

Plan for the rest of the quarter

Today: Climate variability in models (and observations), begin sea ice

Wednesday: Sea ice and ocean modeling

Monday: The IPCC process. Can we believe climate projections?

Wednesday: Climate modeling of the past

Last homework/project:

This Friday: I will show you how to run the diagnostic package and work with you on your analysis. Please have your runs done (or some of them anyway).

Next Friday: Present your project in 8-10 min. Plan to explain what you did, show ~4 figures. Write up ~2 pages plus figures due Thursday of finals week with take home final that I will distribute next Friday.

MATLAB script correl.m

```
ncf='/home/disk/p/atms380/b30.004.cam2.h0.TS.0600-01_cat_0699-12.nc';
```

This model output file was created using NCO tools

on the unix command line, cat stands for concatenate:

```
ncrcat -v TS b30.004.cam2.h0.* b30.004.cam2.h0.TS.0600-01_cat_0699-12.nc
```

You could do an average too:

```
ncra -v TS b30.004.cam2.h0.* b30.004.cam2.h0.TS.0600-01_mean_0699-12.nc
```

MATLAB script correl.m

```
ncf='/home/disk/p/atms380/b30.004.cam2.h0.TS.0600-01_cat_0699-12.nc';
```

% Read in monthly means, Compute annual means, discard monthly means

```
TS=getnc(ncf,'TS'); % 3D Temperature field (months, lat, lon)
```

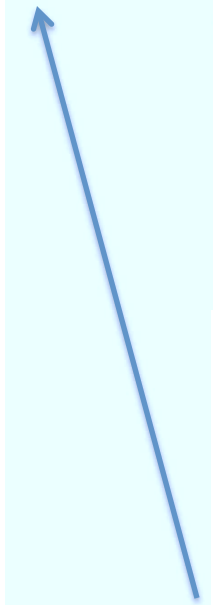
```
TSann=squeeze(mean(reshape(TS,12,100,64,128)));
```



Makes TS a 4D field (month, year, lat, lon)



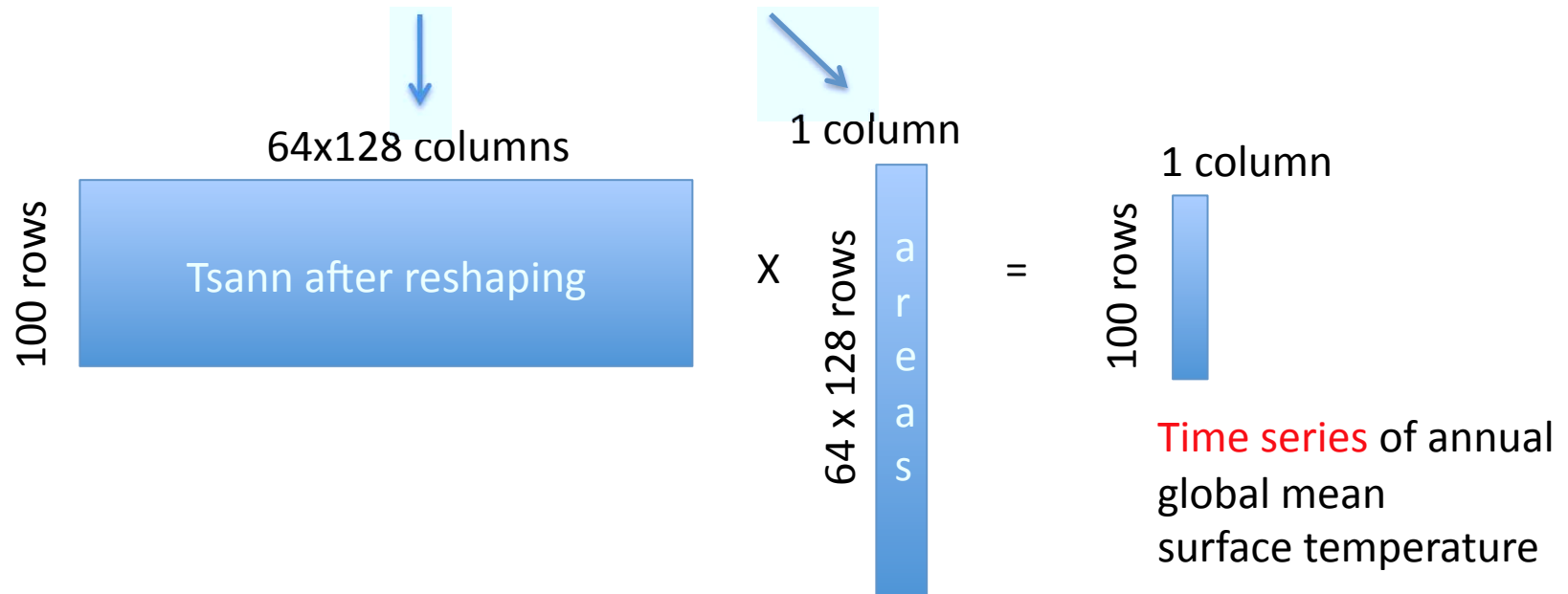
mean of first dimension, here it is month, leaving a TS(1,year,lat,lon)



gets rid of the 1, leaving a TSann(year,lat,lon)

MATLAB script correl.m

```
% Compute global mean of the annual means, weighting mean by grid cell area
lat=getnc(ncf,'lat'); lon=getnc(ncf,'lon');
areas=camareas(lat,lon); % this script computes grid cell areas on a sphere
sphere_area=sum(areas(:)); % area of surface of sphere
TSann_glob=reshape(TSann,100,64*128)*areas(:)/sphere_area;
```



MATLAB script correl.m

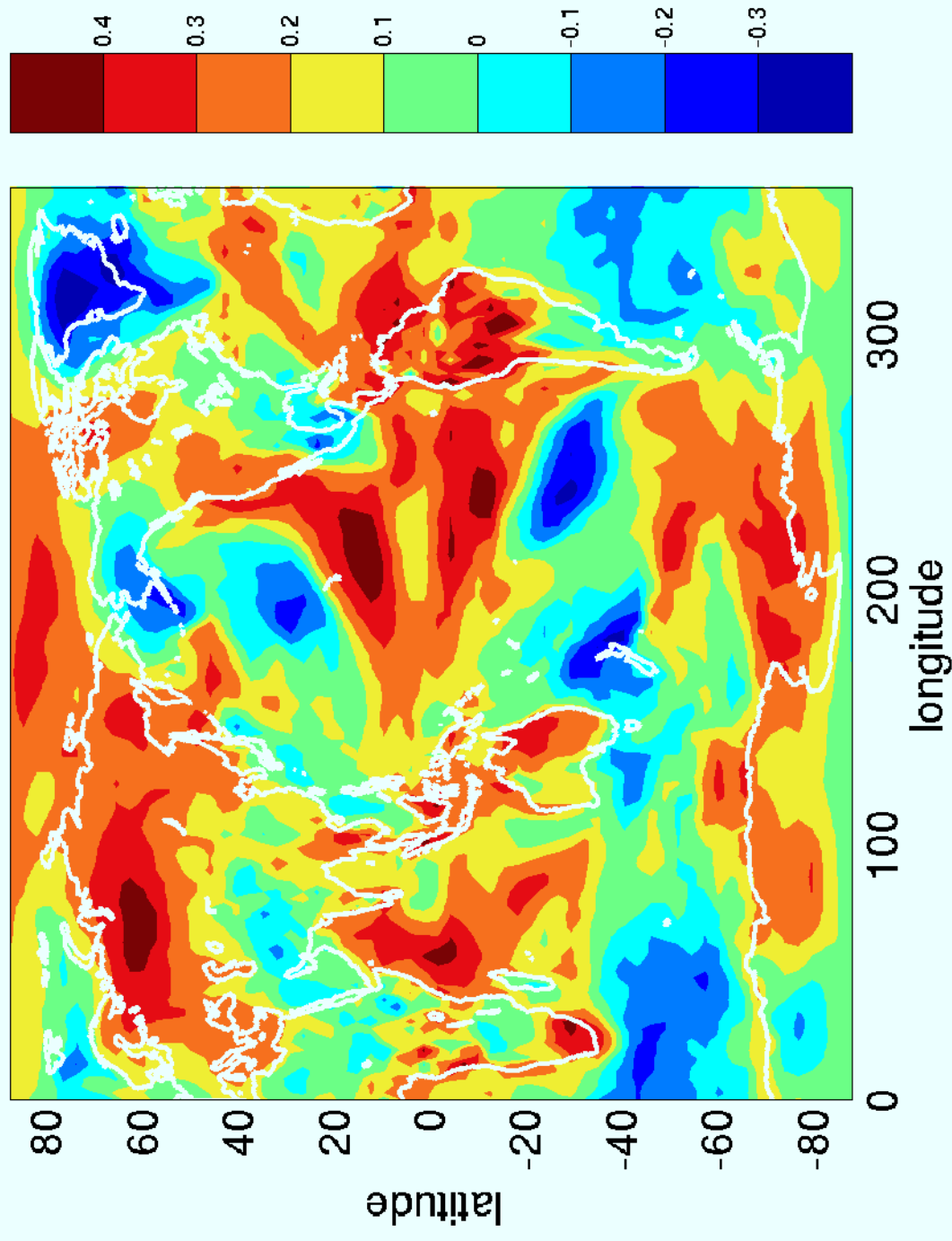
```
TScorr=zeros(64,128); % make an array of zeros
for k=1:(64*128);    % raster through the globe correlating each grid cell
    c=corrcoef(TSann_glob,TSann(:,k)); % corrcoef makes a 2x2 matrix
    TScorr(k)=c(1,2); % need only this part of the matrix
end
```

the correlation has output:

$$c = \begin{bmatrix} 1 & \text{TScorr} \\ \text{TScorr} & 1 \end{bmatrix}$$

Notice that you can index TSann(year,lat,lon)
with a single variable “k” for both lat and lon
This avoids making a double loop.

