Fast and Slow Response of Sea ice and the Southern Ocean to Ozone Depletion

by Cecilia Bitz

University of Washington now visiting University of Otago

and

David Ferriera and John Marshall MIT
Annual Minimum Sea ice extent 1979-2013

Data from passive microwave satellite
Antarctic sea ice trends and mean for 1979-2011

Not discussing this region
Antarctic February Sea Ice Area
CMIP5 Models RCP4.5

Southern Hemisphere February Sea ice extent (historical_rcp45)

Sea ice extent \((10^6 \text{ km}^2)\)

Years

1980 2000 2020 2040 2060 2080 2100

Figure by F Massonnet
Antarctic Extent in CMIP5 Models

Zunz et al. (2013)
Theories for sea ice expansion outside of the Bellingshausen and Amundsen Sea

1) Winds trends from Southern Annular Mode (SAM) trends (driven by ozone primarily), direct effect on sea ice and ocean

2) Freshwater trends (ice bergs, ice sheet/shelf melt, precipitation, sea ice melt/freeze), may be indirect effect of winds

I think this one is right!!!

But I’m going to explain why (1) is wrong
Colors show fast response warming/cooling. But there are other factors that dominate on slower timescales and change the response eventually.

Thompson et al (2011)
Simulated Surface Currents and Sea Ice Extent Around Antarctica

1 degree Simulation

0.1 degree Simulation

Current Speed in cm/s for randomly chosen October

Animations of these runs are at http://www.atmos.uw.edu/~bitz/bothmovies/bothmovies.html
Simulations using Community Climate System Model Version 3.5 with Ozone Anomaly from AC&C/SPARC datasets for CMIP5 to test if CMIP models are failing due to coarse resolution (Bitz and Polvani, 2012)

At two ozone levels:
- High Ozone (1940s) or “Normal”
- Low Ozone (1990s) or “Most depleted”

At two resolutions:
- Coarse – 1° ocean and sea ice
- Fine – 0.1° ocean and sea ice

Four runs in total, each 50 yr long – ramp ozone 20 yr and hold fixed for 30 yr. Results shown are differences of last 30 yr giving the quasi-equilibrated (slow) response
DJF Sea Level Pressure Response to Depleting Ozone

High resolution or high top model is not necessary
Annual Mean Sea Ice Concentration Response to Ozone Loss

0.1° Simulations

1° Simulations

Legend:
- 0°: SIE climatology
- 0.1°: SIE response
- 1°: SIE response

Color Bar:
- 0°: SIE climatology
- 0.1°: SIE response
- 1°: SIE response

Graphs:
- Annual SIE response and climatology for 0.1° and 1° simulations.
Annual Mean Surface Air Temperature
Response to Ozone Loss

Further results shown are 1° only
(analyses was done at both resolutions)
All further results use the 1° model
Regress sea ice concentration on DJF SAM index in control run

This figures proves that the model resembles the observed SAM – sea ice relationship on interannual variability. Sea ice extent increases but area is little changed in DJF because sea ice is transported from near continent towards edge. In MAM, it is cold enough to freeze the gaps that are left near the continent.
Climate Response Function to $O_3$

Abruptly deplete $O_3$ at year zero:

![Diagram showing the climate response function with $O_3$ levels and years.]

20 ensemble members from 20 different branch points in high $O_3$ run. Run all for 28 months. Run six for 20 years.
The fast response to abrupt ozone depletion resembles the regression of SAM on sea ice – as it must. But in only 3 years the pattern is very different and resembles the quasi-equilibrium response in the Bitz and Polvani (2012).
SST Response to Abrupt O₃ Depletion

YEAR 1

YEAR 2

YEAR 3

20 member ensemble mean
SST and Mixed Layer Heating Terms

Fast response* to abrupt ozone depletion

Horizontal advection drives fast SST response & surface flux acts to damp it.

Horizontal advection $\rho \ C_p \ h_s \ v' \ d\bar{T}/dy$

*All quantities are anomalies in year 2-3 except $\bar{T}$
SST and Mixed Layer Heating Terms

Fast response* to abrupt ozone depletion

Sea ice and clouds are key to increasing absorbed shortwave

Horizontal advection $\rho \ C_p \ h_s \ v' \ d\bar{T}/dy$

*All quantities are anomalies in year 2-3 except $\bar{T}$
DJF Temperature Response to Abrupt \(O_3\) Depletion

First year (rapid response)

Arrows illustrate anomalous Ekman current

Depth in m

Latitude

°C
DJF Temperature Response to Abrupt O$_3$ Depletion

First year (rapid response)

Vertical arrows illustrate anomalous vertical current
DJF Temperature Response to Abrupt O₃ Depletion

YEAR 1

YEAR 2

YEAR 3

YEARS 10-19

Depth in m

latitude

°C

0.55  0.275  0  -0.275  -0.55
Overturning Streamfunction Response to Abrupt $O_3$ Depletion with Unperturbed Temperature for Reference

$dT/dz > 0$ here

Vertical advection response causes eventual transitions to higher SST, after $\sim 3$ years
Surface westerly winds on the Southern Ocean cause
- Ekman-driven Eulerian-mean circulation moves heat northward, while eddies move heat southward
- Upwelling of CDW brings heat to the surface in the S. Ocean
Hence heat exits ocean near Antarctica and enters near ACC
When the surface westerly winds shift southward and blow harder:
- Anomalous Ekman circulation cools at ~60S and warms at ~45S
- Upwelling of CDW is enhanced near Antarctica
- Eddy southward heat transport is enhanced (low confidence)
- Enhanced shortwave absorption from sea ice and cloud change
SST Response to Abrupt Ozone Depletion
(at year zero)

Fast response is lower SST at 60°S that after ~3 years transitions to higher SST
MIT gcm has much greater cooling response than CCSM3.5 and it lasts several decades. Why? The surface westerlies are too far north and surface feedbacks are much weaker (motionless sea ice).
The rapid response to ozone depletion does cause sea ice to expand... But ozone depletion is not abrupt.

Ozone depletion (and increased surface westerly winds) would drive slow response and hence is not the cause of sea ice expansion, according to CCSM3.5.