CCSM Ocean Model (POP) :

- The ocean modeling problem
- The Primitive equations for ocean models
- Grids (spatial discretization)
- Algorithms
- Parameterizations
- Coupling and time discretization (stepping)
- Execution (C. Shields)
- Output and post-processing (K. Lindsay)

The Ocean Modeling Problem

- Irregular Domain
  - Complex coastlines
  - Multiply connected
  - Narrow straits and passages
- Spatial Scales of the Flow
  - Eddy length scale O(10 km)
  - Eddy kinetic energy >> mean kinetic energy
  - Top, bottom and side boundary layers

The Ocean Modeling Problem

- Long Equilibration Time Scale
  - deep adjustment time :
  $H^2/\kappa = (5000 m)^2 / (10^{-5}\ m^2/s) = 10,000$ years

- Bottom Line for Climate
  - Equilibrium at eddy resolution can't be reached
  - Must parameterize most energetic flow

The Primative Equations

- 7 equations in 7 unknowns :
  {U,V,W} , 3 velocity components
  θ, potential temperature
  S, salinity
  ρ, density
  p, pressure
- Plus 1 equation for each passive tracer, e.g. CFC, Ideal Age
- Plus 1 equation for each prognostic, or diagnostic biogeochemical quantity

The Primative Equations

- (1,2) Horizontal Momentum : $D_t \mathbf{U}$ **=**

  $- f \, \mathbf{k} \times \mathbf{U}$ **,** Coriolis

  $- \nabla(p/\rho_o)$, pressure gradient

  $+ \mathbf{D(U)}$, lateral viscosity

  $+ \partial_z \, \nu(\partial_z \, \mathbf{U})$, vertical mixing

  $- \mathbf{U} \bullet \nabla\mathbf{U}$, horizontal advection

  $- w \, \partial_z \, \mathbf{U}$, vertical advection

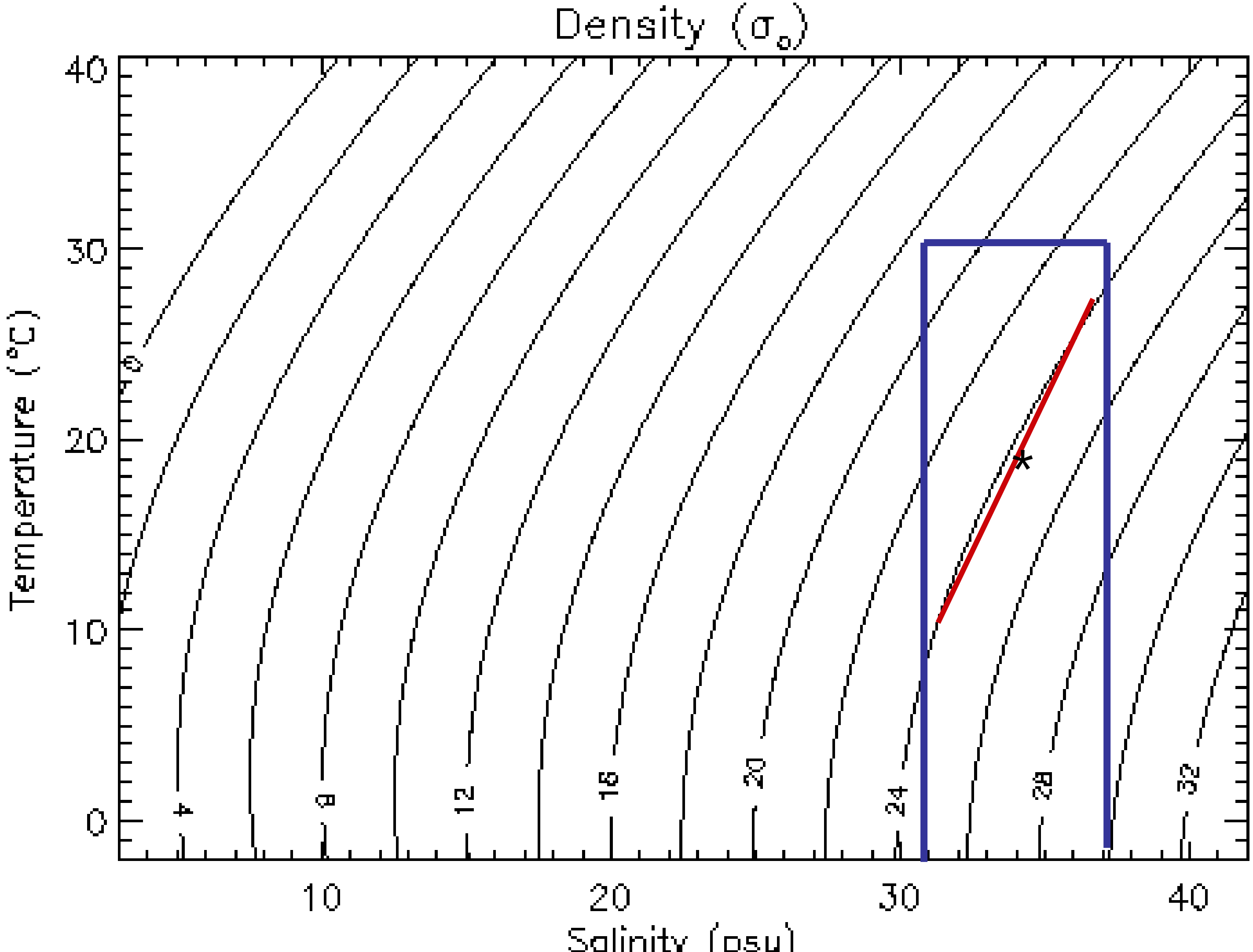
The Primative Equations

- (3) Vertical Momentum : $D_t W = 0 = \partial_z p + g \rho$, hydrostatic

- (4) Continuity : $\nabla \bullet \mathbf{U} + \partial_z W = 0$

- (5) State : $\rho = \rho(\theta, S, p)$

(5) Equation of State $\sigma_o = \rho(\theta, S, p{=}SLP) - 1000 kg/m^3$



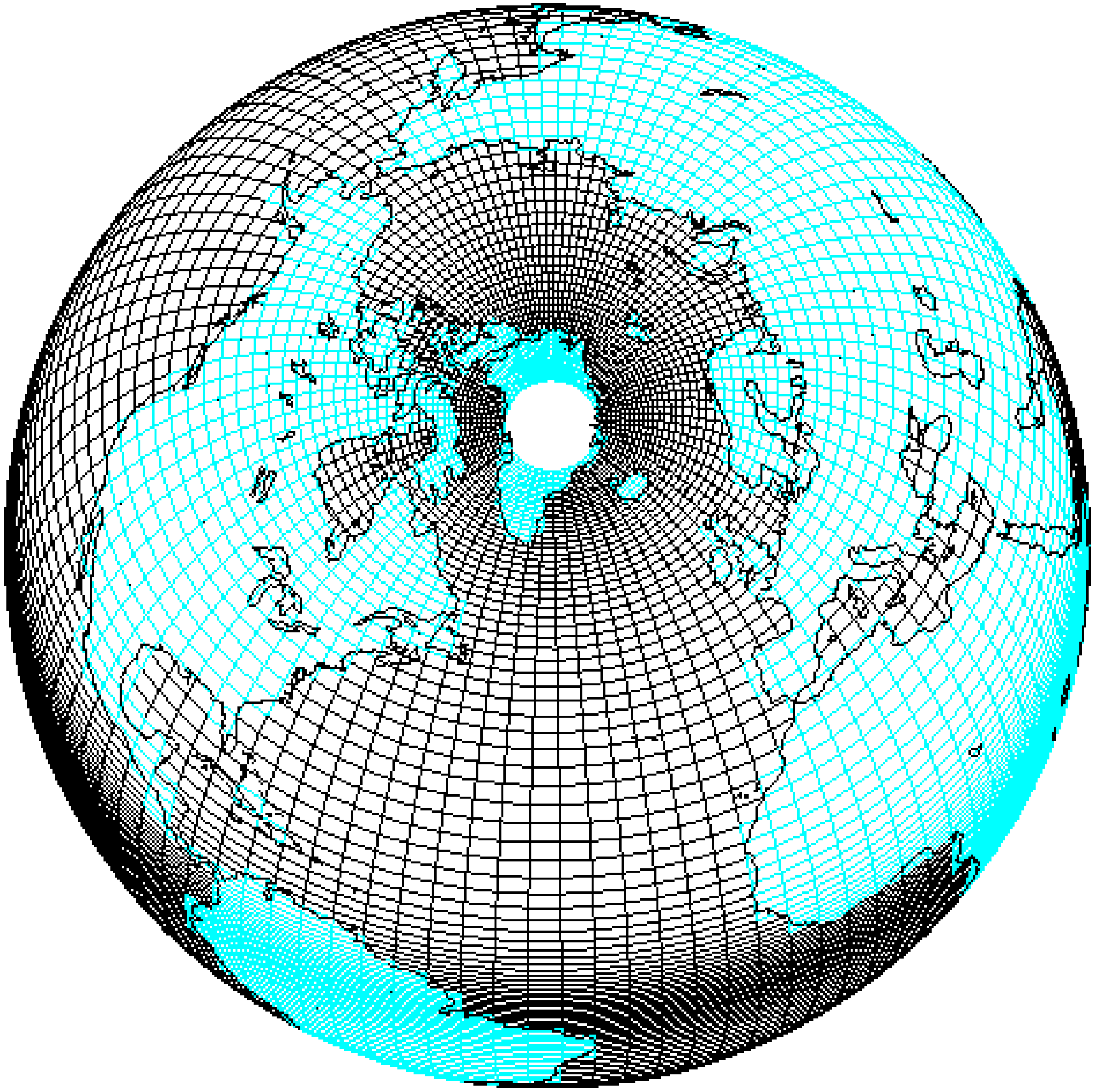
Cabbelling : Mixing of 2 water parcels of equal density yields mixed parcel of higher density

