2011).
  - Shellfish hatchery operations have already seen differences in calcification rates in selection programs, thereby proving its usefulness as a breeding strategy (Waldbusser et al., 2010).
  - Selection of salinity tolerant catfish strains in the Mekong Delta, Vietnam is being advocated to mitigate effects of flood waters (Nguyen et al., 2014).
- Specific climate change resistant traits should be incorporated into broodstock selection programs in a controlled manner assessing family variation or retain as much genetic variability as possible in the breeding core
- Maintaining genetic diversity could ensure preservation of rare alleles that may be associated with resistance to a future disease or increased survival in the presence of disease and environmental stressor

Mitigation: Genetics and Biotechnology

- If the rate of climate changes exceeds breeding schemes based on recorded phenotypic data, adding molecular selection techniques (e.g., genomic selection) to phenotypic selection programs may prove essential
- Some genomics approaches to identify genes associated with resistant traits are underway, such as:
  - Quinn et al. (2011) identified genes associated with heat tolerance in Arctic charr exposed to acute thermal stress.
  - Genomic biomarker development in shellfish (Hüning et al., 2013)
- Recent advancements in commercial scale cryopreservation enable ‘gene banking’ or retention of genetics from one parent (male) regardless of continued inclusion in a breeding programs

Mitigation: Species Diversification

- Avoid overreliance on one-species…if one crop fails
- Diversification either at the regional level or at the farm level as Integrated Multi-Trophic Aquaculture
- Species-specific responses to target more resilient species (Cooley et al., 2012)



Mitigation: Governance

- Effective aquaculture governance requires accountability, effectiveness and efficiency of governments, equity, and predictability of the rule of the law
- Sustainability of the industry is the principal goal of aquaculture governance and incorporates four aspects:
  1. Economic viability
  2. Environmental integrity
  3. Social licence
  4. Technical feasibility
- Regional cooperation will be required in such areas as the gathering and sharing of data on forecasted changes in the coastal environment, animal health issues, invasive species and sharing of best practices
- The aquaculture industry may also need to join with other resource sectors in the coastal zone to influence policies and ensure that governments provide relevant data in a timely and effective manner

Now What?

- Do we know enough to rank threat potential?
- How does this change as a function to region and species?
- What research should be prioritized?
- How should this be done to maximize resources and minimize redundancy?

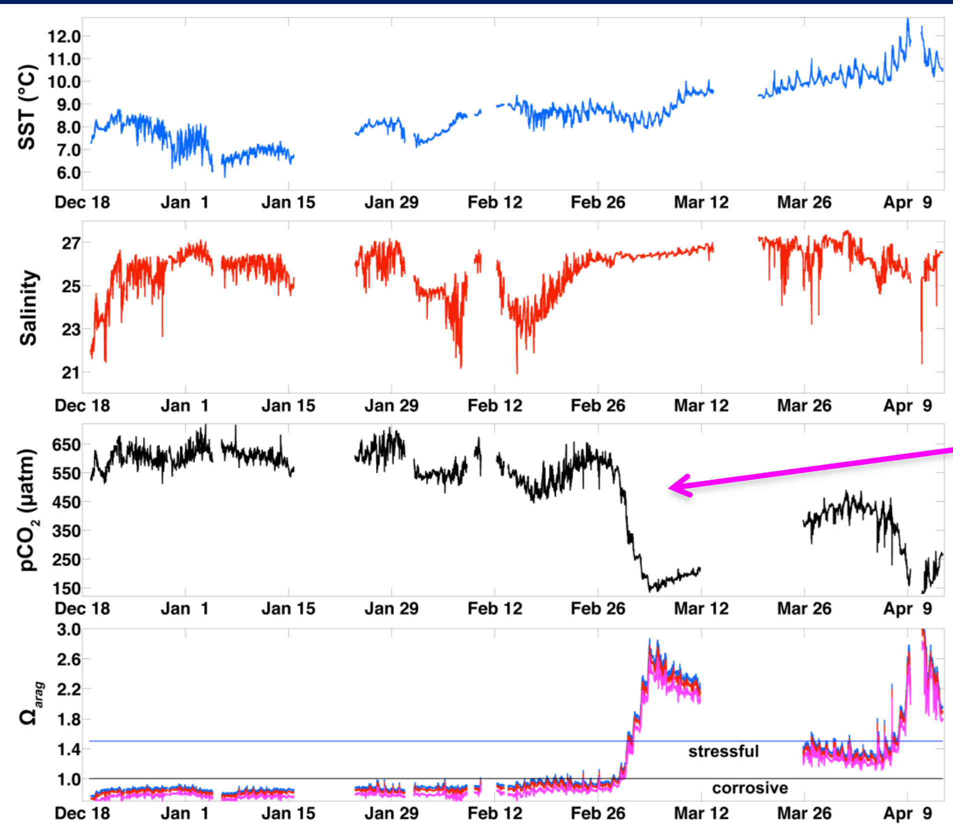
END

Questions ?

