Application of water isotope modeling to quantifying climate variability from proxy records
(What can models do for you?)

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Motivation: Climate reconstruction 101

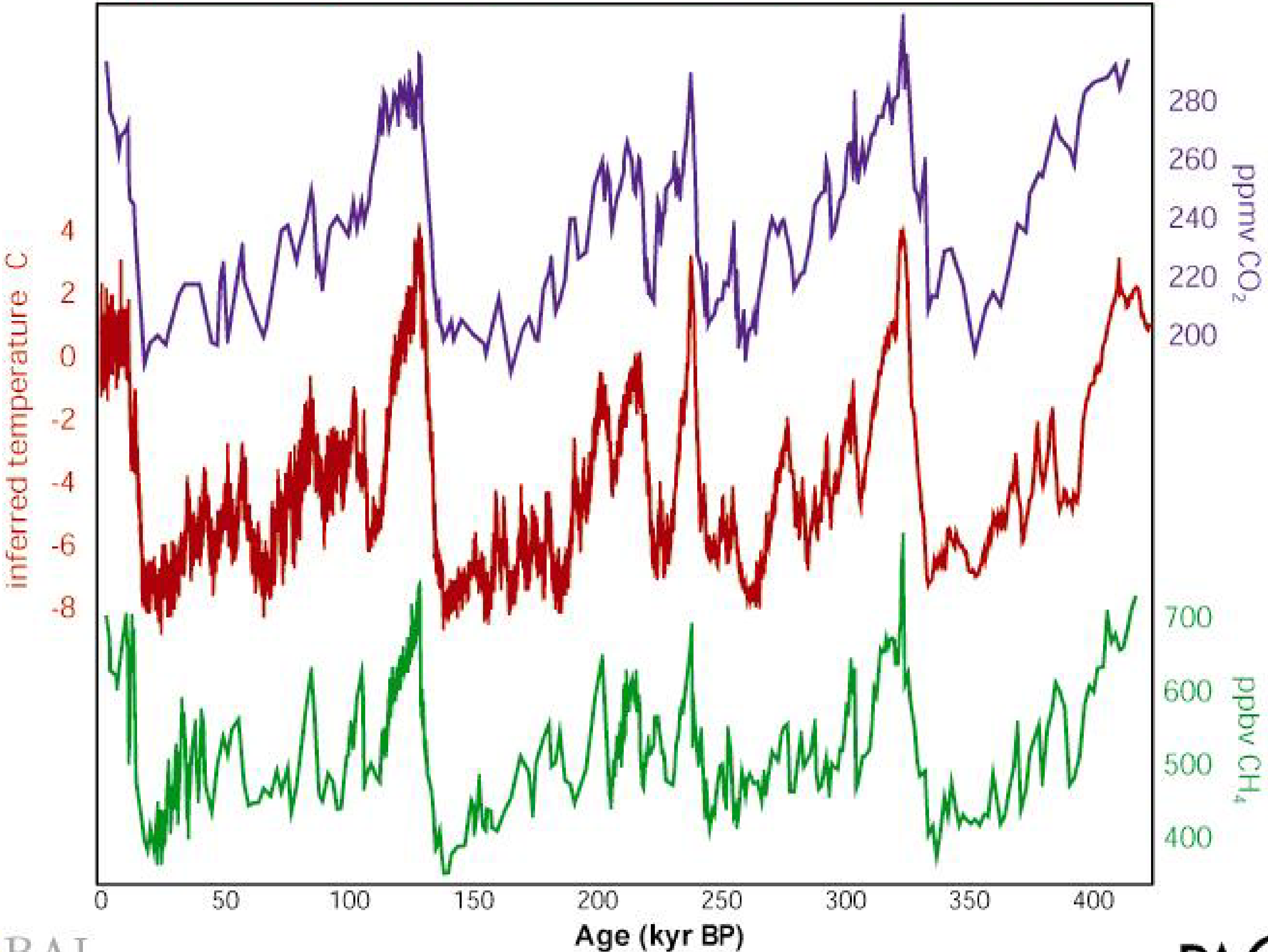
- Deduce relationship between isotope and the parameter of interest, and apply it to isotopic variations seen in ice cores.

1. From observations regression of mean temperature and ^{18}O (global/regional spatial, seasonal, etc).
   $\Delta T_{past} = [dT/d\delta]_{present} \Delta\delta_{proxy}$
2. From theory, using Rayleigh distillation (for ice cores, etc)
   $\delta = (\delta_0 + 1)F^{a(T)-1} - 1$ estimate ΔT_{past}.

Both empirical approaches seem to agree and work!

Can we do better with physical modeling?

4 glacial cycles recorded in the Vostok ice core



GLOBAL IGBP CHANGE

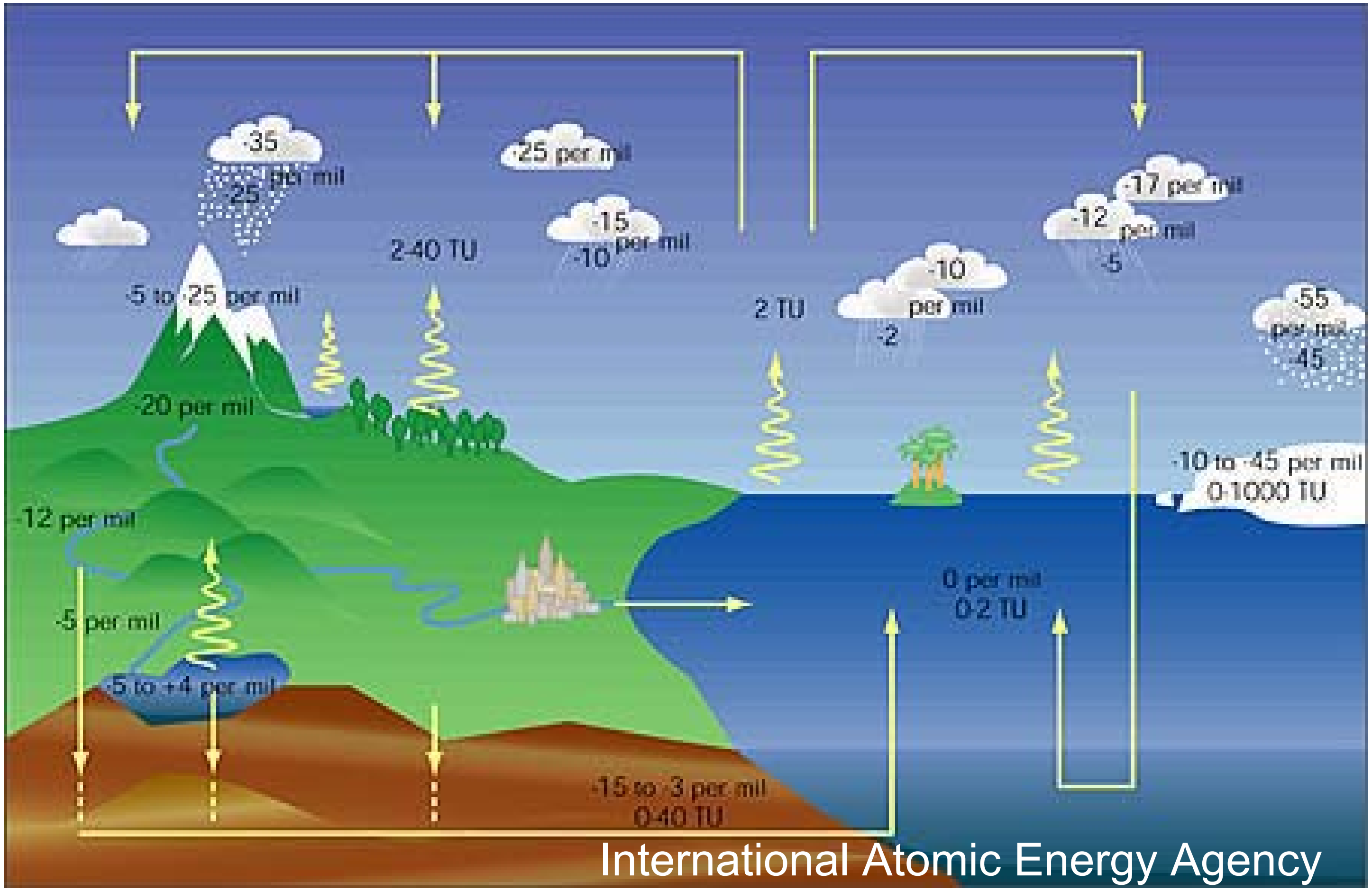
J.R. Petit et al., *Nature*, **399**, 429Ð36, 1999.