The Primative Equations

- (6) Heat : $\partial_t \theta$ =
  $-\partial_x(U\,\theta)$ $-\partial_y(V\,\theta)$ $-\partial_z(W\,\theta)$, Advection +
  $R(\rho, \theta)$, Eddy mixing +
  $\partial_z \kappa (\partial_z \theta - \gamma_\theta)$, Vertical mixing +
  $\partial_z SW$, Solar radiation

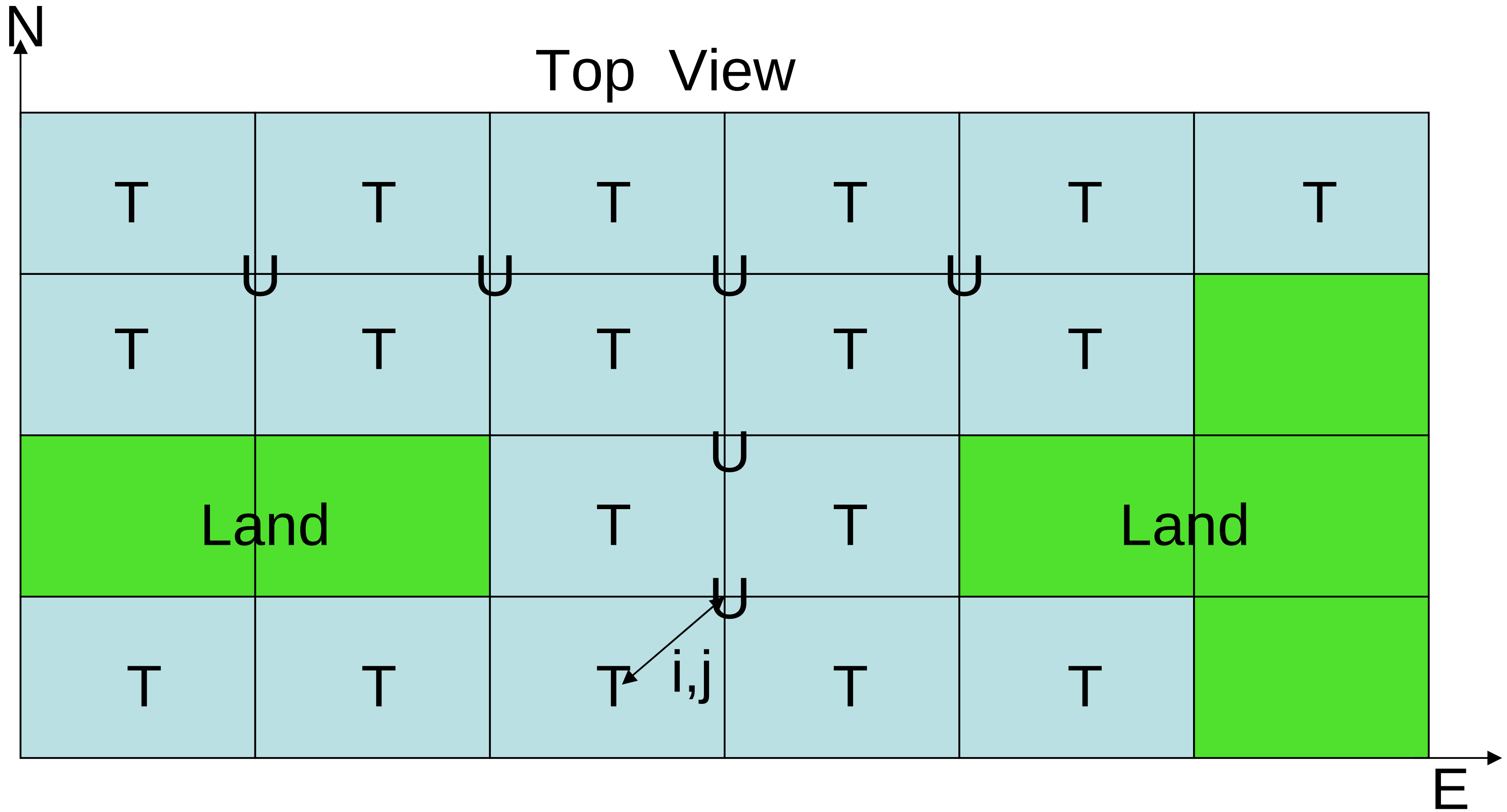
- (7) Salt : $\partial_t \theta$ =
  $-\partial_x(US)$ $-\partial_y(VS)$ $-\partial_z(WS)$, Advection +
  $R(\rho, S)$, Eddy mixing
  $+ \partial_z \kappa (\partial_z S - \gamma_S)$, Vertical mixing

