Modeling the dynamics of temperature with a view to weather derivatives

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Motivation

• Weather conditions affect the activities of a large number of firms.

• Weather derivatives have emerged as a new class of derivatives.

• The vast majority of weather derivatives is temperature derivatives.
  - Listed in CME for a number of European & US cities.

• There is a fast growing literature on the pricing of temperature derivatives. Models differ on
  - The specification of the process that governs the dynamics of temperature.
  - The assumptions about the market price of risk of temperature.
Motivation (cont’d)

• What is the process that temperature follows empirically?
  - Time trend + seasonal term + stochastic component.
  - The derivatives pricing literature has examined the above question only in-sample.
  - An out-of-sample setting should be used.

• Addressing the above question is important for
  - The pricing of temperature derivatives.
  - Any firm or country that is exposed to weather risk.
  - Stock investors (Cao & Wei, 2005).
This Paper

• We investigate what is the best temperature model in terms of its out-of-sample forecasting performance.

• We make three contributions to the literature

1. Employ an extensive data set of temperature values from U.S. & European cities over a long period (1973-2007).

2. Conduct a horse race among a number of models to forecast temperature
   - A latent -factors model is developed.

1. Examine whether the CME temperature indices can be forecasted.

• Related studies:
Outline

• Motivation – This Paper.

• The Dataset.

• The Models: Description.

• Out-of-sample performance.

• Forecasting temperature indices.

• Conclusions & Suggestions for future research.
The dataset

• Daily minimum and maximum temperature data are recorded from January 1, 1973 to December 31, 2007.

☑ 10 U.S & 5 European cities. Earth Sat is the data source; same data used in the CME.

☑ Daily average temperature is used.

☑ Gap filling: average temperature one year before & one year after.

☑ February 29th is discarded in leap years to maintain 365 days per year.

• Point forecasting.

☑ 01/01/1973 – 31/12/2003: In-sample estimation.

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Temperature: Europe & U.S.

London

New York
Models: The naive ones

- Let $T_{t,k}$ denote the average temperature of the $k$th city observed at time $t$.

- Random walk (RW, persistence forecast):

  \[ T_{t,k} = T_{t-1,k} + \epsilon_{t,k} \]

- AR(1):

  \[ T_{t,k} = \epsilon_{t,k} + \rho T_{t-1,k} - \epsilon_{t,k} \]
Models: The (modified) Benth & Saltyte-Benth (MBSB, 2007)

\[ T_{t,k} = c_{0,k} + c_{1,k}t + \sum_{i=1}^{3} \sigma_{c,k} \cos \frac{2\pi i}{365} d(t) + \sigma_{s,k} \sin \frac{\pi i}{365} + u_{t,k} \]

\[ \hat{\mu}_{t,k} = \rho_{t-1,k} \hat{\mu}_{t-1,k} + \xi_{t,k}, \quad \xi_{t,k} = \sigma_{t,k} \varepsilon_{t,k}, \quad \varepsilon_{t,k} \overset{i.i.d}{=} N(0,1) \]

• The model
  - Delivers closed-form solutions for the CME temperature derivatives.
  - Nests previously developed models.
Models: Campbell-Diebold (CD, 2005)

\[
T_{t,k} = c_{0,k} + c_{1,k} t + S_{t,k} + \sum_{l=1}^{L} \rho_{t+l,k} T_{t+l,k} + u_{t,k}, \\
u_{t,k} = \sigma_{t,k} \varepsilon_{t,k}, \quad \varepsilon_{t,k} : (0,1)
\]

\[
S_{t,k} = \sum_{i=1}^{P} \sigma_{c,i,k} \cos 2\pi i \frac{d(t)}{365} + \sigma_{s,i,k} \sin \pi i \frac{d(t)}{365}
\]

\[
\sigma_{t,k}^2 = C_k + \sum_{q=1}^{Q} \gamma_{c,q,k} \cos \pi q \frac{d(t)}{365} + \gamma_{s,q,k} \sin \pi q \frac{d(t)}{365} + \alpha_{1,k} \varepsilon_{t+1,k}^2 + \beta_{1,k} \sigma_{t+1,k}^2
\]

- Choice of lags based on the AIC criteria.

- Maximum Order for $L$, $P$ & $Q$ is 25, 3, and 3, respectively.
Models: The Principal Components (PC) model

- We apply PCA to each one of the two groups (US & Europe), separately.

  - PCA is applied to $\hat{u}_{t,k}$

  $$T_{t,k} = c_{0,k} + c_{1,k}t + \sum_{i=1}^{3} \sigma_{c,i,k} \cos \left( \frac{d(t)}{365} \right) + \sigma_{s,i,k} \sin \left( \frac{d(t)}{365} \right) + u_{t,k}$$

- Six and four PCs are retained for the U.S. & European group, respectively.

