Glacial Cycles (II)

I. Glacial cycles driven by astronomical factors
  A. changes in the eccentricity of the earth's orbit
  B. changes in the tilt angle and orientation (precession) of the earth on its axis
  C. primarily appear to alter the intensity of the seasons

II. But ...
  A. 100 kyr eccentricity cycle is the weakest of the 3 cycles **Fig. 14-8**
    1. has the smallest effect on seasonal contrast
    2. however this sets the fundamental frequency of recent glacial cycles
  B. astronomical theory also predicts smooth changes
    1. ice core record is saw toothed **PAGES fig (Vostok)**
    2. ice grows episodically and then crashes in a few thousand years
  C. N vs. S Hemisphere changes
    1. astronomical theory predicts cyclic changes as well as latitudinal differences
      a. periods of extreme seasonal contrast in one hemisphere should also lead to minimal seasonal contrast on the other hemisphere **Fig. 7-10**
    2. glacial changes however appear to be global
      a. N and S Hemisphere glaciers appear to grow and retreat on the same schedules
        i. timing and intensity of change
      b. not out of phase
      c. similar features in high mountain glaciers worldwide
    3. ice core data from Greenland and Antarctica are very similar
      a. show that both poles cooled and warmed roughly in step
      b. gasses in ice cores (methane and CO_2) show similar trends **PAGES figure**
  D. feedback loops may amplify the initial Milankovitch cycle

III. Why are glacial cycles linked to changes in N. Hemisphere glaciation?
  A. research has shown that N Hemisphere ice sheets have a 100 kyr response time
    1. glaciers appear to respond to eccentricity-induced changes **Fig. 10-1&3**
  B. ice caps respond more to changes in summer radiation than to winter radiation
  C. enhanced seasonal contrast (high summer insolation) leads to less glacier coverage
    1. melting of ice caps during warmer summers is not compensated for by more glacial accumulation in colder winters
    2. net ice melting
  D. reduced seasonal contrast (low summer insolation) enhances survival of glaciers
    1. accumulation > melting
  E. need eccentricity and precession effects to oppose one another in the N Hemis. **Fig. 10-2**
    1. two considerations
      a. magnitude of the distance (eccentricity) seasonality
      b. timing of the eccentricity and precession/obliquity effects on seasonality
    2. results in positive feedback that leads to a cooling **Fig. 14-9**
  F. astronomical forcing therefore "tips the balance" between glacial build-up and retreat
    1. positive feedback to these astronomical "perturbations" leads to onset of glacial periods

IV. Glacial periods are initiated when Milankovitch orbital variations lead to reduced seasonal differences in N Hemisphere

- A. If orbital cycles drive glacial cycles by affecting N. Hemisphere ice sheets, then the response in the high northern latitudes must be strong enough to override the effects of opposing changes in the southern hemisphere
- B. need to translate these northern hemisphere changes in seasonal contrasts worldwide
- C. what types of feedback mechanism might be important?

V. CO_2 data suggests that the oceans may play a role

- A. ocean processes strongly control atmos CO_2 on these time scales
  1. air-sea exchange, bottom water flow and biological pump
  2. occurs because ocean also contains 60x more carbon than atmos.
- B. glacial ocean may have operated differently
  1. distinctly different glacial vs. interglacial patterns of how the ocean/atmos. system operates
  2. changes in ocean circulation then alter global heat transport and atmospheric circ.
  3. this may have then further enhance ice sheet formation
     a. acts to further reinforce glacial conditions – positive feedback
- C. also other positive feedback mechanisms that affect atmos. CO_2
  1. may be a system with positive feedback modes of operation

VI. Ocean circulation **conveyor belt figure**

- A. suggestion that deep water circulation dramatically altered/shut off during glacial times
- B. NADW formation
  1. the formation of this water occurs as a result of cooling processes that give off heat
     a. equal to ~30% of the annual direct input of solar energy to the N Atl.
- C. appears that this conveyor was shut down or modified during glacial times **Fig. 12.11**
  1. based on a variety of paleoceanographic tracer studies in sediment cores
  2. this would clearly affect heat transport in the N Atl.
     a. affect the climate of the region
     b. allow glaciers to extend south
     c. another pos. feedback mechanisms that enhances cooling/glacial conditions
- D. present-day NADW shut down until the end of the last ice age - 14 kyr bp
  1. at the same time we also see retreat of glaciers, rise in atmos CO_2
  2. suggests a strong ocean/atmos coupling
- E. suggests that there may be glacial and inter-glacial modes of operation of the joint ocean/atmos. system
  1. may affect the heat and salt balance of the N Atl
  2. these changes may then affect the shutting on/off of NADW formation

VII. What causes glacial/interglacial CO_2 changes?

- A. what are the links between orbital forcing, changes in N Hemisphere glaciers, changes in ocean/atmos operation, climate and CO_2?
  1. complex process
- B. important for understanding the potential impact of anthropogenic/fossil fuel CO_2
  1. likely complex feedbacks

C. changes in CO_2 and CH_4 appear to be a response of the biogeochemical cycles and atmos. chemistry to an initial climatic forcing, most likely orbital in origin
1. these then may set the stage for positive feedbacks which amplify temp changes and changes in atmos. gas concentrations

E. Magnitude of drop in atm. CO_2 **show Table 11-2**
1. results are equivocal
2. can lead to significant decreases in atm CO_2
3. 3 main factors
   a. solubility effects
   b. increased efficiency of the biological pump
   c. changes in ocean circulation

F. efficiency of the biological pump
1. changes in N inventory or Fe fertilization could also a role in the positive feedback involving an increase in the intensity of the oceanic biol. pump **Fig. 14-13**
2. enhances oceanic uptake of CO_2
   a. may be related – Fe is required for N fixation