gx3v4 : GRID



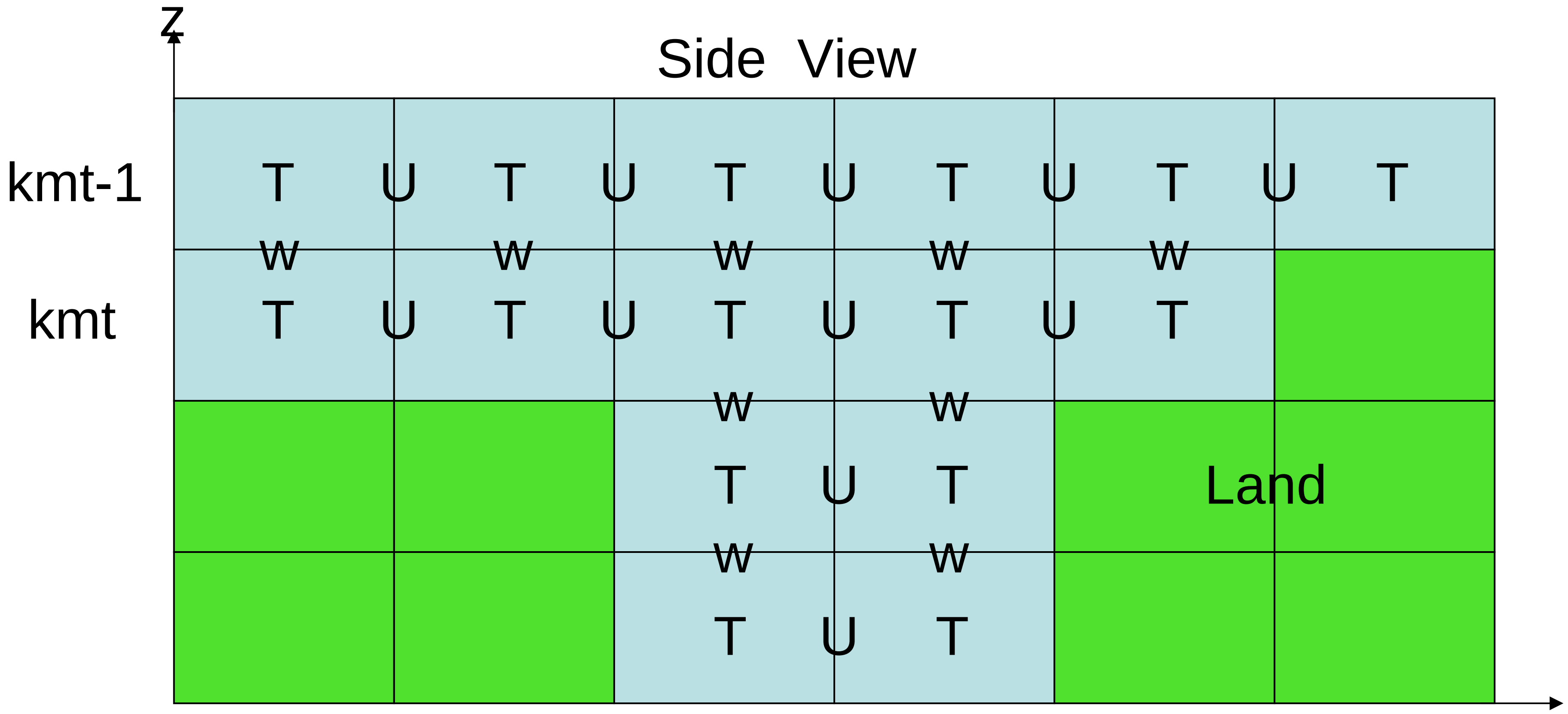
Grid Cells

B-grid, velocity (U) and tracer (T) grids



Grid Cells

B-grid, velocity (U) and tracer (T) grids



KMTmax = number of levels = 40 or 25

Algorithms : Barotropic + Baroclinic Flow

- Issue : CFL stability condition associated with fast (200 m/s) surface gravity waves.
- Split flow into depth average barotropic plus vertically varying baroclinic
- New unknowns

η	sea surface height
<**U**>	depth averaged flow

Algorithms : 1^{st} Baroclinic **U'**

- Solve for scalars $\partial_t(\theta, S, T) = \text{RHS}$ using time delayed **<U>** and **U'**
- Explicit time marching problem (implicit vertical mixing), $\partial_t \mathbf{U'} = \text{RHS}$
- Surface pressure not involved

Algorithms : 2^{nd} Barotropic $\langle \mathbf{U} \rangle$

- Free surface boundary condition $W_o = \partial_t \eta$

- Implicitly solve shallow water equations for
  $\partial_t \eta \quad + \quad \nabla \cdot (\langle \mathbf{U} \rangle H) \quad = \quad 0$
  $D_t (H \langle \mathbf{U} \rangle) + f\, H\, (\mathbf{k} \times \langle \mathbf{U} \rangle) = g\, H\, \nabla \eta + F(\mathbf{t}^{n,n-1})$

