POLAR SCIENCE
FOR PLANET EARTH

eCSE03-09

Adjoint ocean modelling with MITgcm and OpenAD

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Webinar starts at 15:00

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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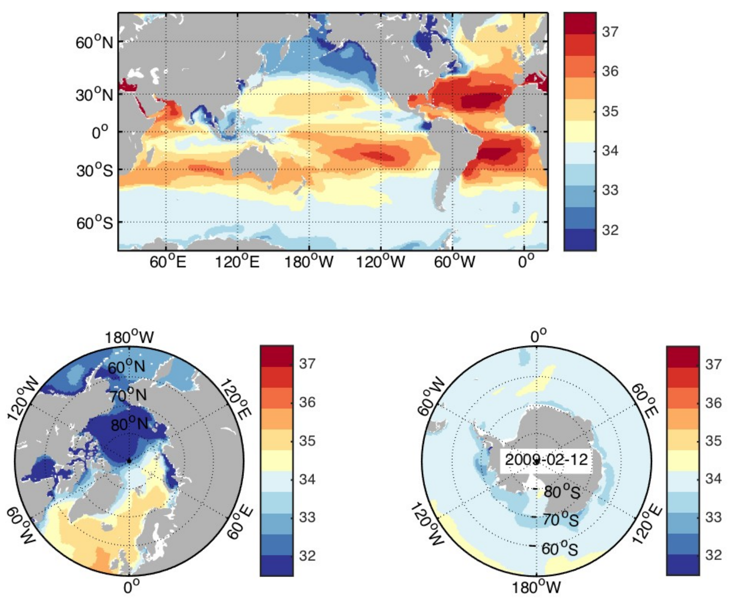
MITgcm (mitgcm.org)

Sea surface salinity (psu)



- MITgcm is an open-source numerical model that can be used to study the ocean, atmosphere, and climate
- Useful features:
  - Lots of pre-packaged experiments
  - Non-hydrostatic mode
  - Adjoint modelling capability
  - Active support community

Data: ECCOv4
Plotted using gcmfaces

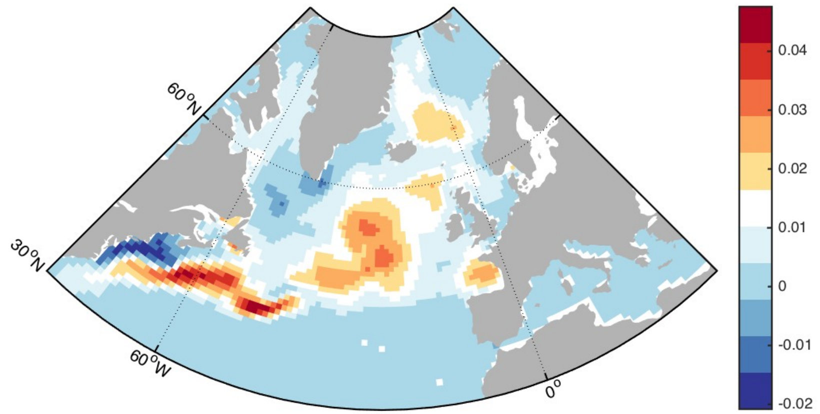
http://mitgcm.org/mailman/listinfo/mitgcm-support

What is adjoint modelling?

- Generally speaking, adjoint modelling is about calculating gradients:

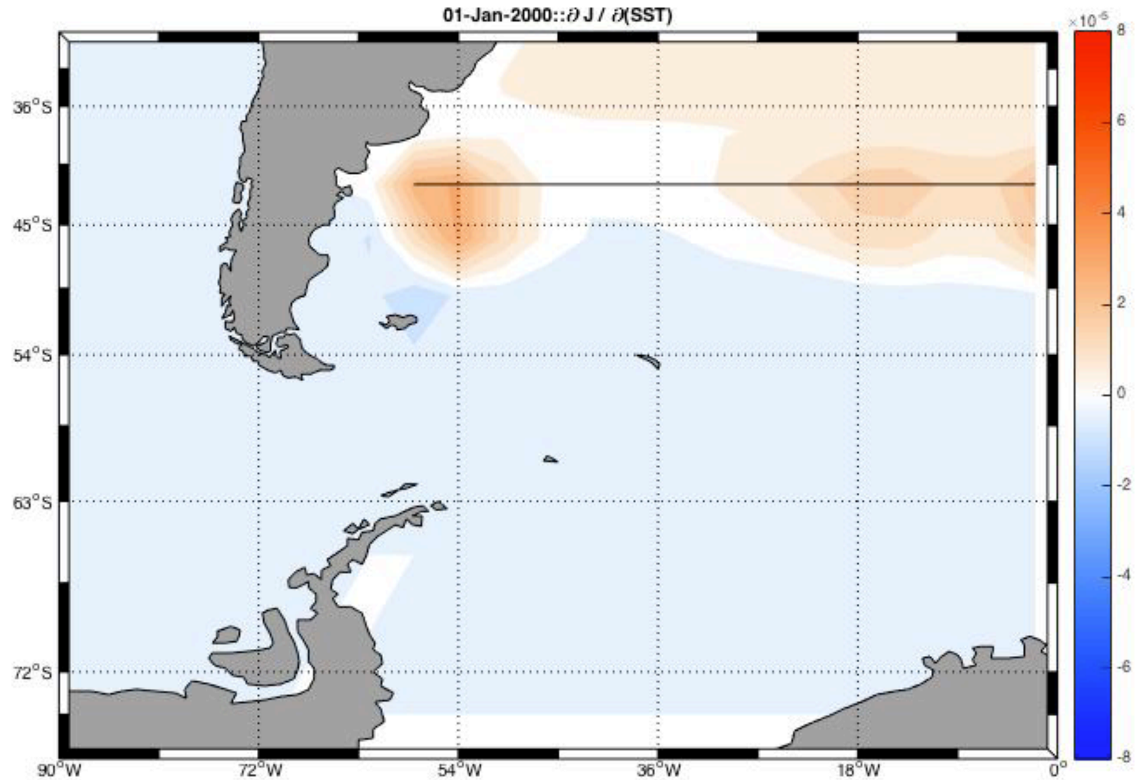
$$\frac{\partial J}{\partial \mathbf{f}}$$

- Gradients are useful for many applications, including:
  - Sensitivity experiments
  - State estimation problems (e.g. ECCO project)



Example gradient field
(for illustration purposes only)

Example sensitivity fields



Objective function: heat transport across black line

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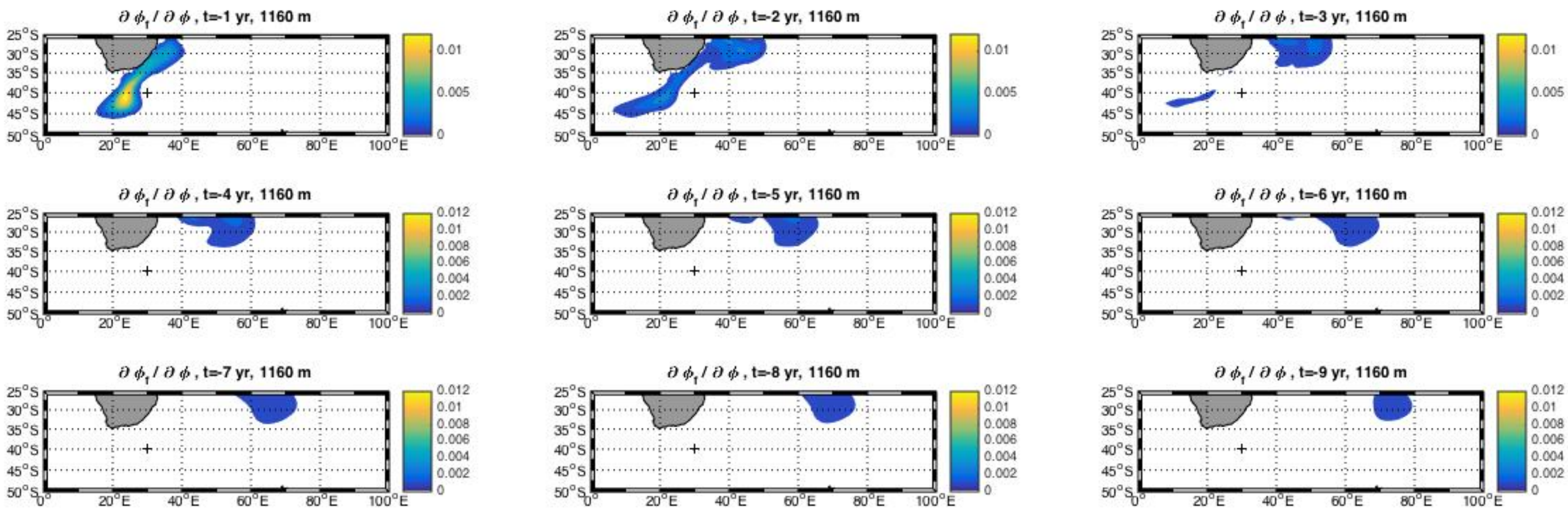
Example sensitivity fields