PAGES PAST GLOBAL CHANGES

Overview

- Global models with isotopes
- Part 1: Importance of underlying processes
    - Sensitivity to underlying processes: e.g. Antarctic sea ice
- Part 2: Signals of internal variability on proxies
    - E.g. Antarctic Oscillation, ENSO
- Part 3: Forward modeling proxies
    - A more insightful method for reconstruction (Implications of ENSO variability on coral proxies)
- Final remarks

Hydrologic cycle with isotopic exchange



“Delta values” $\delta^{18}O = (R/R_{standard}-1)x1000$ R = moles of $H_2{}^{18}O$/moles of $H_2{}^{16}O$

Water isotopes ($H_2{}^{18}O$, HDO) in the Melbourne University AGCM

- Spectral primitive equation model
- Interpolating semi-Lagrangian advection of constituents
- Prescribed ocean state (SST & sea ice from satellite obs.)
- Simple land surface treatment (bucket hydrology, no stomata/canopy)
- Evaporation, large scale condensation, moist convective adjustment
- Hydrology tracks water vapor, as well as $H_2{}^{18}O$, HDO

- Isotopic fractionation applied at each phase change (surface exchange, condensation, equilibration during rainfall)
- Equilibrium and kinetic fractionation
- Capability to track water from given source region

- Experiments at quasi-equilibrium

Noone and Simmonds, *J. Climate,* 2002

Global hydrologic cycle

- Conservation of (water) species with sources
  $$Dq/Dt = S$$

  $$dq/dt = -\mathbf{V}.\nabla q - C + E_{atm} + E_{srf}$$

- Equivalently for isotope species, q_i
  [define isotope ratio $R_v = (m/m_i) * q_i/q$]

  In the ocean, there are no isotope sources except for at the surface due to evaporation and rain water input

Evaporation from open water (ocean)

$$
\begin{aligned}
E_{srf} &= \rho C_d |\mathbf{V}| \left(q_{sat} - q_{surface}\right) \\
&= \rho C_d |\mathbf{V}|\, q_{sat}(1 - h)
\end{aligned}
$$

$$E_{i,srf} = \rho C_{di} |\mathbf{V}| \left(q_{sat} R_{ocean} / \alpha(T_s) - q_{i,surface}\right)$$

- Water vapor (and its isotopes) approach equilibrium with ocean surface
  (“Newtonian cooling”different for different isotopic species)
- Rate of equilibration depends on:
  1. turbulence regime
  2. dryness of near surface vapor
- Different isotopic species have differing “dryness” which leads to source water isotope variation
  (humidity term dominates, not temperature)

Cloud processes (at each time step)

Condensation (C)

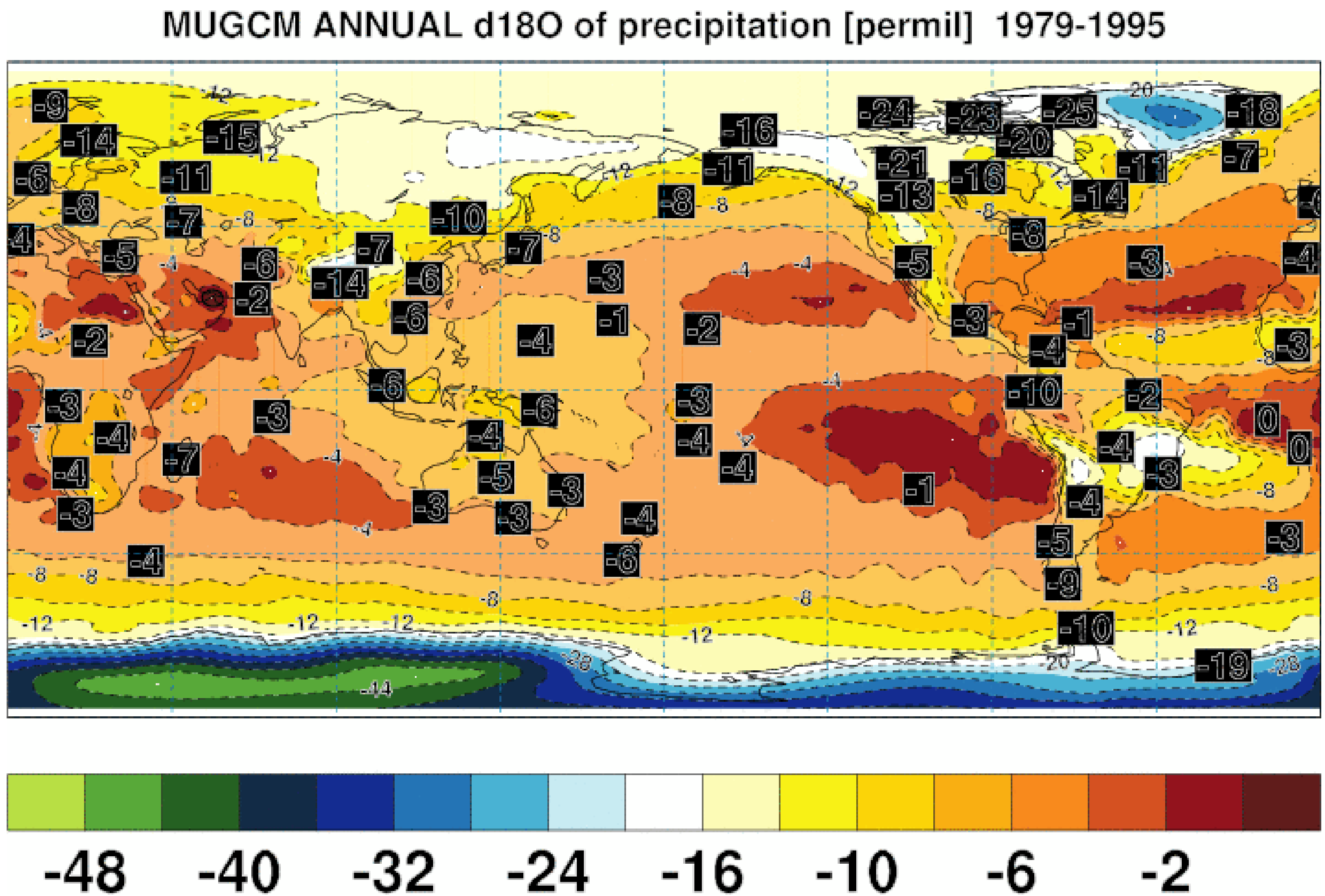
- Slow condensation assume to occur at equilibrium: $R_c = \alpha R_v$ (stratiform cloud water)
- Rapid condensation as a Rayleigh process: $dR_v = \alpha R_v$ (convection and condensation to ice)
- Condensation to ice account for supersaturation (modify α to include kinetic effect)

Evaporation (E_{atm})

- Evaporation of ice without fractionation
- Evaporation of liquid assumes system approached equilibrium (modified α to account for diffusion limitation kinetic effect)

More complex schemes can be constructed along the same lines in presence of cloud water and ice

Modeled distribution of ^{18}O



Noone and Simmonds, *J. Climate,* 2002

Part 1: Assessing importance of contributing mechanisms

- Understand the transport of water, as it is constrained by the flow regime

- It is this which imparts the isotopic signal, but various components may influence the signal differently. We need to know this association for accurate proxy interpretation.

Sensitivity of Antarctic isotopes to sea ice

Ice ***concentration*** decreased from:
100%, 85%, **50%,** 15% and 0%
Ice ***extent*** changed by:
-2, -1, +1, **+2**, and +3 grid boxes

Response associated both with change in:

1. "source region"
2. transport processes
   (flow regime, condensation regime)