Algorithms : Advection

- Conservative Flux Form X = {U,V,θ,S,T} :
  >> $\mathbf{U} \bullet \nabla X = \partial_x (UX) + \partial_y (VX) + \partial_z (WX)$
  Sum of other terms, $X (\nabla \bullet \mathbf{U} + \partial_z X) = 0$

- $X = \sum A_n \cos (\omega_n \lambda + \psi_n)$
  discretization ==>> dispersion errors
  leading to “false extrema” error

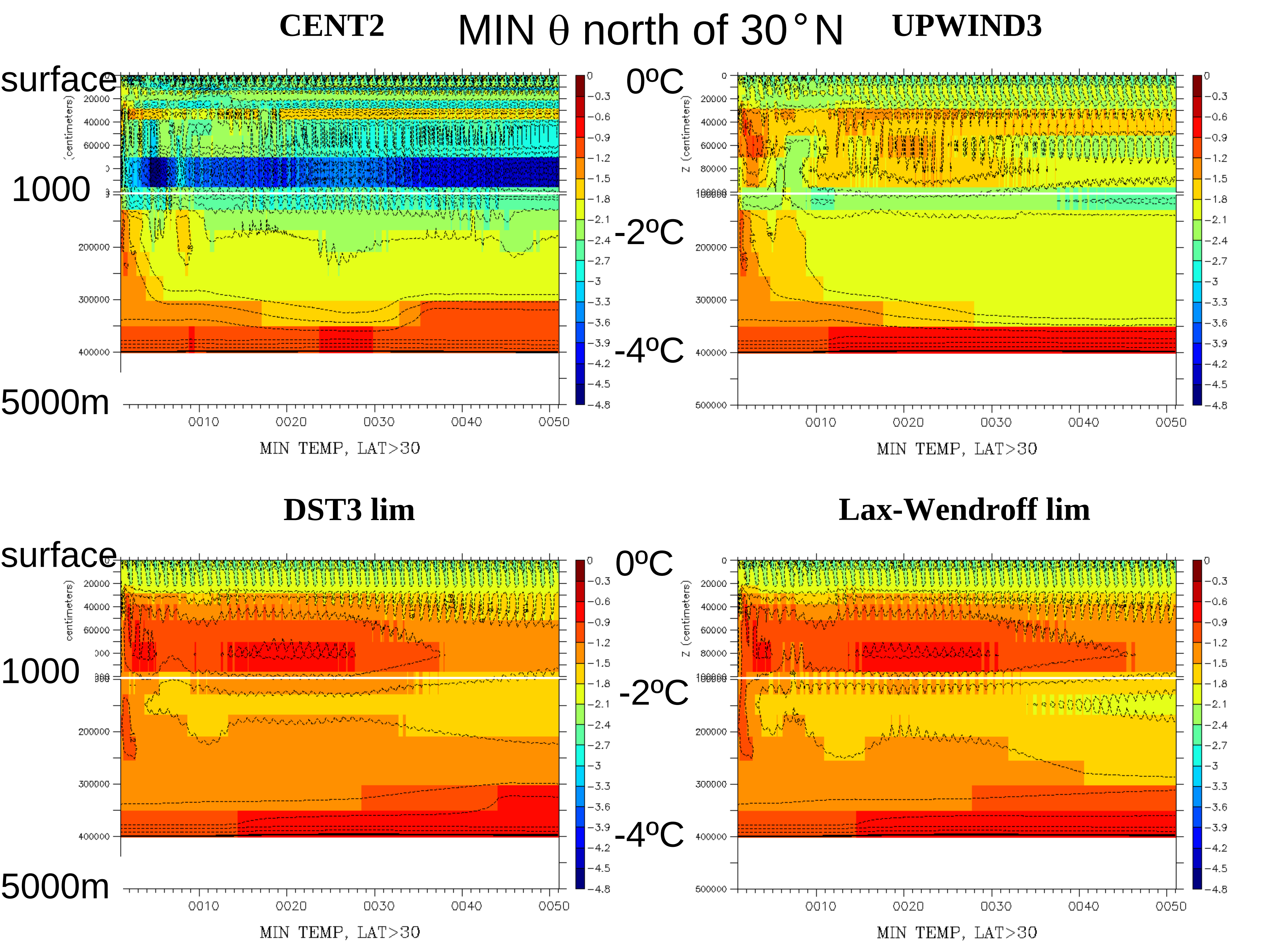
- Breaks 2nd law of thermodynamics : heat flows from hotter to colder.

