Logistics

• Goof up  P? R?
• Can you log in?
  – Teragrid yes?
  – NCSA no?
• Requests for:
  – Anders
  – Colberg
  – Syrowski
  – Curtis
  – Rastogi
  – Yang
  – Chiu
Introduction to Numerical Weather Prediction

Thanks: Tom Warner, NCAR
A bit of history

• Richardson’s grand experiment
• WP was born at the Institute for Advanced Study in Princeton in 1940’s – first electronic computer
• Since then, NWP has been one of the heaviest users of supercomputers.
Figure 3: The ENIAC computer in 1948. The operators are changing the plug-in wiring. (PLATZMAN, 1979).
What is a Model?

• Take the equations of fluid mechanics and thermodynamics that describe atmospheric processes.
• Convert them to a form where they can be programmed into a large computer.
• Solve them so that this software representation of the atmosphere evolves within the computer.
• This is called a “model” of the atmosphere.
Scales of models – area coverage and resolution

- **Global models** - span the planet, represent large-scale atmospheric processes
- **Limited-area synoptic scale and mesoscale models** – span continental, to state, to metro-areas; represent smaller-scale atmospheric processes
- **Computational fluid-dynamics (CFD) models** – resolve flow around buildings, in street canyons, aircraft, etc.
## Scales of processes/models

<table>
<thead>
<tr>
<th>Global</th>
<th>Synoptic</th>
<th>Meso</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Long waves</td>
<td>• Jet streams</td>
<td>• Thunderstorms</td>
<td>• Street-canyon flows</td>
</tr>
<tr>
<td>• El Nino</td>
<td>• High and low pressure centers</td>
<td>• Convective complexes</td>
<td>• Channeling around buildings,</td>
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<tr>
<td></td>
<td>• Troughs and ridges</td>
<td>• Tropical storms</td>
<td>wakes</td>
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<tr>
<td></td>
<td>• Fronts</td>
<td>• Land/sea breezes</td>
<td>• Vertical transport on upwind</td>
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<tr>
<td></td>
<td></td>
<td>• Mountain/valley breezes</td>
<td>and warm faces of buildings</td>
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<td></td>
<td>• Downslope wind storms</td>
<td>• Flow in subway tunnels</td>
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<td>• Gap flows</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>• Cold air damming</td>
<td></td>
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<td></td>
<td></td>
<td>• Nocturnal low-level jets</td>
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<td>• Lake-effect snow bands</td>
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</tbody>
</table>
Basic equations

• Apply to many different types of atmospheric models
  - operational weather prediction models
  - global climate models
  - building-scale urban (CFD) models
  - research atmospheric models
  - models of flow over an airfoil

• In all cases, they are the equations of fluid dynamics applied to the atmosphere
Governing equations

• Conservation of momentum (Newton’s 2’d law)
  – 3 equations for accelerations of 3-d wind \((F = Ma)\)

• Conservation of mass
  – 1 equation for conservation of air (mass continuity)
  – 1 equation for conservation of water

• Conservation of energy
  – 1 equation for the first law of thermodynamics

• Relationship among \(p\), \(V\), and \(T\)
  – 1 equation of state (ideal gas law)
More on the equations

• Almost every model uses a slightly different set of equations.

• Why?
  – Application to different parts of the world
  – Focus on different atmospheric processes
  – Application to different time and spatial scales
  – Ambiguity and uncertainty in formulations
  – Tailoring to different uses
What do we mean by “solve the equations”? – a conceptual approach

• The equations describe how the atmosphere changes with time.
• For example, one equation would be
For a single point in the atmosphere

\[ \frac{\partial T}{\partial t} = \text{solar} + \text{IR(gain)} + \text{IR(loss)} + \text{conduction} + \text{convection} + \text{evaporation} + \text{condensation} + \text{advection} \]
How the Model Forecasts

Model-calculated T changes

Temperature

T now (observed)

Time ➔
• This equation is solved for a three-dimensional “matrix” of points (or a grid) that covers the atmosphere from the surface to some level near the top of the atmosphere.

• Here is a 2-dimensional slice through the grid........
100 millibars

Ground

East-West Distance

Grid points

Altitude

Computational levels
Horizontal grid structures

From Randall (1994)
Hexagonal

Triangular

(a)

(b)
Unstructured: Omega Model

From Boybeyi et al. (2001)
Domains

• Shape

Spherical

From mitgcm.org (2006)

Nested grids

From Rife et al. (2004)
An important concept

Grid-point spacing

Smaller-scale processes need smaller grid spacings – 5-10 grid points per wave length
An example differential equation – rate of change of the east-west component of the wind

\[
\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial x} + f v + F r_x
\]

\( u \) = east-west wind component, positive eastward
\( v \) = north-south wind component, positive northward
\( w \) = vertical wind component, positive upward
\( P \) = pressure
\( \rho \) = density
\( f \) = Coriolis parameter \((2 \times \text{rotational frequency of Earth} \times \text{sine of latitude})\)
\( F \) = frictional force in \( x \) direction
Example vertical coordinate
Numerical solution to the equations
Governing equations

• An example of one momentum equation: 1-d wind accelerated by only the pressure gradient force

\[
\frac{Du}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x}
\]

Computers cannot analytically solve even this very simple equation!
• **The problem:** computers can perform arithmetic but not calculus

\[ + - \times \div \]

\[ \times \frac{d(f)}{dx} \quad \int (f) \, dx \]