Objective function:

Tracer value at location ‘+’ at the end of the simulation

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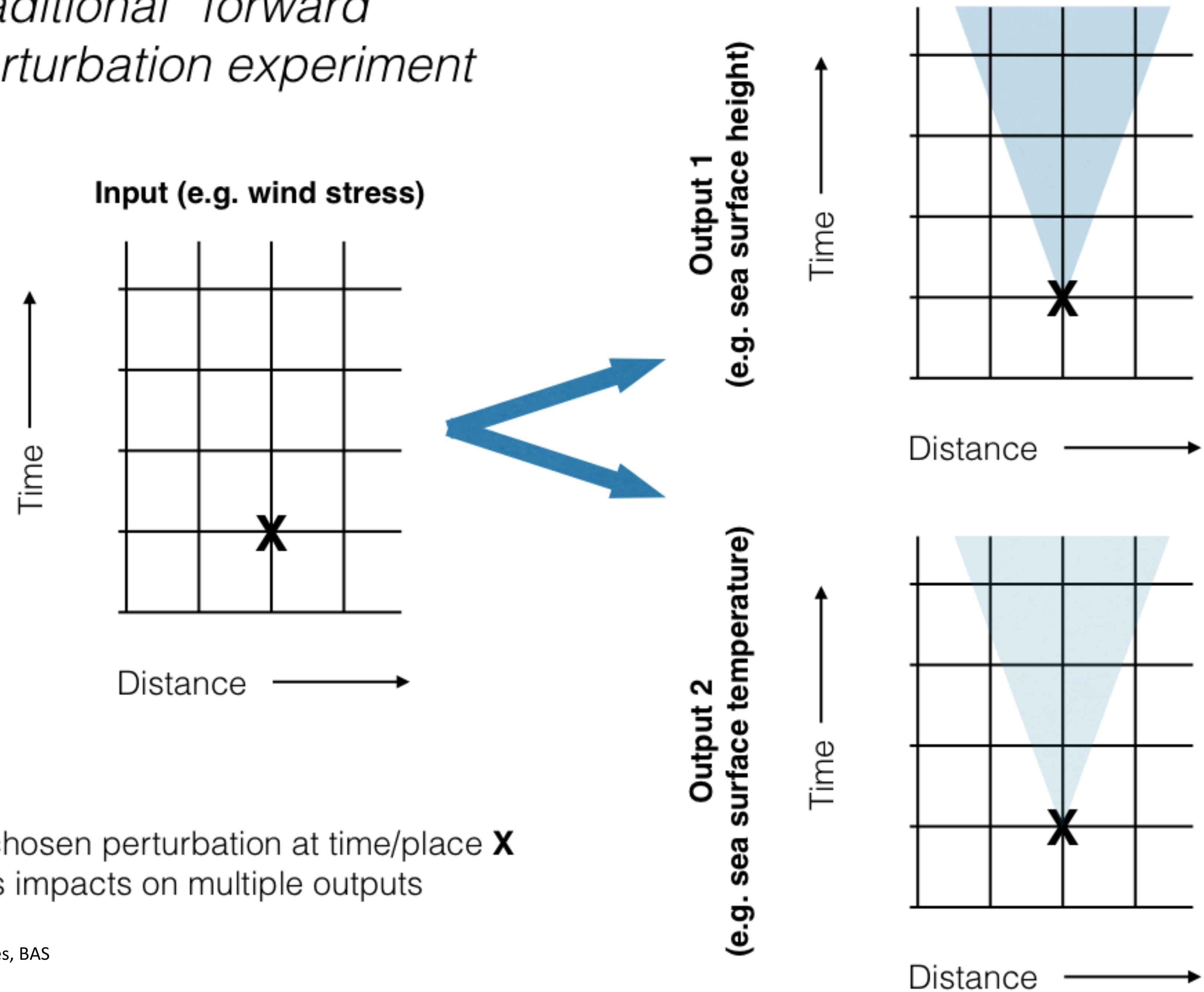
Traditional "forward" perturbation experiment