G. changes in ocean circulation back to **Fig. 11-22**
1. increase CO_3^{2-}
2. allows for enhanced uptake of atm CO_2
3. $CO_3^{2-} + CO_2 + H_2O \rightarrow 2HCO_3^-$

IX. Unlikely that atmos CO_2 itself triggered climate change
A. changes in CO_2 provide feedbacks for climate change
B. processes that lower CO_2 will amplify cooling
1. positive feedback

C. terrestrial processes may provide some negative feedback **Fig. 14-7**
D. however, the Vostok data suggests that the system largely responds with positive feedback
1. CO_2 and temp changes are near synchronous

VII. How do changes in the ocean/atmos system lead to global cooling?
A. Decrease in greenhouse gasses (CO_2 and CH_4)
B. Other factors could play a role
C. Dust also appeared to be higher in glacial times
1. may lead to cooling by increasing reflection of sunlight
2. dust is also a source of iron to stimulate oceanic primary prod. and draw down CO_2

D. high dust and low methane suggest a dry glacial climate
1. methane predom. produced in swamps and freshwater wetlands

E. water vapor (from Broecker)
1. changes in the atmospheric water vapor inventory may also be important
2. water vapor is also a greenhouse gas
   a. actually more important than CO_2
3. a change in the convective activity of the tropical atmosphere leads to a decrease in water vapor content of tropical atmos
4. water vapor may be important in two ways
   a. provides a means of providing the “extra” cooling of the glacial Earth
   b. also a means of producing abrupt changes in global climate

i. atmos. circulation is rapid
ii. important for explaining other rapid climate changes not necessarily associated
iii. with glacial cycles (D-O events)

5. must also be some linkage between this atmospheric activity and changes in thermohaline circulation
    b. not well understood

X. Other negative feedbacks eventually lead to some climate stabilization
- A. once N Hemisphere ice sheet is fully developed conditions may change so that they don't favor the further growth of N Hemisphere glaciers
- B. a relaxation of orbital forcing may be important
  1. larger N Hemisphere seasonal contrasts (warmer summers) that then lead to net ice melting
- C. some of the same positive feedbacks that led to cooling may now still act in a positive feedback mode
  1. coral reef hypothesis (start with a decline in glacial ice volume) **Fig. 14-5**
     a. provides a positive feedback for continued warming

XI. Transitions between glacial and interglacial conditions represents a jump between two different but stable modes of climate operation
- A. consistent with the observed near synchronous global changes
  1. global changes driven by gradual astronomical forcings, amplified by CO_2, etc.
- B. ice core records also show evidence of rapid changes in climate not predicted by Milankovitch cycles **Fig. 15-1**
- C. other studies have shown that many of these rapid climate events events are global events
  1. express themselves differently

XII. Younger Dryas
- A. rapid, short retreat to glacial conditions during last deglaciation
- B. YD appears to be centered in N Atl region
  1. other near synchronous climate changes occurred in other parts of the globe
- C. YD appears to be related to the decrease in NADW formation
  1. start of interglacial leads to a startup of NADW formation
  2. leads to a warming of northern high latitudes - deglaciation
  3. leads to a pulse of meltwater from the melting of Laurentian/N Atl ice sheet
  4. travels down St. Lawrence R into N. Atl – **Ruddiman figure**
  5. decreased density/salinity of sfc water
     a. prevents it from sinking
     b. temporarily shuts down NADW and cools northern regions
  6. general circulation models suggest that indeed this can occur
     a. entry into YD and exit from YD were rapid - order of decades

XIII. YD was a part of a series of other rapid short-term climate changes during glacial times
- **A.** Dansgaard-Oeschger events
- B. interstadial events in the last glacial that lead to rapid warming **Fig. 15-1**
  1. 5-10° warming

2. similar changes in atmos.dust, snow accumulation, atmos CH_4 and perhaps CO_2
3. these changes can occur rapidly- order of decades
4. quasi-periodic – every ~1,500 yr

C. these events can be seen in a variety of other climate records around the globe
1. effects may be more pronounced at high latitudes

D. again suggest that re-organization of ocean-atmos. system can occur rapidly
1. two stable modes of operation

E. may also be valid to look at this from the standpoint of a hysterisis loop **Fig. 1**
1. small changes can lead to rapid shifts between the two

F. may also be able to thin of in terms of chaos theory, stochastic resonance **Fig. 15-2**

G. linkages between D-O events and other climate events not well understood

XIV. The occurrence of these more short-term global climate events requires more than a reorganization of oceanic thermohaline circulation

A. see a global extent for many of these rapid climate changes
1. oceans can't respond fast enough

B. changes in atmos. water vapor content may be important

C. may also be changes in the global carbon cycle that play a role here

D. some evidence that these rapid changes in climate are also seen in interglacials
1. e.g., Holocene Little Ice Age and Medieval Warming Period **Fig. 12.12**

E. appears that the ocean-atmos system is more sensitive to these types of changes during glacial conditions

XV. Implications

A. global climates and greenhouse gasses change over glacial/interglacial time scales

B. also changes over more shorter time scales

C. appear to be related to some reorganization of the ocean-atmos system
1. changes can occur rapidly – decades or less

D. in general the system tends to operate in a positive feedback mode
1. how exactly these feedbacks operate are not well understood

E. will increasing CO_2 act as a positive feedback to lead to further warming

F. will this also lead to a shift to a third, much warmer quasi-stable state

G. will the strength and speed of such a shift be as dramatic as we have seen for DO events or Heinrich events