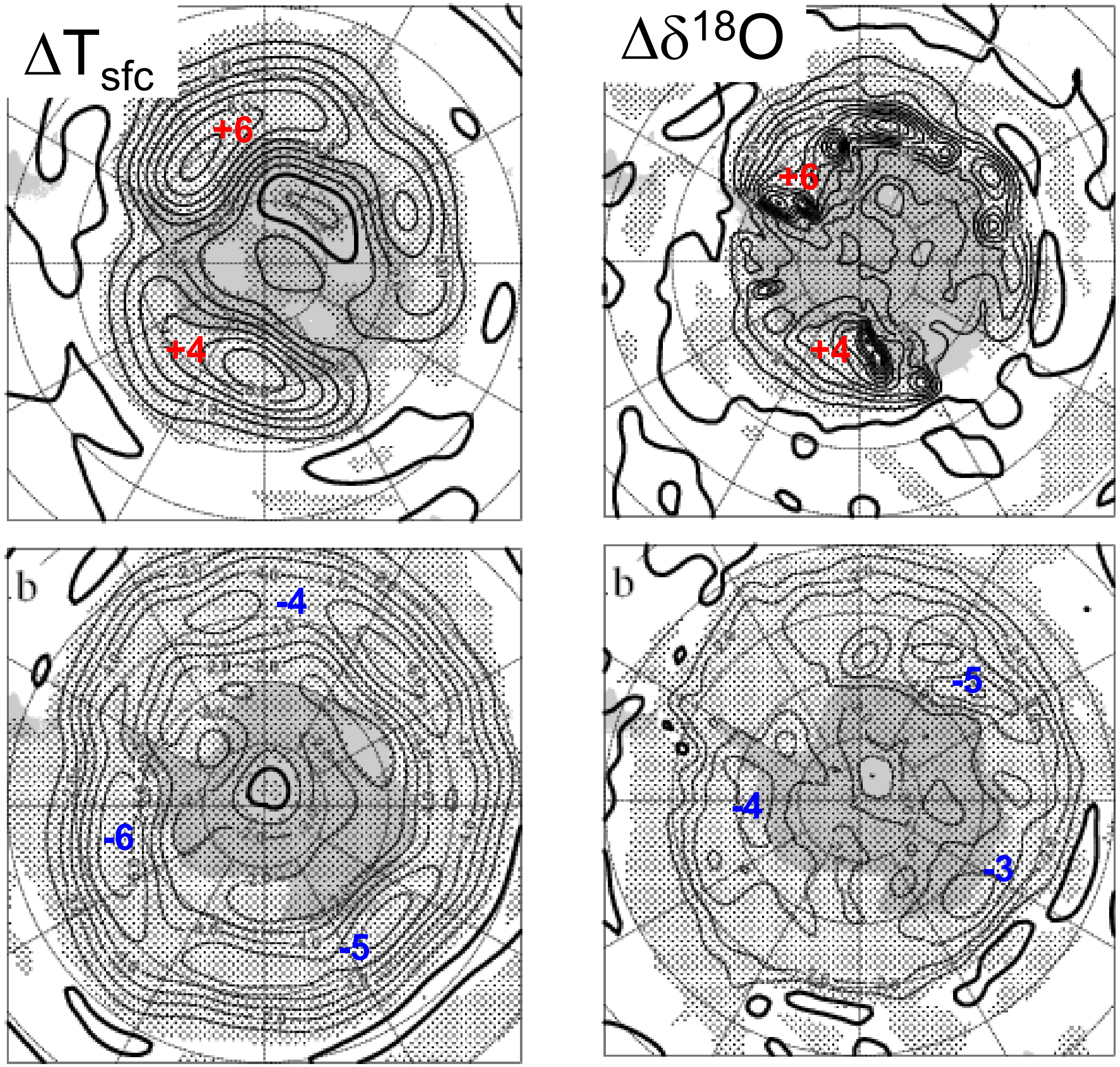
Wintertime only

Noone and Simmonds, *J. Geophys. Res.*, 2004

Model change in temperature and d^{18}O

Reduced ice concentration

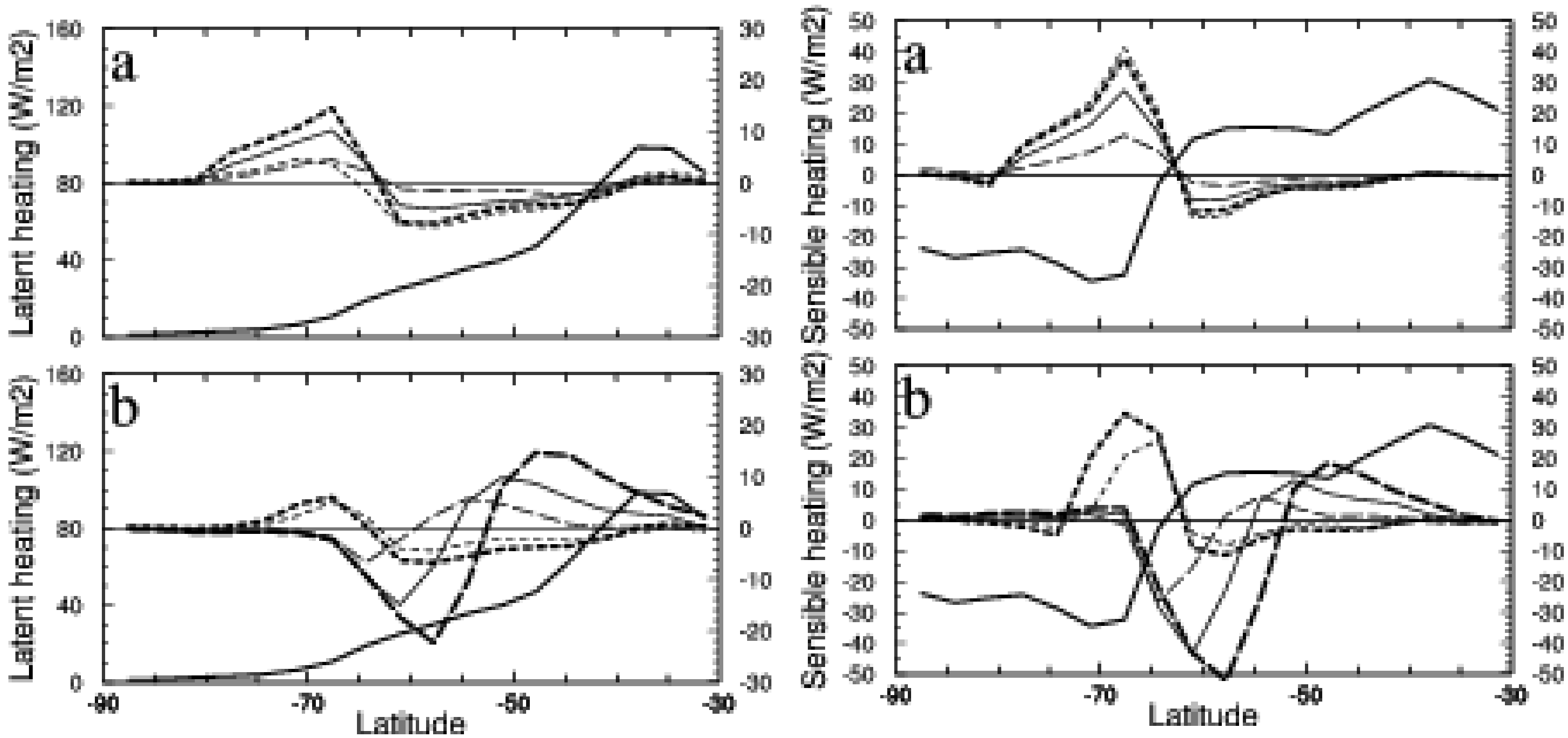
Increased ice extent



Change in source and heating over ice

Reduced ice concentration

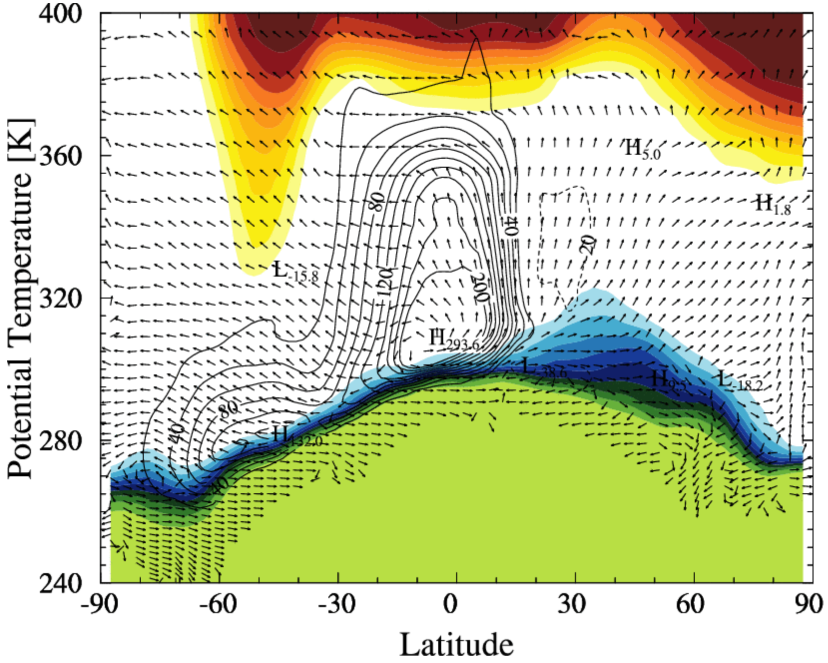
Increased ice extent

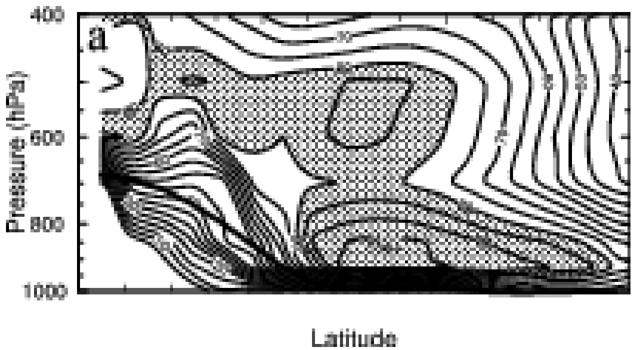


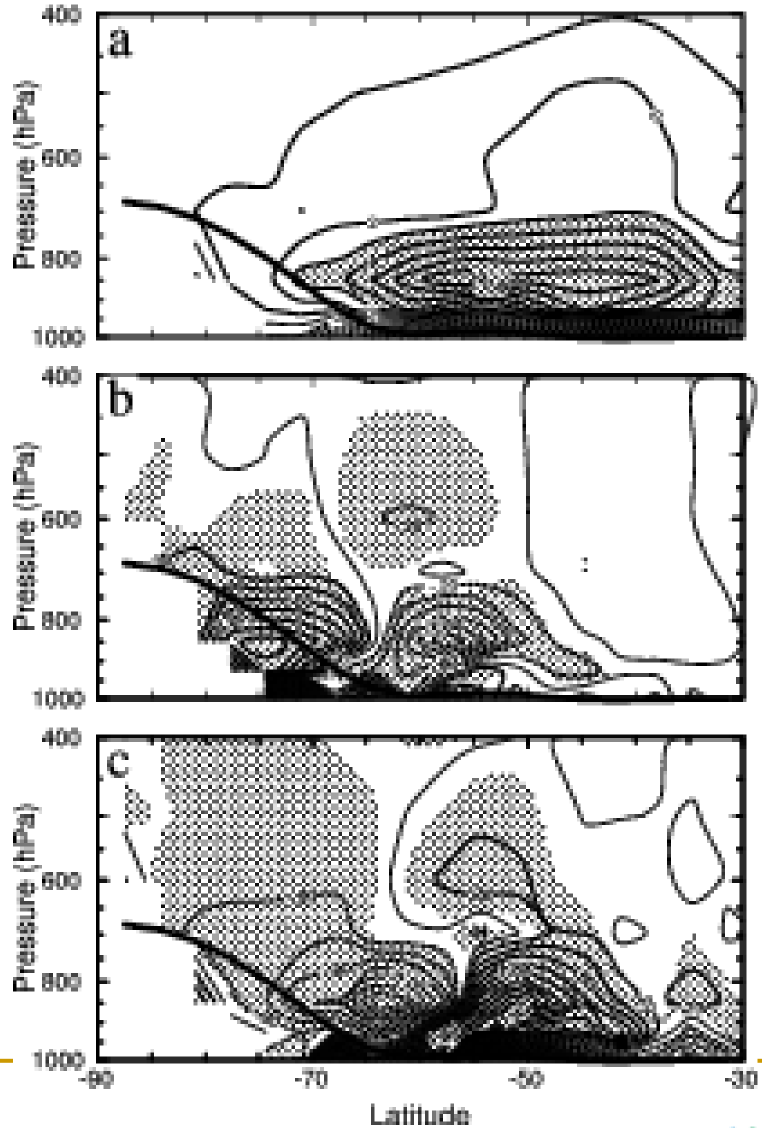
•Effects seen upstream of ice pack

•Sensible heating 2.5 times larger

Changes in condensation history







Why constrained to the coast?

- Consider the conversion of kinetic energy to potential energy in an adiabatic barotropic layer near the surface.

  $Fr = (PE/KE)^{1/2}$

- The kinetic energy from windspeed ($mU^2/2$)
- Potential energy related to the vertical stratification

  ($d\theta/dp$ or "N^2")
- Arrive at a "Froude number": $Fr = Nh/U$

If h is 2km, $Fr < 1$ implies flow can not ascend topography (and instead goes around, to form an easterly coastal jet)

