Accumulation-rate changes through the Holocene from ice-core records and radar data

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Earth and Space Sciences

Outline

- Basics deriving accumulation histories from ice-core records

- Ice and accumulation histories from Central WAIS

- Extending ice-core accumulation records spatially with radar
  - Central West Antarctica (shallow layers)
  - Taylor Dome (deep layers)

- Context for recent climate change
  - Antarctic peninsula Holocene temperature history
  - Last 2,000 years of WAIS ice and climate change

Why this matters…

- Ice-core records have high temporal resolution; compare independent records to each other
- Specifics of past climate are a necessary boundary condition to run ice-evolution models for ice-sheet reconstructions
- Radar-detected internal layers are an increasingly abundant data set that can add spatial information
- Holocene climate change gives an interesting and necessary context to modern records

Takeaway points…

- Deriving climate histories from ice-core records requires knowledge/assumptions about the ice-sheet history

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- Gain insight into *what* the continent experienced, then *why*

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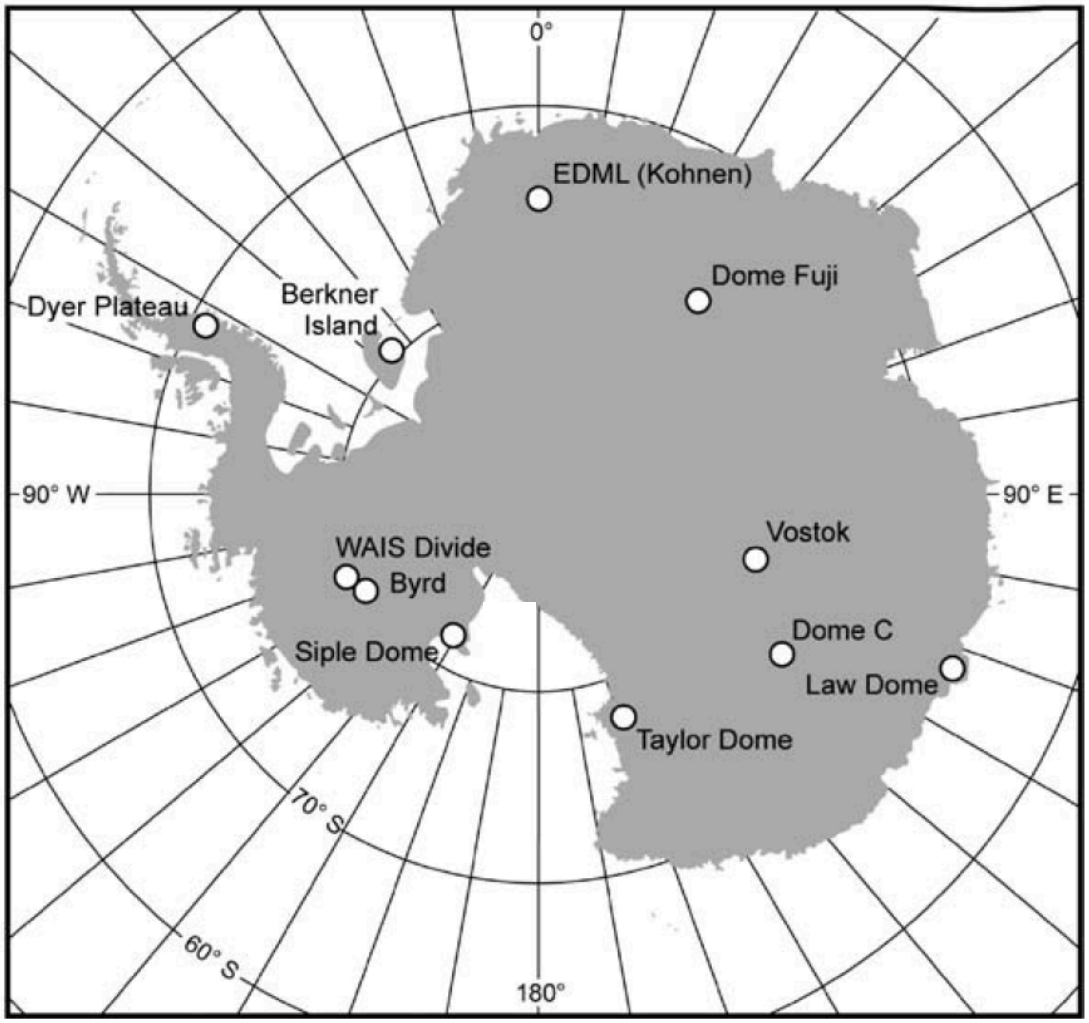
- Ice cores are tremendous archives – but using them with radar data brings distinct value (for past and recent change)
- Gain insight into *what* the continent experienced, then *why*
- Ice-sheet model reconstructions constrained by ice cores
- Temperature histories provided by ice-core data put modern change in context with the past

Deep ice-core sites



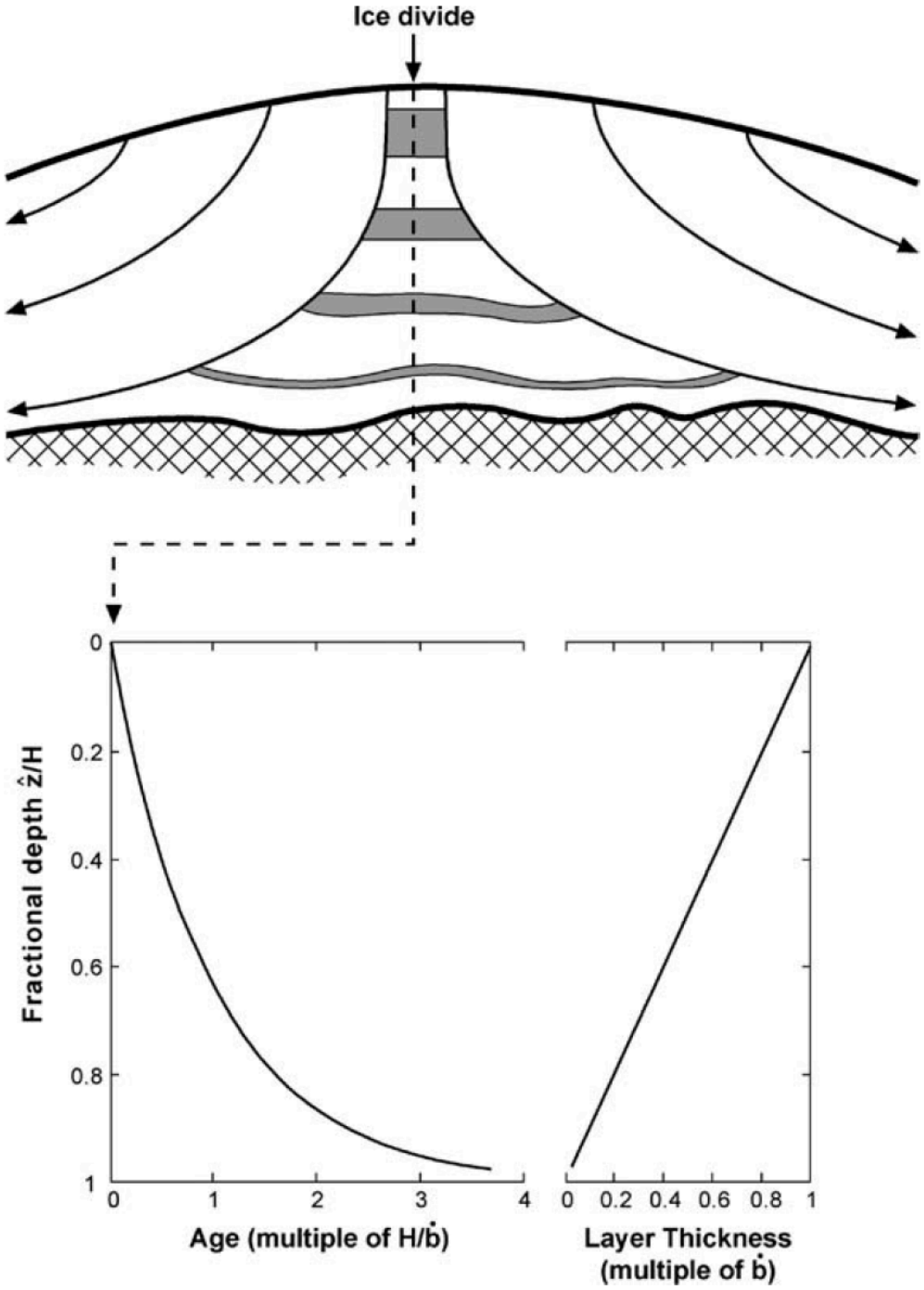
+ South Pole

+ Roosevelt Island

+ James Ross Island

Cuffey and Paterson (2010)

Where to drill an ice core …
theoretically



Assume uniform strain rate and no melting

Accumulation constant

In reality, strain rate varies with depth

Cuffey and Paterson (2010)

Table 15.1: Ice core ages at 80% of total depth.

Core Site	Ice thickness (m)	Accum. rate ($m\,yr^{-1}$)	Theoretical age (kyr)	Actual age (kyr)	Reference
Agassiz Ice Cap	111†	0.098	1.8	5	(1)
Law Dome	1220	0.7	2.8	4	(2)
Taylor Dome	550	0.06	15	50	(3)
GISP2	3050	0.23	21	50	(4)
EDML††	2774	0.07	64	105	(5)
Dome C	3275	0.027	195	350	(6)

† Ice-equivalent value.

†† EDML stands for "EPICA Dronning Maud Land."

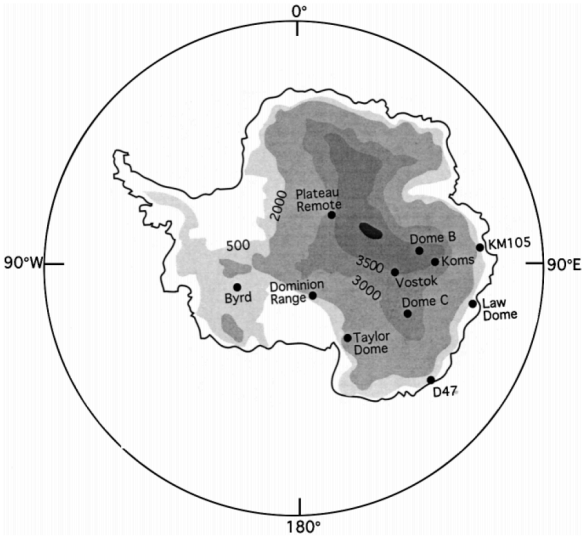
References: (1) Fisher et al. 1995; (2) Morgan et al. 1997; (3) Steig et al. 2000; (4) Meese et al. 1997; (5) EPICA Community members 2006; (6) Parrenin et al. (2007).

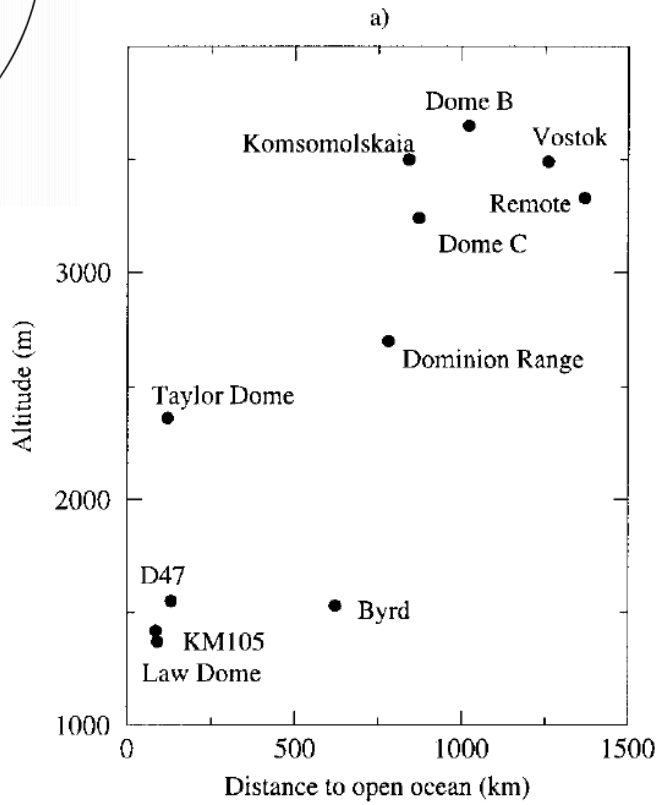
Cuffey and Paterson (2010)

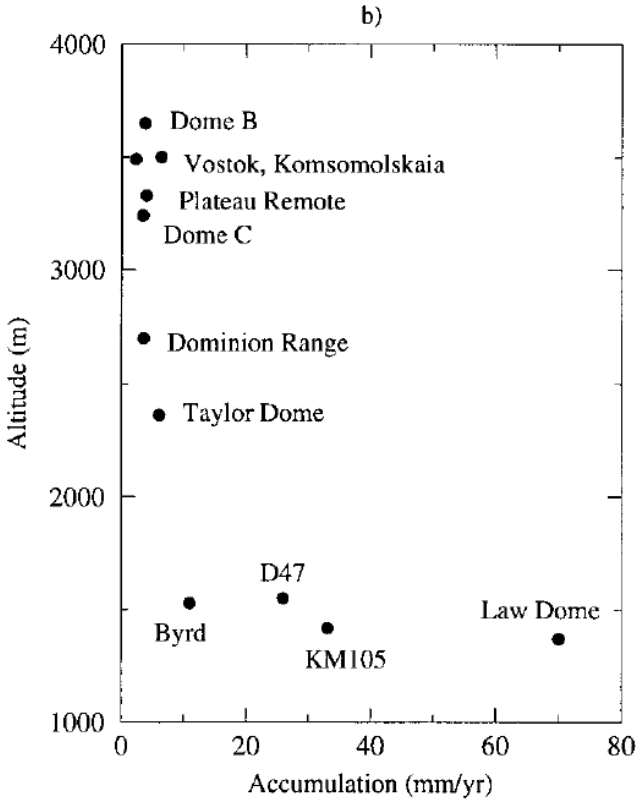
Basics of deriving a climate record: Age scale

- Annual layer counting (chemistry, dust, electrical conductivity)
- Volcanic, cosmogenic, and other marker horizons
- Markers related to globally mixed gases
- Oxygen and hydrogen isotopes of ice
- Physical characteristics (e.g. bubbles)
- Ice-flow model with depth-varying strain rate

Holocene ice-core records across Antarctica







Masson et al. (2000)