Alternative Tracer Advection Scheme for POP

- Why? Reduce dispersion errors, evidenced by artificial extrema, while not creating excessive diffusive errors

- Current practice :
  - 3º : 2nd order centered (as for all momentum)
  - 1º : Upwind biased quadratic interpolation to cell faces (QUICK)
  - Each coordinate direction treated concurrently

MIN θ north of 30°N



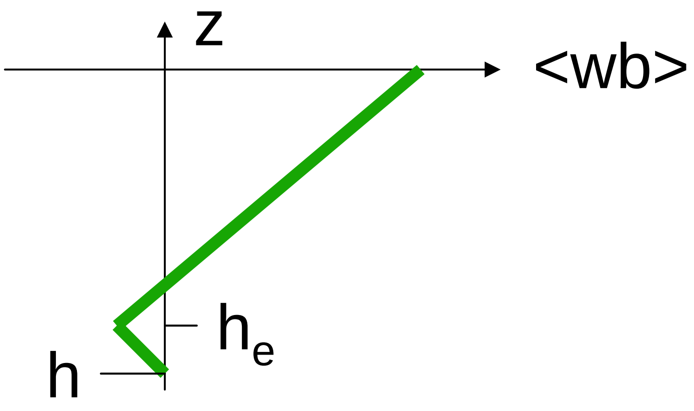
Parameterizations : KPP Vertical Mixing

$\langle wx \rangle = \partial_z K_x (\partial_z X - \gamma_x)$: $X = \{ \mathbf{U}, \theta, S, T \}$

Diagnose boundary later depth, h, where $Ri_b = Ri_c = 0.3$

$$Ri_c(h) = \frac{[b(0) - b(z) + \mathbf{0}]\, h}{[\, |\mathbf{U}(0) - \mathbf{U}(z)|^2 + \mathbf{V_t^2}]}$$

$\mathbf{V_t^2 \propto h\, w_T\, N}$: $\mathbf{\langle wb \rangle_e = -0.2 \langle wb \rangle_o}$; $u^* \rightarrow 0$



Parameterizations : KPP Vertical Mixing

$\langle wx \rangle = \partial_z K_x (\partial_z X - \gamma_x)$: $X = \{ \mathbf{U}, \theta, S, T \}$

Interior -z > h,

$\gamma_x = 0$,

$K_x = \nu_x^W + \nu_x^S + \nu_x^D + \nu_x^C + \ldots + \ldots.$

Internal Waves : $\nu_T^W = 10^{-5}\ m^2/s$**, $\nu_M^W = 10^{-4}\ m^2/s$

Shear $\nu_x^S = f_1(Ri_g)$; □$Ri_g = \Delta b\ \Delta z / |\Delta V|^2 = N^2 / Sh^2$

Double Diffusion $\nu_T^D = f_2(R_\rho)$; $R_\rho = (\alpha\ \Delta\theta) / (\beta\ \Delta S)$

Convection $\nu_x^C = f_3(Ri_g)$

KPP Vertical Mixing

$\langle wx \rangle = \partial_z \mathbf{K_x} (\partial_z X - \gamma_x)$: $X = \{ \mathbf{U}, \theta, S, T \}$

Boundary Layer $\mathbf{-z < h}$ $\mathbf{0 < \sigma = -z/h < 1}$;

$\mathbf{K_x} = \kappa\, h\, w_x\, G(\sigma)$

$w_x = u^*/\phi(u^*, Bo) \rightarrow w^* = (B_s/h)^{1/3}$ as $u^* \rightarrow 0$

$G(\sigma) = \sigma (1 + \mathbf{a_2}\, \sigma + \mathbf{a_3}\, \sigma^2)$,

: K_x and its first derivative match interior at $\sigma = 1$

$\gamma_M = 0$; $\gamma_T = C \langle wT \rangle_0 / (w_x\, h)$

Parameterizations : Eddy transport

Gent McWilliams (1990) :

Mimics effects of (unresolved) baroclinic eddies as a sum of

(1) Diffusive mixing of scalars, R, parallel to density surfaces

(2) PLUS an additional advection of scalars by a “bolus” or eddy induced velocity , {**U***, W*} :

$$D_t X = \partial_t X + (\mathbf{U}+\mathbf{U}^*) \bullet \nabla X + (W + W^*) \partial_z X$$

>>> Flattens isopycnals, thereby reducing PE

>>> Dominates ACC transport (Drake Passage) and MOC (cancels much of Eulerian Deacon Cell)

>>> Eliminates need for horizontal diffusion (Veronis Effect)

Parameterizations : Lateral viscosity

Reynolds Stress $\sigma_{ij} = -\langle u_i' u_j' \rangle = (-1/3)\, \delta_{ij} \langle u_k' u_k' \rangle + d_{ij}$

Deviatoric Component $d_{ij} = T_{ijkl} \; e_{kl}$

Shear of resolved flow $e_{kl} = 0.5 \; [\; \nabla_k U_l + \nabla_l U_k \;]$

T_{ijkl} a 4th order tensor with 21 of 81 elements independent

$T_{1111} = T_{2222} = A + B$; $T_{3333} = A + K_M$; $T_{1212} = B$
$T_{1313} = T_{2323} = K_M$; $T_{1133} = T_{2233} = B - K_M$

Other elements 0, where not related by the symmetries
$T_{ijkl} = T_{jikl} = T_{ijlk} = T_{klij}$.