Part 1: Conclusions

- Sea ice modifies coastal isotope signal directly by latent heating (*similar* to temperature)
- Inland isotopes not changed too much (!)
- Coastal near-surface air constrained unless it can ascend diabatically (increased with degraded ice state, but still trapped by topography)
- Inland isotopes change due to modification of eddy transports and moist diabatic processes upstream – near the ice edge

1) Leads to better account of pertinent atmospheric dynamics/thermodynamics when interpreting proxy records
2) Quantify influence of components, not easy to obtain from observations.

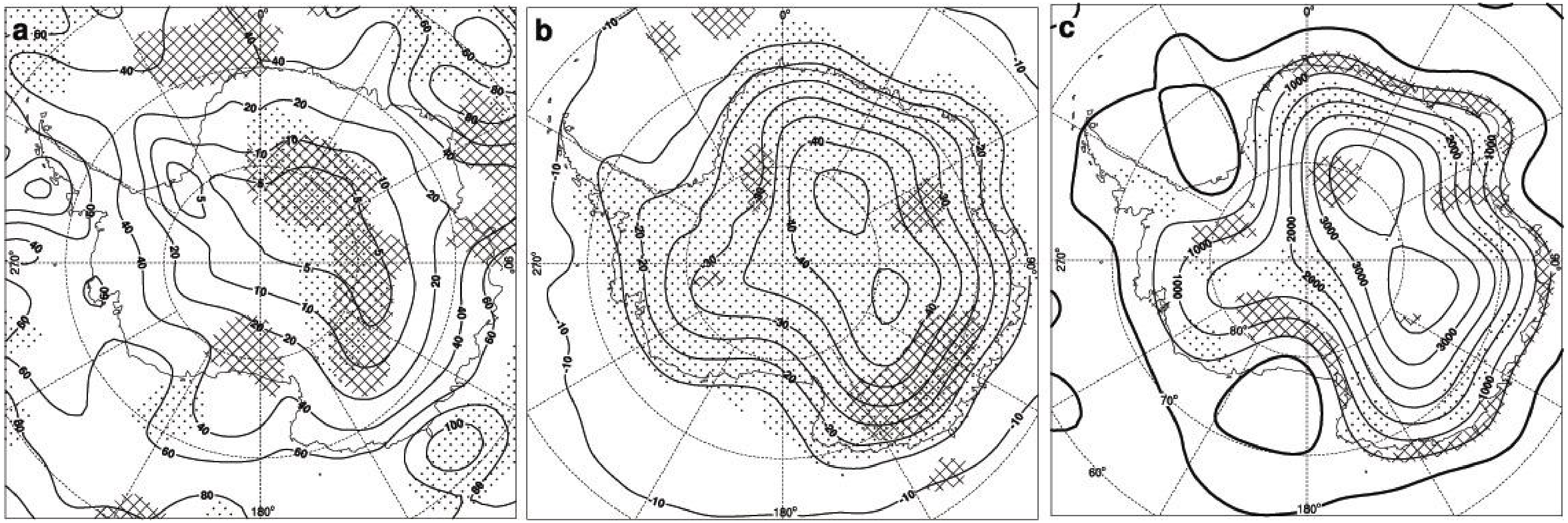
Part 2: Using models to assess importance of internal modes

- Climate system has internal modes (e.g., ENSO, Annular Modes, …) which cause systematic shift in proxies
- These influences need not be constant over time, but can be modeled

1) Need to understand how modes impat the singal

2) How modes can change under different climate states

Modeled annual mean (1979-1995)