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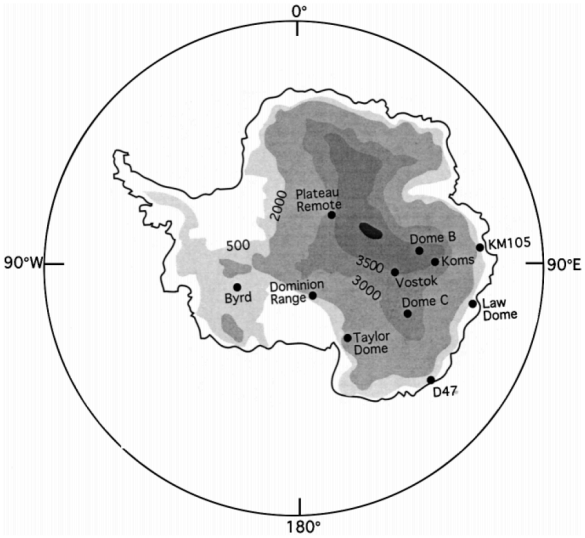
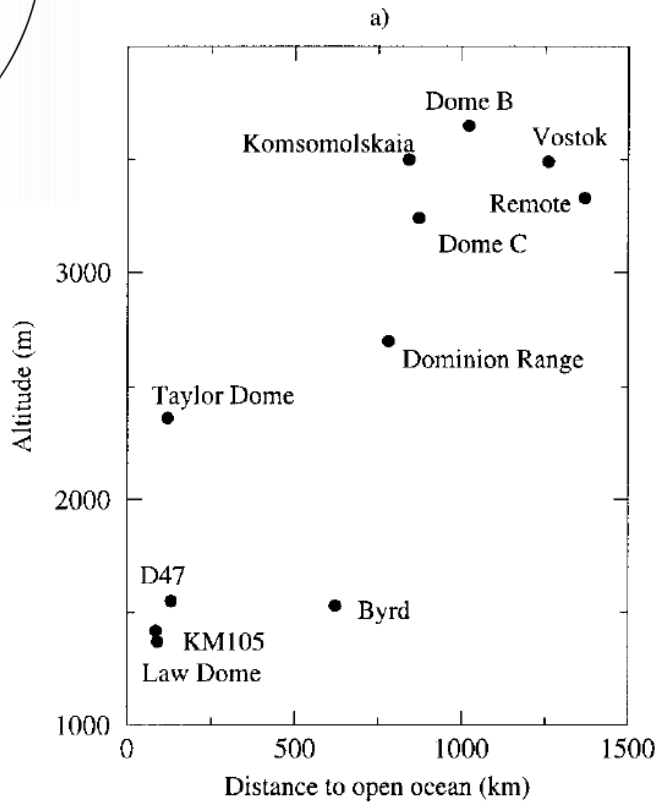
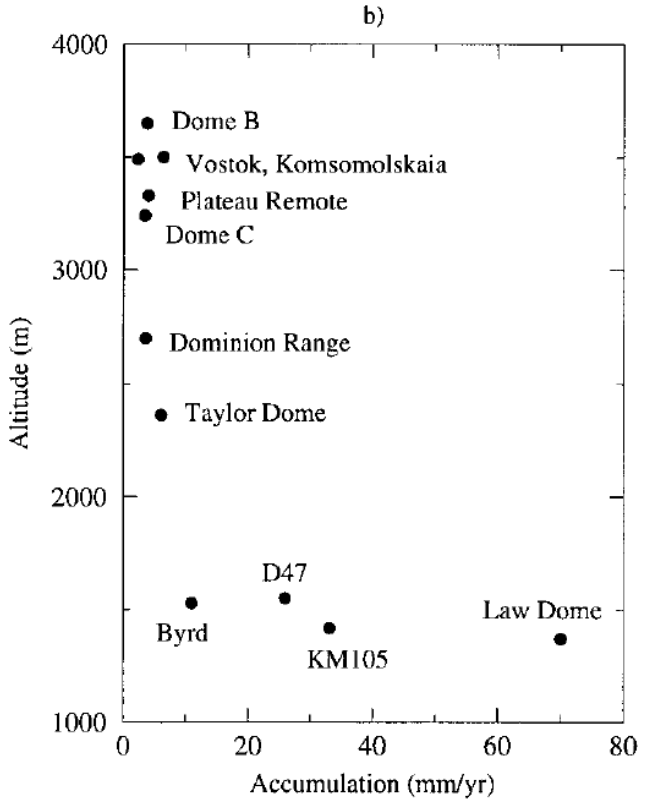


Ice-sheet elevation changes may be superposed on common climatic fluctuations

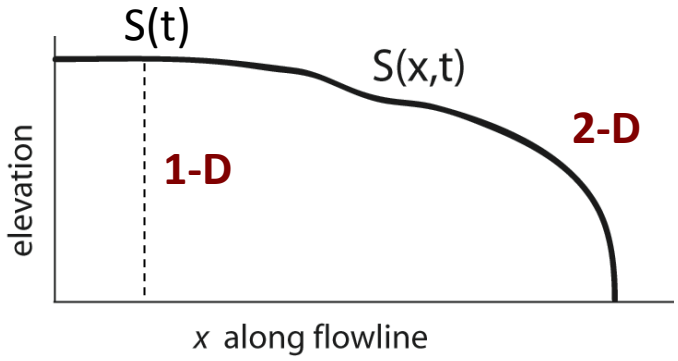


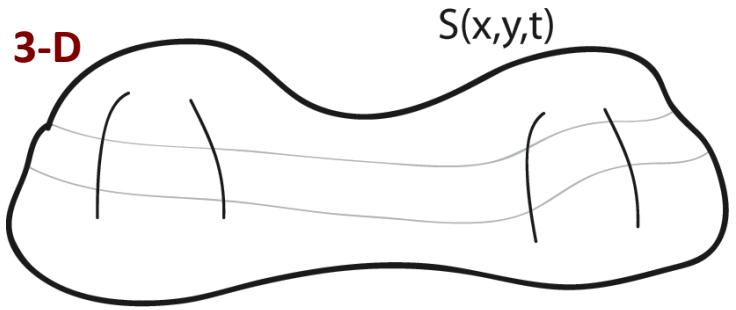


Masson et al. (2000)

Basics of deriving a climate record: Accumulation rate

Need to apply **ice-flow models** in order to estimate accumulation history at a core site from measured layer thicknesses





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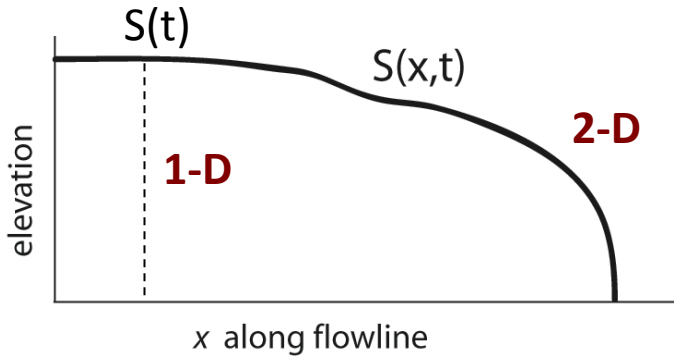
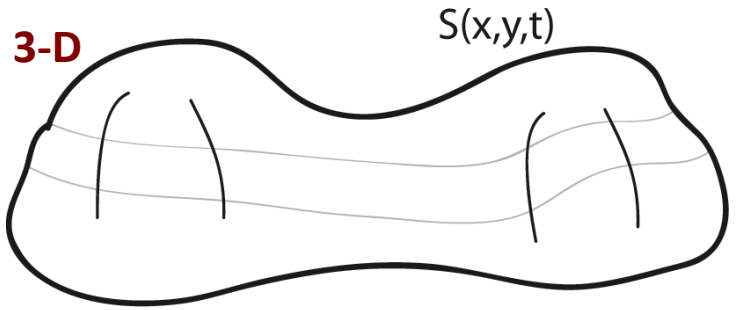




Inferred accumulation rate:

$$\dot{b}_{core}(t) = \frac{\lambda(t)}{\Lambda(t)}$$

Layer thickness -- measured

Thinning function -- calculated

Basics of deriving a climate record: Accumulation rate

Separate the influence of ice flow vs. climate on ice-core record

Sometimes this is easy … *but, sometimes this is hard…*

Inferred accumulation rate:

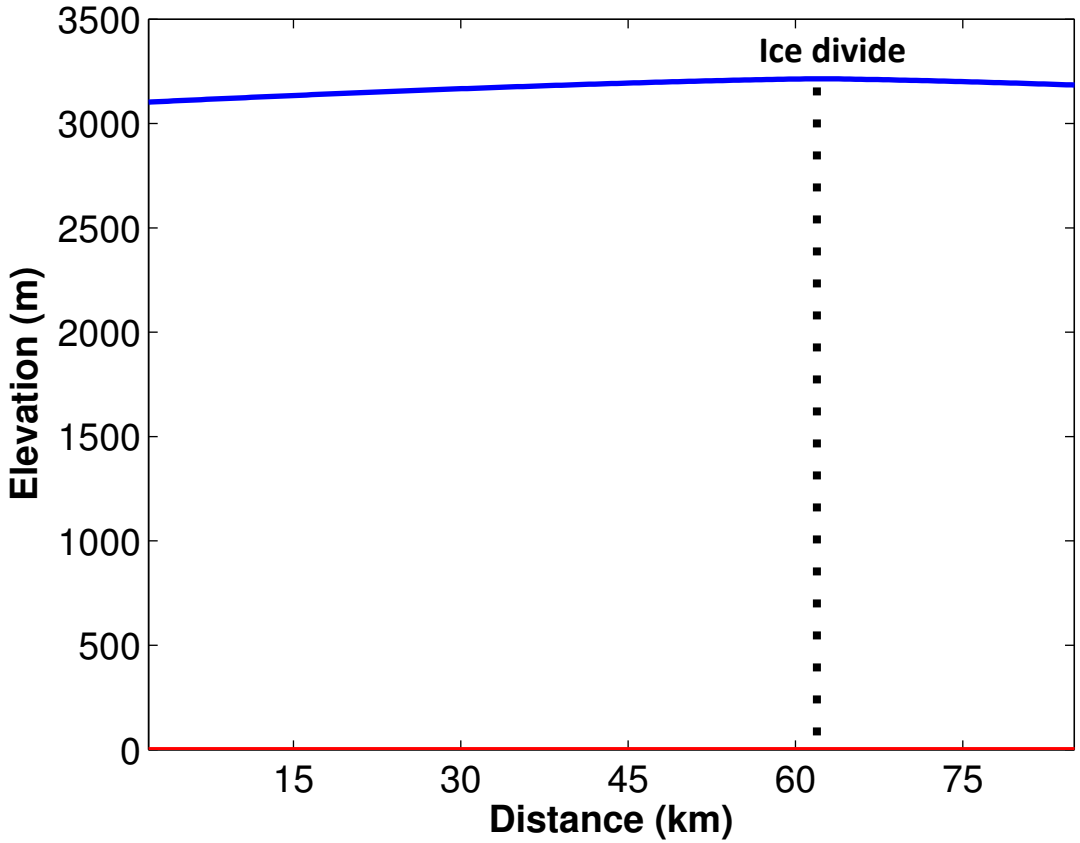
$$\dot{b}_{core}(t) = \frac{\lambda(t)}{\Lambda(t)}$$

