Acknowledgements

• IOC

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• IOC WG
  – IGMETS
  – TrendsPO

• University of British Columbia, Department of Fisheries and Oceans, Canada, Commonwealth Scientific Industrial Research Organisation (CSIRO) Australia, University of Tasmania.

• Family & colleagues
Why phytoplankton?

- Food
- Health
- Carbon

- Climate Change
- Photons to Carbon cycles
  - \( \sim 2 \times 10^{38} \) photons/second
  - \( \sim 50\% \) of global primary production annually (\( \sim 10^{10} \) tonnes y\(^{-1} \))
  - Most* of the \( \text{CaCO}_3 \) \( \sim 10^9 \) t y\(^{-1} \)

*4 to 10 times that of corals
Phytoplankton: biomass vs species

• Growth can be reasonably predicted from major drivers.

• What are the predictions for a future ocean?

• How well do these predictions seem to be working?

• “Paradox of the Plankton” (Hutchinson, 1961)

• Classical ecology theory predicts competitive exclusion (Volterra, 1928; Lotka, 1932)

• Best explanation – highly selective grazing (Record et al., 2014)
  e.g. zooplankton are very fussy eaters
How will phytoplankton respond to climate change?

What are the limits to phytoplankton?

- Abiotic Limits
  - Light
  - Temperature
  - Nutrients (C, N, [Si], Fe, P, etc.)
  - pH
  - Salinity
- Biotic
  - Competition (allelopathy)
  - Grazing
- Others

“Give me a half tanker of iron, and I will give you an ice age.” - John Martin

- MODELS
- LABORATORY STUDIES
- FIELD STUDIES
- OBSERVATIONS
Climate impacts on Pelagic Ecology: what do we expect?

- Modelling predicts:
  1. warming
  2. = Increased stratification
  3. = Less nutrients mixed up from depth
  4. = Less DO, less phytoplankton, fewer diatoms, less zooplankton, less fish. 😞

- Is this really happening?
- Not everywhere.....
Expectations from physiology: Temperature

- Meta analysis
- >200 species and 439 strains
- Critical transition at ~ 27°C?

World ocean temperatures June 2019.

- A significant fraction of the ocean exceeds 27°C.
- It is increasing.

LIKELY IMPACT of rising temperatures: a loss of biodiversity

https://www.seatemperature.org
Nutrients as potential limits to growth.

Predicted: Nutrient limitation will increase across most of the tropical and temperate oceans and persist for longer each year.*

*The coastal zone now receives 100% more N than pre-industrialization.
Physiological responses to light.

Growth of phytoplankton is strongly determined by the available irradiance.

In clear oceanic waters around Australia light sufficient for growth reaches ~100m.

Light Insolation

- Solar radiation at the ocean’s available to phytoplankton has very strong temporal variation from a wide sources at a range of time steps (waves, clouds, storms, earth’s rotation, seasons).

- Long term mean insolation is not stable over the years, but undergoes changes on decadal timescales.
Light, mixing and nutrients

- **Summer**
  - Warmer surface waters
  - Shallower mixed layer depth
  - Nutrients depleted

- **Winter**
  - Cooler surface waters
  - Deeper mixed layer depth
  - More nutrients, less light

- Climate is also changing the MLD
Examples from Regional Hotspots

*26 fastest warming regions over the last 50 years.

Climate HOTSPOT – SE Australia

• Mean chlorophyll $a$ has risen significantly

• Autumn bloom has grown strongly in last 10 years
Autumn bloom: MLD ↑ LIGHT↑

MLD has shallowed by 40m!

LIKELY IMPACT:
• Mid latitude regions will increase phytoplankton and primary production.

McDonald et al., in review
Impacts of pH on phytoplankton?

- Meta analysis of 49 published papers
- 154 conditions of pCO2 from 380 to 1000μatm.
- Grow rates increase for diatoms, large taxa, and diazotrophs (N₂)

_Dutkiewicz et al. 2015. Nature Climate Change 5, 1002–1006_
Monitoring tells us that Coccolithophore populations are healthy, possibly increasing, in many locations including the North Atlantic and Southern Ocean.

Δ sea–surface pH [−]
Salinity: phytoplankton are broadly tolerant of salinity BUT it is a strong driver in the coastal zone and estuaries

- Growth rates of oceanic and coastal species are influenced by salinity.
- Impacts of changing precipitation patterns are likely to be most evident in estuaries and in the coastal zone.