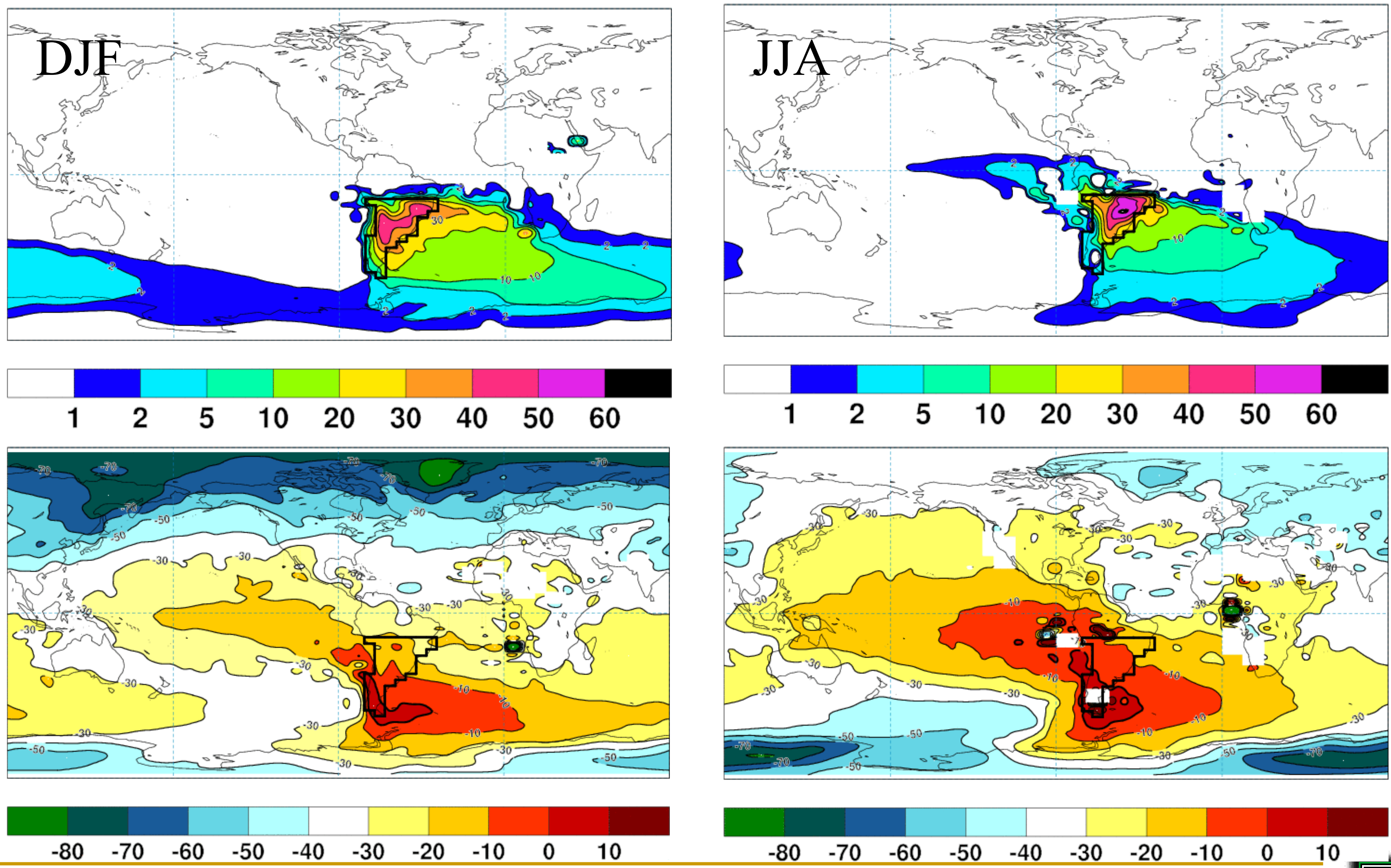


Precipitation [cm] | $\delta^{18}O$ [permil] | Topography [m]

Annual cycle >35% variance

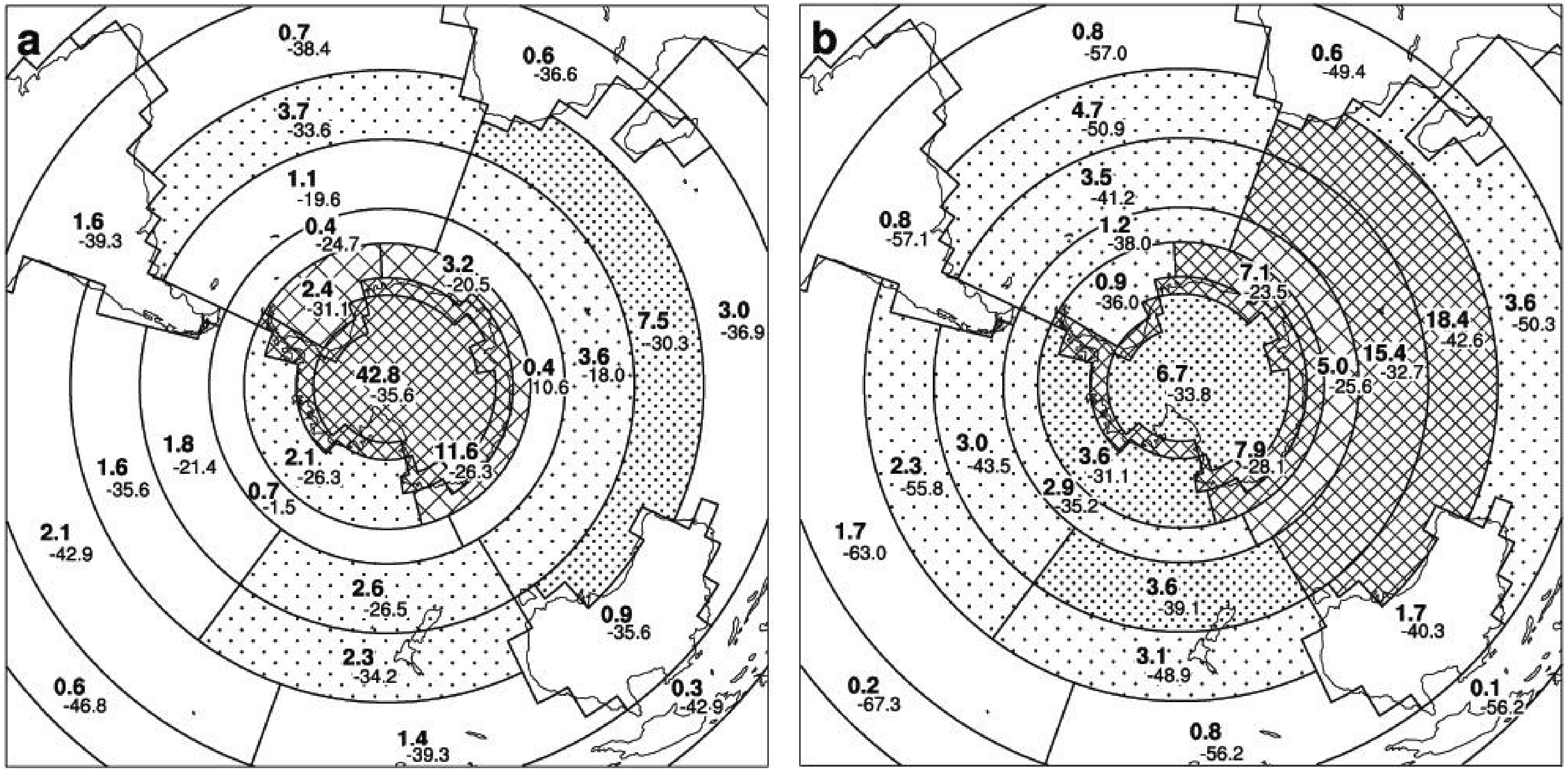
Semi-annual cycle >15% variance

Fate of water from South America



^{18}O content of rain with South American source (permil)

Source of Antarctic precipitation

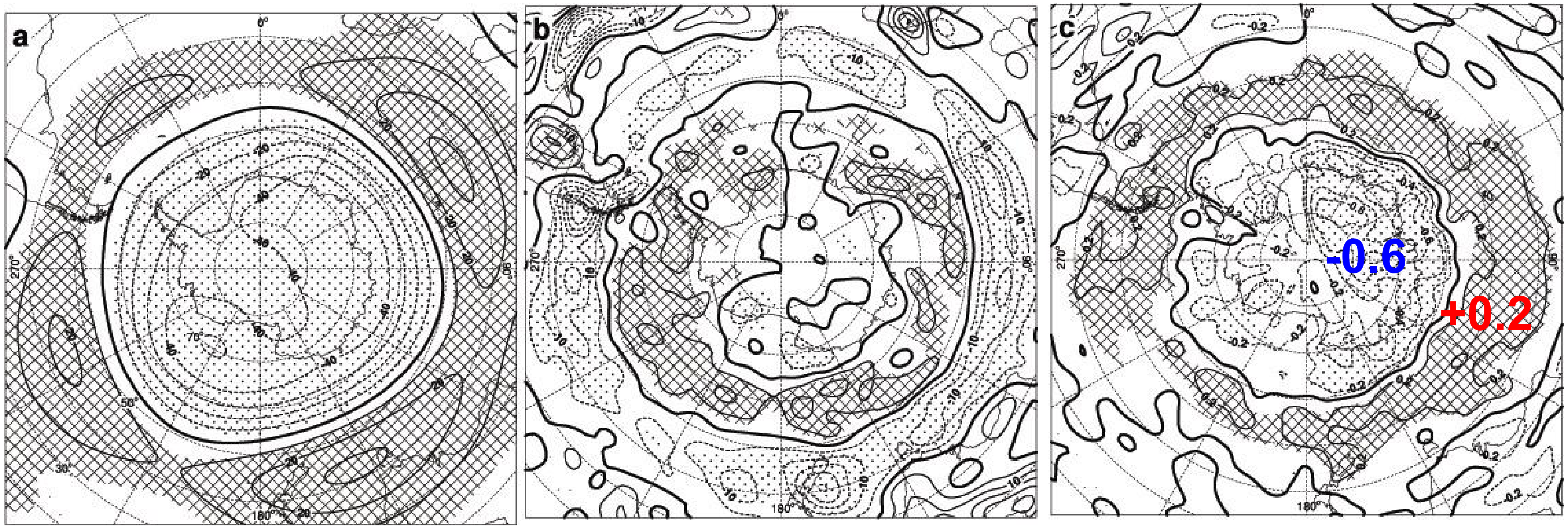


Summer (DJF) Winter (JJA)