Layer thickness -- measured

Thinning function -- calculated

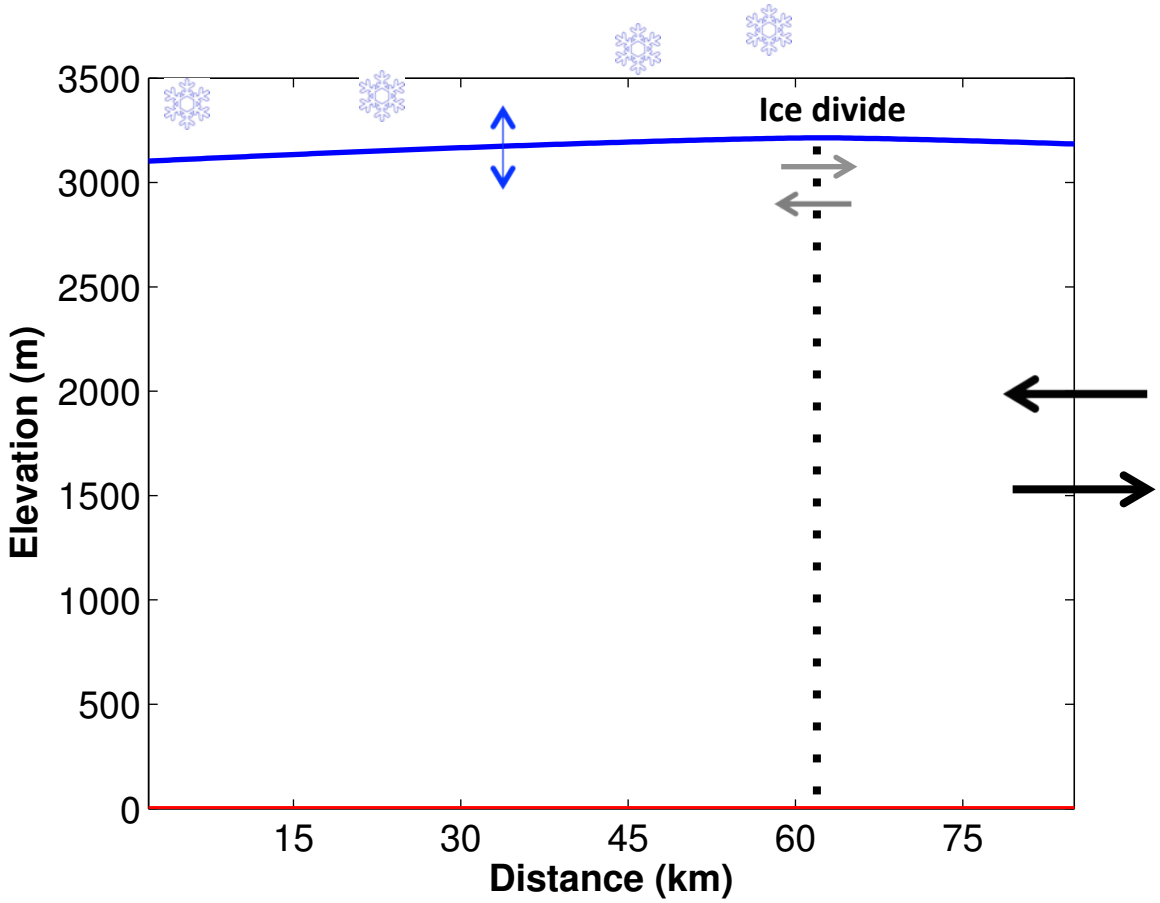
Interior of Antarctica

Assume that we can describe ice flow in ice-sheet interior



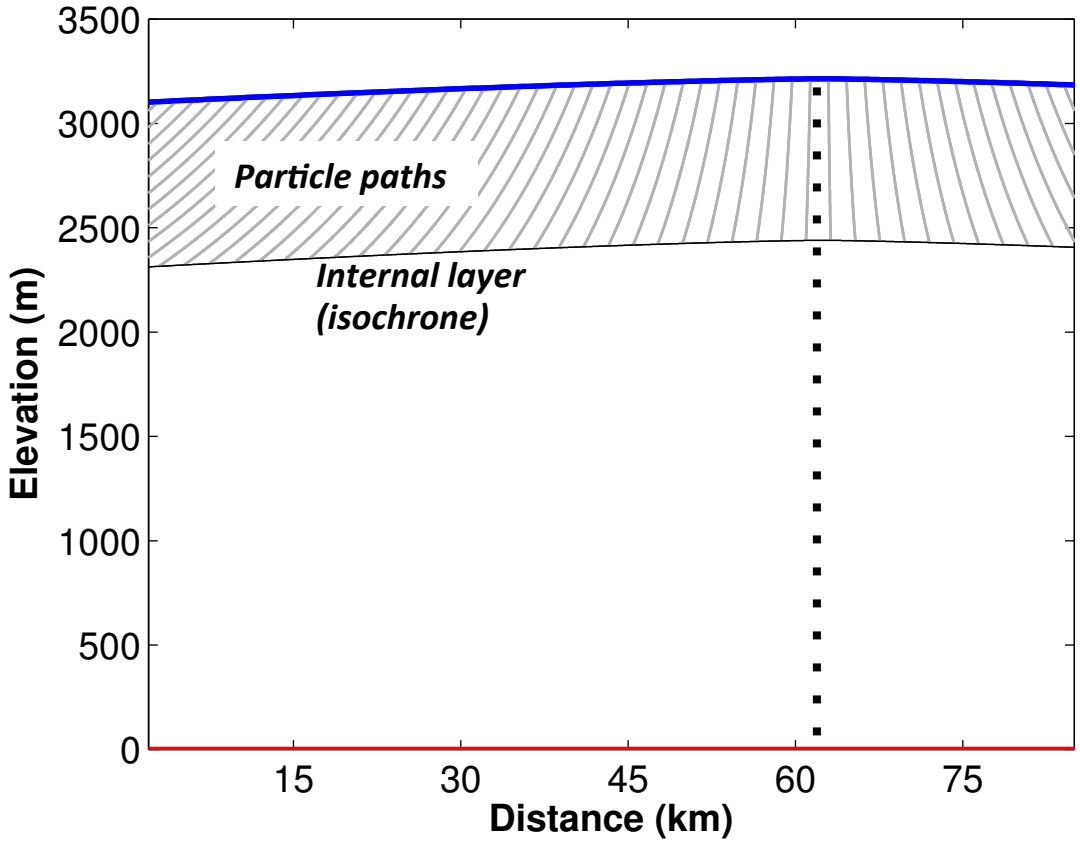
Interior of Antarctica

As the ice sheet evolves over thousands of years, accumulation rate and flow rate change



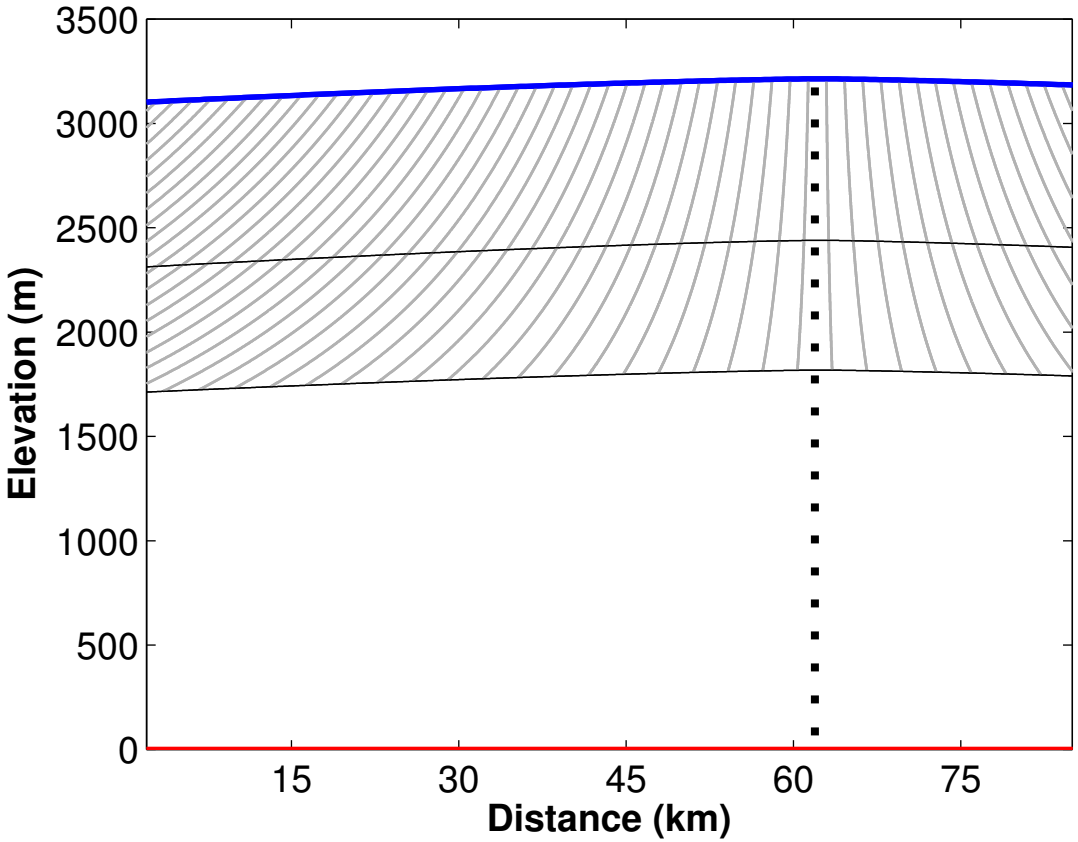
Interior of Antarctica

The rate, pattern, and time-variation of climate and ice dynamics affect particle paths



Interior of Antarctica

Deeper layers from further back in time



Interior of Antarctica

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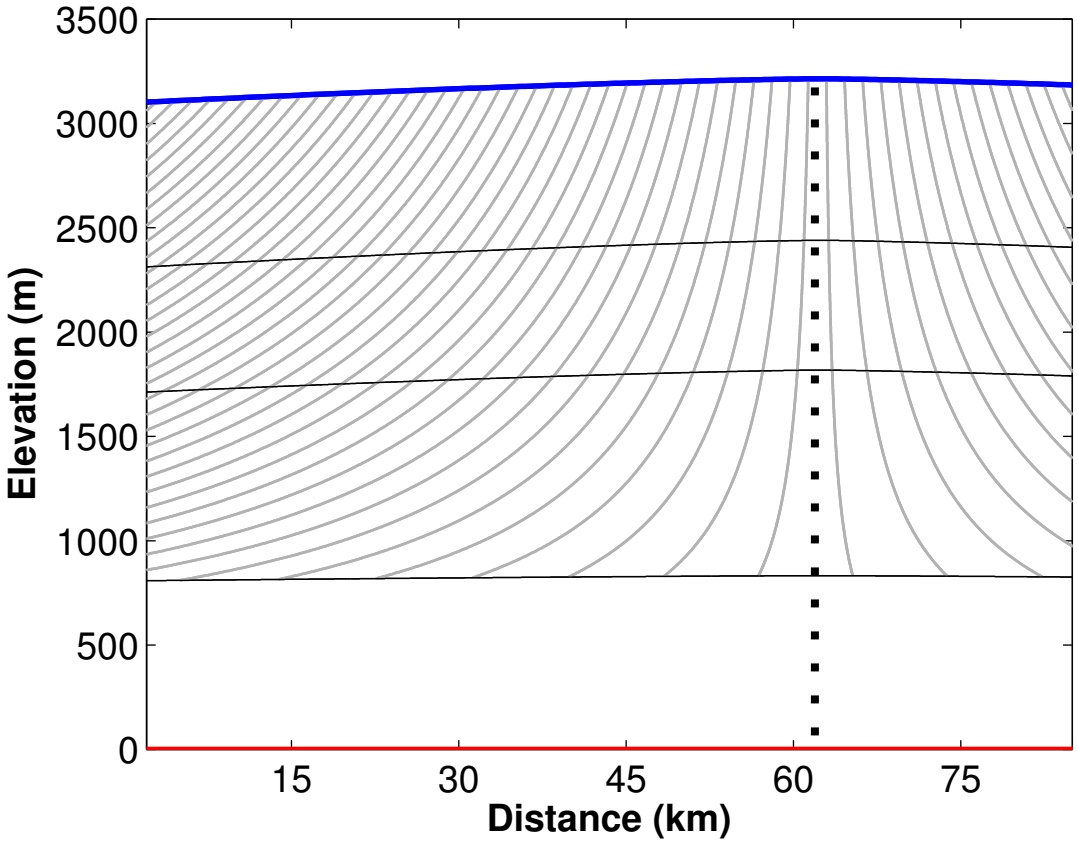

Interior of Antarctica

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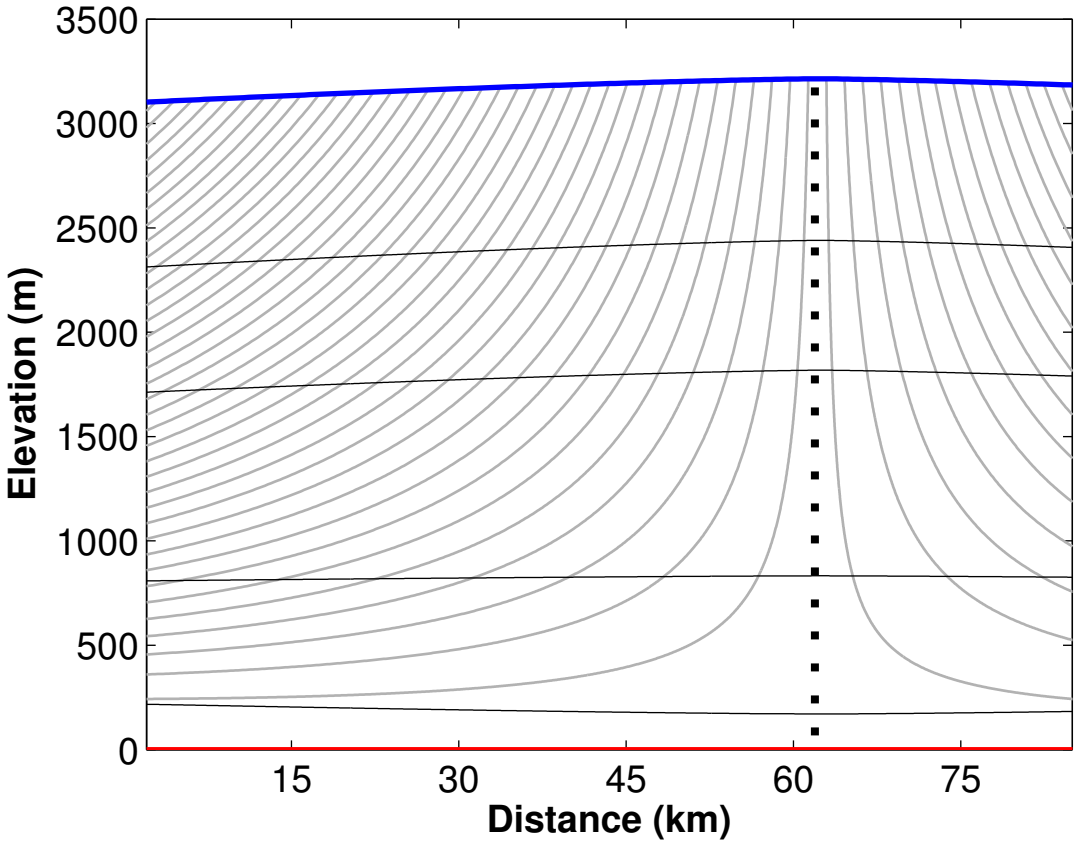
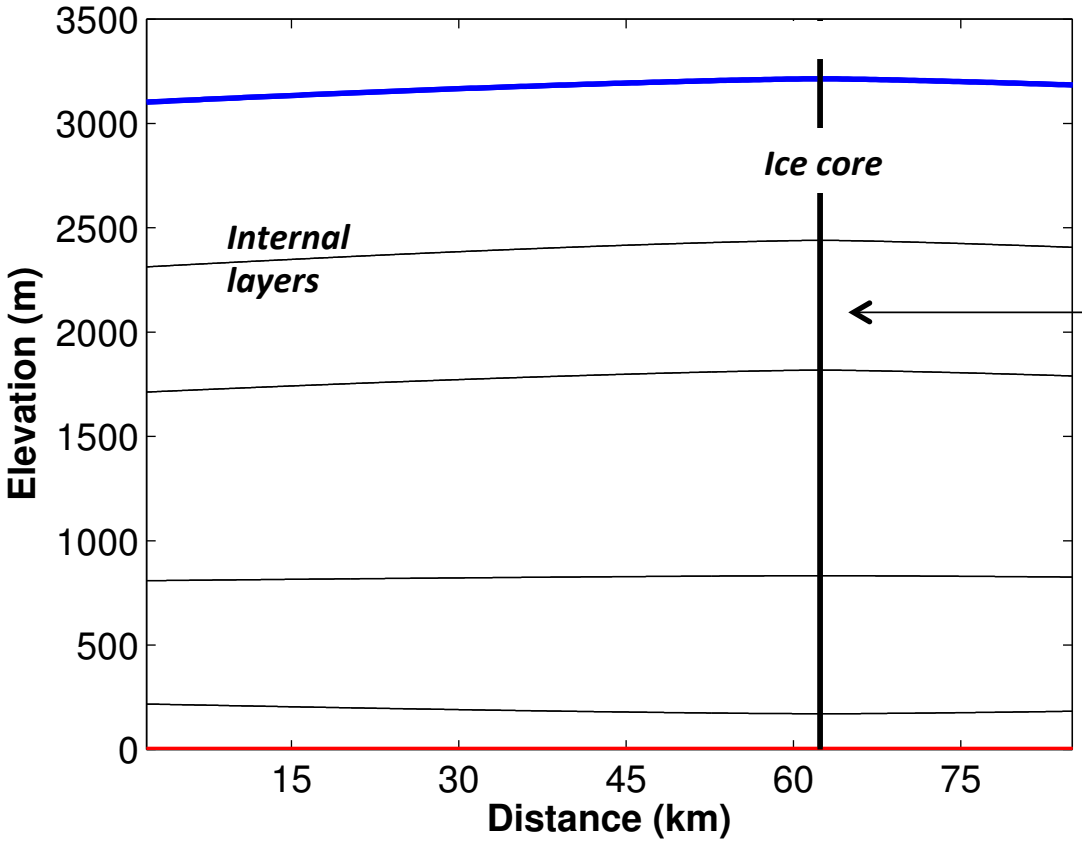