Lateral viscosity

Spatially Uniform, Cartesian (for illustration)

$D(U) = A\ U_{xx} + B\ U_{YY}$

$D(V) = B\ V_{xx} + A\ V_{YY}$

Anisotropic $A \neq B$, and spatially varying :
satisfy numerics ONLY where needed

Grid Reynolds Number $\rightarrow$ Large ($A\ U_{XX}$) or ($A\ V_{YY}$)
if required by resolution

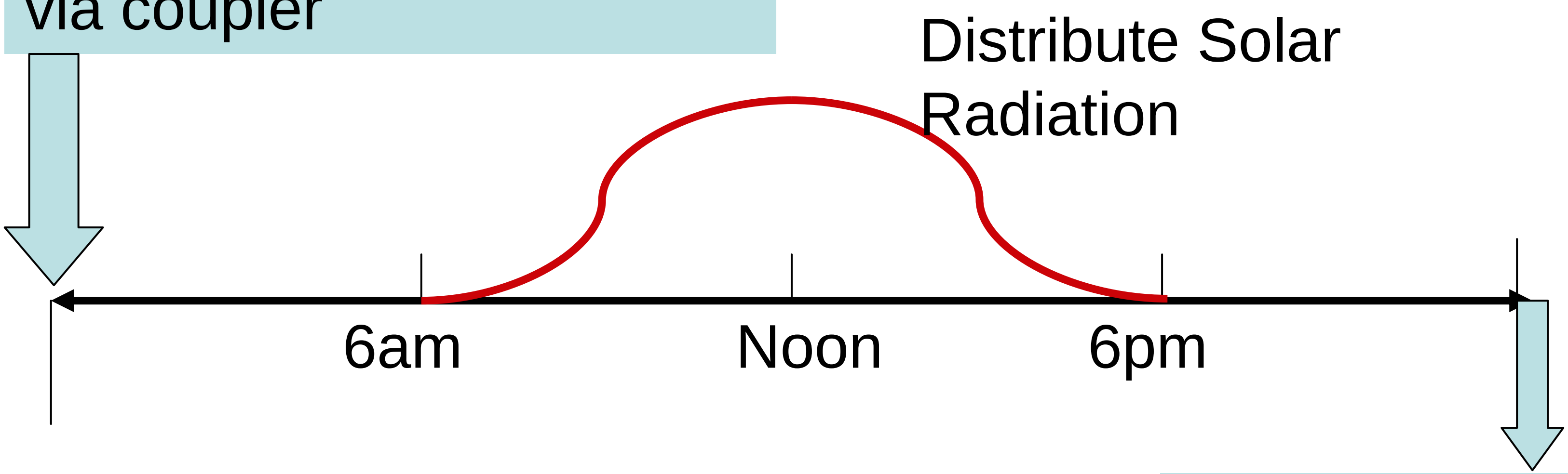
Munk: Resolve WBC $\rightarrow$ Large ($B\ V_{XX}$)
only near western boundaries

Strong EUC $\rightarrow$ Small ($B\ U_{YY}$)