More distant source more depleted

Isotopic signal of Annual Mode

(1s.d. projection onto EOF1 of 500 hPa height)



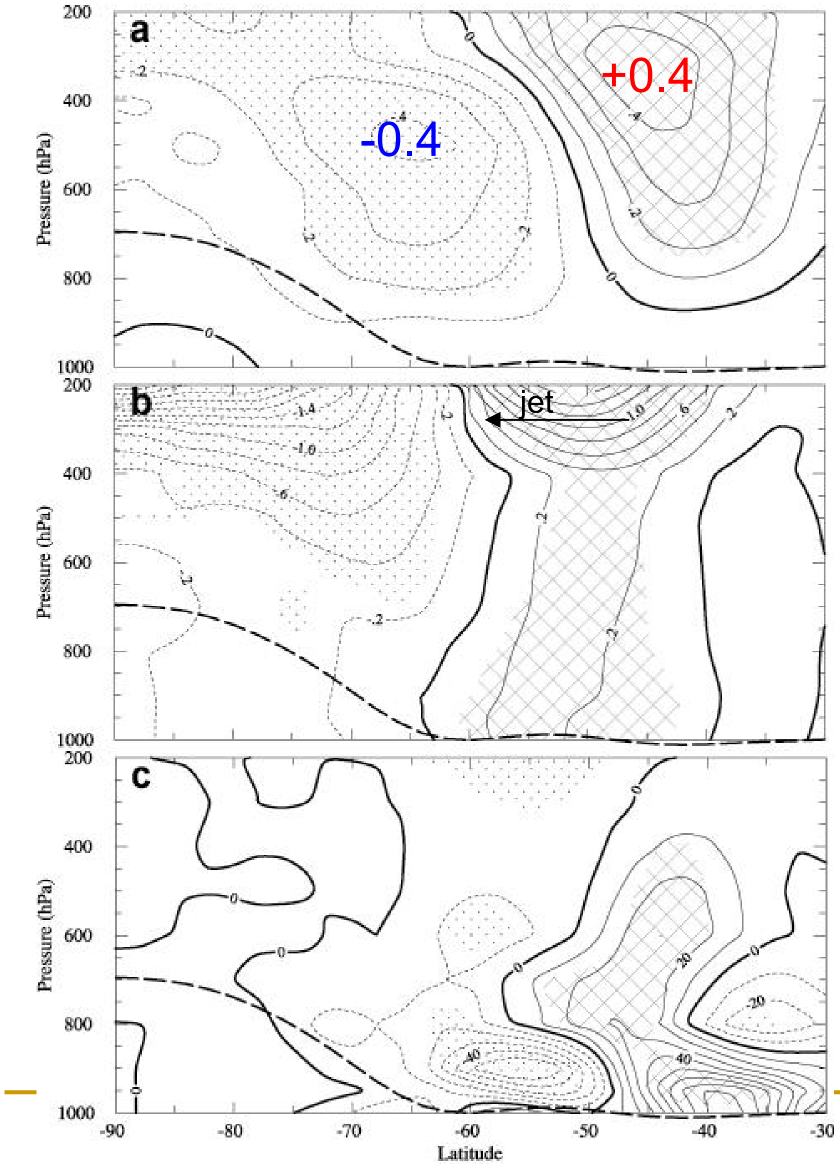
Z500 [dm]   Precipitation [mm/day] $\delta^{18}O$ [permil]

~30% V.E.

About ¼ of glacial/interglacial difference

About ½ for 2 s.d. variations

Condensation and fractionation variation



Temperature

Moisture above subcritical layer colder when condensation occurs

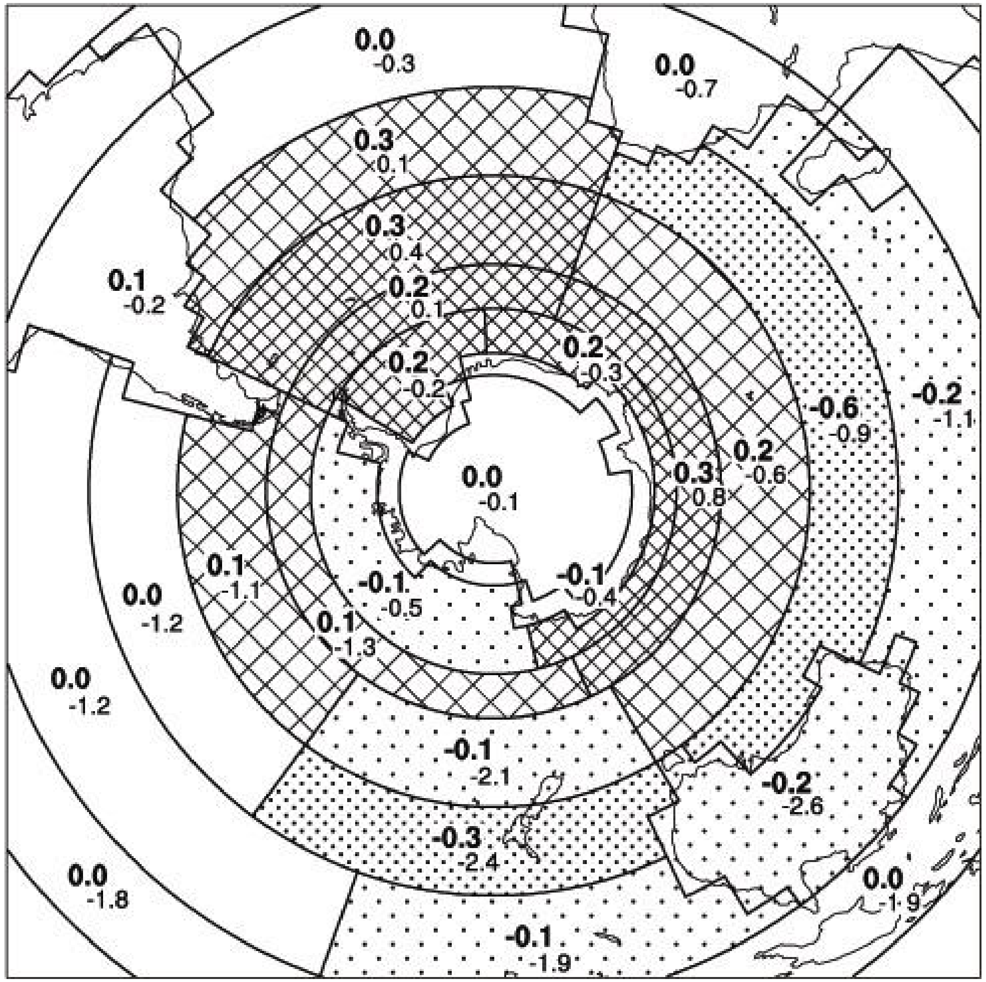
Water vapor

Low level moisture influenced by different condensation location

Moisture divergence due to cloud processes

(dq/dt<0 ; precip)

AAO modification of source



Positive phase AAO: (deeper vortex, stronger jet, poleward storm track)

Source poleward, greater entrainment of less depleted water AND entrained water even less depleted.

However, ***increased distillation during of long range water transport dominates***

Competition of distillation/surface mixing: distillation wins (this time)

Part 2: Conclusions

- Large scale atmospheric transport imparts observable, organized signature on isotopes (here, changing conditions of the storm track)
- Isotope records are not simply “temperature”
- Isotope variations congruent with AAO provides mechanism for reconstructing AAO history from ice core records
- Water tagging provides a powerful tool for interpreting interaction of hydrologic processes
- Requires comprehensive and accurate (forward) model (*or, isotope measurements can diagnose limitations of model*)

Part 3: Forward modeling of proxy variations

$$\delta^{18}\mathrm{O}_{coral} = \delta^{18}\mathrm{O}_{ocean} + \boxed{a(SST) + b}$$

"biological fractionation"

- $\delta^{18}O_{ocean}$ varies with SST due to circulation, so reconstruction needs implicit solution
- Aim to use a model to produce change in both which is self consistent and physically sound

Mixed layer freshwater/isotope budget

$$\frac{\partial Q}{\partial t} = (P - E) + k(h - Q)$$

$$\frac{\partial Q_i}{\partial t} = (P_i - E_i) + k(hR - Q_i)$$

Similar level of complexity as a mixed layer model of mixed layer heat.