Interior of Antarctica

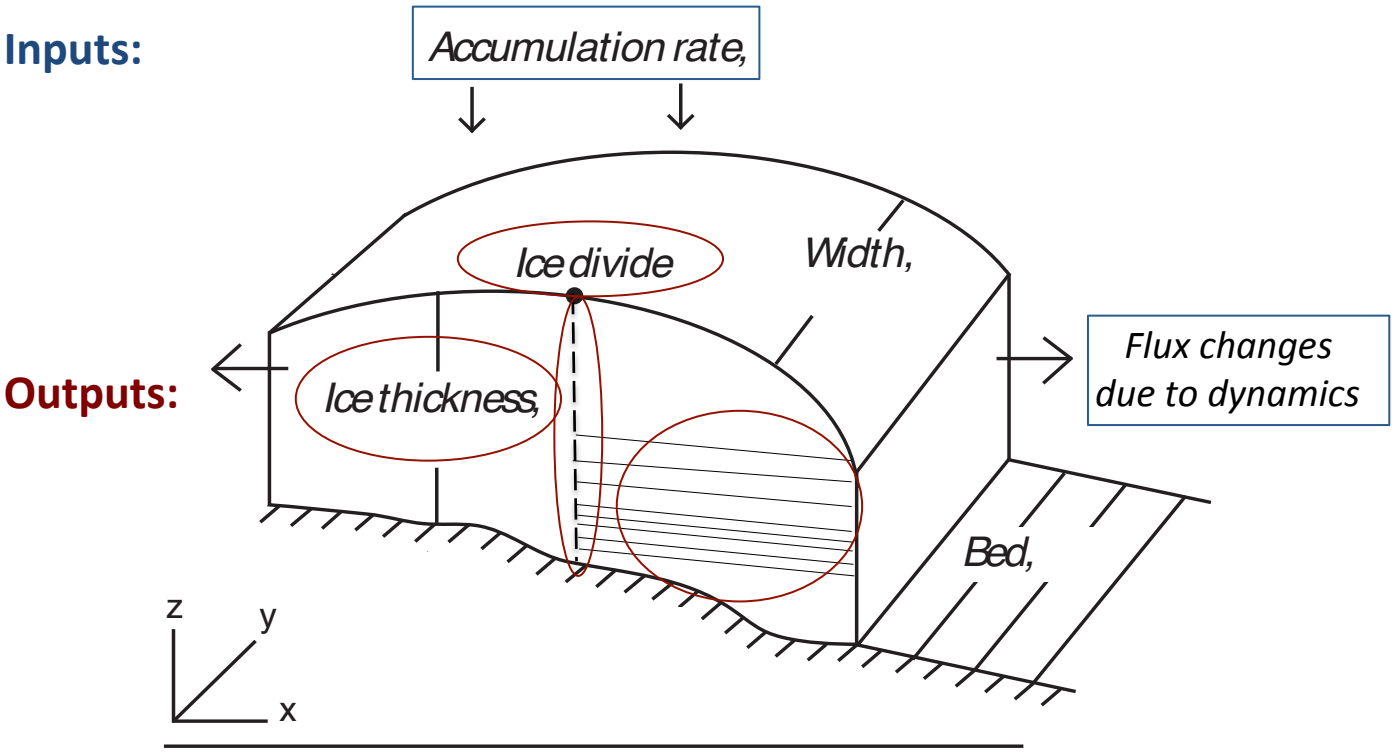
Dynamic and climatic histories recorded in the internal layers and in an ice core:



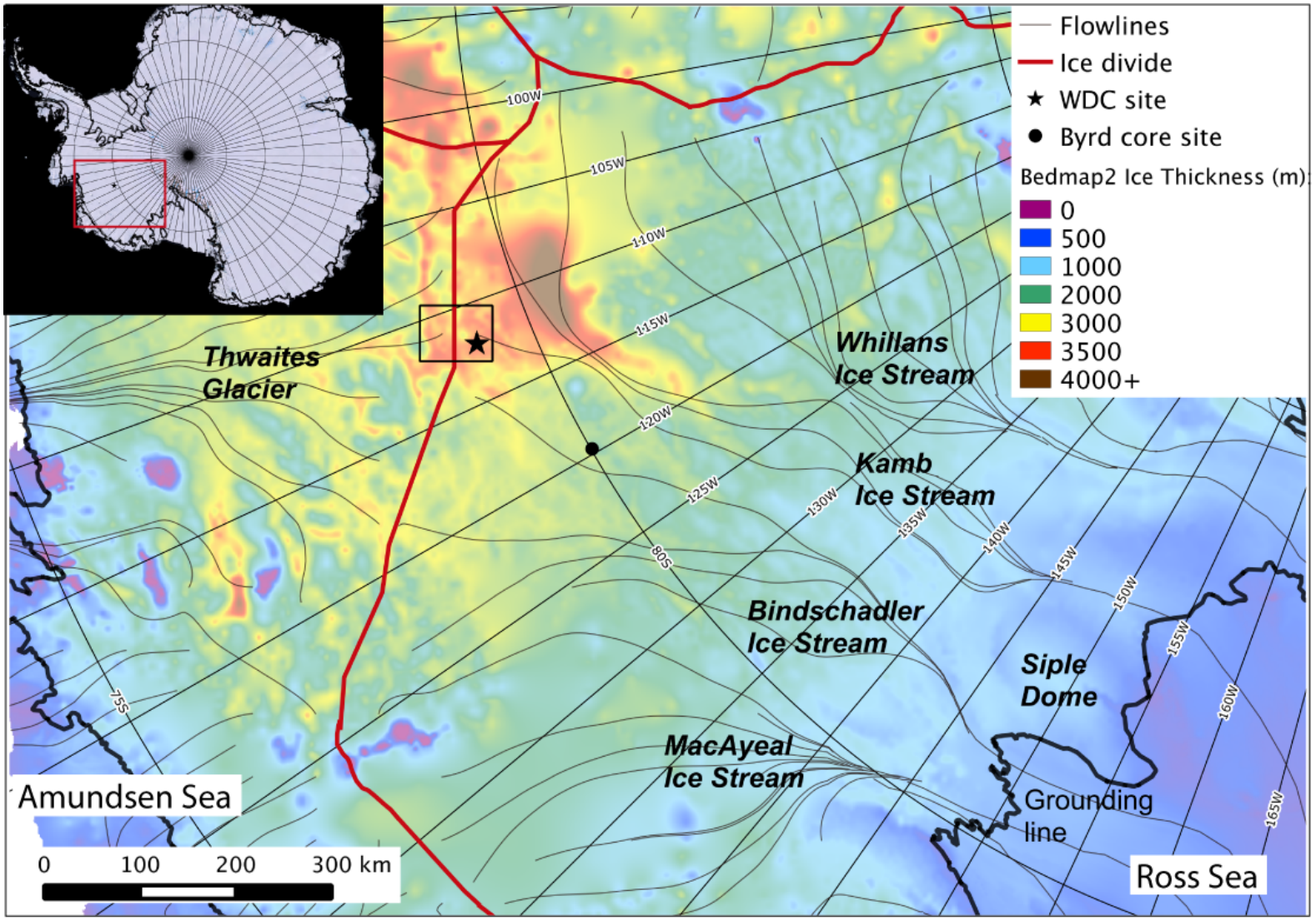
At the divide OR on the flank

Flowband (ice flow) model

We can use the ice-core record and layers together with an ice-flow model to *constrain* ice-sheet history

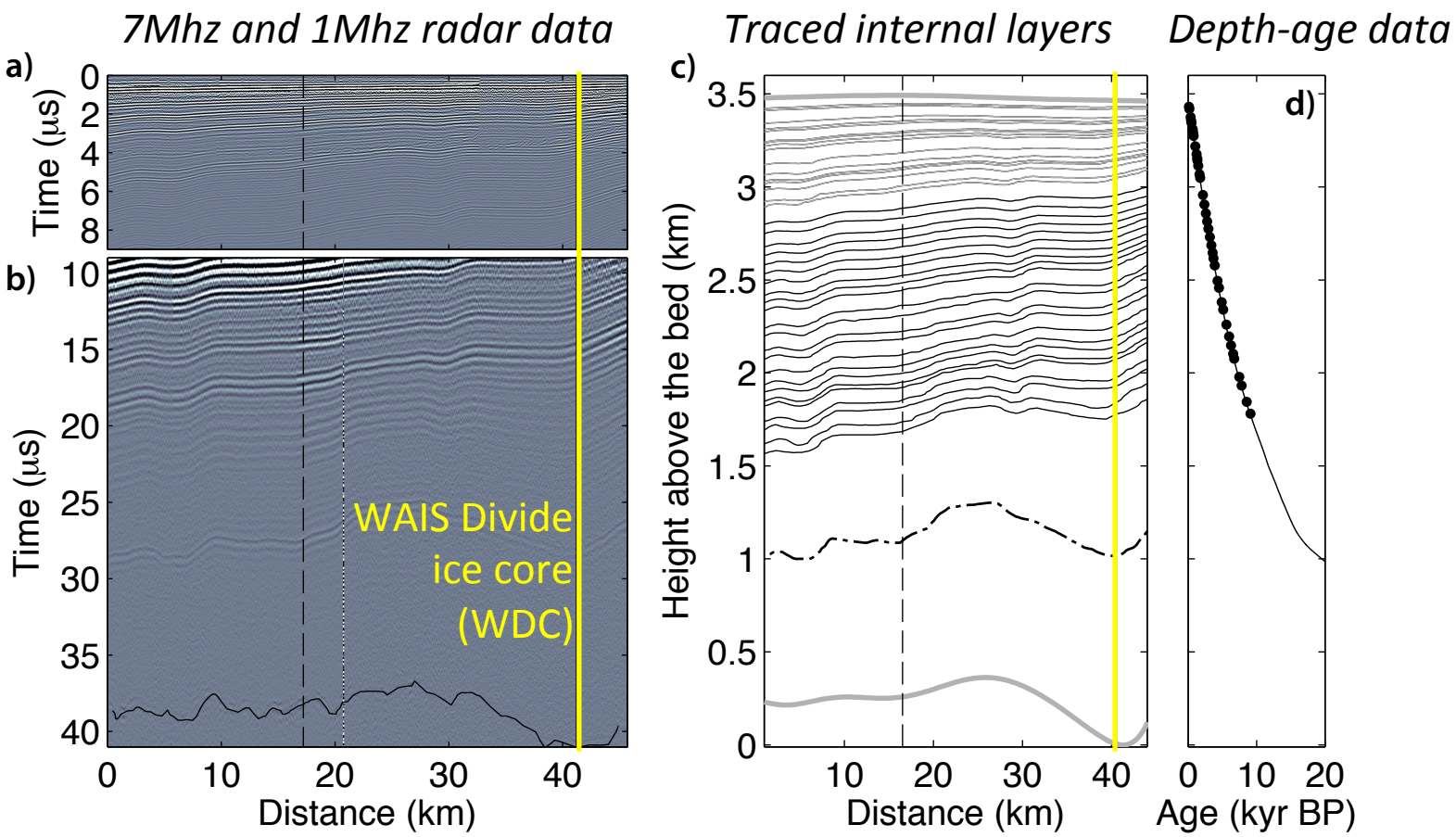


Central West Antarctica



Koutnik et al. (2016)