A chosen perturbation at time/place **X** has impacts on multiple outputs

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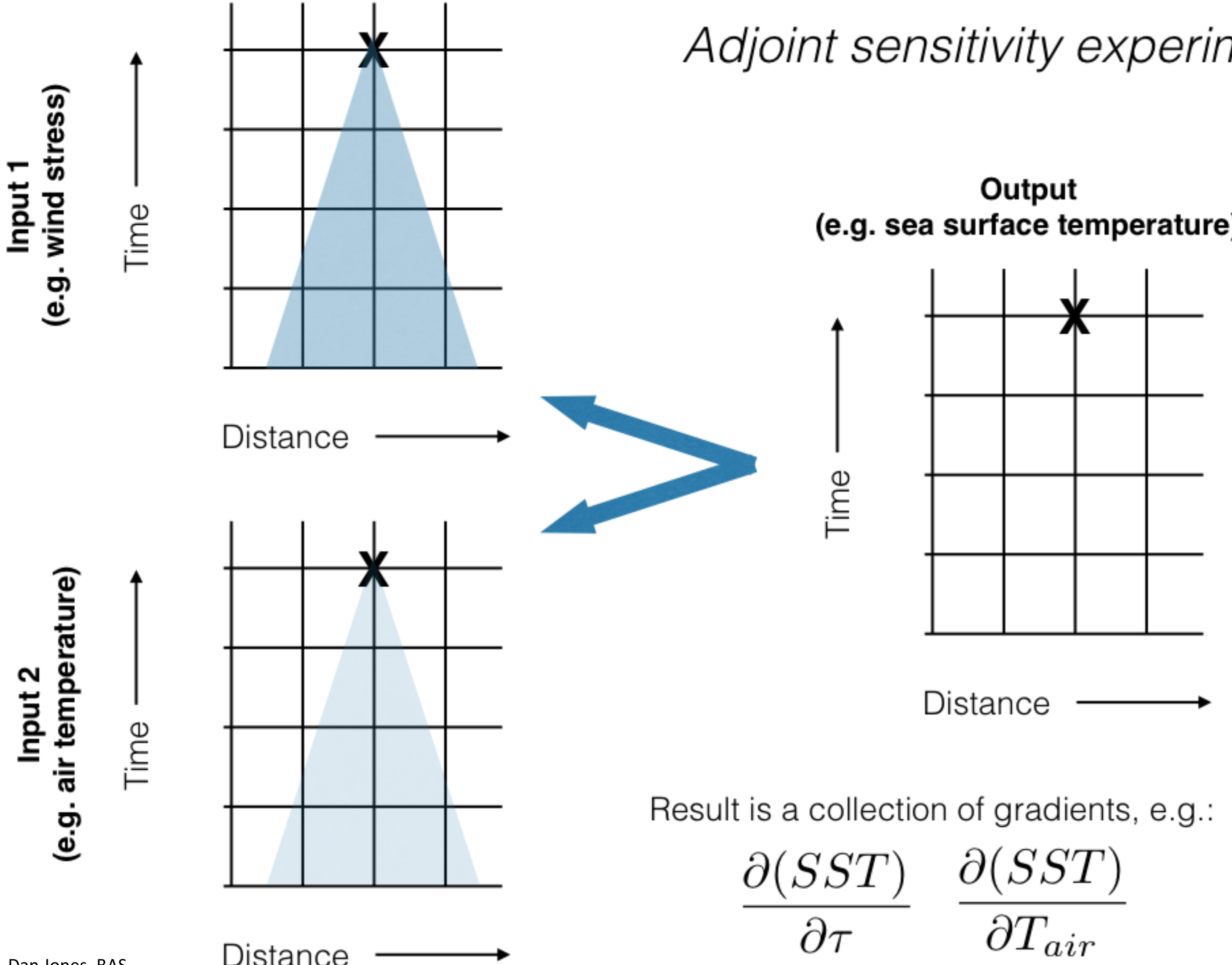
Adjoint sensitivity experiment



Result is a collection of gradients, e.g.:

$$\frac{\partial(SST)}{\partial\tau} \quad \frac{\partial(SST)}{\partial T_{air}}$$

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What is adjoint modelling?