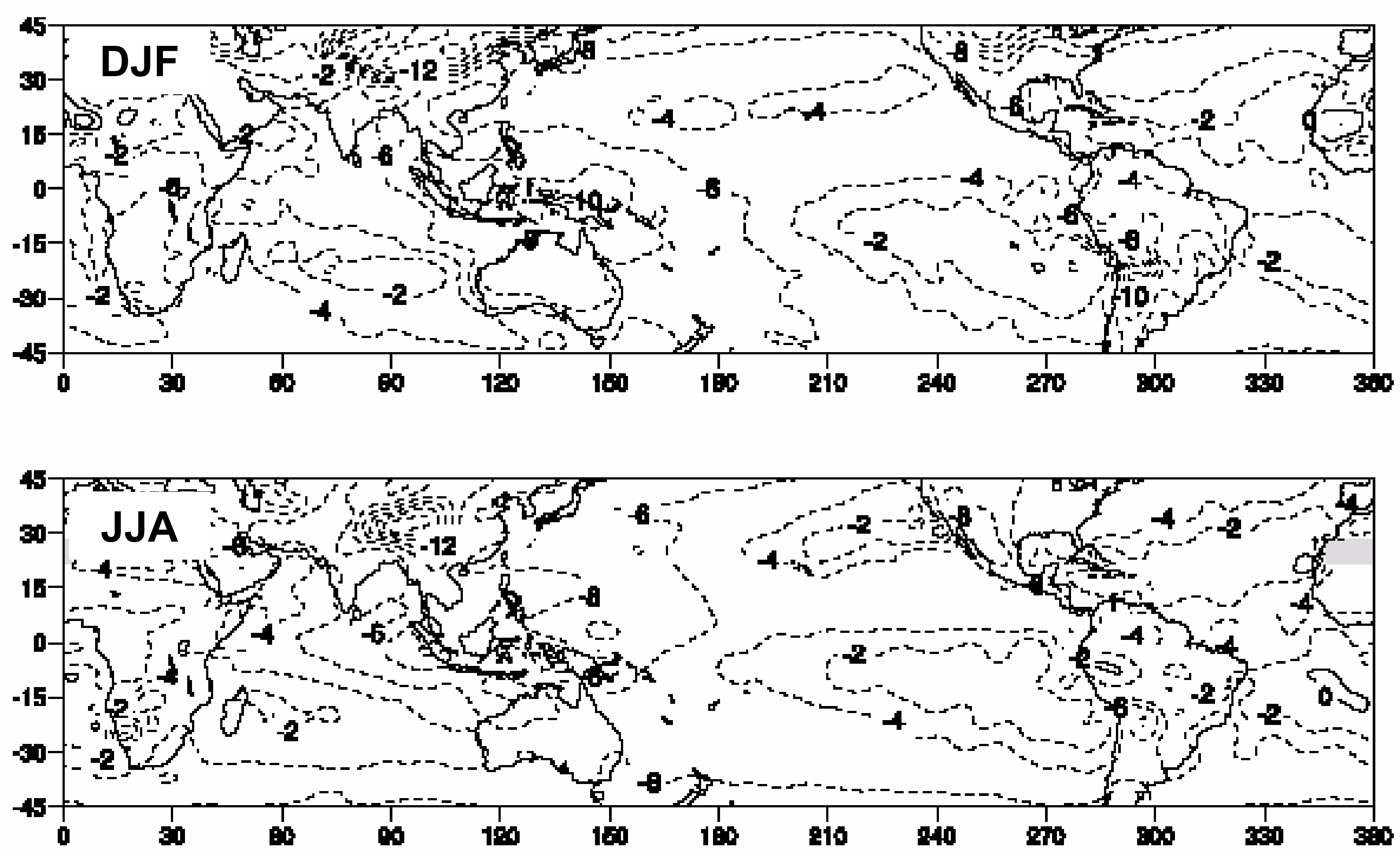
(Note: we ignore horizontal transport/upwelling, and river input)

Water input to a layer of water, with adjustment back to deeper water conditions with a characteristic time scale.

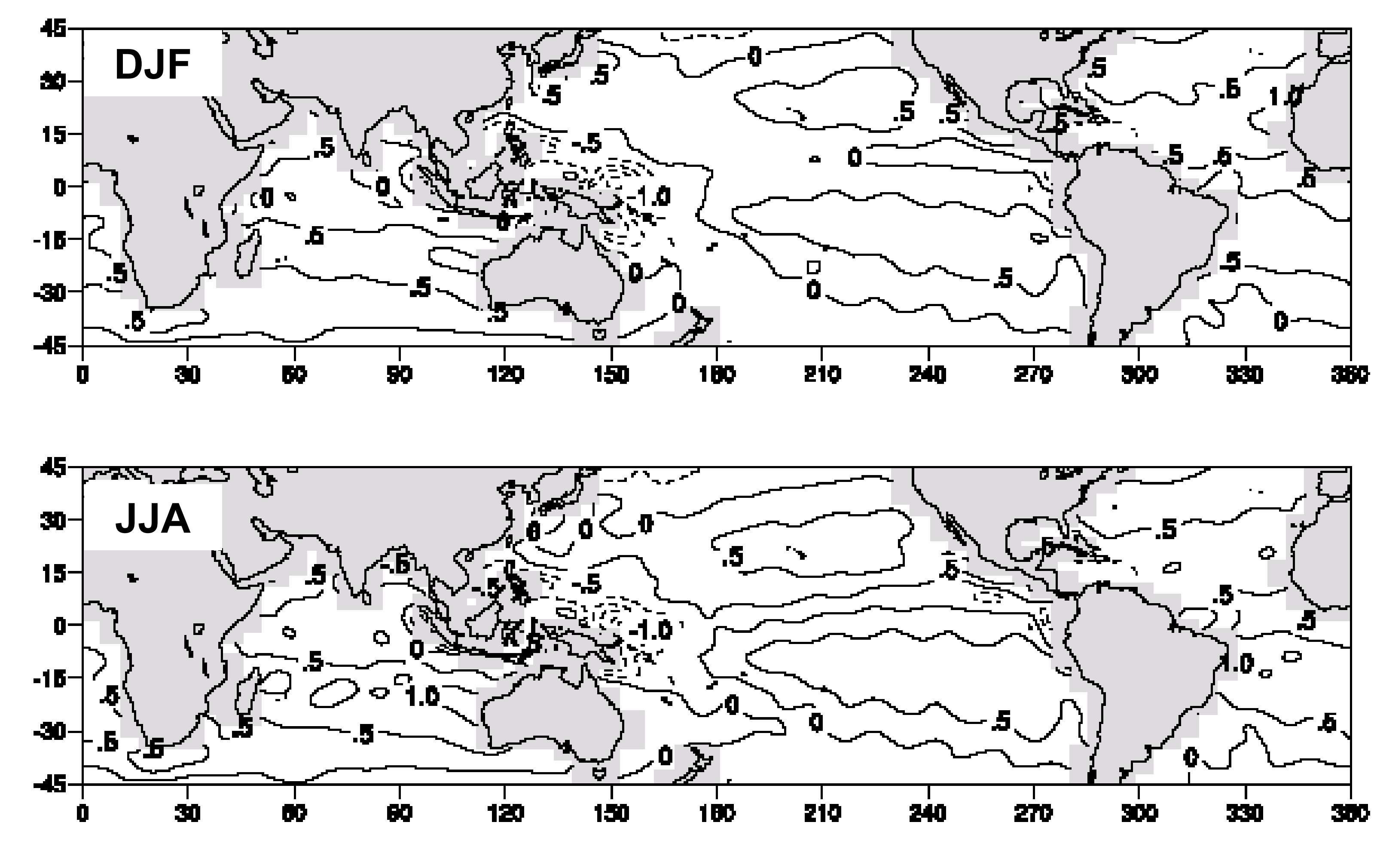
In general, Q_i, represents "tracer concentration" and applicable for salinity also.