Central West Antarctica: Data



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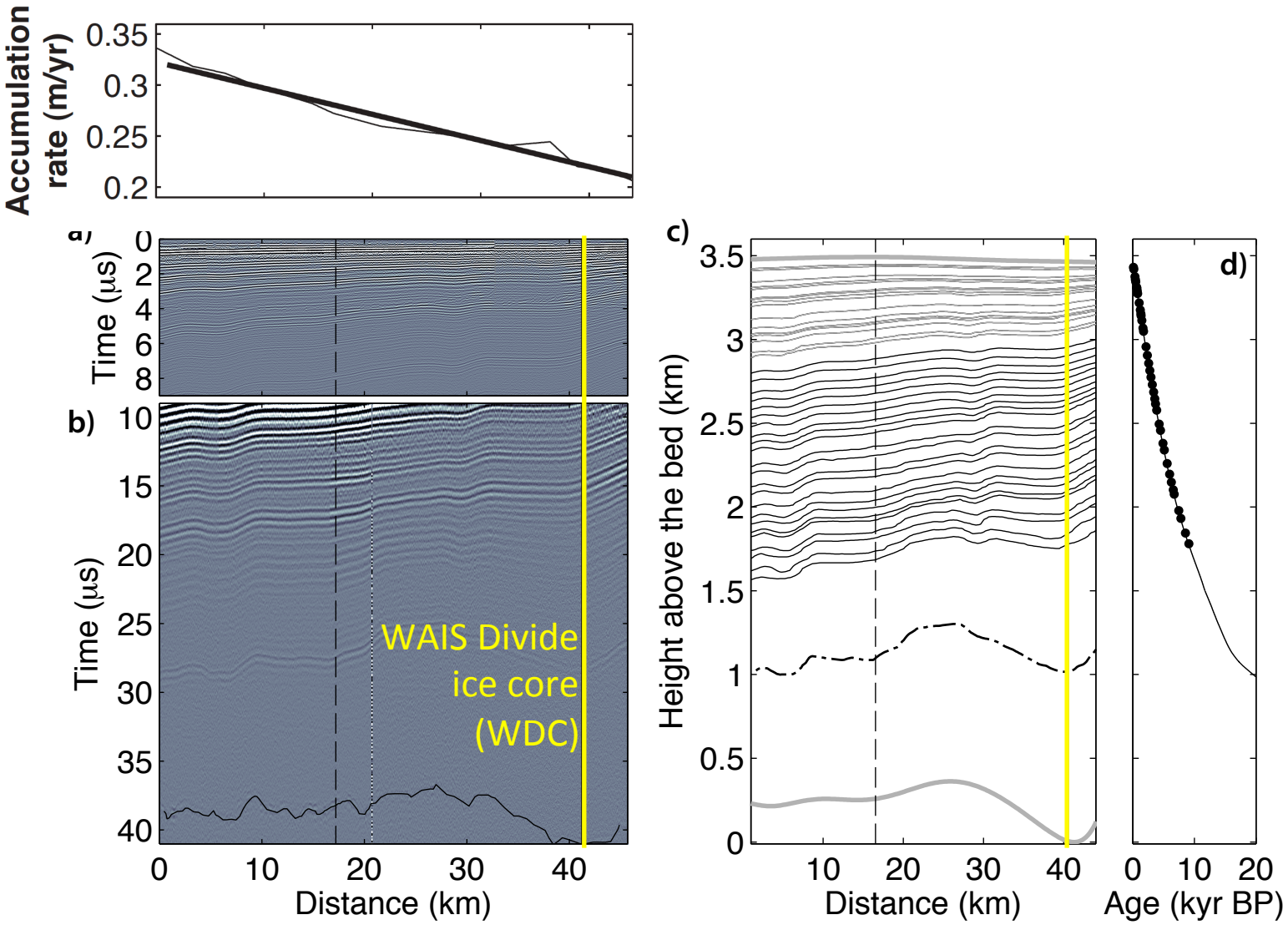
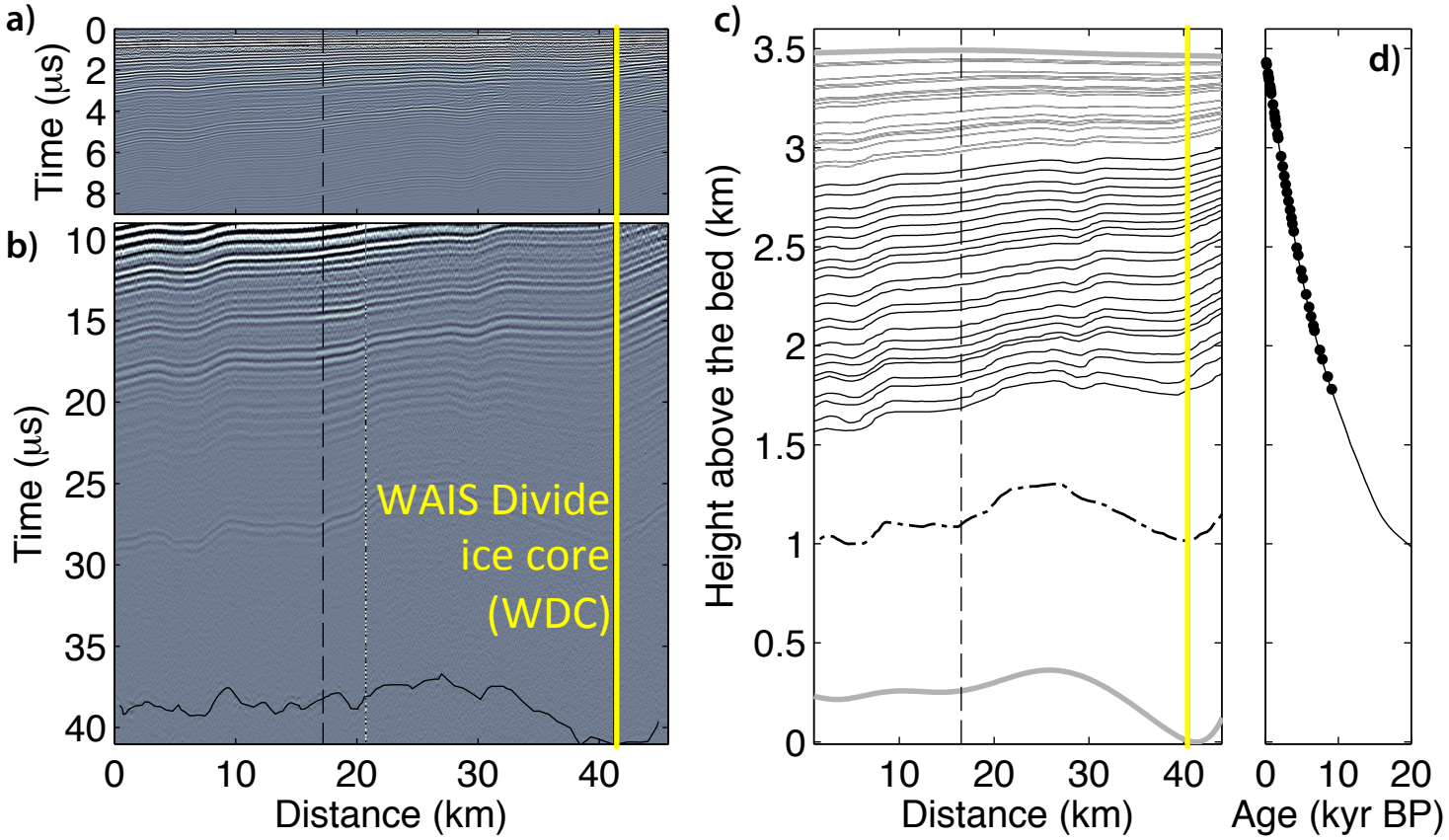


Central West Antarctica: Data

What is the Holocene accumulation history at the ice-core site?

Ice divide is migrating today, did it migrate in the past?



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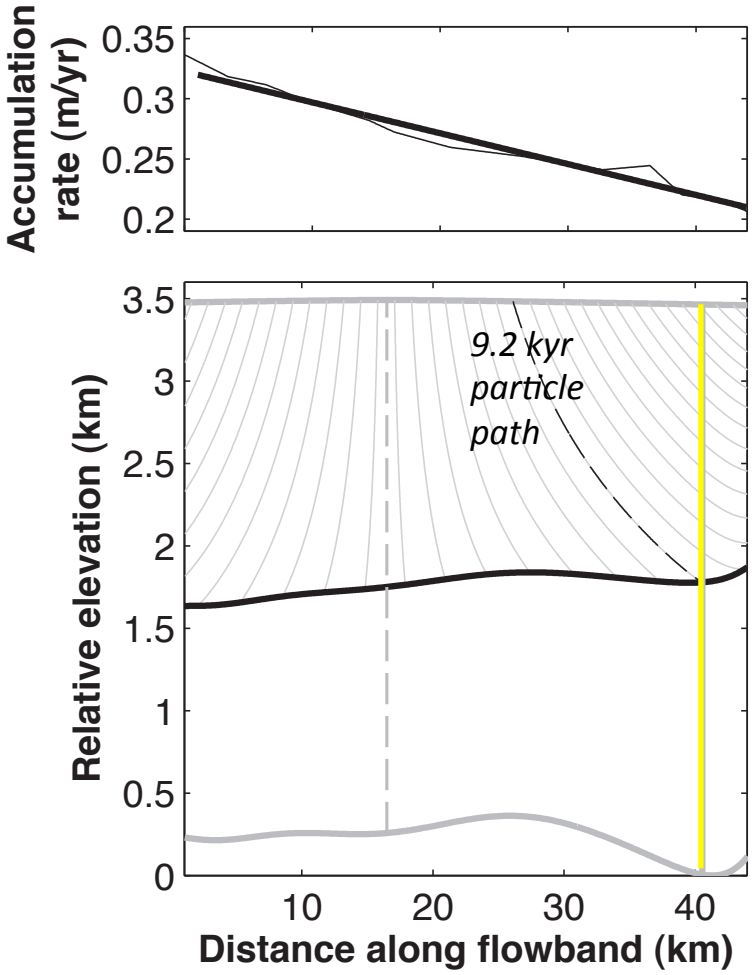


Inferring ice and climate histories from the ice-core record must be done carefully…

1. Ice in core originated upstream

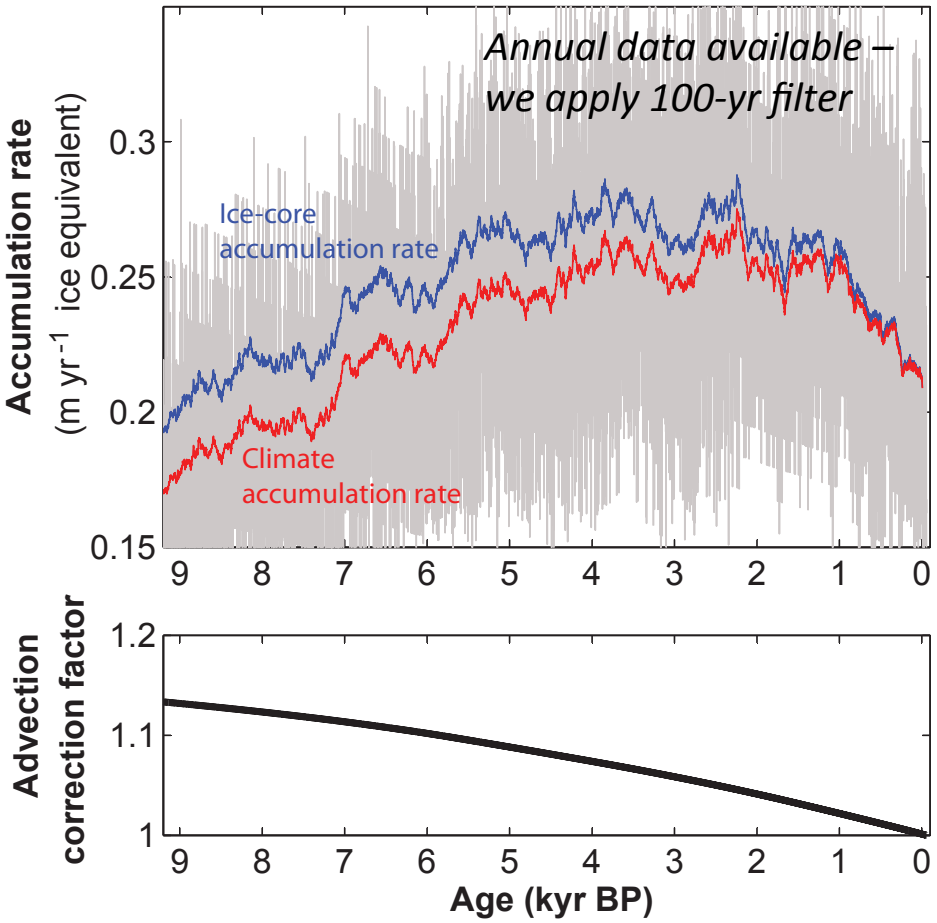
2. Apply thinning function from a 1-D model (*Buizert et al.*, 2015)

Then, advection correction to estimate accumulation history …

Central West Antarctica: Simple estimate of accumulation

Ice-core accumulation rate:

Accumulation at locations where ice in core originated upstream



Central West Antarctica: Simple estimate of accumulation

Ice-core accumulation rate:

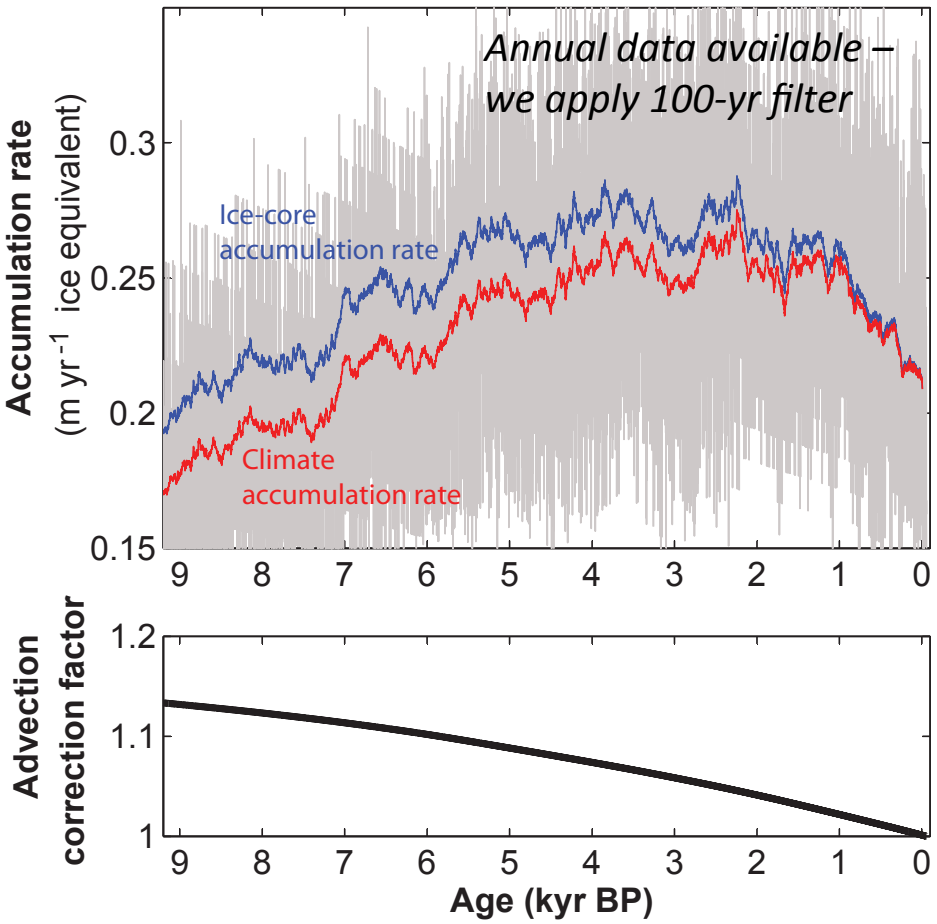
Accumulation at locations where ice in core originated upstream

Climate accumulation rate:

Accumulation at fixed location (core site)

Climate accumulation rate =

$$\frac{\textbf{Ice-core accumulation rate}}{\textbf{Advection correction factor}}$$



Central West Antarctica

Inferring ice and climate histories from the ice-core record must be done carefully…