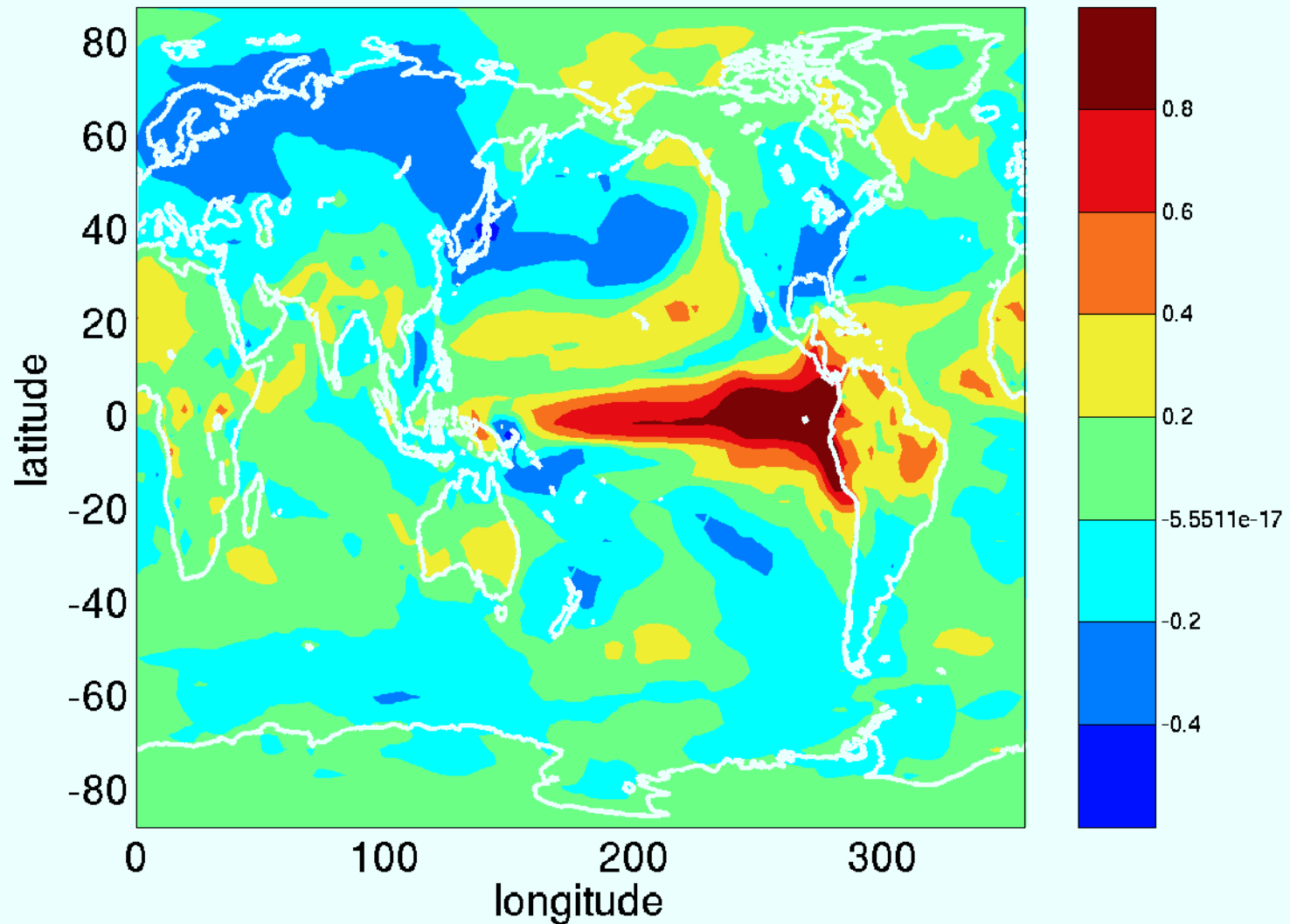
Correlation Coefficient of local TS with global mean TS



MATLAB script correl.m

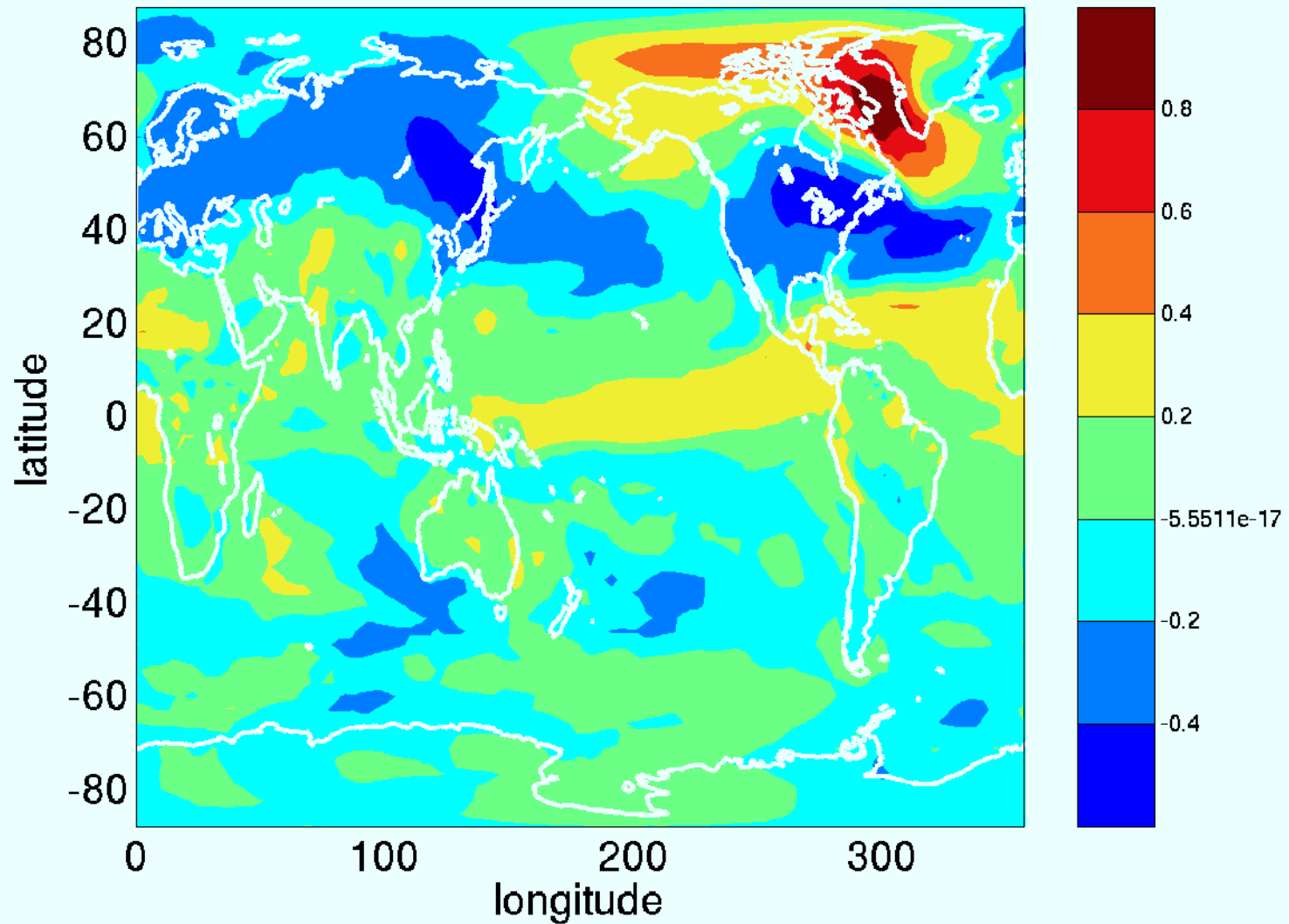
```
TScorr=zeros(64,128); % make an array of zeros
for k=1:(64*128);    % raster through the globe correlating each grid cell
    % c=corrcoef(TSann_glob,TSann(:,k));
    c=corrcoef(squeeze(TSann(:,56,108)),TSann(:,k)); % try me instead of the previous line
    TScorr(k)=c(1,2);
end
```

Correlation Coefficient of local TS with Galapagos TS



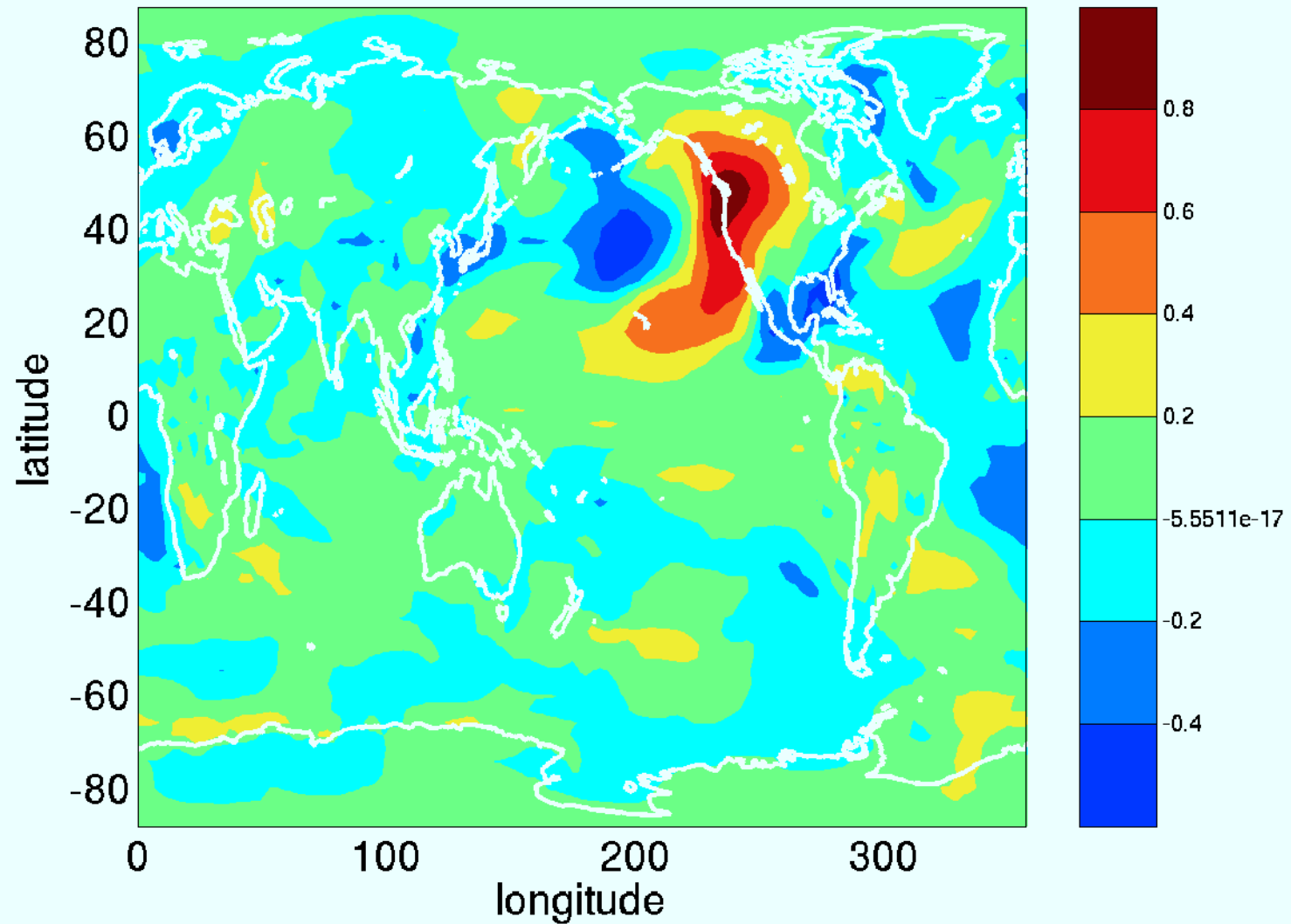
This is also called a one-point correlation map