  - $\hat{u}_{t,us,k} = r_{0,us} + \sum_{j=1}^{2} r_{1,j,us,k} PC_{t-j,us} \pm + \sum_{j=1}^{4} r_{6,j,us} PC_{t-j,us} + \epsilon_{t,us,k}$

  - $\hat{u}_{t.eu,k} = r_{0.eu,k} + \sum_{j=1}^{2} r_{1,j.eu,k} PC_{t-j.eu} \pm + \sum_{j=1}^{4} r_{4,j.eu,k} PC_{t-j.eu} + \epsilon_{t.eu,k}$
Models: Equal Weighted Forecast (EWF)

• Construct equally weighted forecasts generated by averaging the forecasts of the MBSB, CD & PCA models.

\[ \hat{T}_{t|t-1,k}^{E W} = \frac{1}{3} \sum_{i=1}^{3} \hat{T}_{t|t-1,k}^{i} \]
Evaluation Metrics

• Three out-of-sample performance metrics are employed:
  
  - Root Mean Squared Prediction Error (RMSE):
    
    \[
    RMSE_k = \sqrt{\frac{1}{M} \sum_{t=1}^{M} (\hat{T}_{t,k} - T_{t,k})^2}
    \]

  - Mean Absolute Prediction (MAE):
    
    \[
    MAE_k = \frac{1}{M} \sum_{t=1}^{M} |\hat{T}_{t,k} - T_{t,k}|
    \]

  - Mean Correct Prediction (MCP):

    MCP = % of observations for which the forecasted change in the variable of interest has the same sign as the realized change.
Point forecasts: Statistical evaluation

- The random walk model is used as a benchmark.

- The following test is carried out:
  
  $H_0$: The “model” and the random walk perform equally well
  $H_a$: The “model” outperforms the random walk

- The Modified Diebold-Mariano test statistic (MDM, Harvey et al. (1997)) and a ratio test are used.
### One-Day Ahead forecasts: U.S.

#### Panel A: RW

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#### Panel B: AR(1)

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#### Panel C: MBSB

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#### Panel E: PCA

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#### Panel F: EWF

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### One-Day Ahead forecasts: Europe

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#### Panel B: AR(1)

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#### Panel D: CD

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#### Panel E: PCA

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#### Panel F: EWF

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One-day ahead forecast: Best model per city

- Which model performs best among the MBSB, CD, PCA & EWF?

  - Change the benchmark sequentially.
  - 12 MDM test statistics are calculated for every city.

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Robustness tests: Forecasting in longer horizons
5-days, US

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Robustness tests: Forecasting in longer horizons
5-days, Europe

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Temperature Indices

• Temperature derivatives are written on temperature indices.

• Let the heating degree days ($HDD_t$) and cooling degrees days ($CDD_t$) variables defined as

\[
HDD_t = \max[\alpha - T, 0], \quad CDD_t = \max[T - \beta, 0]
\]

• CME temperature indices:

\[
CumHDD = \sum_{t=1}^{n} HDD_t, \quad CumCDD = \sum_{t=1}^{n} CDD_t, \quad CAT = \sum_{t=1}^{n} T_t
\]
Forecasting temperature indices

• Study monthly CumHDDs & CumCDDs.
  - The former is calculated for Jan, Feb, Mar, Apr, Oct, Nov, & Dec.
  - The latter for Apr, May, Jun, Jul, Aug, Sep, Oct.
  - We have also applied the analysis to CAT indices for the European cities over the “summer” months.

• A dynamic forecasting approach is followed.
  - Standing at time $t$, forecasts are generated recursively for the remaining days of the month using the obtained at each step forecasts.
  - The HDD and CDDs are calculated and then the cumulative indices are computed.
### Forecasting temperature indices: Results

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#### Panel B: Europe

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<th>MAE</th>
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<tr>
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Conclusions

• We have examined the forecasting performance of a number of temperature models in an out-of-sample setting.

• The robustness of the results has been investigated by
  - Employing various forecasting horizons.
  - Using an extensive dataset.
  - Forecasting a number of temperature indices.
Conclusions (cont’d)

• We found that
  - All models outperform the random walk model.
  - A PC model performs best for most of the U.S. cities.
  - A EWF model performs best for most of the European cities.
  - It is harder to forecast the CumHDD index than the CumCDD index.
  - The European indices can be forecasted easier than the U.S. ones.
Implications- Suggestions for future research

• Our results have at least four implications:

1. PC models may have something to tell us.

2. More than one random shocks should be used to price a derivative written on U.S. temperature.

3. A Bayesian approach could be used to price a derivative written on European temperature.

4. Trading strategies employing derivatives written on European temperature may be more profitable than the ones written on US temperature.

5. CumCDD indices may also yield greater profits.

• Future research should assess

- PC forecasts vs. meteo forecasts.
- The economic significance of the obtained forecasts.
- The performance of the alternative processes in terms of pricing derivatives.
Thank you for your attention and time!

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