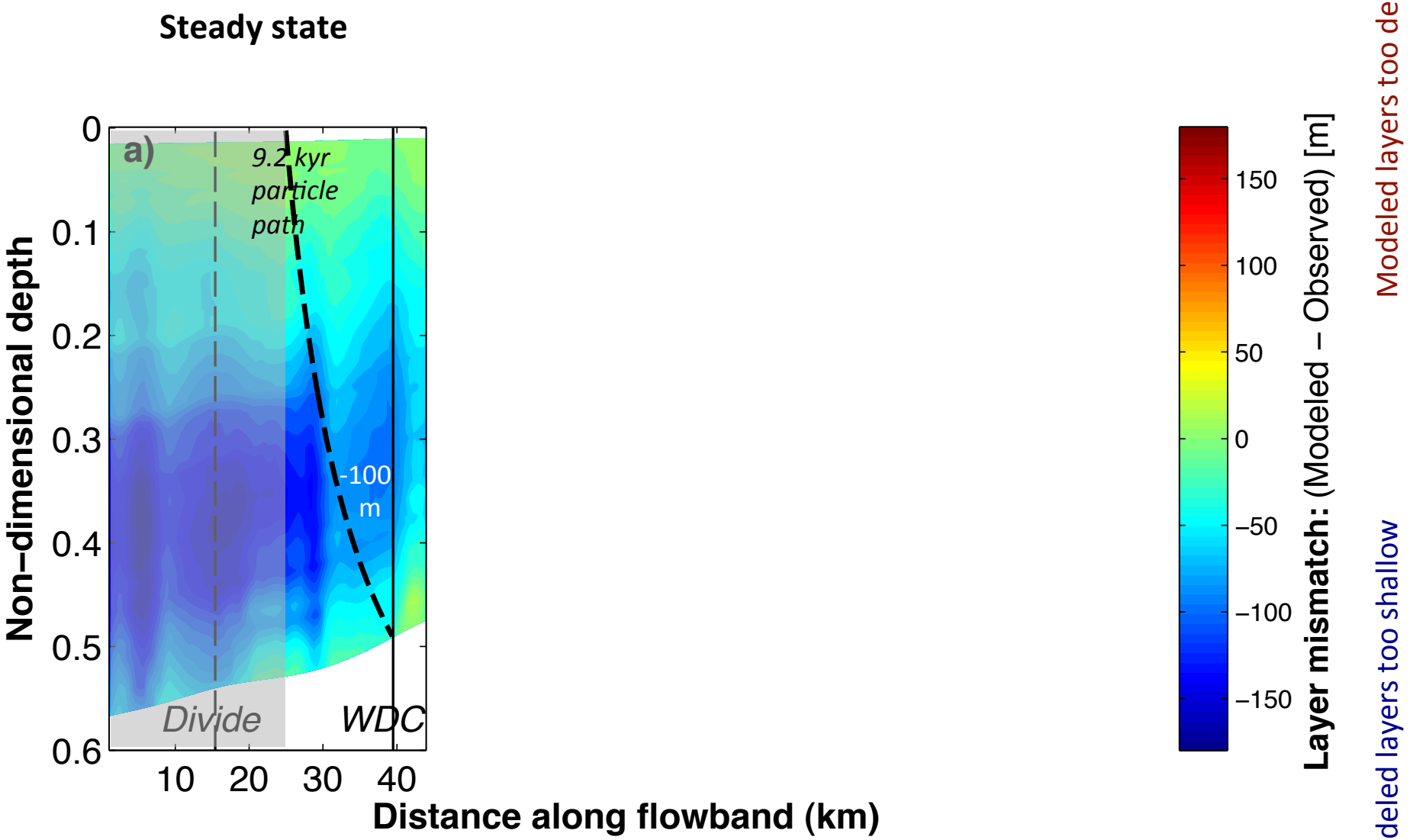
1. Ice in core originated upstream

2. Apply thinning function from 1-D model and then simple advection correction

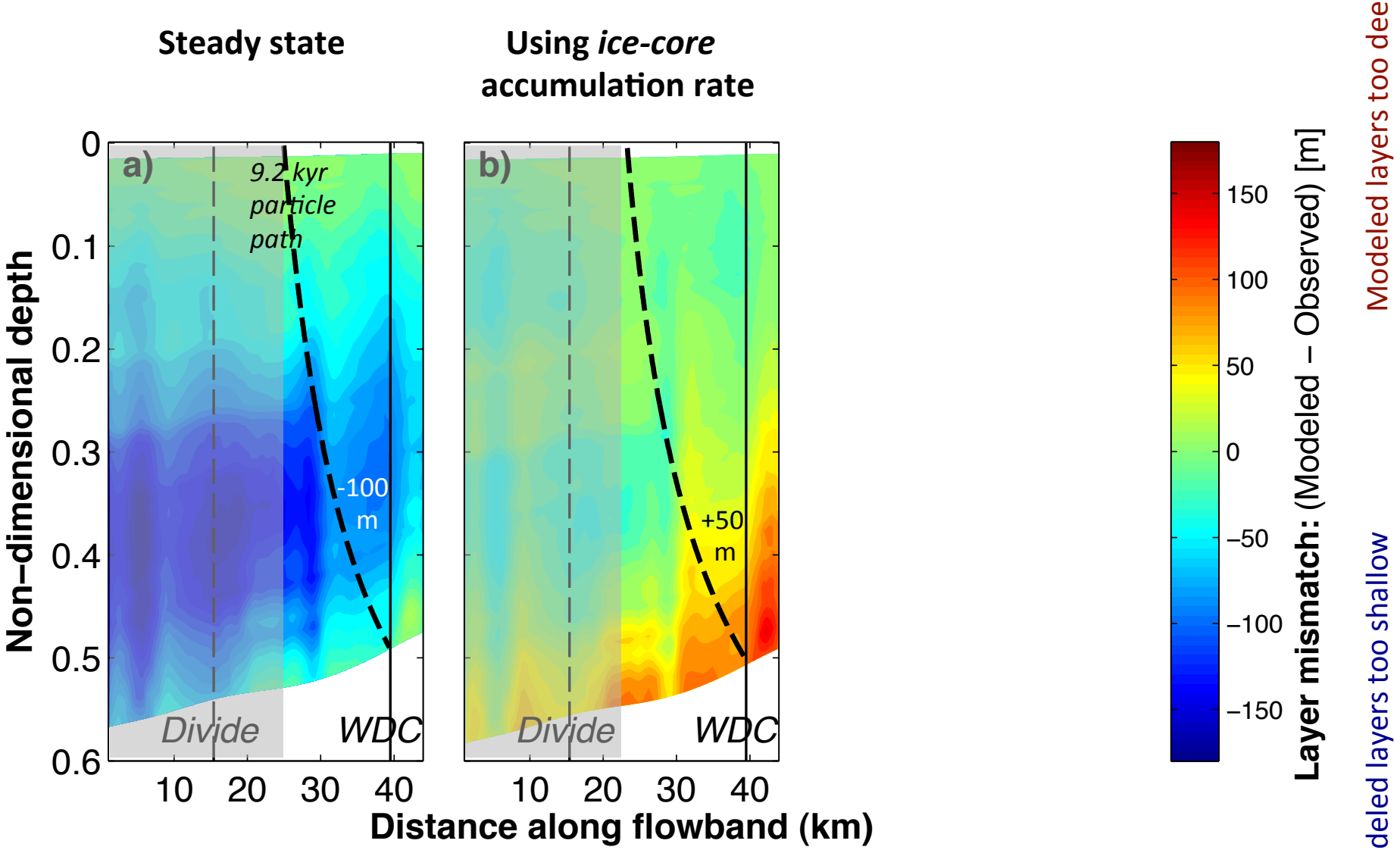
3. Use climate accumulation history in 2.5-D model to generate layers

4. Do modeled layers match observed?

Central West Antarctica: Flowband model calculations



Central West Antarctica: Flowband model calculations



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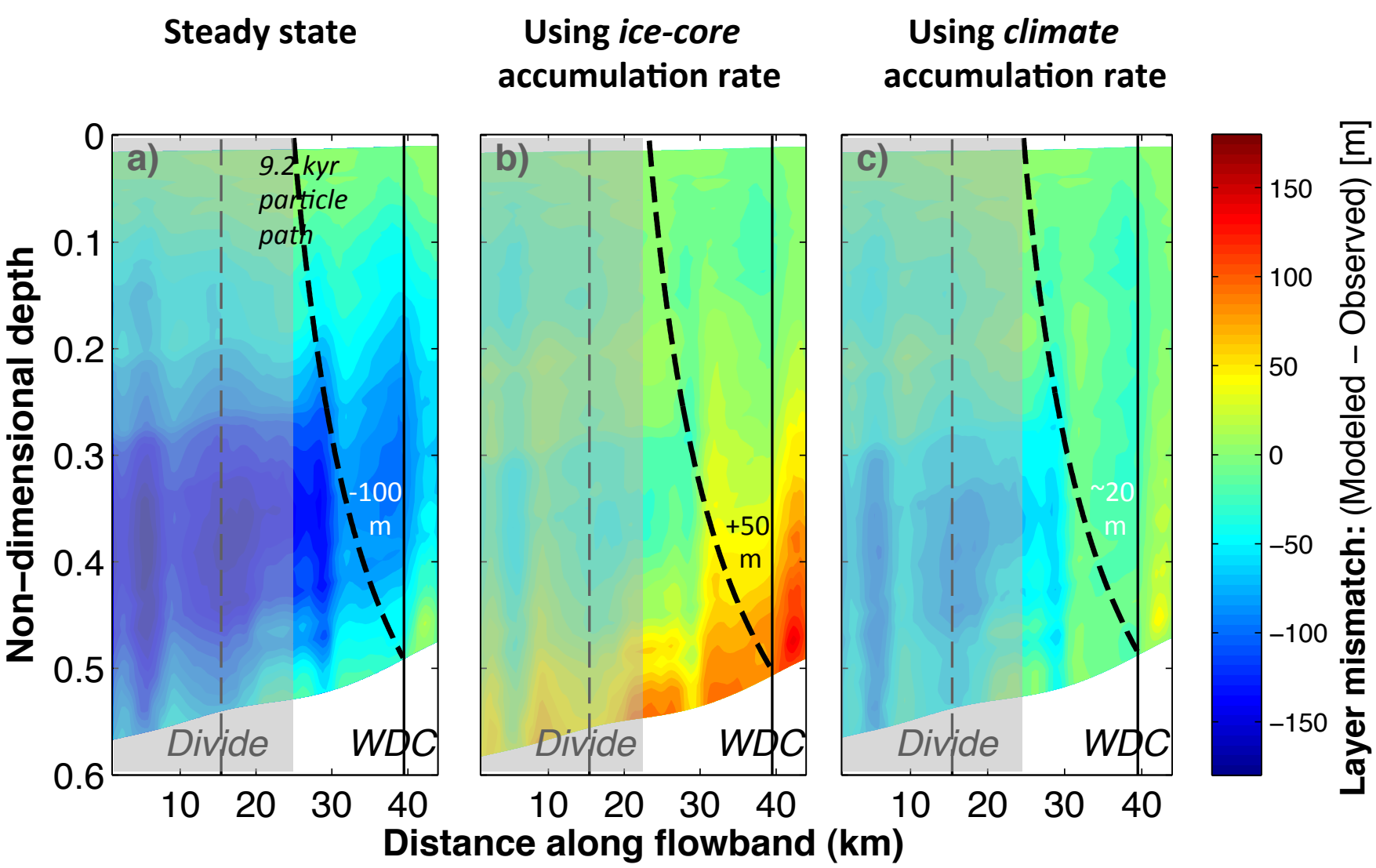

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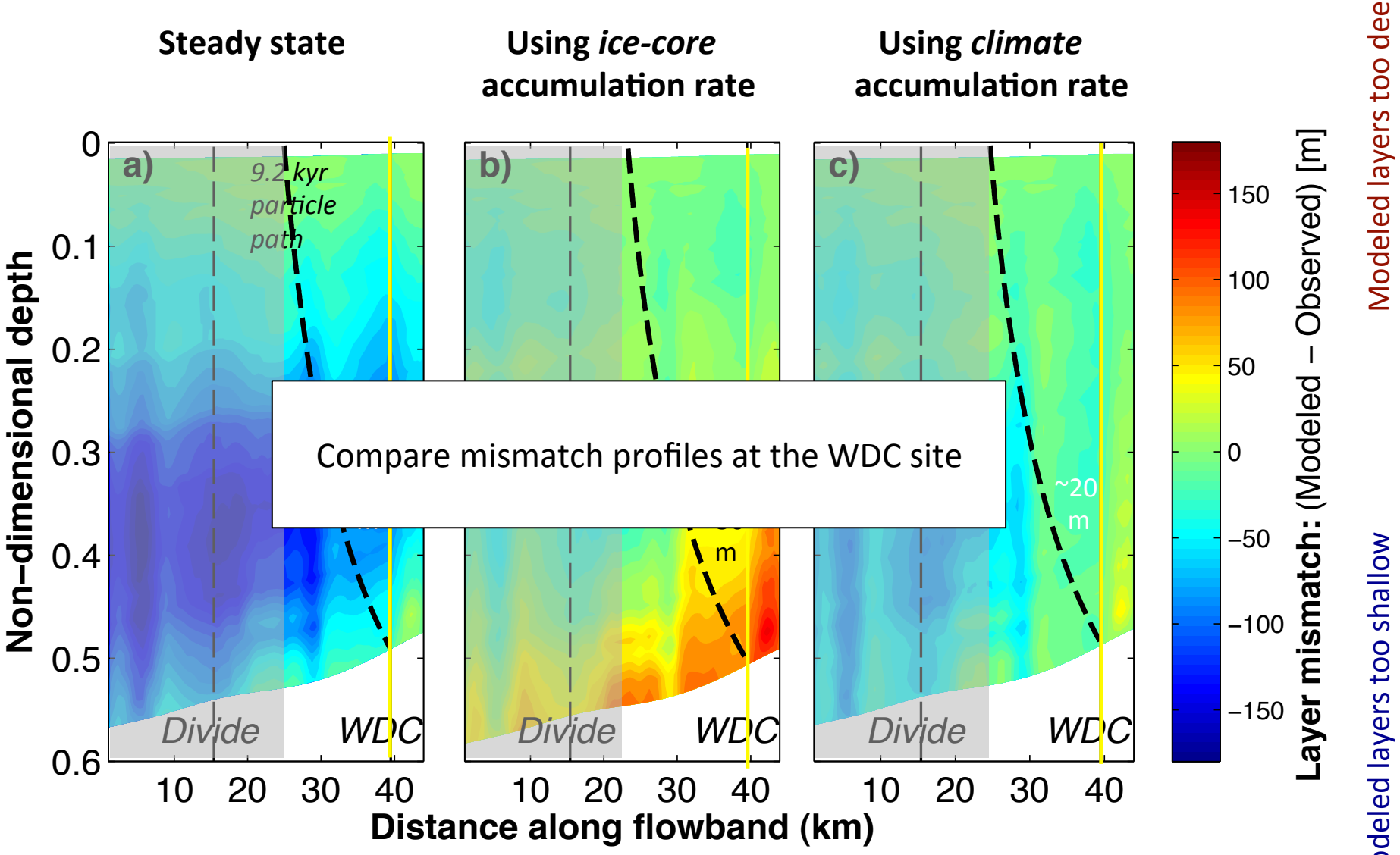
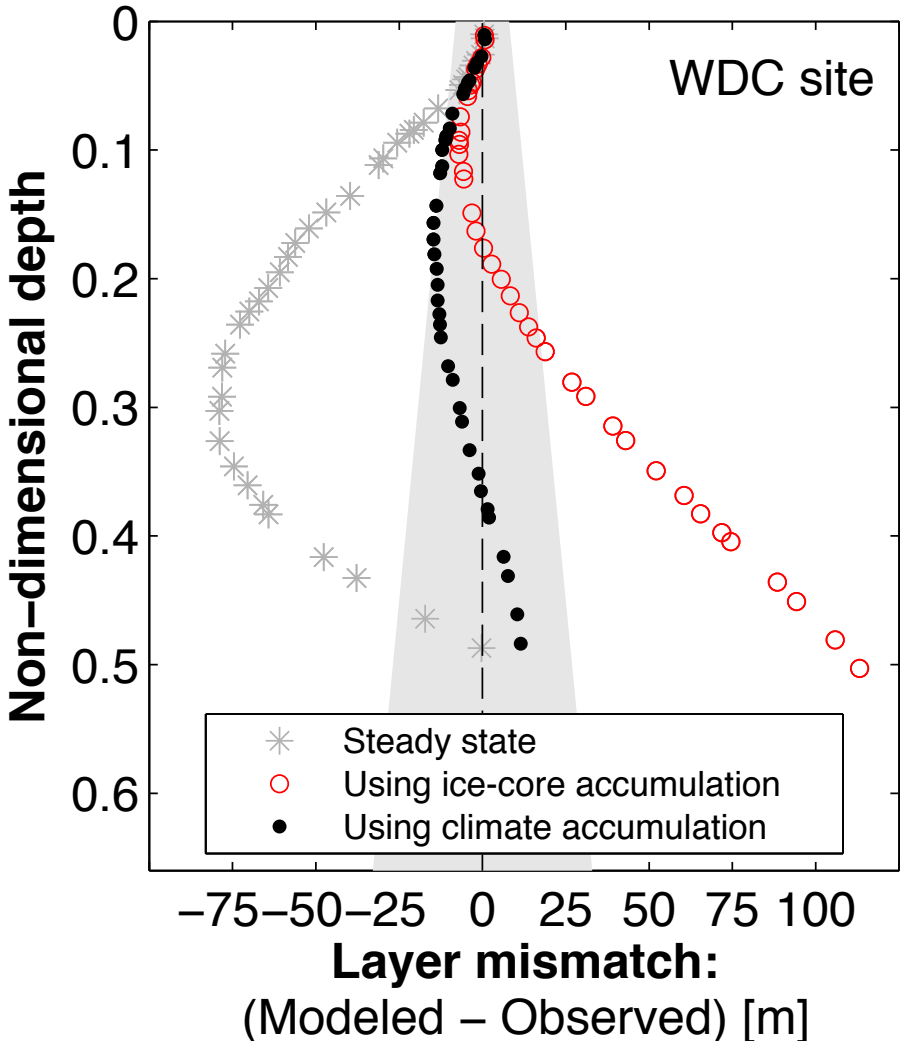