Correlation Coefficient of local TS with Baffin Bay TS



This is also called a one-point correlation map

Correlation Coefficient of local TS with Seattle TS

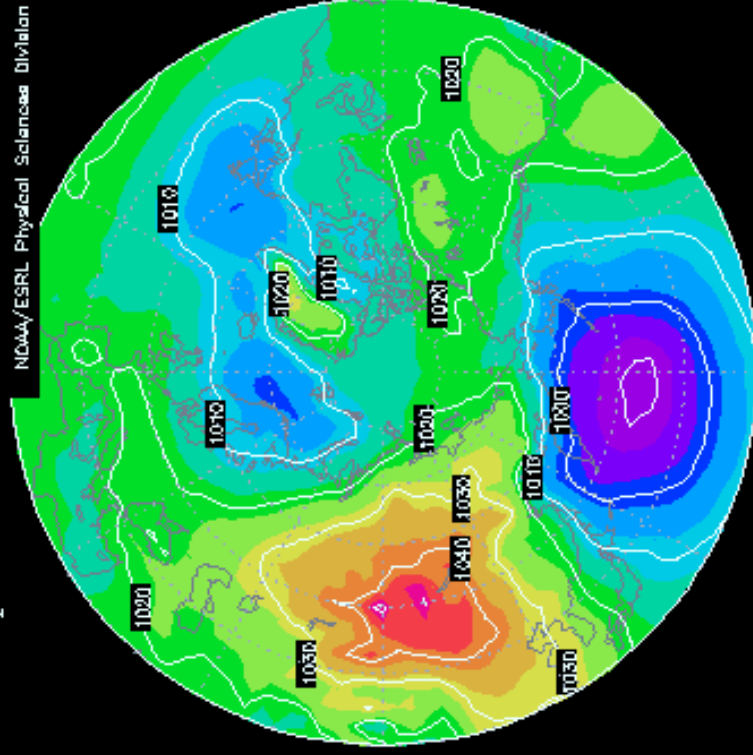


This is also called a one-point correlation map

lon: plotted from 0.00 to 360
 lat: plotted from 30 to 90.00
 t: Jan 2011
 lev: 0

Mean slp millibars

NOAA/ESRL Physical Sciences Division



CEP Reanalysis Products Surface Level GrADS image

lon: plotted from 0.00 to 360

lat: plotted from 30 to 90.00

t: Jan 2011

lev: 0

Mean slp millibars

NOAA/ESRL Physical Sciences Division



Real-time Products Surface Level GrADS image

lon: plotted from 0.00 to 360

lat: plotted from 30 to 90.00

t: averaged over Jan 1990 to Jan 2011

lev: 0

Mean slp millibars

NOAA/ESRL Physical Sciences Division



Sea Ice Extent
02/27/2011



National Snow and Ice Data Center, Boulder, CO

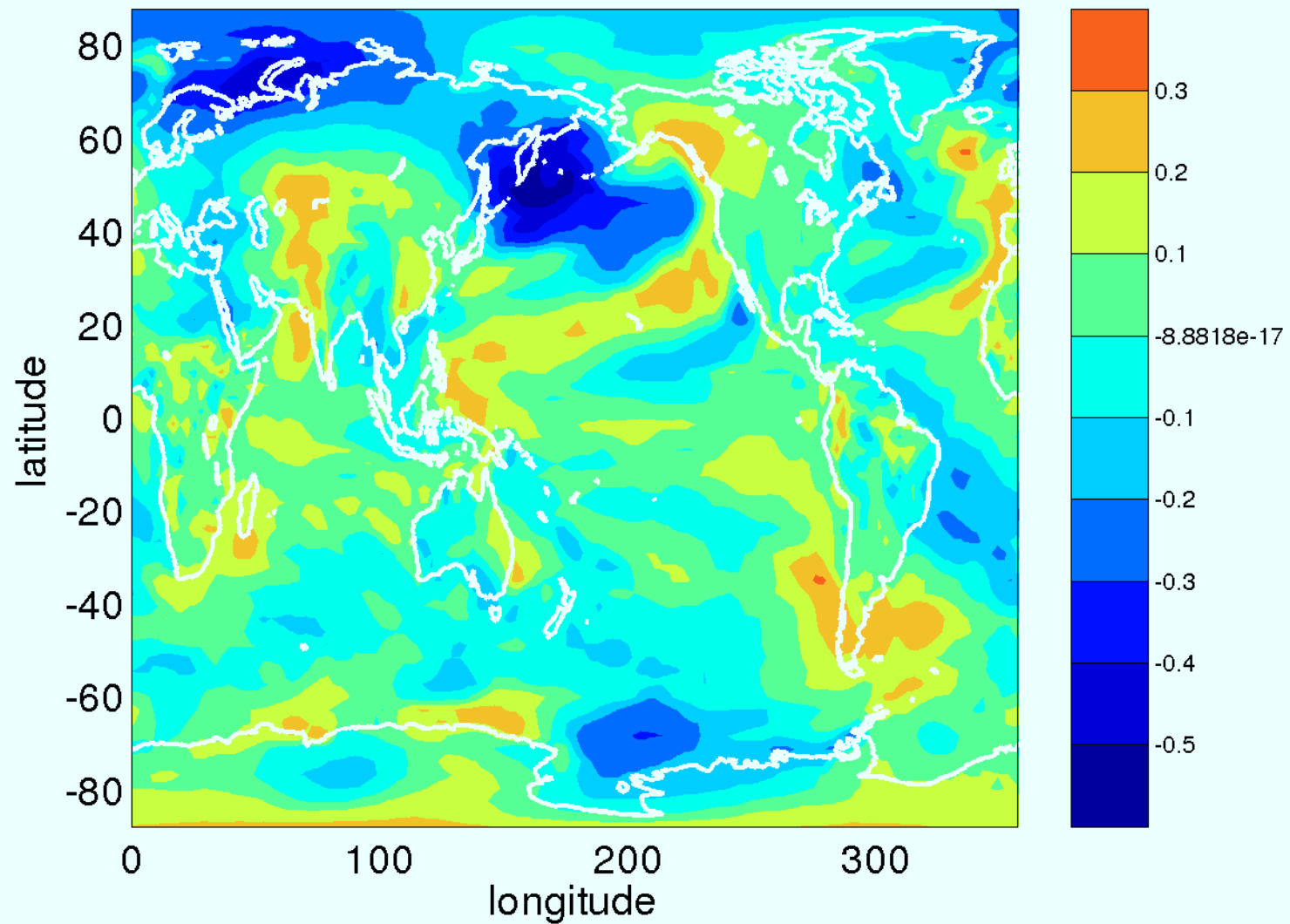
median
1979-2000

MATLAB script correl.m

ice = mean (etc) % compute the ice area mean of your choice

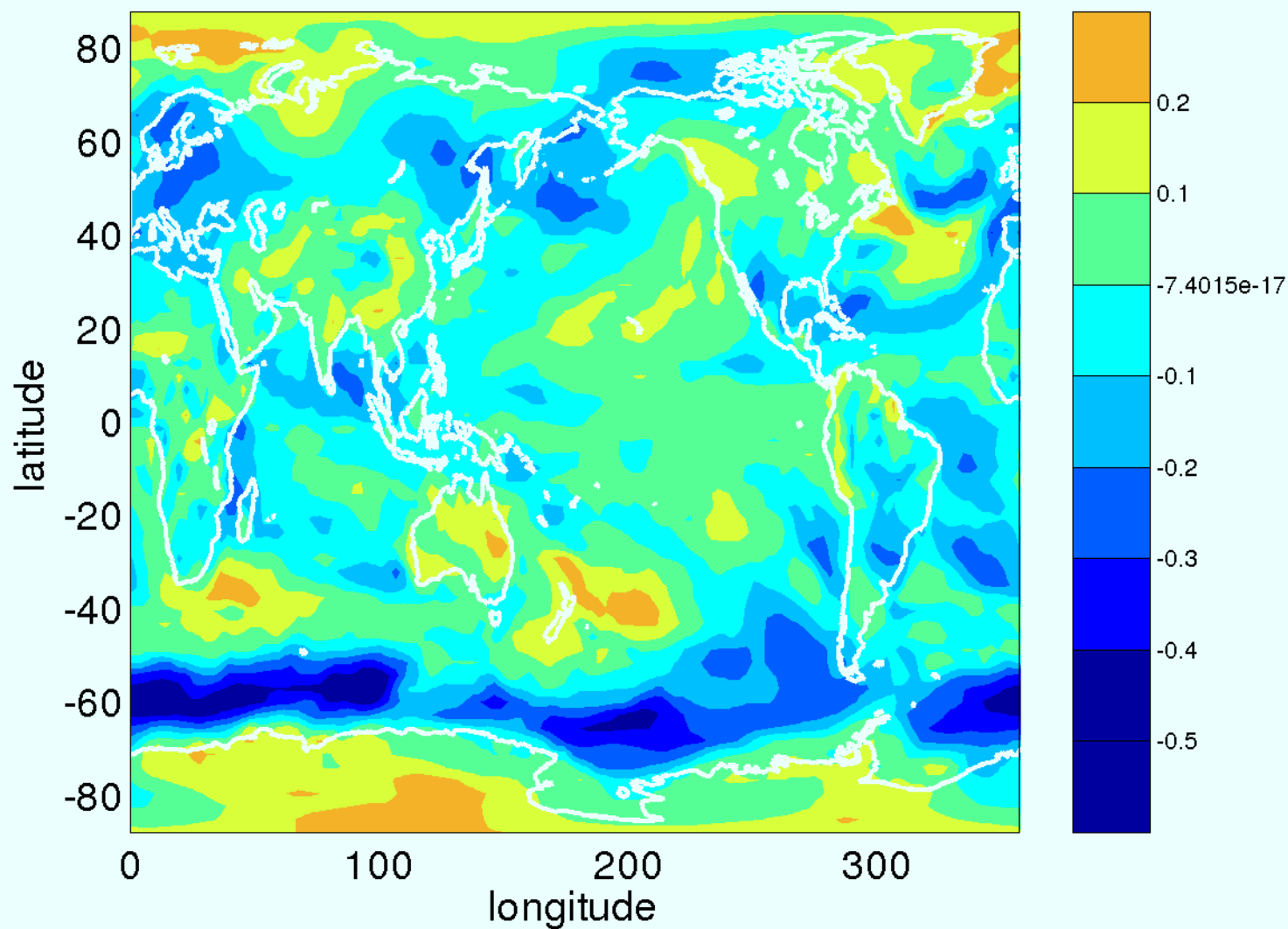
```
TS_Ice_corr=zeros(64,128); % make an array of zeros
for k=1:(64*128); % raster through the globe correlating each grid cell
    % c=corrcoef( TSann_glob, TSann(:,k)) ;
    c=corrcoef( ice, TS(:,k) );
    TS_ice_corr(k)=c(1,2);
end
```