• **The solution:** numerical methods
Integration of the equations

Nonlinear advection

\[
\frac{\partial U}{\partial t} = U \left( \frac{\partial U}{\partial x} \right)
\]

\[
\frac{U_{i}^{k+1} - U_{i}^{k}}{\Delta t} = U_{i}^{k} \left( \frac{U_{i+1}^{k} - U_{i-1}^{k}}{2\Delta x} \right)
\]

Time step

\[
\Delta t < \frac{\Delta x}{U_{i}^{k}}
\]

Choose time step based on expected wind speeds and grid spacing
Time Step Criterion \[ \Delta t < \frac{\Delta x}{c} \]

100-km Model Grid

The COMET Program
Sources of model error

- Numerics
- Physics (radiation, turbulence, moist processes)
- Initial conditions - define the atmosphere’s current state…the starting point
- Lateral boundary conditions - define the atmosphere’s state at domains’ edges
- Lower boundary conditions – conditions at Earth’s surface
Example of error growth
Nesting of different models to represent a range of scales
“Nested” grids

• Grids can be telescoped, or nested, to zoom in on a small area

Large grid-point spacing – say 90 km

30 km

10 km
Example – The Pentagon Shield forecast system
Physical process representations
Parameterizations

- Parameterizations approximate the bulk effects of physical processes that are too small, too complex, or too poorly understood to be explicitly represented.
Parameterizations

• In the WRF Model, parameterizations include:
  – Cumulus convection
  – Microphysics of clouds and precipitation
  – Radiation (short-wave and long-wave)
  – Turbulence and diffusion
  – Planetary boundary layer and surface layer
  – Interaction with Earth’s surface

• Some of the biggest future improvements in the WRF Model will be in parameterizations
Verification of model skill

Purposes

• Inter-compare skill of different models
• Determine whether model changes led to improvement
• Assess whether model meets user needs
Why Not Use Standard Validation Metrics? High-resolution Becomes a “Liability”

RMSE = \frac{1}{N} \sum_{i} (F - O)^2 \quad \text{RMSE 1 > RMSE 2 > RMSE 3}

Coarse-res given best score, even though it predicts no feature at all!
Another example

Consider forecasts and observations of some dichotomous field on a grid:

From Davis et al. (2005)

\[
\text{RMSE (a) = RMSE (b) = RMSE (c)}
\]
\[
\text{POD = 0 and FAR = 1 for (a)-(d)}
\]
\[
\text{POD > 0 and FAR < 1 for (e)}
\]
What are the Alternatives?

• Object-based evaluation of weather forecasts.
  – Events (time series)
  – Features (temporal or spatial)
  – Anomalies (time or space)
Coupling atmospheric models with special-application models

- Transport and diffusion models
- Sound-propagation models
- Ocean wave models
- Ocean circulation models
- Parachute-drift models
Ensemble Forecasting: Goals

• To forecast the uncertainty, and most likely outcome – i.e., produce a probabilistic forecast
Example of error growth
Uses of Atmospheric Models

- Daily weather prediction (let models run into the future for 1-10 days)
- Climate prediction (let models run for years): 
  "what-if" experiments, e.g., what will happen if we double the CO$_2$?
  simply let the model run forward
- Research – Study the model solution when you don’t have good observations of real atmosphere
Example of Atmospheric Models Applied in Arid Areas
Operational prediction
Research -
Small-Scale Winds in the Great Basin Desert
The Mountains in the Study Area
Observed Winds at 2:00 PM
Observed Winds at 5:00 AM
What ‘Local Effects’ Might be Responsible for These Winds?

- Lake breezes
- Mountain-valley breezes
- Heating contrasts between the salt flat (playa) and surroundings (salt breeze)
Why Would There be Daytime Heating Contrasts Around the Playa?

• High albedo of the playa – cooler than surroundings
• Substrate and surface is often moist
  - greater evaporation (cooler than dry surroundings)
  - greater downward conduction of heat during the day (cooler during day, warmer at night)
Summary

• Day – air over the playa is cooler than over the surrounding sandy desert
• Night – air over the playa is warmer than over the surrounding sandy desert
Say 900 mb surface

(a)

(b)

PGF

H (920 mb)

L

880 mb

(c)
Research Question

• How much, and where, do the following processes contribute to the spatial variations in the observed winds?
  - the lake breezes from the Great Salt Lake and Utah Lake
  - the playa breeze (or “salt breeze”)
  - mountain-valley circulations (upslope during the day and downslope at night)
We Can Answer This Question Using Experiments With Models

• A model normally uses observed surface conditions – therefore the model solution contains the lake breeze, the salt breeze, the mountain-valley breeze.

• We can isolate the effect of something by removing it from the model and then comparing it with the normal model solution.
For Example, To Determine How the Salt-Flat Influences the Local Winds and Other Weather:

• Run a “control experiment” with the correct surface conditions.
• Run another experiment with the playa removed, and replaced with the same kind of sandy substrate that surrounds it.
• Subtract the two model solutions, and the difference shows exactly how the salt-breeze contributes to the local winds.
The Model Setup
Another Experiment – Remove the Lakes

Lake-No Lake Difference at 7:00 PM

Lake Breeze
Some common NWP models

- U.S. National Centers for Environmental Prediction (NCEP)
  - Global forecasting system
  - Weather Research and Forecast model (WRF)
- NCAR
  - Mesoscale model - version 5 (MM5)
  - Weather Research and Forecast model (WRF)
  - EuLag CFD model
  - (various climate models)
- European Center for Medium Range Weather Forecasting (ECMWF) model
- British Meteorological Office
- U. S. Naval Research Lab. – COAMPS, NOGAPS
- Air Force Weather Agency - WRF