(Output) = (Operator)(Inputs) $$\mathbf{y} = G\mathbf{f}$$

Objective function: $$J = J(\mathbf{y})$$

Adjoint models estimate gradients: $$\frac{\partial J}{\partial \mathbf{f}(\mathbf{x}', t')}$$

Giering and Kaminski (1998), Verdy et al. (2014)

Adjoint sensitivities are **not** correlations

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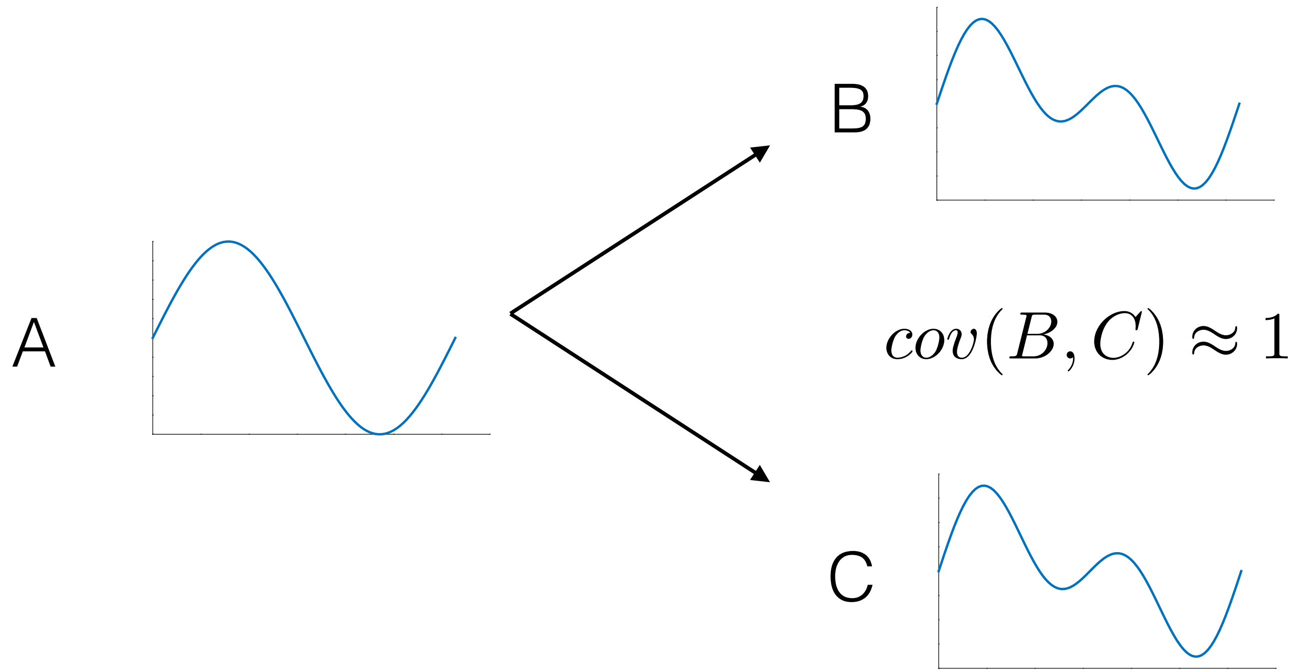

$$cov(B, C) \approx 1$$

- A drives B
- A drives C
- B and C are correlated but are **not** physically related