Correlation Coefficient of NH sea ice area with TS

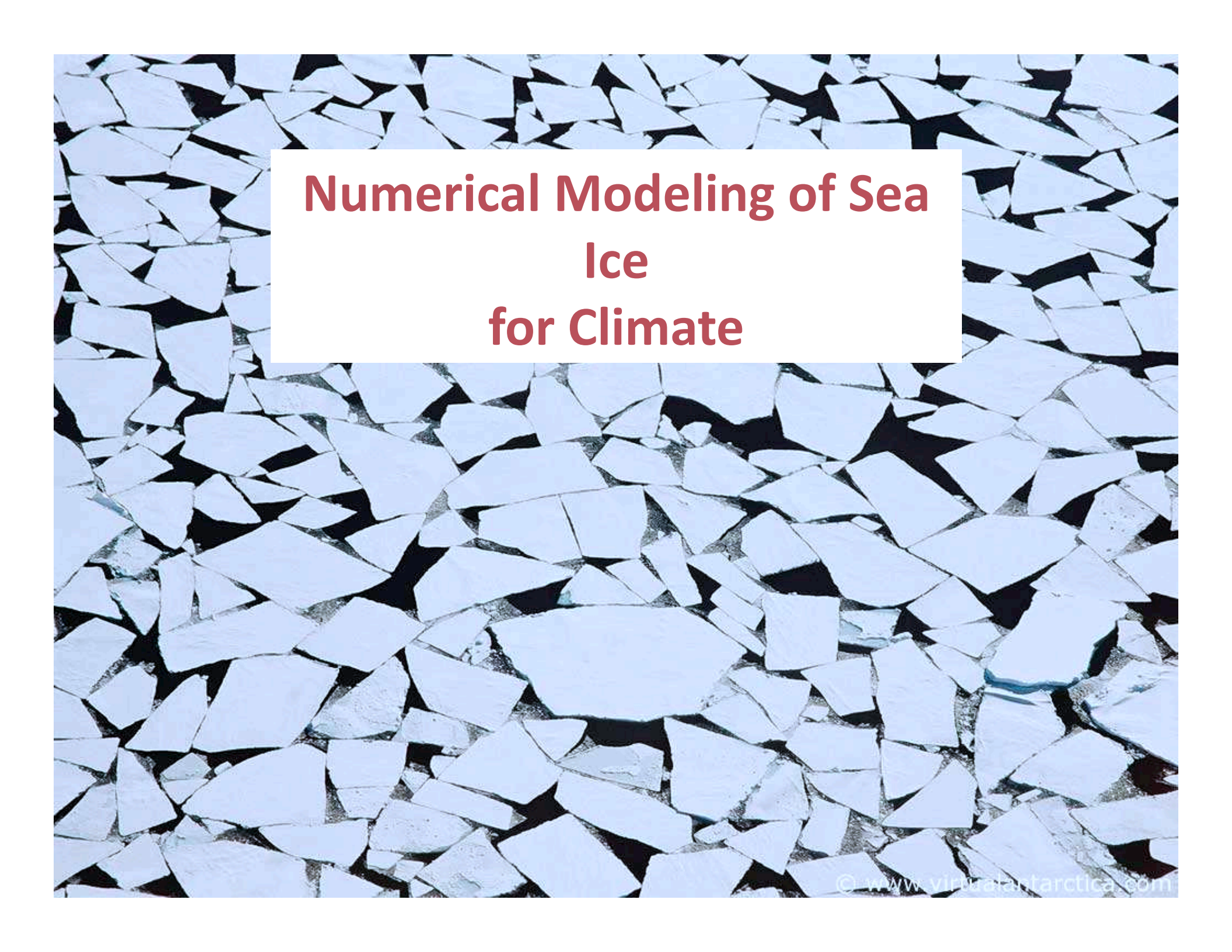


I just used Jan-Apr sea ice area

Correlation Coefficient of SH sea ice area with TS



I just used Jun-Sep sea ice area

An aerial photograph showing a dense field of sea ice floes. The floes are irregular in shape and size, ranging from small fragments to larger, more substantial pieces. They are a pale blue-white color, contrasting with the dark, open water between them. The overall pattern is a complex, mosaic-like arrangement of ice and water.

Numerical Modeling of Sea Ice for Climate

Repartitions shortwave radiation in the climate system

Moderator of air-sea heat and moisture exchange

Freshwater storage and transport

Brine rejection and its influence on water-mass formation, thermohaline circulation, etc.

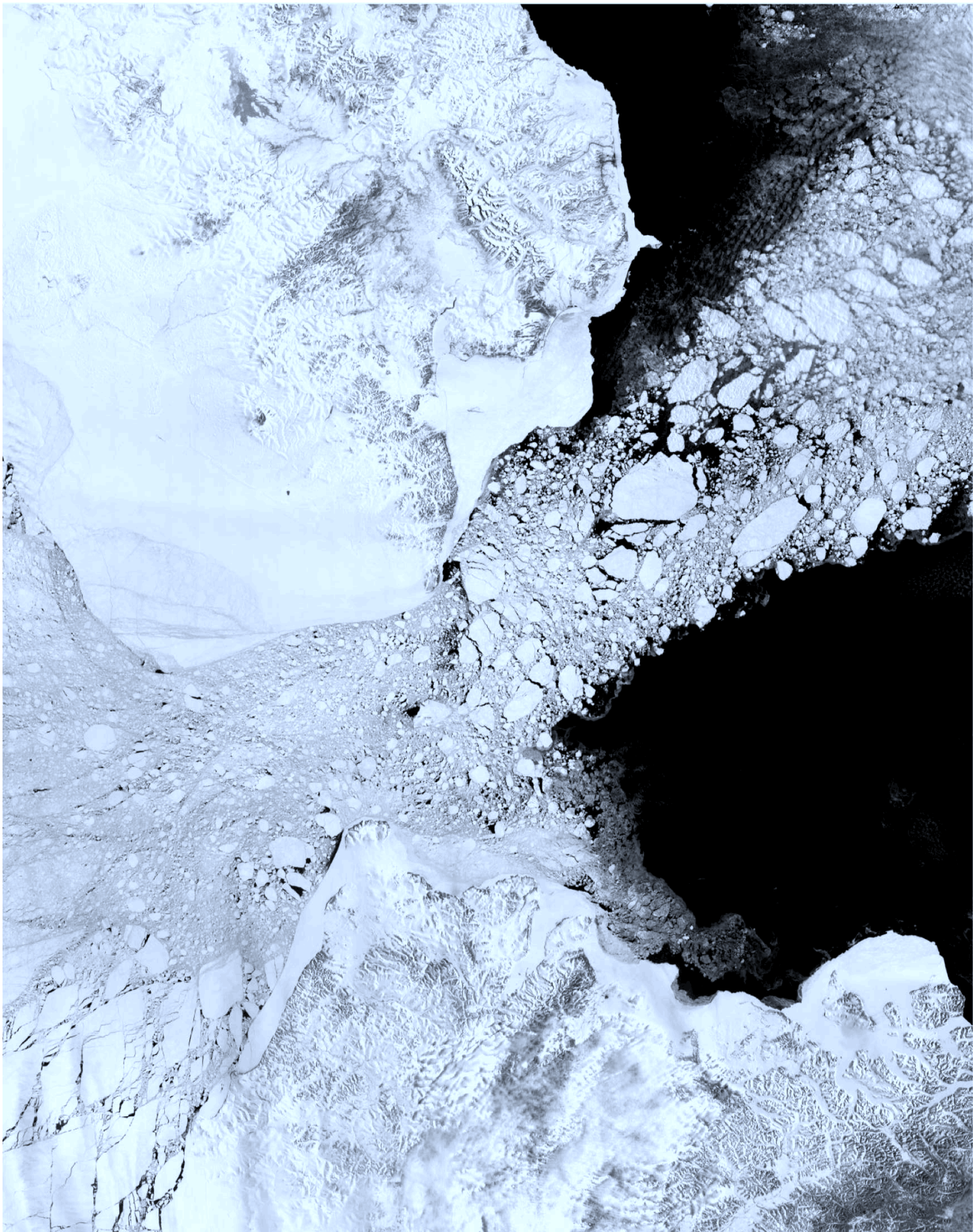
What is essential in a numerical sea ice model for climate studies?

Simulate the climatological mean annual cycle of the ice and snow

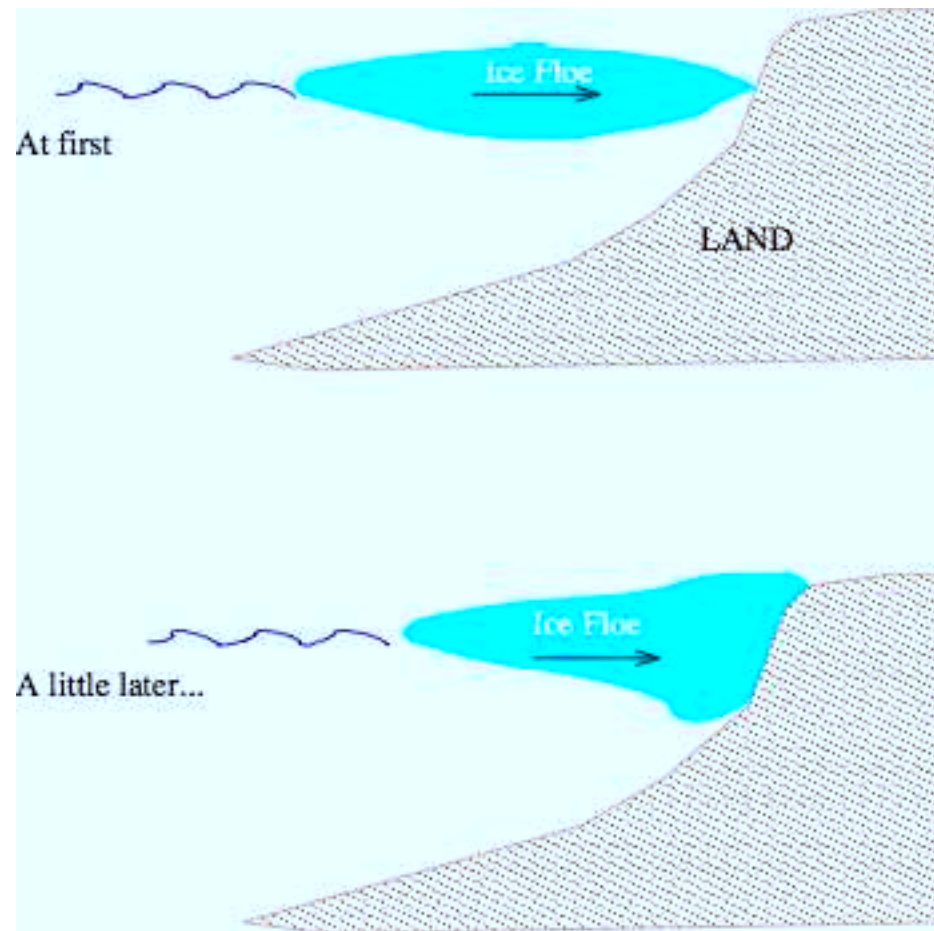
Represent the sensitivity to perturbations - must have the key feedbacks

Accuracy - depends on the problem

Physics appropriate to the model's spatial scale,
parameterizations for sub-scale behaviors