Coupling and Time Stepping

Consider a 1 day Coupling Interval with other components

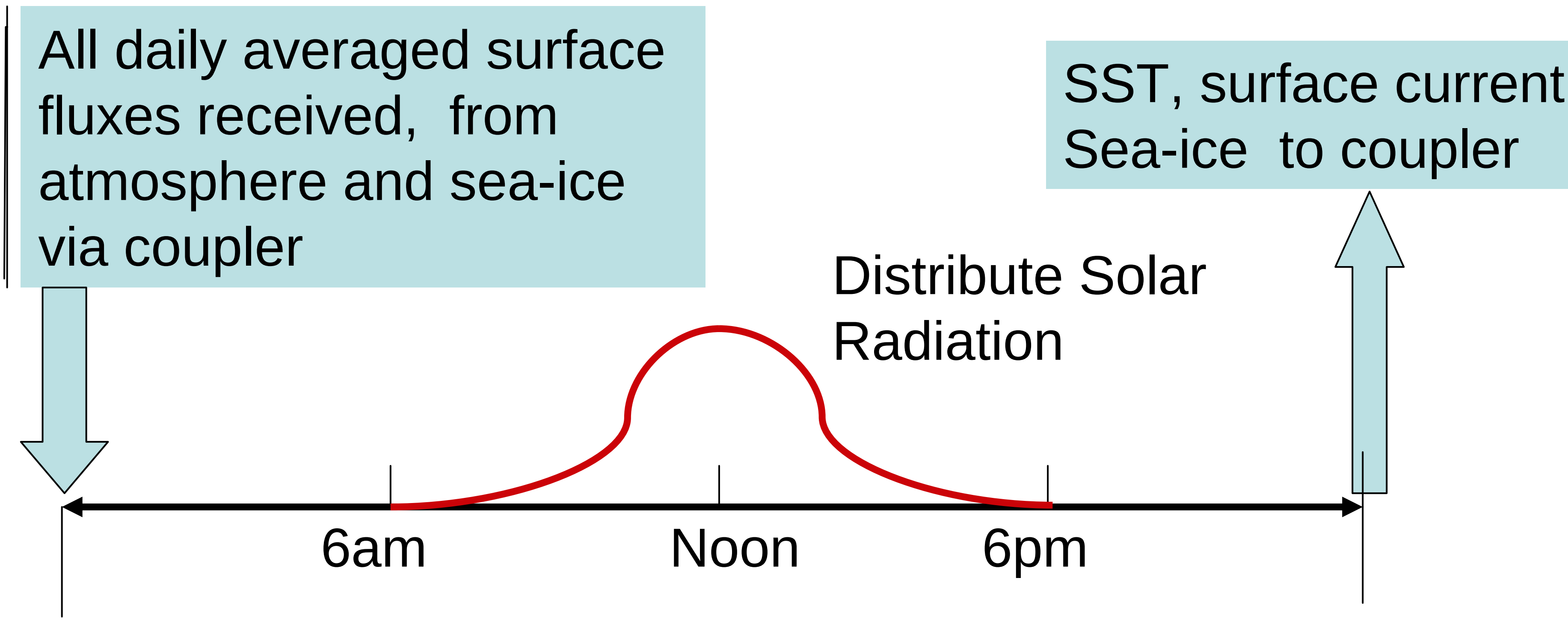
All daily averaged surface fluxes received, from atmosphere and sea-ice via coupler



SST, surface current
Sea-ice to coupler

Coupling and Time Stepping

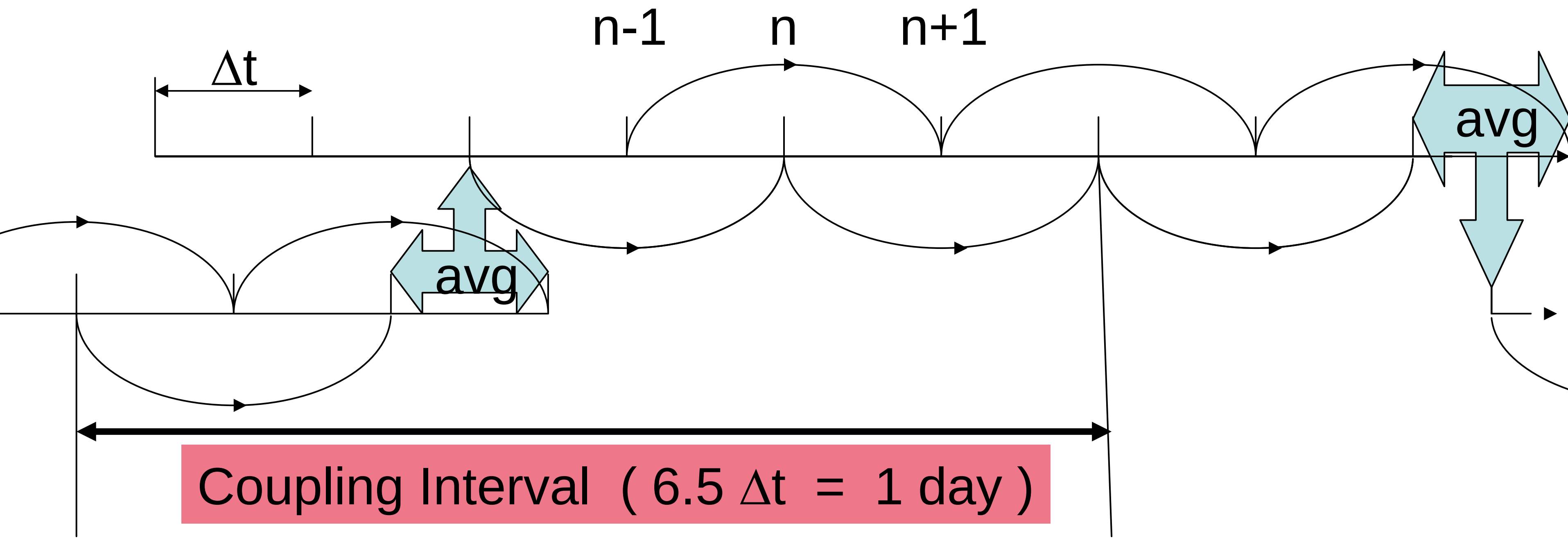
Consider a 1 day Coupling Interval with other components



Time Stepping and Coupling

Leap Frog (n-1 to n+1) with periodic time averaging (avg)

DT_COUNT = 6 (full time steps per day) < TIME_MIX_FREQ = 17



DT_COUNT = 23 > 17 : add extra 1/2 step = 24steps / day

THE END