Adjoint sensitivities are **not** correlations

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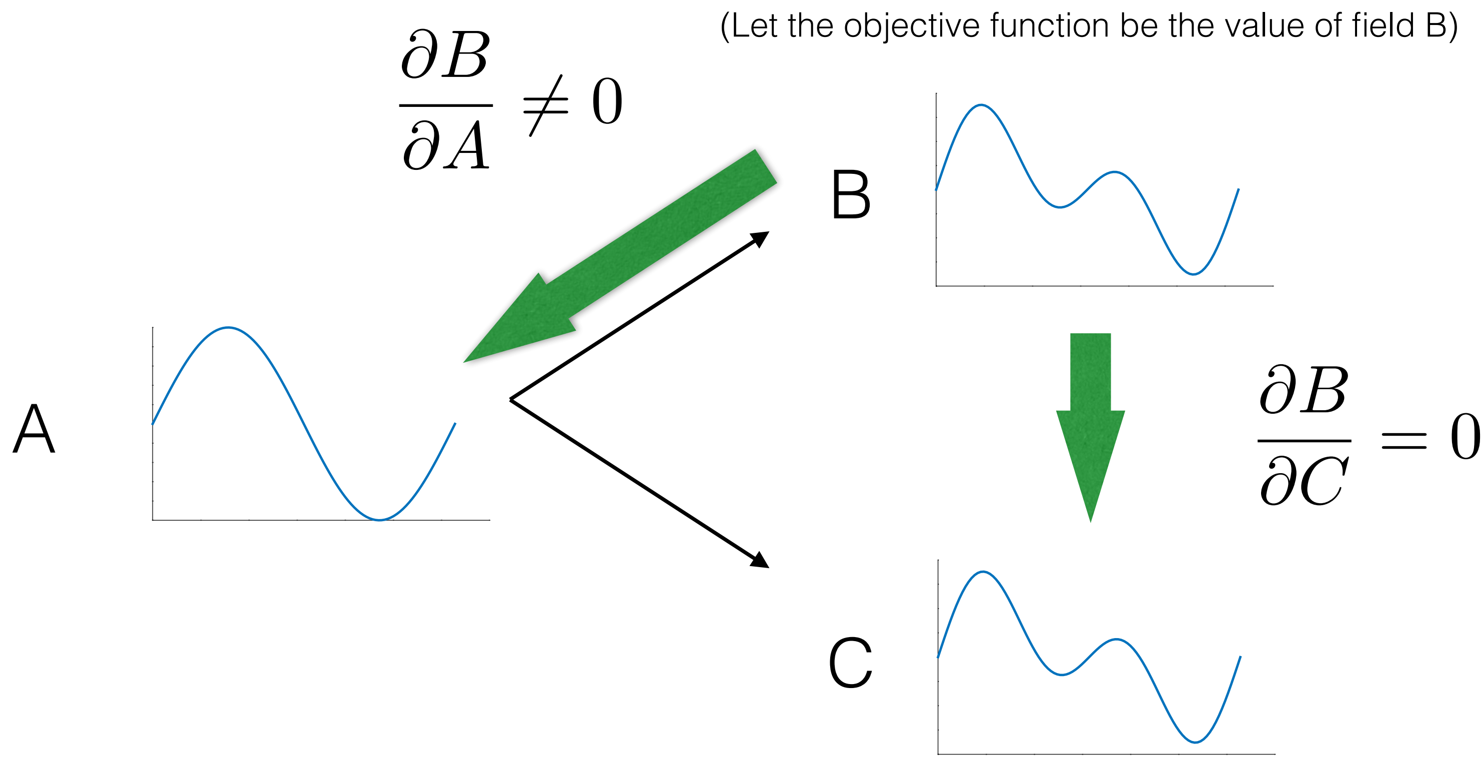
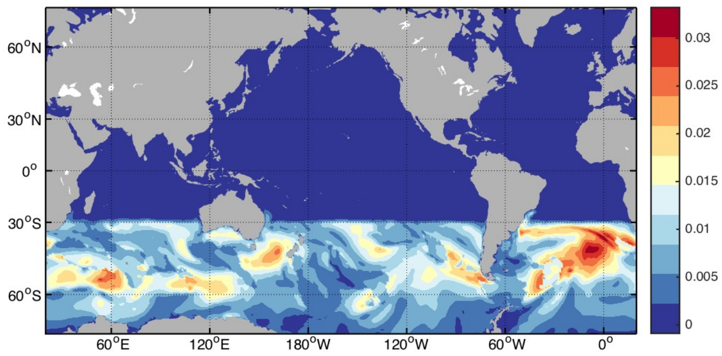