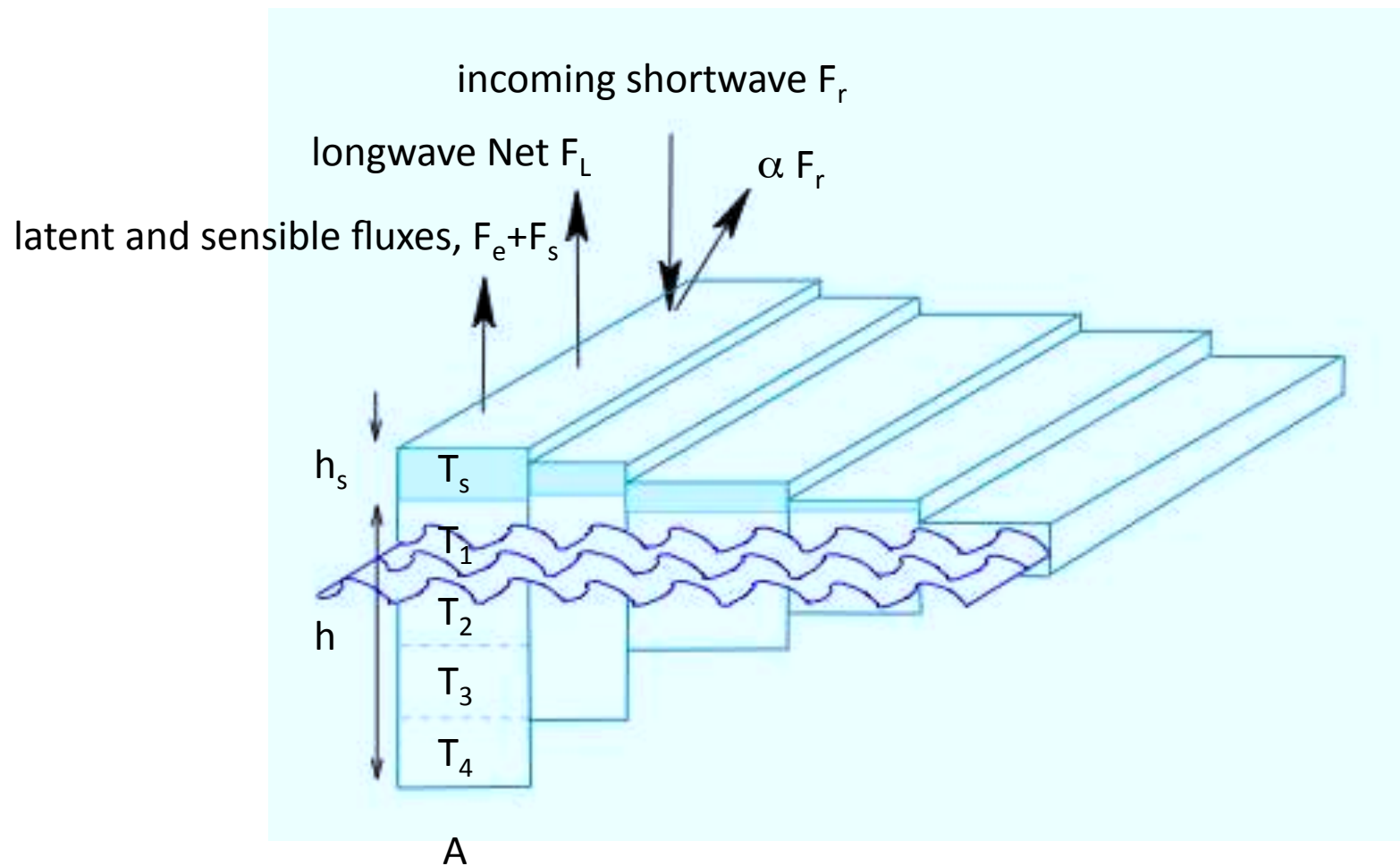


Sea Ice Dynamics in climate models



Past ad hoc method was to stop ice from moving at a critical thickness, sometimes called stoppage

Schematic of model representation of $g(h)$ in five ice “categories”

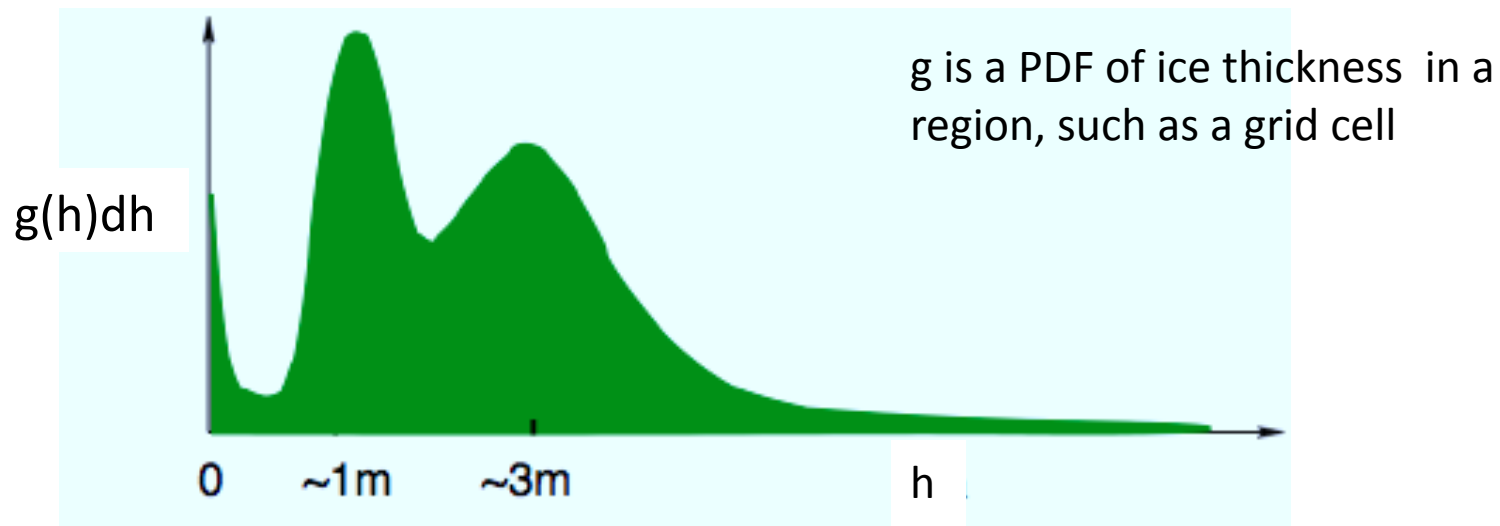


A =fractional coverage of a category

1st Governing Equation

Ice thickness distribution $g(x,y,h,t)$ evolution equation from Thorndike et al. (1975)

$$\frac{Dg}{Dt} = -g \nabla \cdot \mathbf{u} + \psi - \frac{\partial}{\partial h} (fg) + \mathcal{L}$$



$$\underset{1}{\frac{Dg}{Dt}} = -\underset{2}{g\nabla \cdot \mathbf{u}} + \underset{3}{\Psi} - \underset{4}{\frac{\partial}{\partial h}(fg)} + \underset{5}{\mathcal{L}}$$

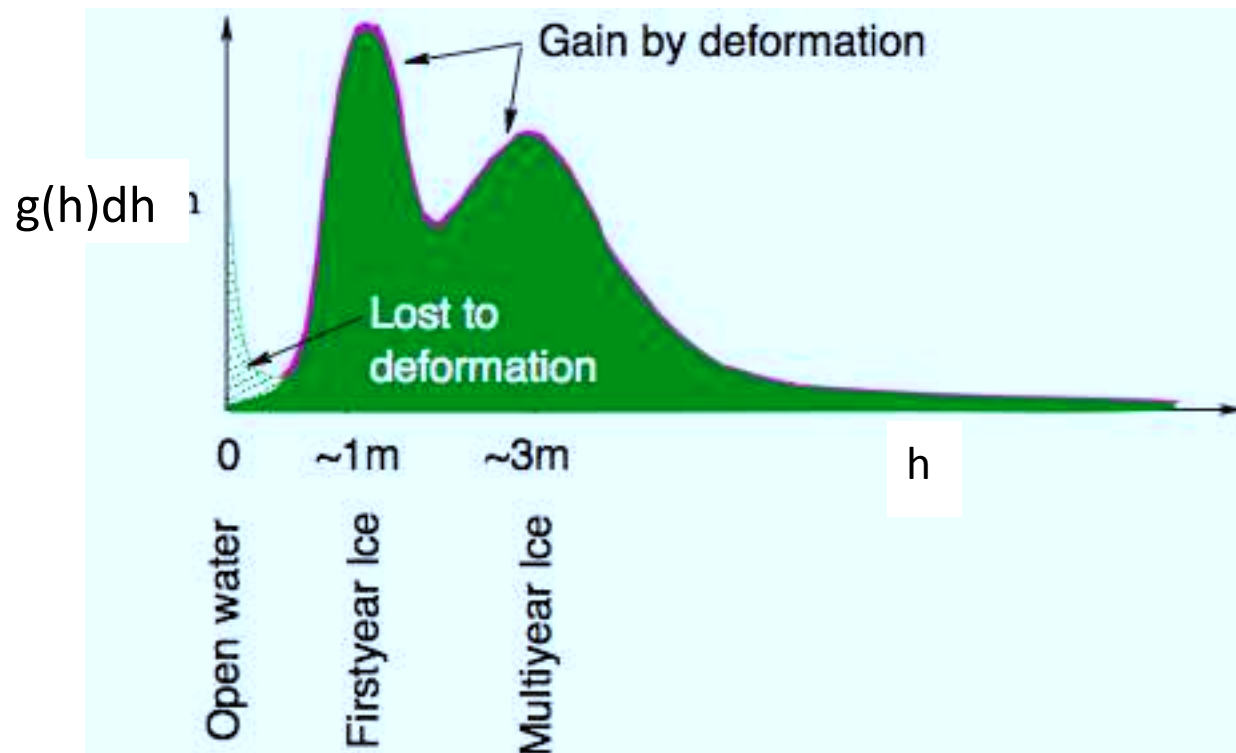
1. Lagrangian time derivative of g following “parcel”
2. Convergence of parcel
3. Ψ = Mechanical redistribution
4. Ice growth/melt results in “advection of g in thickness space”
5. $\mathcal{L}$ = Reduction of g from lateral melt