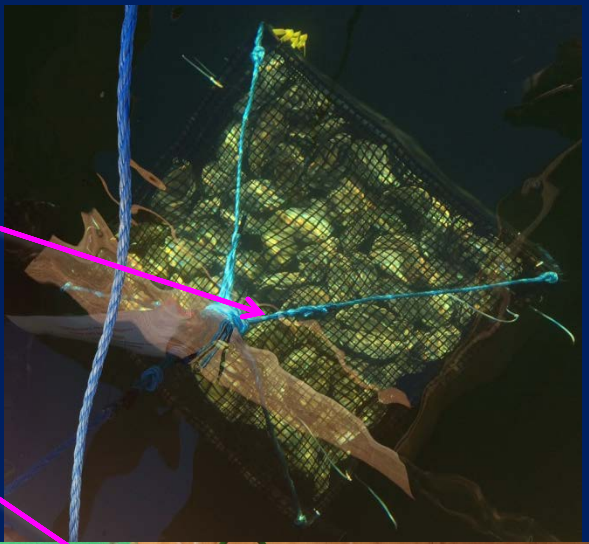
UNB | VANCOUVER ISLAND UNIVERSITY | NSERC CRSNG | HUNTSMAN Ocean Sciences Océaniques | New Nouveau Brunswick CANADA | NSERC Canadian Integrated Multi-Trophic Aquaculture Network Réseau canadien d'aquaculture multitrophique intégrée du CRSNG | Fisheries and Oceans Canada Pêches et Océans Canada

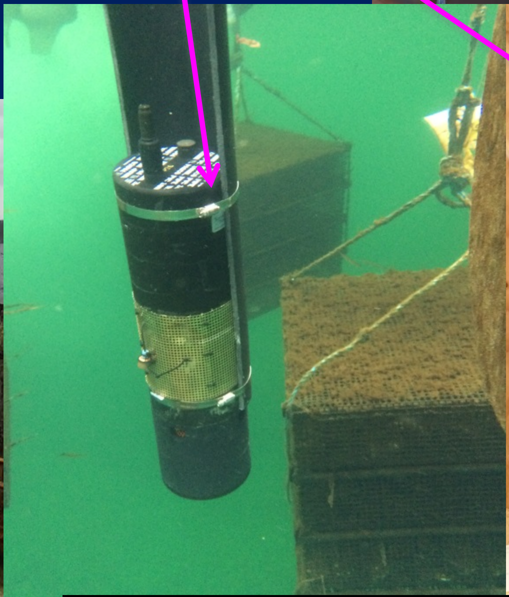
Simultaneous observations of functional genomics and $CaCO_3$ mineral corrosivity in the northern Salish Sea

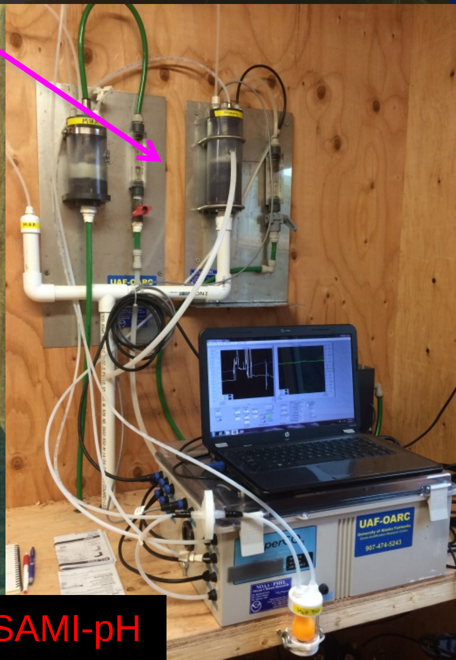
H. Gurney-Smith and W. Evans



Coupling high-speed chemical sampling with cutting-edge genomics on *in situ* populations







Sunburst $SuperCO_2$ and SAMI-pH