- A drives B
- A drives C
- B and C are correlated but are **not** physically related
- Adjoint sensitivities indicate **physical relationships** in the model

Make your own experiment

1. Download and install MITgcm (mitgcm.org)
2. Download and install OpenAD (or use TAF by FastOpt)
3. Modify test case ("verification" exercises)
4. Compile
5. Run



MITgcm on ARCHER

- MITgcm is NOT centrally installed/maintained on ARCHER
- Get the MITgcm source code: http://mitgcm.org/public/source_code.html
- Remember that the "home" filesystem is backed up, but the "work" filesystem is not. You may want to compile on the "home" filesystem and run on the "work" filesystem.
- Try the verification exercise "tutorial_tracer_adjsens"

MITgcm on ARCHER: build options file

- ARCHER/Cray build options file now part of MITgcm source code:
  - MITgcm/tools/build_options/linux_ia64_cray_archer

- Maintained by David Ferreira (U. Reading)
- Checked nightly in automated testing

If you receive a “relocation truncated to fit” error when compiling, try uncommenting these two lines at the end of the build options file:

```
#FFLAGS='-h pic -dynamic'
#CFLAGS='-h pic -dynamic’
```

Build options files are also available for the Intel and Gnu environments, but they are not tested/maintained.

Script used to compile MITgcm on ARCHER (not adjoint case)

```
#!/bin/bash
#
# Compile MITgcm case on ARCHER
# - Designed for use with default modules as of 07/03/16
#

# Define MITgcm directory (select source code to use)
export HOMEDIR=~
export ROOTDIR=$HOMEDIR'/MITgcm'

# Select build options file
optfile=$ROOTDIR/tools/build_options/linux_ia64_cray_archer

# To enable NetCDF:
module load cray-hdf5-parallel
module load cray-netcdf-hdf5parallel

# Compile with mpi
../../../tools/genmake2 -ieee -mpi -mods=../code -of=$optfile
make depend
make
```

Should point to the “root” of your MITgcm installation

The “mods” flag points to the folder containing your source code modifications

OpenAD on ARCHER

- OpenAD is an open source “algorithmic differentiation” tool that can be used to generate adjoint models from MITgcm source code.

- Get the source code here:

  http://www.mcs.anl.gov/OpenAD/

- Install in home directory

- Note: OpenAD is under active development. There are some limitations (e.g. “cal”, “exf” packages not yet supported), but new features/packages will be added in the future.

OpenAD on ARCHER

Some adjoint-relevant MITgcm packages:

- **autodiff**: support for algorithmic differentiation, active file handling
- **cost**: the cost function is defined here. Simple test cost functions are included (e.g. heat transport across 26N)
- **ctrl**: control variables are defined here.
- **grdchk**: gradient check package; used to verify that the adjoint gradients agree well with gradients calculated using finite differences.

Modifications for compiling with OpenAD

```
# Manually link the c++ libraries
# -this step is needed, confirmed by ARCHER support (early 2016)
export LD_LIBRARY_PATH=/opt/gcc/4.9.2/snos/lib64:$LD_LIBRARY_PATH

# Set OpenAD environment variables (i.e. OPENADROOT)
workingDir=$(pwd)
cd ~/OpenAD/
source ./setenv.sh
cd $workingDir
echo "OPENADROOT is set to: "
echo $OPENADROOT

# Use genmake2 to build make file
$ROOTDIR/tools/genmake2 -oad -mpi -mods=../code_oad -of=$optfile

# Use makefile to build adjoint using OpenAD
make adAll
```