h = ice thickness

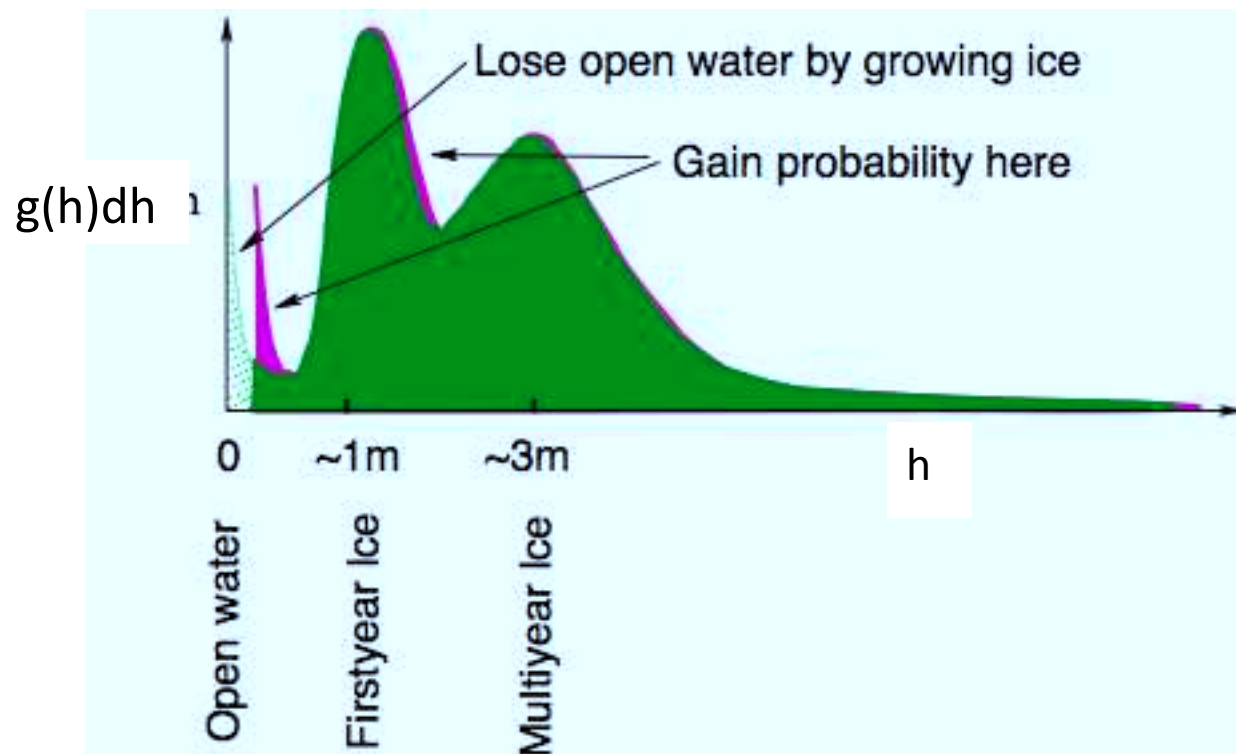
$\mathbf{u}$ = ice velocity

f = growth rate

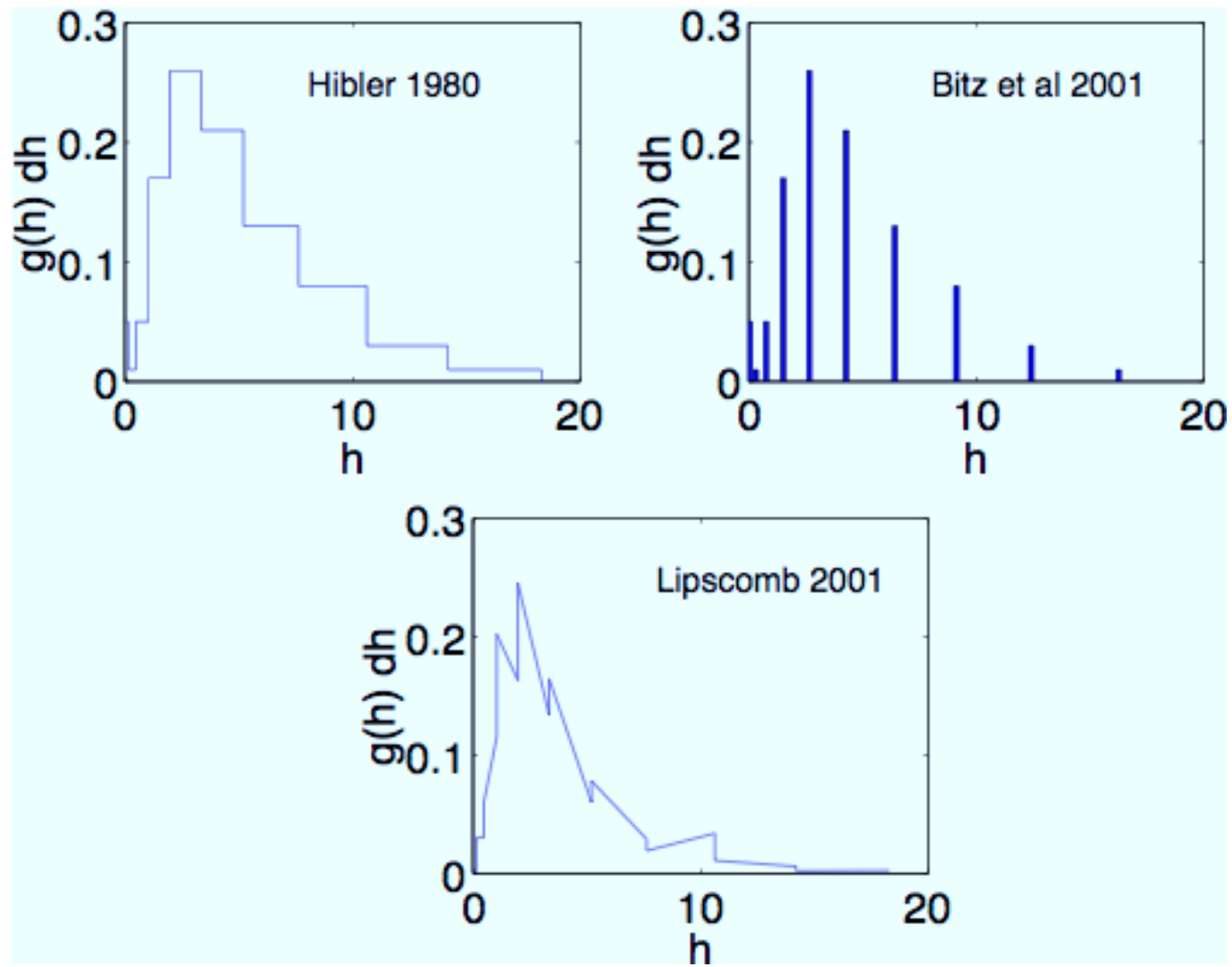
Ψ = Mechanical redistribution



Advection in thickness space from growth



Discretizations of $g(H)$ for thickness advection



Equation for the ice thickness distribution (describing the evolution of the distribution of thicknesses in a grid cell)

$$\frac{Dg}{Dt} = -g \nabla \cdot \mathbf{u} + \Psi - \frac{\partial}{\partial h}(fg) + \mathcal{L}$$

Other equations in the sea ice are:

Conservation of momentum (Just like ocean or atmosphere fluid but there is atmosphere and ocean stresses acting on the ice, a term for the tilt of the ocean surface, and a funny term that relates how the ice pushes back owing to its compressive strength)

Constitutive Law (needed because ice really is a solid, which determines how strong the ice is in the face of forces that try to deform it. This is complicated.)

Conservation of mass and energy, including melt/growth of sea ice and transport of the ice from the ice motion field

Heat equation to describe vertical conduction of heat from ocean to the atmosphere, with radiative transfer from absorption and scattering of light

The number of equations and complexity rivals the atmosphere

Sea Ice Dynamics Constitutive Law

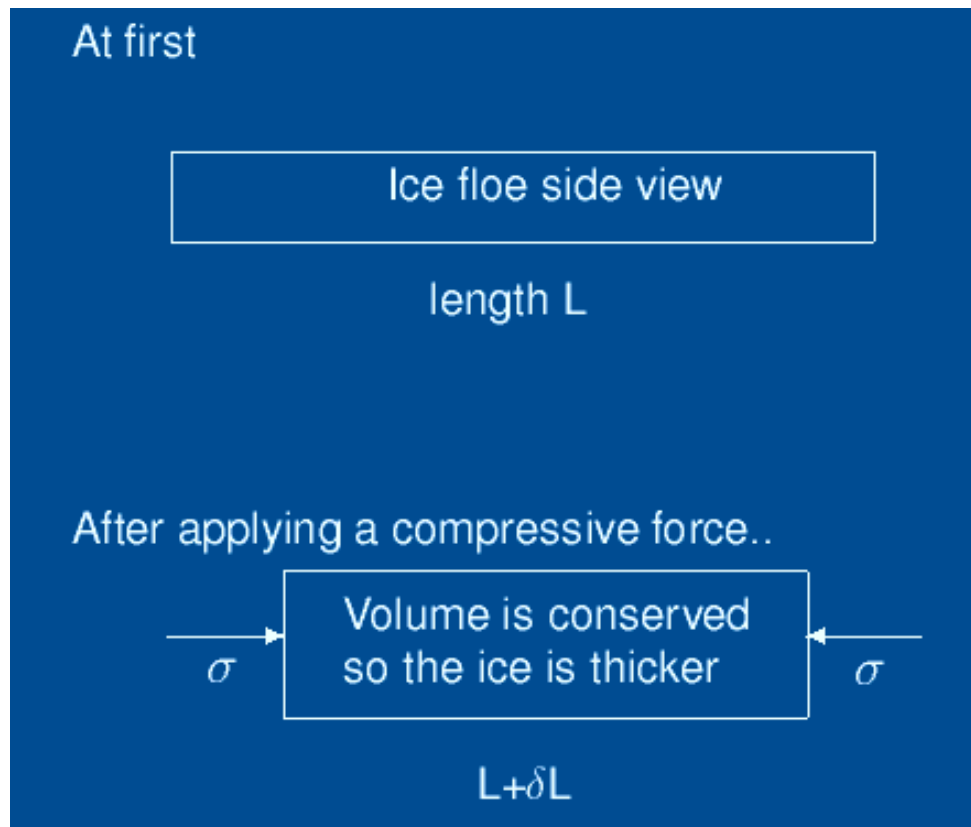
A constitutive law characterizes the material properties

The rheology used in most models is from Hibler 1979, where the sea ice is treated as a continuum that is plastic at normal strain rates and viscous at very small strain rates.