Data from Brand L. E. 1984. Estuarine, Coastal and Shelf Science 18, 543-556.
Detecting Climate Impacts - Plankton

- Spatial and temporal variability from many sources!
- **Seasonal cycles** ~100%
- **Climate cycles** ~10%
- **Climate trend** ~1%

- Need a long time series with consistency in location & methods.
Leadership (2017 - 2021): L→R
- Laura Lorenzoni (NASA/USF/IOCCP)
- Heather Benway (WHOI)
- Kirsten Isensee (IOC-UNESCO)
- Todd O'Brien (NOAA/COPEPOD, Metabase and time series analysis coordinator)
- Peter Thompson (CSIRO)
- Andrew Ross (Canada-DFO)

(1) getting data from the time-series scientists
(2) large areas of world with little or no spatiotemporal coverage.
What are marine ecological time series telling us about the Ocean?

Cycles: temporal window influences results........

Figure 2.10. Sea surface temperature (SST) trends within the IGMETS-defined North Atlantic region for the 10-year time-window (left panel) and 20-year time-window (right panel) (Table 2.3).

- Robust estimates of climate signals requires a long time series
RESULTS: Warming of sea surface

- 87% of the global ocean is warming...
- More of the Indian Ocean (95%) is warming than any other ocean.
- The Southern Ocean is resisting warming.
- recent increase in rate of warming?

Data from Todd O’Brien NOAA IOC-IGMETS
Global Trends in chlα 1998 - 2018

43% of the ocean is increasing in chlα.

- Southern Ocean, Baltic, North Atlantic, eastern boundary currents ↑

- tropics and central gyres ↓

Data from Todd O'Brien NOAA IOC-IGMETS
**Example from Time Series Explorer**

- **TR** – choose variable
- **Ct** – correlation with T, chla, or climate index

**Click on any time series to see more!**
Interactive Time Series Explorer  
(http://igmets.net/explorer)

• Amazing analysis of patterns, trends and anomalies in plankton and related parameters (nutrients, temperature, salinity, wind etc.).
IOC IGMETS time series: all locations

- Sites vary in frequency and variables (nutrients, chla, phyto, zoo). Bias to North Atlantic, Med.
Trends from IGMETS in-situ observations

Thirty year trends across all sites:
- Falling O$_2$ (correctly predicted)
- Rising Diatom abundance (incorrectly predicted)
- Increasing chlorophyll a (incorrectly predicted)
*Global patterns of covariation in temperature and chlorophyll a

• Warming and increasing in chla ~ 21.6%
• Warming and decreasing in chla ~ 9.7%

Drivers?

*From Dunstan et al. 2018
Open Ocean

Model Predictions

• Surface layer of the Ocean gets warmer
• = Increased stratification (density gradient between surface and depth)
• = Less nutrients mixed up from depth, falling O₂
• = Less phytoplankton, fewer diatoms, more dinoflagellates, less zooplankton, less fish. 😞

Observations*

Warmer (correctly predicted)
• Falling O₂ strongest signal (correctly predicted)
• Increasing Diatom abundance (incorrectly predicted)
• Increasing chlorophyll a (incorrectly predicted)

*Relatively small number of observations
Examples from Regional Hotspots*

*26 fastest warming regions over the last 50 years.

Changing conditions: nutrients, light and translocation.

- Australia: polar-ward currents on both coasts.
- EAC – strengthening South Pacific Gyre spin-up
- Leeuwin Current – strong ENSO signal
Changing Currents – translocating pests – *Noctiluca scintillans*

From absent to dominant in 40 years!

Photos by Suthers, Marshall, Hallegraeff
Fish and Phytoplankton moving poleward.

- Yellow tailed kingfish
- ~240km south
- Summer fishing season for these fish off Tasmania in the future

**Species movements** – Predictable using niche modelling and species traits

Champion et al., Marine and Freshwater Research, 2019, 70, 33–42
• Spatial precipitation patterns vary strongly.
• Nutrient inputs vary with precipitation and runoff.
Regional nutrient inputs: Si an essential element for diatoms

- Resulting oceanic surface waters are amongst the freshest and least dense on the planet.

Peter Thompson, Todd O'Brien, Hans Paerl, Benjamin Peierls, Paul Harrison, Malcolm Robb.
Australian Runoff

- Mostly little runoff
- Highly variable

Top panel shows mean annual runoff, as an average of 10 model simulation results. Bottom panel shows the coefficient of variation of the model results.