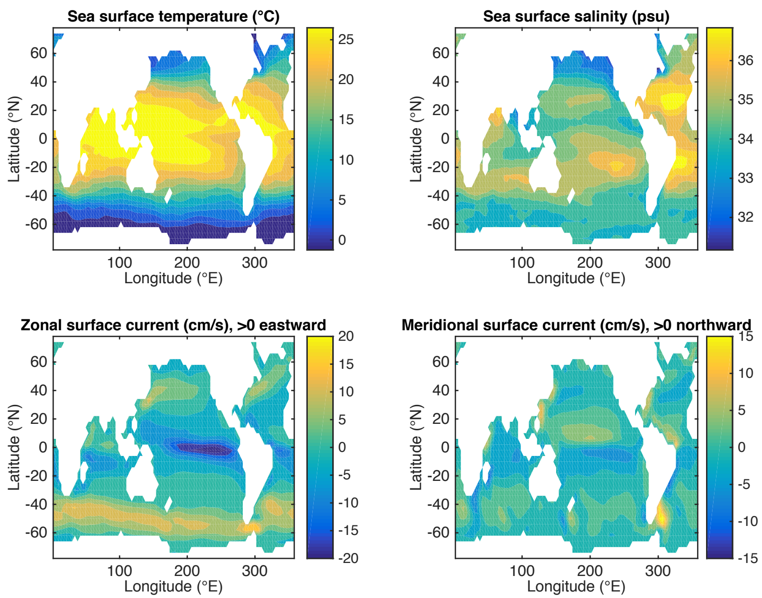
Path edit may be required

Set environment variables

Need "oad" flag to use OpenAD

Adjoint test case: tracer sensitivity

(Found in verification/tutorial_tracer_adjsens)



Global ocean tracer advection

$$\frac{\partial C}{\partial t} = -U \cdot \nabla C - \mu C + \Gamma(C) + S$$

Objective function (total outgassing from the ocean)

$$J(t=T) = \int_{t=0}^{T} \int_{V} \mu C \, dV \, dt$$

Hill, C. et al. (2004). Evaluating carbon sequestration efficiency in an ocean circulation model by adjoint sensitivity analysis. *Journal of Geophysical Research*, *109*(C11), C11005. http://doi.org/10.1029/2002JC001598

Directories in test case

- build : compile forward (i.e. non-adjoint) model here
- build_ad : compile adjoint model here (TAF)
- code_ad : source code modifications (TAF)
- code_oad : source code modifications (OpenAD)
- input : input files for forward model run
- input_ad : input files for adjoint run (TAF)
- input_oad: input files for adjoint run (OpenAD)
- results : sample standard output (including some for ARCHER)
- run : empty run directory

Gradient check

```
uname@eslogin:results> grep adjoint_gradient STDOUT.0000
(PID.TID 0000.0001)  ADM  adjoint_gradient       = -3.23177881094467E+07
(PID.TID 0000.0001)  ADM  adjoint_gradient       = -2.14754889771434E+07
(PID.TID 0000.0001)  ADM  adjoint_gradient       = -4.43487002860037E+07
(PID.TID 0000.0001)  ADM  adjoint_gradient       = -3.09483516589104E+07
(PID.TID 0000.0001)  ADM  adjoint_gradient       = -3.26073245310869E+07
uname@eslogin:results> grep finite-diff_grad STDOUT.0000
(PID.TID 0000.0001)  ADM  finite-diff_grad       = -3.23178125000000E+07
(PID.TID 0000.0001)  ADM  finite-diff_grad       = -2.14756250000000E+07
(PID.TID 0000.0001)  ADM  finite-diff_grad       = -4.43487500000000E+07
(PID.TID 0000.0001)  ADM  finite-diff_grad       = -3.09482812500000E+07
(PID.TID 0000.0001)  ADM  finite-diff_grad       = -3.26075000000000E+07
```

Collaborators

- **Thanks to:**
  - Gavin Pringle (EPCC, The University of Edinburgh)
  - Chris Johnson, Terry Sloan, and many others at EPCC
  - Sudipta Goswami (British Antarctic Survey)
  - David Ferreira (University of Reading)
  - Dan Goldberg (University of Edinburgh)
  - Paul Holland (British Antarctic Survey)
  - Patrick Heimbach (MIT & The University of Texas at Austin)
  - Sri Hari Krishna Narayanan (Argonne National Laboratory)

Also available:

- New OpenAD applications in glaciology
- OpenAD DIVA implementation (enables adjoint restarts)
- Two "forward" test cases for ARCHER
- Two "adjoint" test cases modified for ARCHER

Project website:

http://www.archer.ac.uk/community/eCSE/eCSE03-09/eCSE03-09.php

Resources and contact info

Project website:

http://www.archer.ac.uk/community/eCSE/eCSE03-09/eCSE03-09.php

eCSE technical report available here:

http://www.archer.ac.uk/community/eCSE/eCSE03-09/eCSE03-09_White_Paper.pdf

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Thank you!