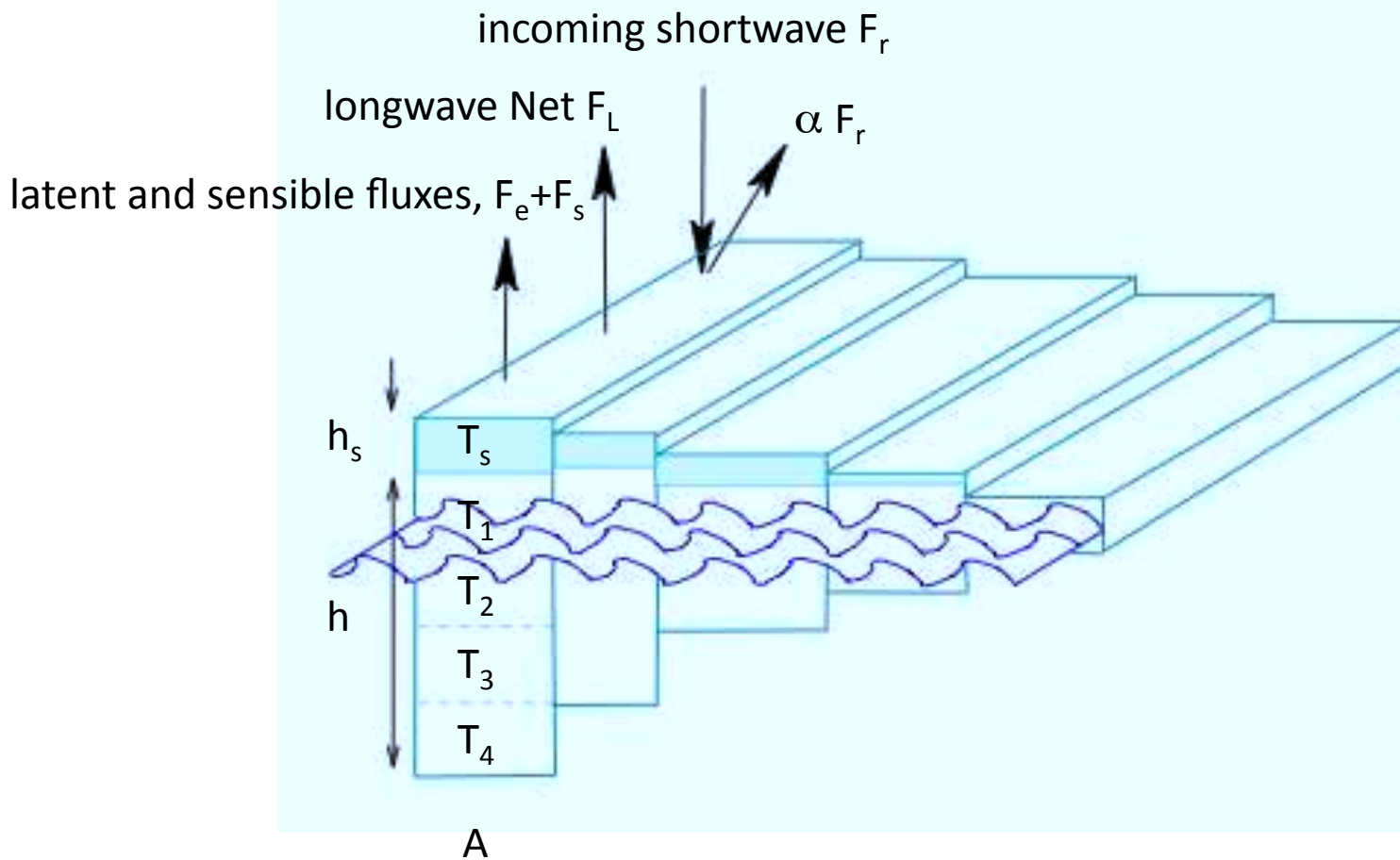
Imagine concrete. It is strong when you compress it but can't withstand much pulling.

The viscous part is just a numerical trick. It means the ice creeps when it should be doing nothing.

Engineering Compressive Stress Test



The rheology defines the relationship between σ = ice stress and strain δL (or strain rate)



In case it isn't obvious... Sea ice grows at the base from accreting seawater and can melt on any edge. Snow can weight down the surface and when seawater floods, it can freeze – typical only in the Antarctic.

Sea ice is like the inverse of a cloud... It also can melt internally because it traps salt in inclusions. The salt is highly concentrated, which depresses the freezing point.

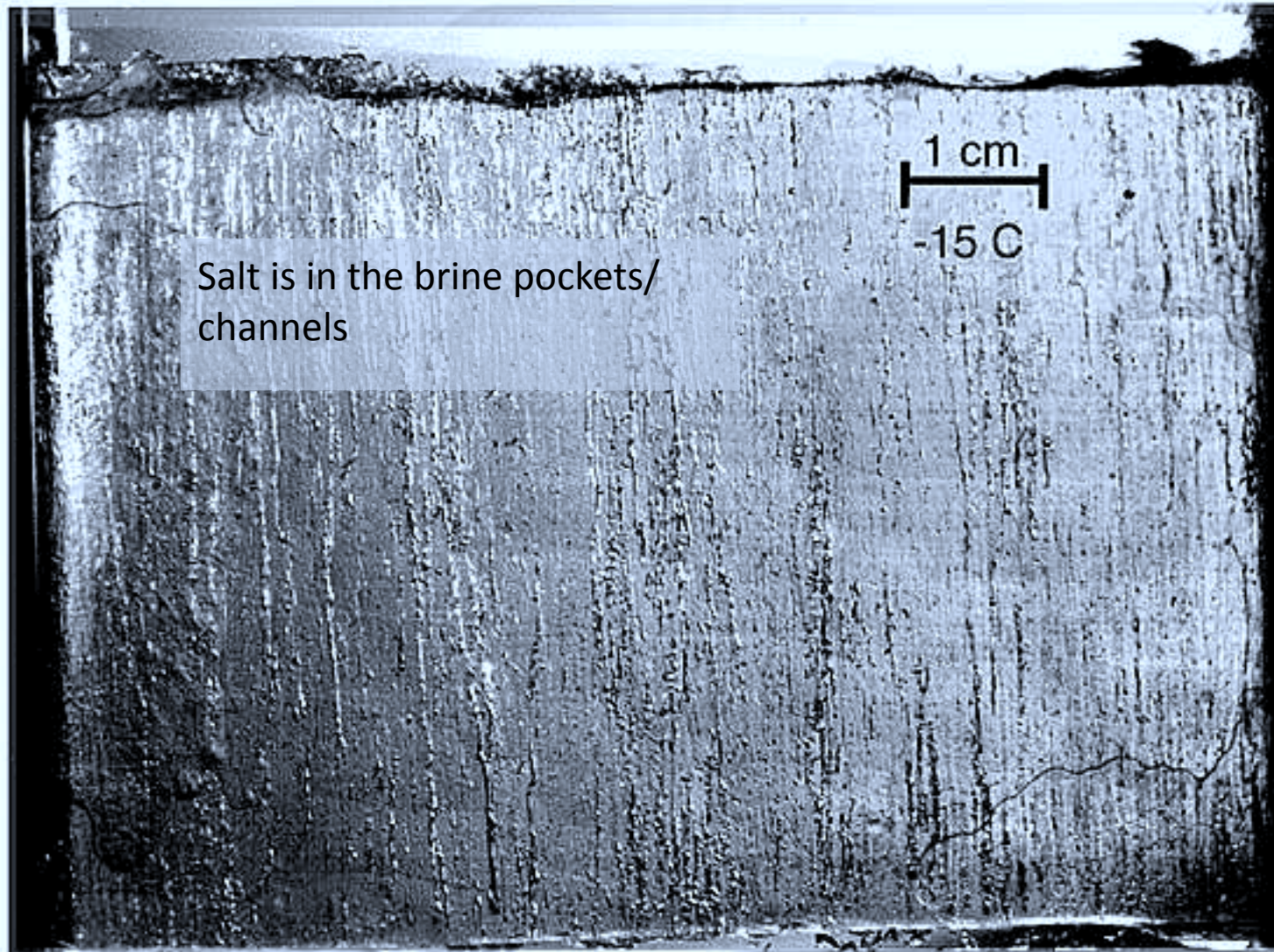


Photo by B. Light

Timing to run sea ice component in a climate model*

~15% cpu time of climate model given to sea ice

Out of which

2/3 is given to sea ice equations

1/3 is given to “coupling” and I/O

Of the 2/3 given to sea ice equations

55% is for dynamics

15% is for advection**

19% is for thermodynamics

11% is for mechanical redistribution

* for the Community Climate System Model ~1deg resolution ocean and sea ice and T42 atmosphere and land, 5 categories of sea ice

** much higher for older schemes

What limits sea ice model improvements in climate models?

Sea ice and polar climate expertise at modeling centers

Errors in other component models

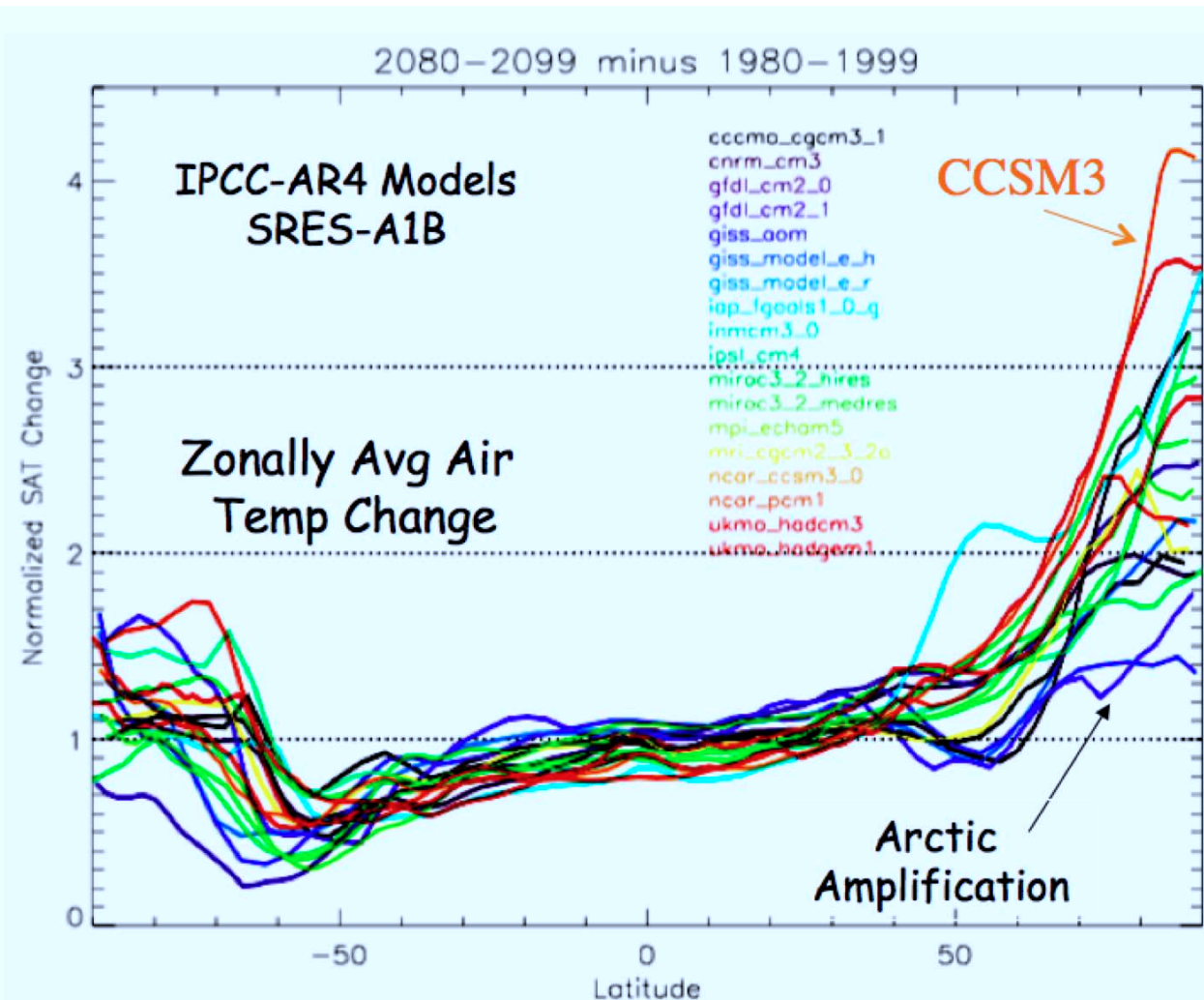
Know-how about sea ice physics

...

Computing power is a small factor

Bottomline: Great problem with good job potential for anyone interested in mathematics and/or scientific computing

Arctic Amplification, high in two models that have ice-thickness distribution physics. Some (me included) have hypothesized they are therefore most responsive. Now there is a mad scramble to include $g(h)$ in all models.