Brown *et al.*, in preparation, (2004)

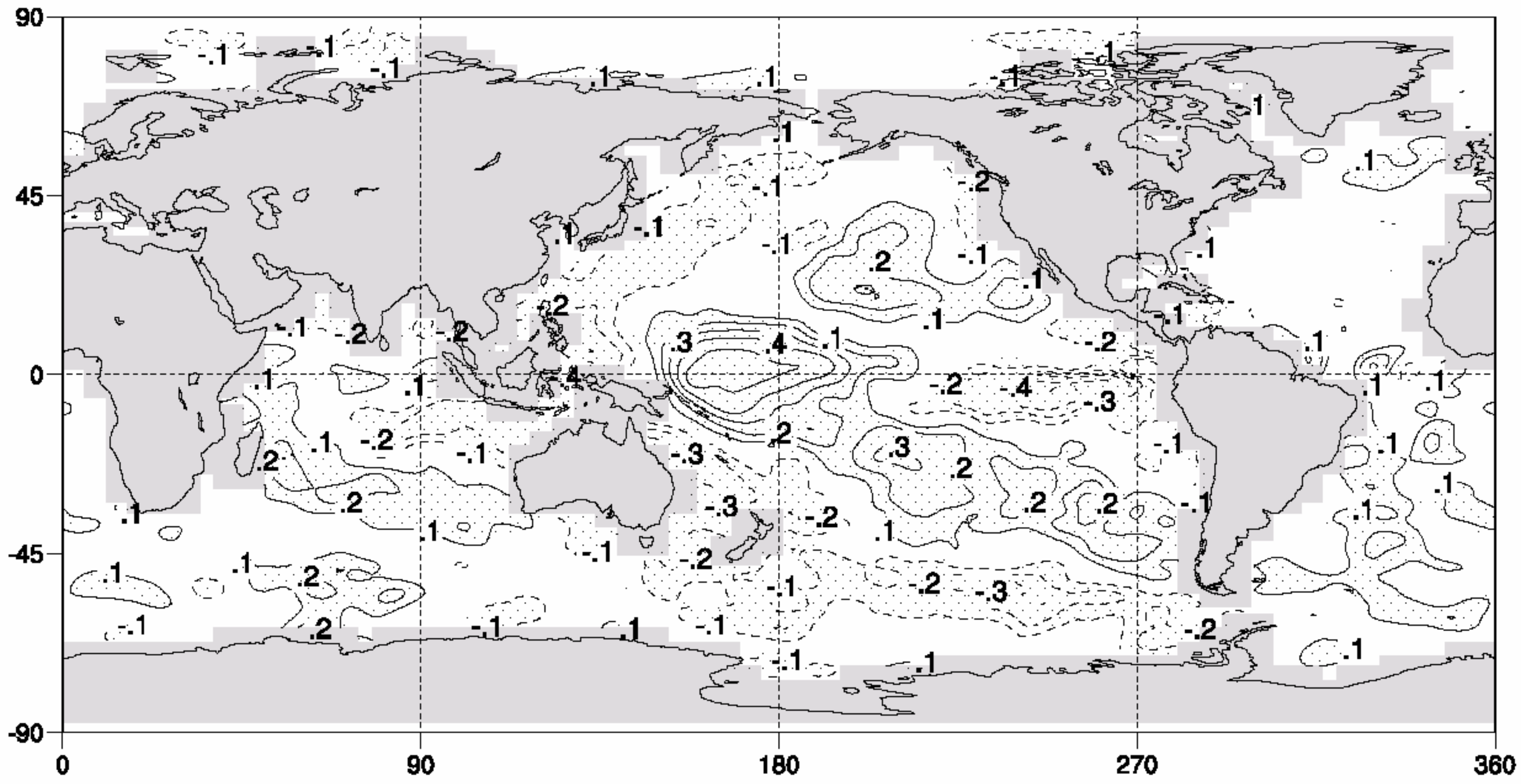
Modeled ^{18}O in precipitation



Modeled surface ocean ^{18}O



Ocean surface ^{18}O and ENSO

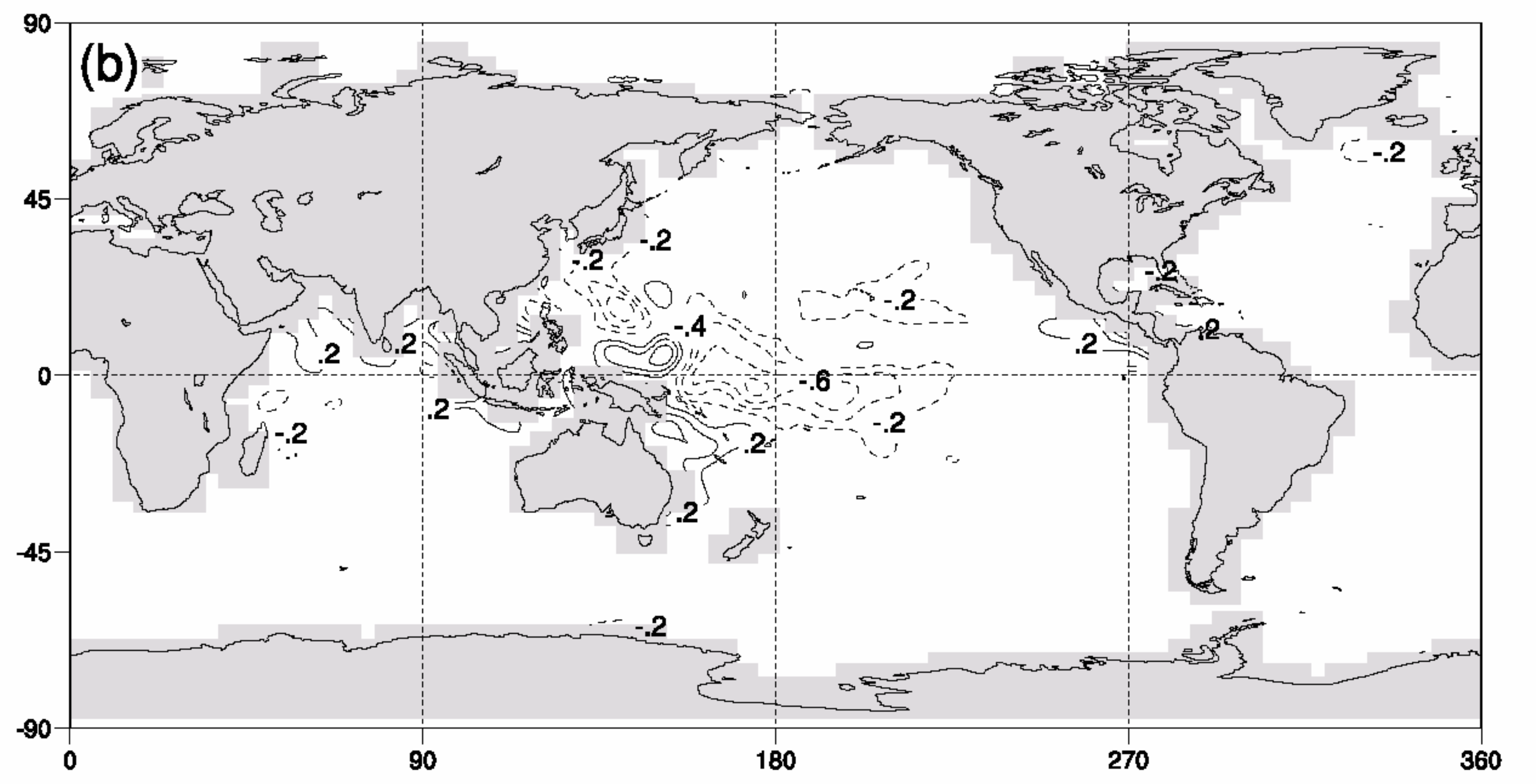


•For reconstruction from corals, we can quantify the "seawater" part

•Similarly, model can give changes in ocean water temperature, and provide a consistency check against inferred temperature

Watch the signs! SOI < 0, more fractionation δ < 0

1950-2002 modeled trend in ocean ^{18}O



•**Strongest signals in regions of enhances precipitation due to more “El Nino-like” conditions**

•**Signal also in region of Indian Monsoon**

•**Limited signal outside equatorial Pacific and Warmpool**

Part 3: Conclusions

- Model guides proxy interpretation by helping quantify some of the unknowns often assumed (constant or otherwise)
- Forward modeling the proxy (rather than the climate parameter on which the proxy is thought to depend) reduces uncertainty in the interpretation by enabling direct comparison
- ***However***, care must be taken to properly characterize model error.
  Like observations, models are not perfect views of truth.

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Final remarks

- Models (even if they are simple transfer functions) are needed to understand proxies, and provide useful interpretation
- Models can provide quantification of sensitivity of the proxy signal to parts of climate system
- The adds to both depth of the interpretation, and ability to quantify error