From Water and Global Change (EU FP6)
Increasing oceanic salinity (Durack and Wijffels 2010)
<table>
<thead>
<tr>
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<th>Maria Island</th>
<th>Port Hacking</th>
<th>Rottnest Island</th>
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<td>3273</td>
<td>9263</td>
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<tr>
<td>Temperature (°C/century)</td>
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<td>Nitrate (µM/century)</td>
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<td>Silicate* (µM/century)</td>
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<tr>
<td>dissolved oxygen</td>
<td>~</td>
<td>~</td>
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changing environment

ENSO & decreasing rainfall drive silica decline in Tasman Sea.
Phytoplankton and changing precipitation


TrendsPO ~ many coastal and estuarine times series.
Phytoplankton & Precipitation
High interannual variability = good data for hypothesis testing.

• “erratic rainfall patterns over much of the country....” (McMahon, 1982).

• Drying is predominantly in Autumn.

Rainfall (mm/month)

May – Perth - Australia

[Scatter plot showing rainfall data over time]
Example: Swan River & Estuary monitoring plankton commenced 1994

- Declining precipitation
- Declining River Flow
- Increasing dinoflagellates

Graphs show:
- June Swan River flow decreasing over time (1980-2010)
- Increasing dinoflagellates in Swan Estuary (Armstrong Spit)
- Relationship between rainfall and dinoflagellates in Blackwall Reach
Global Responses to increasing Precipitation

Thompson et al. 2015. Estuarine, Coastal and Shelf Science 162:119-129.
Regional Conclusions

• Long term trends in currents, precipitation, salinity, river flow, nutrients and temperature are impacting on phytoplankton.

In some locations regional monitoring is sufficient to document the changes but solutions will require regional and global actions.
Knowing our current state; predicting the future

**UNCERTAINTY**

- Global heat flux
  - 46 +/- 3 TW
- Fish (total biomass)
  - 800 to 2000 million tonnes

- Predictive capacity by discipline:
  - Physical state: best
  - Chemical state: better
  - Biological state: poor

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**Current State**

```
  Biology Physics Biology
```

2019................the future
Data access - IGMETS survey

- **Free/Open Access [green]**: The entire data set is available online.
- **Limited/Delayed Access [orange]**: A subset or time-delayed version of the data is online.
- **Restricted Access [red]**: The data are either offline or protected behind a password.
- **Why?** top concern was “having time to publish the data myself”.

![Pie charts showing data access types for different categories: Temperature/Salinity, Nutrients & Pigments, Phytoplankton, Zooplankton.](chart)
Knowing our current state; predicting the future

- 1960-70 → pollution, eutrophication
- 1980 → exploitation, overfishing
- 1990+ → climate

Environmental Management
- Adaptive cycle
- Different sciences have different needs
- Low uncertainty in state and strong predictive capabilities = modelling
- High uncertainty & low predictive capability = monitoring
FINAL CONCLUSIONS: Monitor and evaluate

• Many observed changes have not been predicted by our best models.

• There is a fundamental need for data upon which reliable decisions can be made.

• 1 national reference site per country?

• Global monitoring

• Briggs 1995; Longhurst 1998; Sherman 2005; Spalding 2007

• 12 realms, 62 provinces, and 232 ecoregions
Solutions

• Reducing costs and improving coverage
  • Add more variables (e.g. phytoplankton, zooplankton) to existing platforms (e.g. GO-SHIP).
  • Better co-ordinated development


• Standard set of methods.

• Personal recommendation
  • Optical microscopic methods.
  • Artificial intelligence for image processing.
SDG 14 progress!
The global share of marine fish stocks that are within biologically sustainable levels declined from 90 per cent in 1974 to 69 per cent in 2013.

As of January 2018, 22 million square kilometres of marine waters under national jurisdiction were protected. This is more than double the 2010 coverage level.
Uncertainty often delays action.

Where impacts increase with time (e.g. climate change), delays will increase severity.

https://doi.org/10.1029/2018EF000990
Diatoms under high & low CO$_2$ + UV stress

Multiple Stressors!

High CO$_2$ appears to allow diatoms to grow better when stressed by high UV.

- Jacob J. Valenzuela, Adrián López García de Lomana, Allison Lee, E. V. Armbrust, Mónica V. Orellana, Nitin S. Baliga. *Ocean acidification conditions increase resilience of marine diatoms*. Nature Communications, 2018; 9 (1) DOI: 10.1038/s41467-018-04742-3

**Current status:** At this time changes to pH do not appear to be a major threat to phytoplankton.
Cautions! cycles and climate change

- Annual cycle 100%
- Medium cycle (ENSO) 12%
- Longer term trend 1~2%/decade

• Phytoplankton grow in the surface mixed layer
• Where this is shallow then they have lots of light
• Where this is deep they do not have enough light to grow
• The MLD is changing