(After Holland and Bitz, 2003)

Ocean Modeling for Climate

Direct:

Heat flux to the atmosphere and sea ice

Drag on the atmosphere and sea ice

Evaporation

Flux of gases

Indirect:

It moves freshwater/salt and heat horizontally and vertically, which affects heat flux to the atmosphere and sea ice

More Subtle Issues

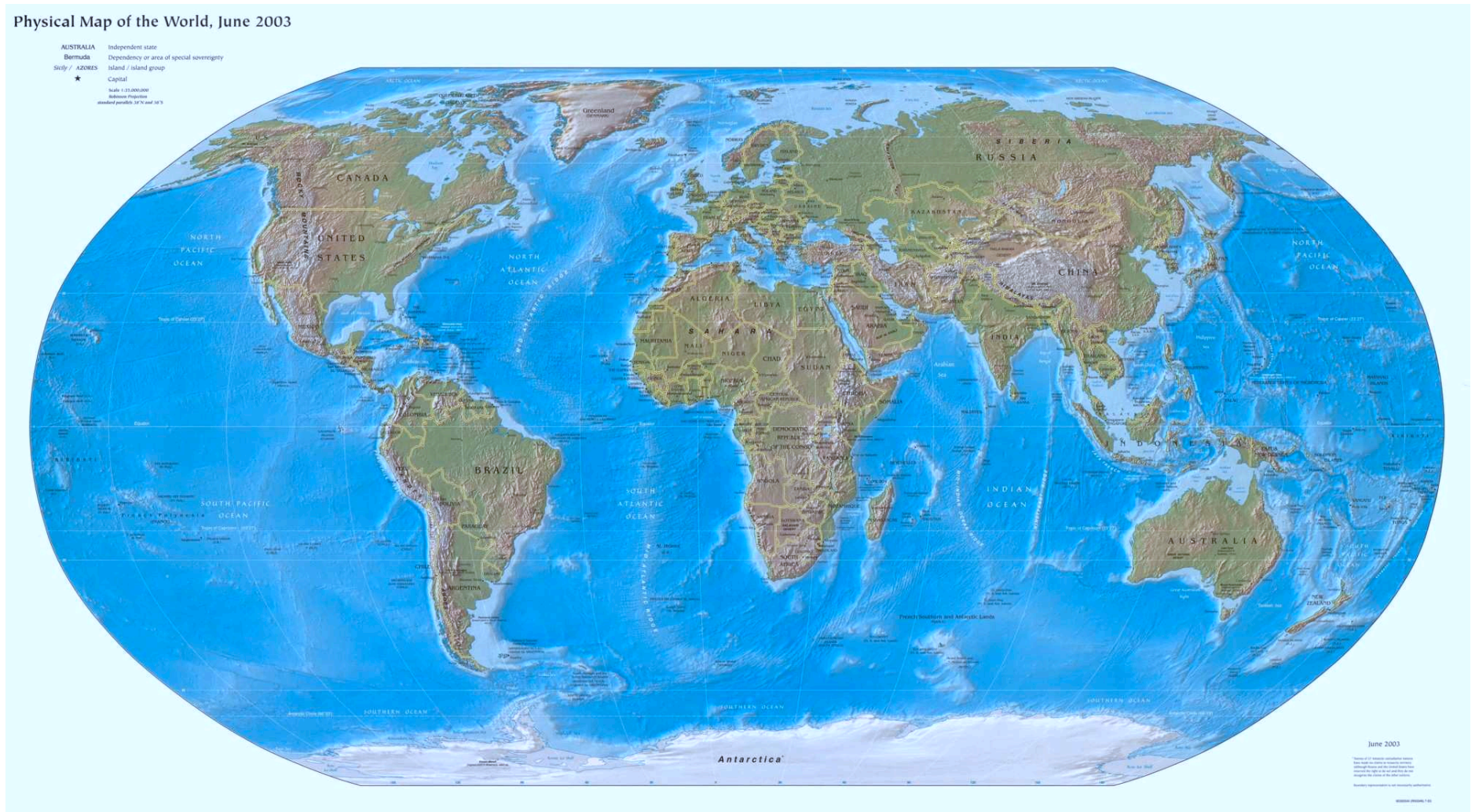
Prescribed SST cause

Inconsistent heat fluxes

Increased local high-frequency variability

Lack of low-frequency variability

Ocean Modeling



Tricky geometry, converging meridians at north pole

This is a tripole grid used in some models to avoid converging meridians. Good luck making maps of the output!



Usually there are more than 20 layers. CCSM4 has 60.

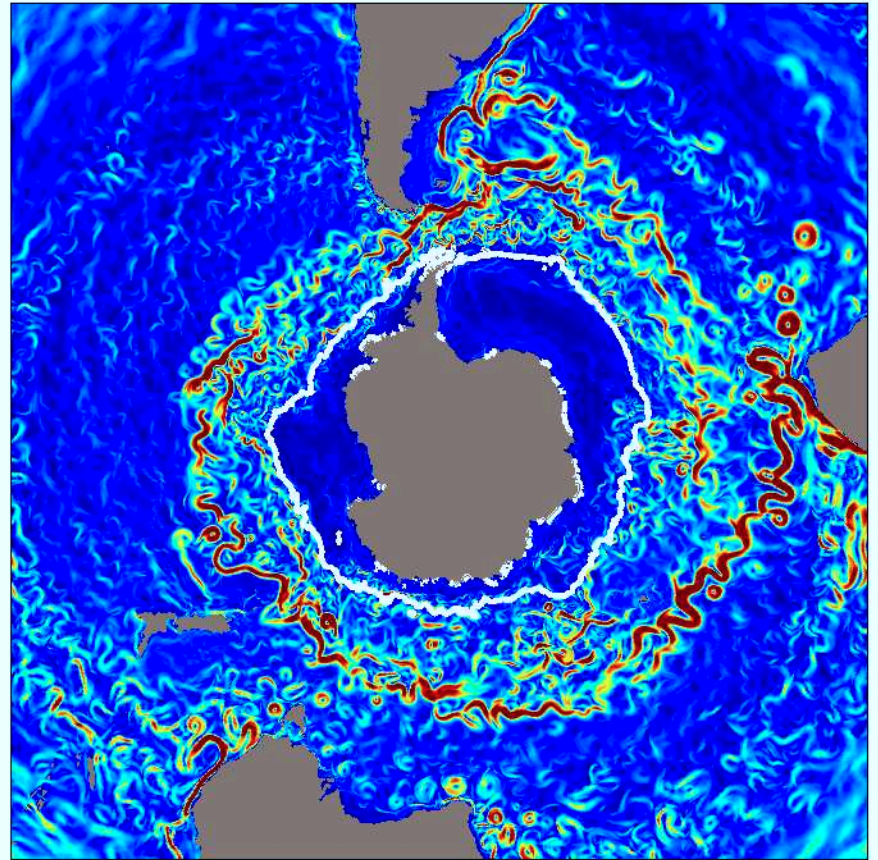
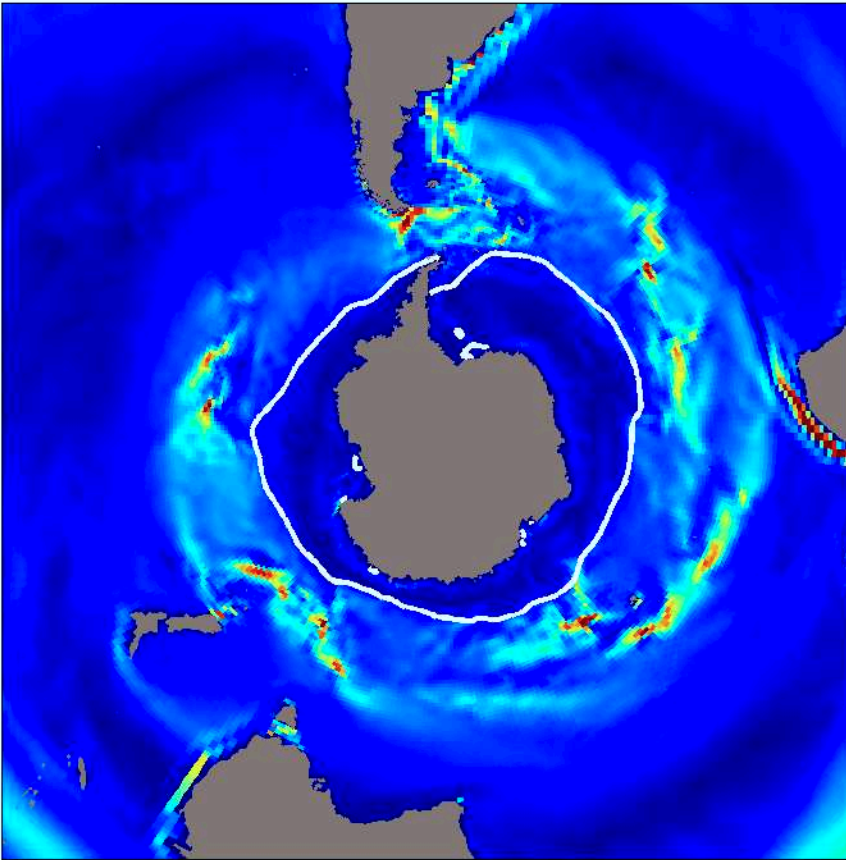
Timescales in the ocean are long...

If diffusion of heat is the main mechanism for communication:

$$H^2/k = 1000^2 \text{m}^2 / 10^{-5} \text{ m}^2/\text{s} = 3000 \text{ years}$$

where k is the diffusion constant

The ocean has eddies. The length scale of ocean waves is 10-100km while in the atmosphere it is ~ 1000 km. Important interactions occur at scales much smaller too.



Long time to adjust and small timescales means

Ocean modeling is about parameterizing subgrid scale phenomena

For example: mixing, flow over steep bottom ridges

Fortunately there are no phase changes (as in clouds, except at the surface)

The density is less variable, so we can assume it is incompressible in some equations

But we must consider density with regard to buoyancy. Density is complicated because of ocean salinity. There is no ideal gas law. Instead there are long, empirical formulas for density as a function of salt and temperature.

Primary 7 equations

Horizontal momentum (2 equations), as in atmosphere but friction is even more important

Vertical momentum is hydrostatic balance (pressure gradient balanced by gravity). Valid approximation except when there is vigorous vertical mixing, which is therefore parameterized.

Conservation of mass, aka continuity equation is simpler because we can assume incompressibility here

Conservation of temperature and salinity (2 equations) with affects of friction (aka mixing)

Equation of state, a long polynomial of $\rho = \rho(p, T, S)$

The majority of development effort is in the mixing terms. Also good problem with potential for plenty of future work (it is hard though).

Numerically Speaking

Ocean surface waves are fast moving (and important for dynamics). Fortunately they involve depth averaged physics, so momentum and continuity equations are solved twice.

Once they are depth averaged and solved at a very short timestep (this is called the barotropic mode). It has a speed of $\sqrt{g H} = 200 \text{ m/s}$

and

A second time they are solved with this mode depth-average removed. The fastest speed here is about 2 m/s, which allows a more leisurely timestep, but in this case the equations are solved at every point in the vertical (this is the baroclinic mode).