Central West Antarctica: Flowband model calculations

Using climate accumulation history gives a really good fit to internal layers

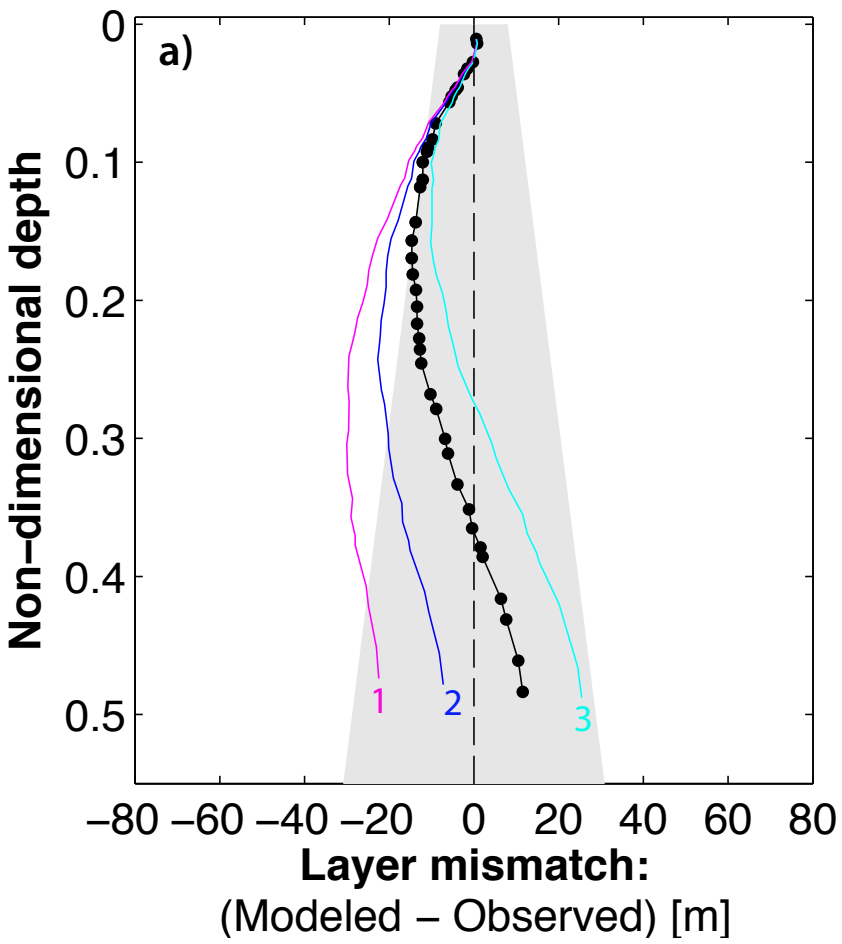
(within uncertainties in layer depths from data collection, processing, travel-time to depth, and layer picking: ± 8-32 m)

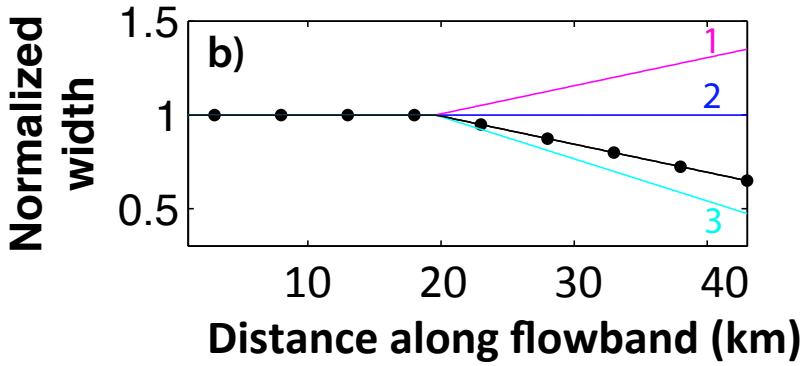


Central West Antarctica: Model sensitivity

Evaluate the goodness of fit at WDC to poorly known model parameters:

Width function

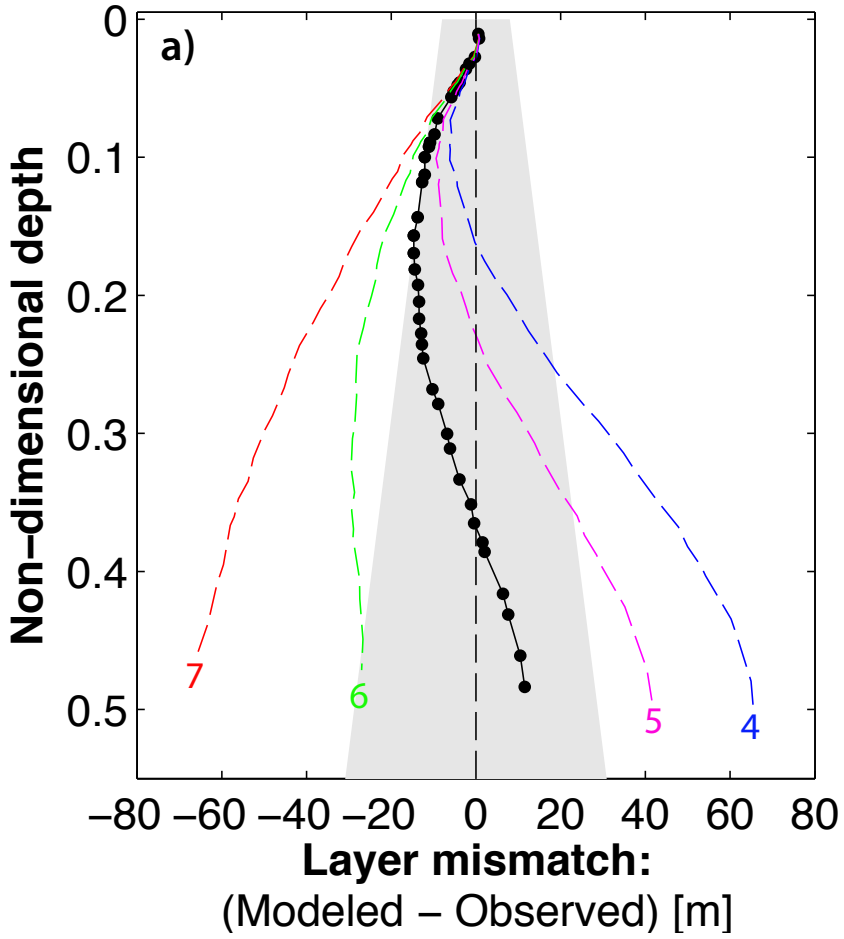


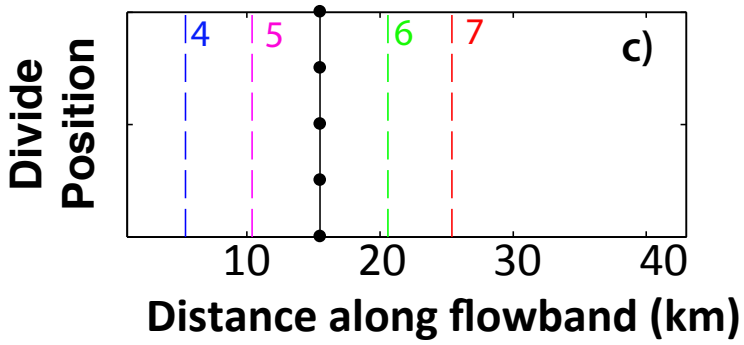


Central West Antarctica: Model sensitivity

Evaluate the goodness of fit at WDC to poorly known model parameters:

Holocene ice-divide position

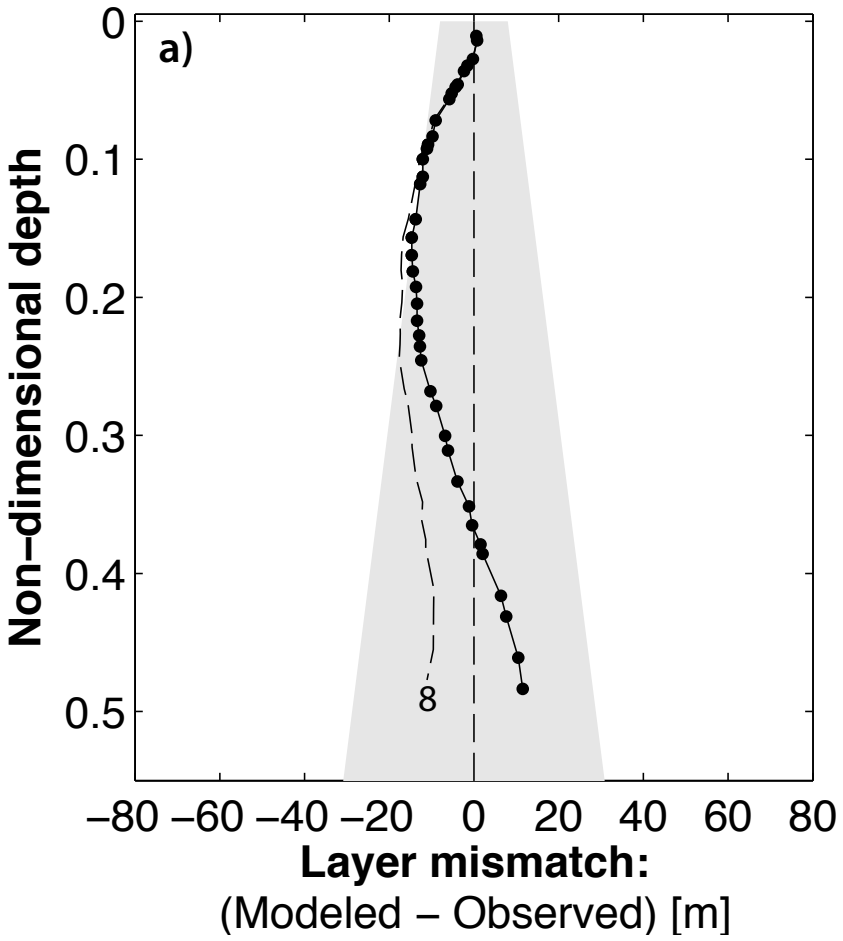


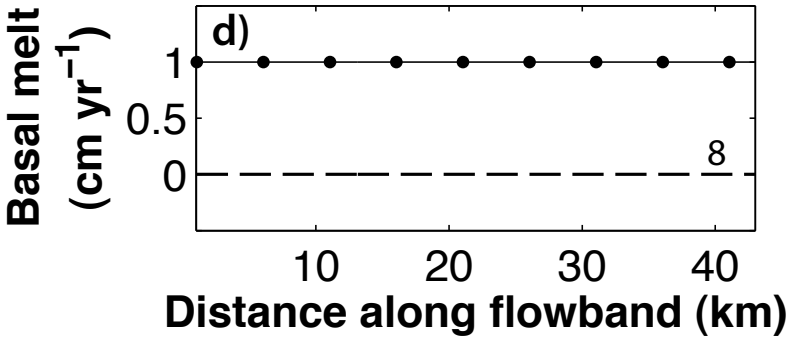


Central West Antarctica: Model sensitivity

Evaluate the goodness of fit at WDC to poorly known model parameters:

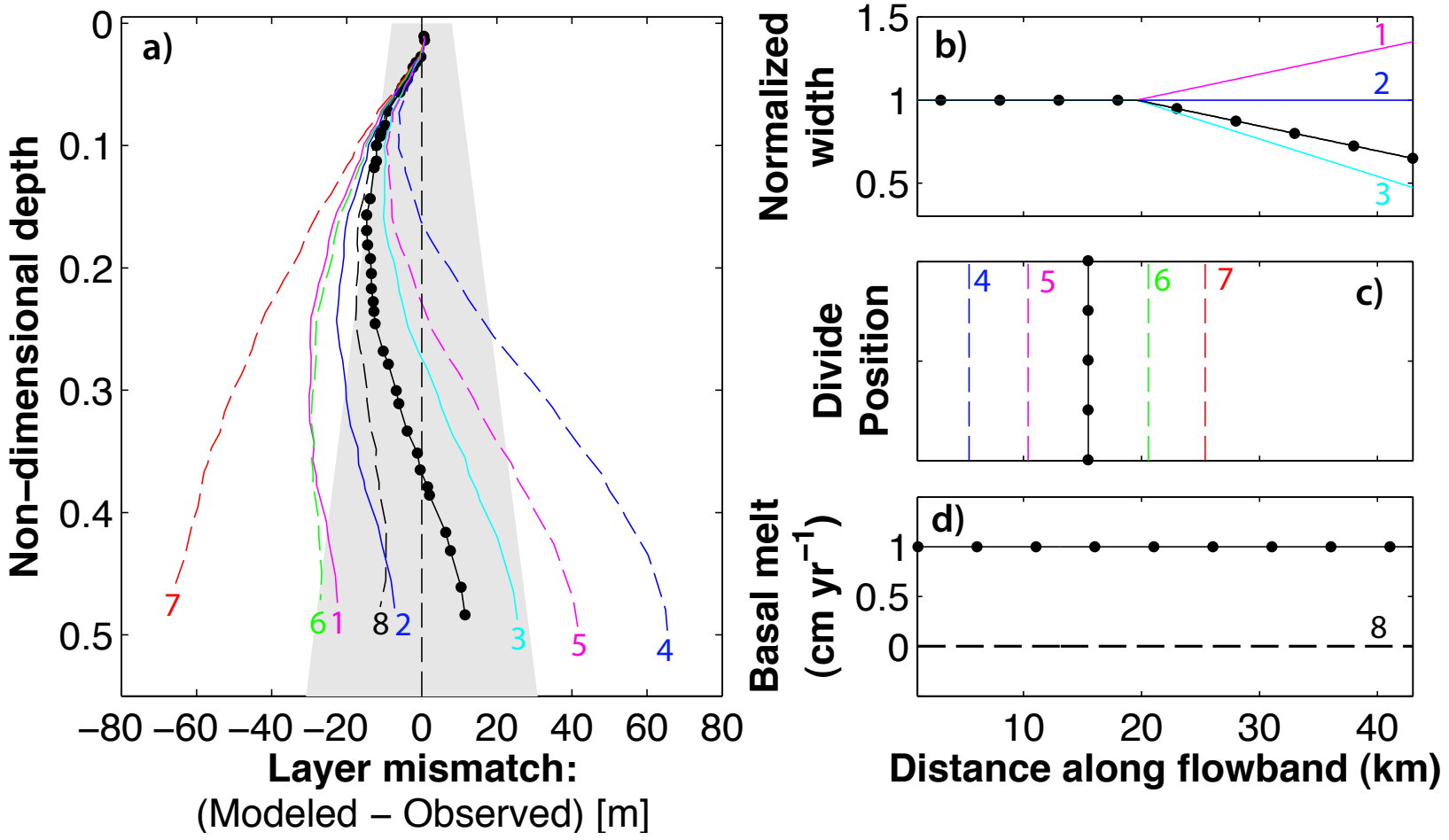
Basal melt rate





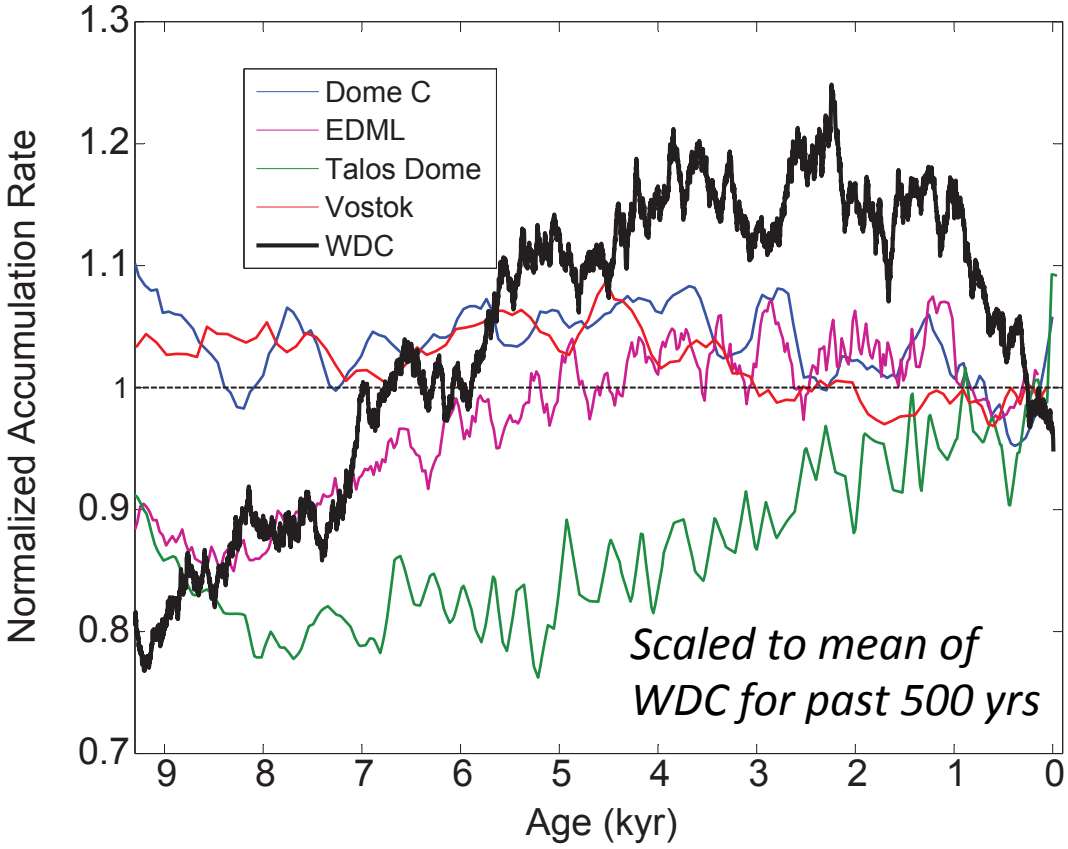
Central West Antarctica: Model sensitivity

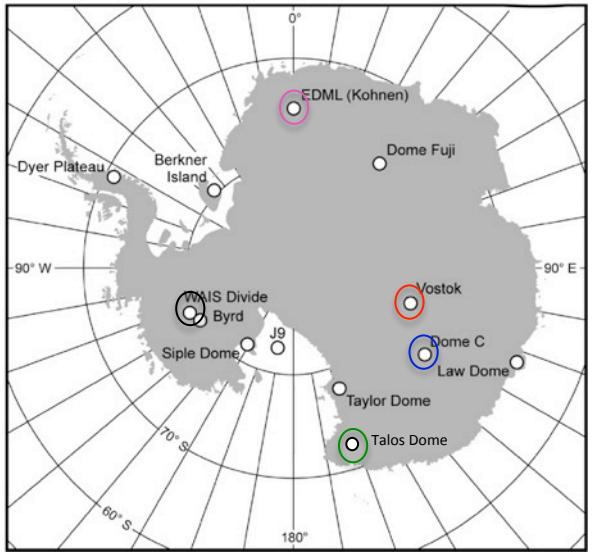
Different width functions and basal melt rates may also be consistent with layers – **different Holocene divide position is not consistent**



Central West Antarctica: Results

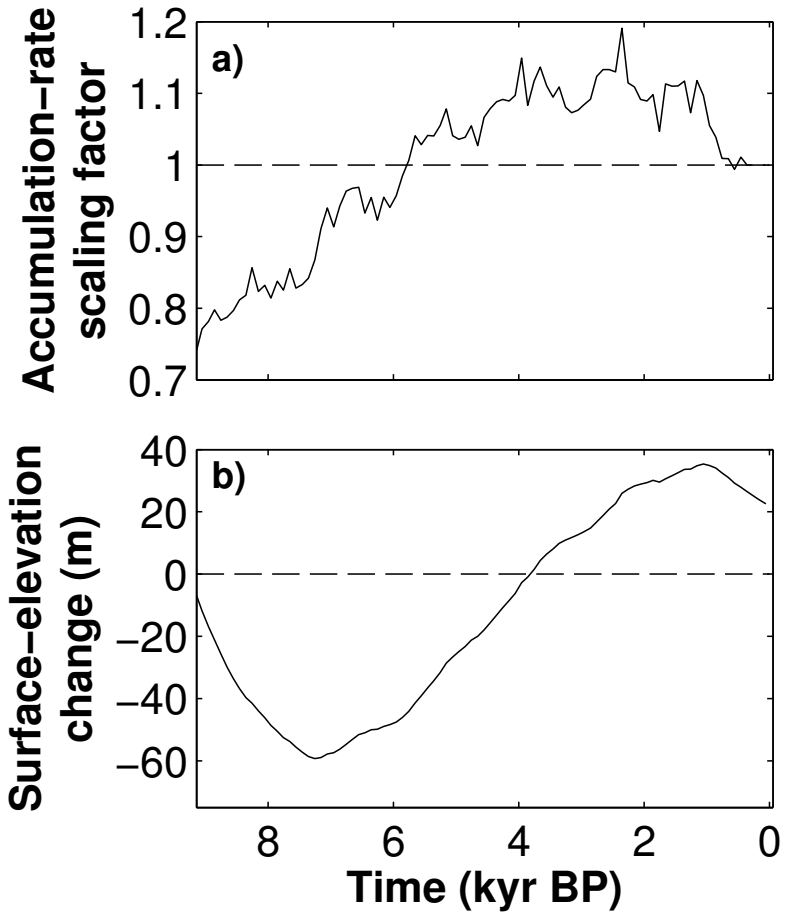
1. Accumulation rate was ~20% lower than present at 9.2 kyr BP, and there was ~40% increase from 9.2 – 4 kyr BP → **big change**





Central West Antarctica: Results

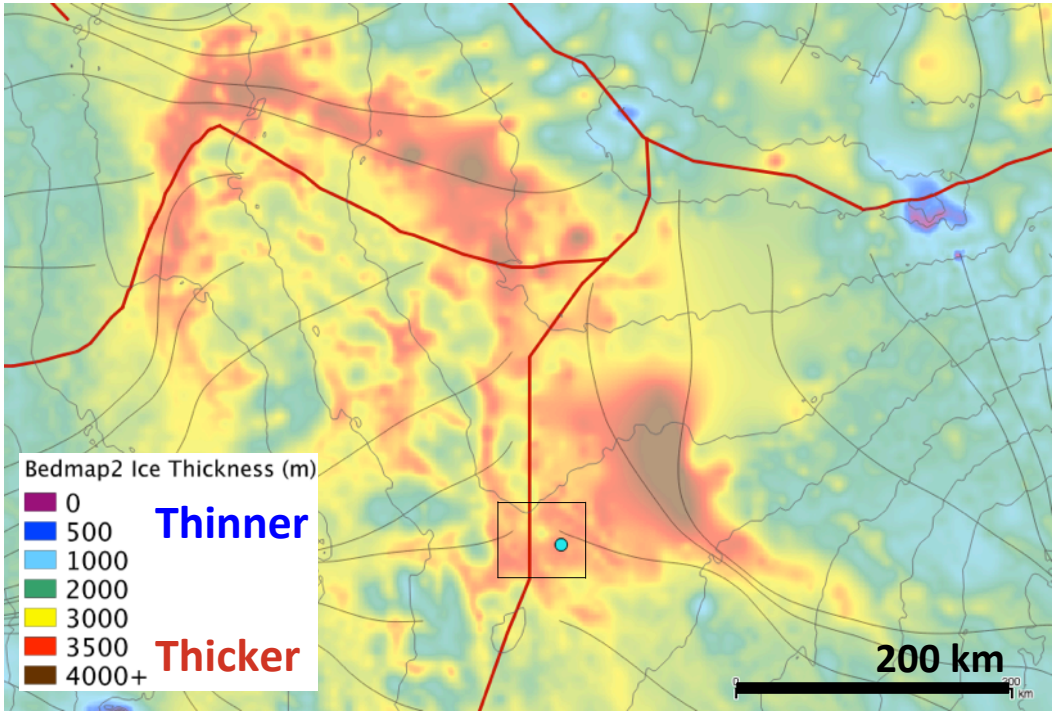
2. Change in accumulation leads to change in interior ice thickness unless compensated by a change in ice dynamics



** Calculated elevation change depends on initial condition

Central West Antarctica: Results

3. The average Holocene divide position likely remained within ~5 km of the modern position

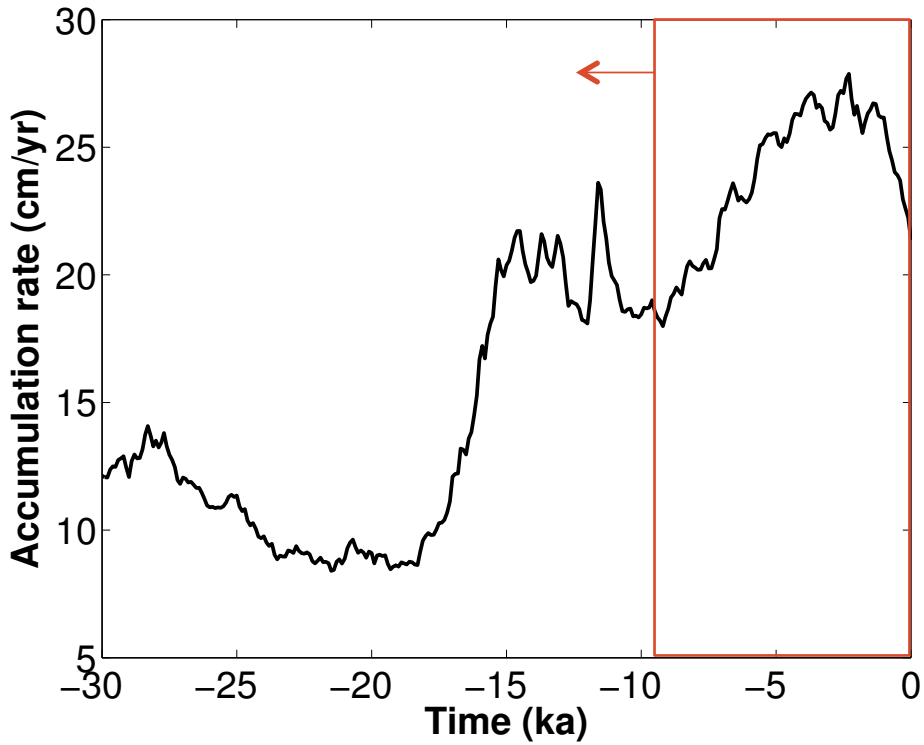


The bedrock topography may have macroscopic control on ice thickness and divide position

Central West Antarctica: Results

Annual layer-counted timescale allowed for the first independent accumulation reconstruction back to 31 ka

Extend prior to the Holocene



Fudge et al. (2016)

Central West Antarctica: Implications

1. To infer the most realistic accumulation history from the ice-core record, need to correct for advection of ice from upstream

2. Climate models extrapolate West Antarctic climate from East Antarctic ice-core records – we can now do better

3. Continent-scale model reconstructions should use this climate forcing, and calculated Holocene changes in ice geometry should include a relatively stable divide near WDC

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What do continent-scale reconstructions show?